DISSERTATION

POST-FIRE RUNOFF AND EROSION AT THE PLOT AND HILLSLOPE SCALE, COLORADO FRONT RANGE

Submitted by

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In partial fulfillment of the requirements

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WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY **JUAN DE DIOS BENAVIDES SOLORIO** ENTITLED “**POST-FIRE RUNOFF AND EROSION AT THE PLOT AND HILLSLOPE SCALE, COLORADO FRONT RANGE**” BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

POST-FIRE RUNOFF AND EROSION AT THE PLOT AND HILLSLOPE SCALE, COLORADO FRONT RANGE

Forest ecosystems in the Colorado Front Range are at very high risk for large increases in runoff and erosion after wildfires. This research was proposed because there is very limited data on post-fire runoff and erosion rates and the factors that control these rates. This research focussed on two different scales: 1) runoff and erosion rates from small plots subjected to high-intensity artificial rainfall, and 2) sediment production rates at the hillslope scale from prescribed and wild fires of different ages. The results will help predict the effect of future fires and design more effective rehabilitation treatments.

On the small plots 70-85 mm of mean rainfall was applied in 60 minutes, and runoff/rainfall ratios generally exceeded 45%. The high rainfall rate meant that runoff/rainfall ratios were only slightly higher from plots burned at high severity than from low severity/unburned plots. Mean runoff/rainfall ratios in recently-burned, high-severity plots decreased by 15-30% from the first to second years after burning, but were still high relative to runoff rates from simulations on the 1994 Hourglass wildfire. Post-fire soil water repellency was the main control on runoff/rainfall ratios.

Mean sediment yields from rainfall simulations on high severity sites in the Bobcat wildfire were 1,280 g m^{-2} in 2000 and 1,230 g m^{-2} in 2001. Sediment yields from high severity sites in the Lower Flowers prescribed fire decreased from 850 g m^{-2} in 2000 to 350 g m^{-2} in 2001. High severity plots yielded 16-33 times more sediment than low severity and unburned plots. Simulations on high severity plots in the 1994 Hourglass wildfire yielded only slightly more sediment than unburned plots, indicating that recovery was nearly complete after 6 years. Univariate and multivariate analysis showed that percent bare soil was the dominant control on sediment yields, although percent silt and the runoff/rainfall ratio were significant factors for high severity sites.

At the hillslope scale sediment production rates exceeded 10 Mg ha^{-1} yr^{-1} from sites burned at high severity in a recent wildfire, and only 0.1-4 Mg ha^{-1} yr^{-1} from high severity sites in recent prescribed fires. High severity sites in the Bobcat wildfire produced 75 times more sediment than moderate severity sites. Summer rainstorms generated at least 73% of the sediment at all sites. Sediment production rates from swales or small drainages were 2-3 times higher than planar hillslopes. Four to six years are required for sediment production rates to approach the values from sites burned at low severity. Multivariate modeling showed that sediment production rates were a function of fire severity, percent bare soil, rainfall erosivity, soil water repellency, and soil particle size. The best model had a R^2 of 0.77, and this declined to 0.62 for a two-parameter model using percent bare soil and rainfall erosivity. Model validation was satisfactory, but more data are needed for complete testing.

The runoff and erosion rates measured in this study are high relative to the results from most other studies in burned areas. Areas burned at high severity are at particularly high risk for at least the first 2-3 years after burning. To be effective post-fire rehabilitation treatments must immediately provide ground cover and maintain this for at least two years. Rehabilitation efforts also should focus on reducing flow velocities in swales and small drainages to reduce channel erosion.

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DEDICATION

To my mother Rosario and my father Gumersindo† for giving me the life,

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1. INTRODUCTION

Under undisturbed conditions forests function as regulators of the hydrologic cycle. Forests intercept precipitation both in the canopy and forest floor, facilitate high infiltration rates and groundwater recharge, and produce minimal overland flow (Hewlett, 1982). The forest floor also protects the soil from erosion as the litter dissipates raindrop energy and increases the resistance to overland flow (DeBano *et al.*, 1998). However, large forest fires can dramatically alter the hydrologic cycle by burning the vegetation, litter and duff layers (Beschta, 1990; Tiedemann *et al.*, 1979). Depending on the magnitude and severity of the fire and the resilience of the ecosystem, the effects of fires may be of short (Prosser and Williams, 1998) or long duration (Helvey, 1980). The changes in runoff and erosion can adversely affect water quality, aquatic ecosystems, and other downstream resources.

Recent studies in the Colorado Front Range indicate an increase in forest densities since European settlement due to fire suppression, reductions in logging and grazing, or a combination of these (Kaufmann *et al.*, 2000a; Kaufmann *et al.*, 2000b; Kaufmann *et al.*, 2001; Huckaby *et al.*, 2001). These changes mean that current and future wildfires may increase in size, intensity, and severity (Dodge, 1972; Kaufmann *et al.*, 2000a; Kaufmann *et al.*, 2001). In addition to this possible increase in the magnitude of forest fires, the risk of post-fire flooding and erosion in the Colorado Front Range is further exacerbated by soil characteristics such as coarse texture and poor aggregation, steep slopes, and the high erosivity of summer convective storms.

In the Colorado Front Range ponderosa pine forests occupy 1.6 million ha dominate the lower montane zone (Gary, 1975). The increased forest density and relatively dry conditions mean that these forests have a particularly high risk for catastrophic wildfires. The 1996 Buffalo Creek fire catalyzed the study of post-fire runoff and erosion in the Colorado Front Range, as this fire caused catastrophic flooding and erosion, and also showed the lack of data and understanding with respect to the magnitude and causes of the observed increases in runoff and erosion (Agnew *et al.*, 1997).

Given the past and potential damage to water resources and the social impact of large wildfires, more work needs to be done to understand post-fire risks and identify effective rehabilitation treatments. It is both costly and logistically difficult to obtain replicated data at the watershed scale. The most efficient means to study post-fire effects on runoff and erosion is at the plot and hillslope scales, as more control can be exerted on such experiments and the studies can more easily be replicated. However, there has been only scattered work in the Colorado Front Range at the plot or hillslope scale (Striffler and Mogren, 1971; Morris and Moses, 1987; Moody and Martin 2001). Hence this study filled a lack of understanding of the post-fire factors causing runoff and erosion at the plot and hillslope scale.

When high severity fires kill the vegetation and consume the organic material on the forest floor, the most obvious changes are the reduction in interception and infiltration (DeBano *et al.*, 1998). From a hydrologic perspective the most important changes are at the forest floor because these directly affect infiltration rates and the magnitude of overland flow (Beschta, 1990). The factors most directly related to increases in overland flow are fire severity (Campbell *et al.*, 1977), ground cover (Prosser and Williams, 1998), rainfall intensity (Moody and Martin, 2001), the formation of a water repellent layer (Scott, 1993), and slope (Shahlaee *et al.*, 1991). Increased surface erosion is another consequence of overland flow, and this also depends on fire severity (Campbell *et al.*, 1977), rainfall intensity (Robichaud and Waldrop, 1994), time since burning (Morris and Moses, 1987), soil water repellency (Krammes and Osborn, 1969), slope (Robichaud and Brown, 1999), and soil erodibility (Giovannini *et al.*, 2001). The following sections discuss the role of each factor on post-fire runoff and erosion and the gaps in knowledge in the Colorado Front Range.

1.1. FACTORS AFFECTING POST-FIRE RUNOFF AND EROSION

1.1.1. Fire severity

The effects of wild and prescribed fires on forest vegetation and soils are not homogeneous due to many reasons, but probably the most important is the different amount of fuels, which result in different rates of fire spread and heat per unit area. Fire severity has been used to stratify post-fire effects on runoff and erosion (Campbell *et al.*, 1977; DeBano *et al.*, 1998; Inbar *et al.*, 1998). Fire severity is a somewhat subjective classification of the effects of fires on the ground surface. Hydrologically the damage at ground level is more important than damage at the crown level because of the direct influence on runoff and erosion processes.

The three main severity classes are high, moderate, and low, and these are defined according to the consumption of surface organic matter and changes to the surface soil (Wells *et al.*, 1979). High severity sites have a nearly complete loss of ground cover, and these areas are of greatest concern with respect to post-fire runoff and erosion. In areas burned at high-severity runoff increases can range from a few percent to many times higher than unburned or low severity sites (Campbell *et al.*, 1977). Increases in erosion can be several orders of magnitude higher than unburned or low severity sites (Campbell *et al.*, 1977; Morris and Moses, 1987; Robichaud and Waldrop, 1994; Inbar *et al.*, 1998; Pierson *et al.*, 2002).

In this study sites were stratified by fire severity. Fire severity may also affect the rate of recovery of runoff and erosion. For example, moderate and low severity sites might recover more rapidly than high severity sites (DeBano *et al.*, 1998). An earlier study in the Colorado Front Range suggested that fire severity can affect the recovery rate with respect to erosion (Morris and Moses, 1987), but they did not have any data on runoff rates. In this research runoff and erosion rates will be compared between fire severities, and rate of recovery will also be evaluated by comparing fires of different ages as well as making measurements from a single fire over time.

1.1.2. Cover

Fire severity has a direct influence on the loss of cover and hence the amount of bare soil. Cover is important in protecting the soil from rainsplash and offering resistance to surface runoff, which then increases ponding and maximizes infiltration rates. The effectiveness of cover in preventing erosion is proportional to the amount of raindrop energy that is dissipated by the vegetation (Osborn, 1954). After fires it has been observed that runoff (Marcos *et al.*, 2000) and sediment production (Inbar *et al.*, 1998; Robichaud and Brown, 1999) decrease with increasing vegetation cover. Cover values from 60% to 80% are needed for effective protection from sheet erosion (Wright *et al.*, 1976; Wright *et al.*, 1982; Morris and Moses, 1987). For protection against rill erosion, more than 70% cover is needed (Pannkuk *et al.*, 2000). Hence is important to quantify the amount of bare soil and vegetation after a fire and track changes over time.

Cover can be quantitatively assessed and correlated with fire severity. There are few data in the Colorado Front Range that relate the reduction in cover due to fires to increases in runoff and erosion. This study measured percent cover after several wild and prescribed fires and quantified the recovery in percent cover over time for all fire severities. The measured percent cover was related to runoff rates at the plot scale and to erosion rates at both the plot and hillslope scale.

1.1.3. Precipitation

Precipitation in the form of rain and snow is related to increases in runoff and erosion. Snowfall affects the size and extent of the snowpack and hence the rate of snowmelt (DeByle and Packer, 1972; Helvey 1972; Helvey 1980; McNabb and Swanson, 1990). Rainfall is probably the most important cause of post-fire increases in runoff and erosion in the lower montane zone in the Colorado Front Range (Agnew *et al.*, 1997; Moody and Martin 2001). The effect of rainfall is related more to intensity than quantity, as rainfall intensity affects raindrop impact and the associated kinetic energy (Wischmeier and Smith, 1958). Low-intensity storms produce little or no erosion (Striffler and Mogren, 1971), whereas high intensity storms produce high amounts of runoff and erosion (Hendricks and Johnson, 1944; Moody and Martin, 2001). However, even moderate intensity storms on areas burned at high severity areas can produce substantial amounts of sediment at the hillslope scale (Megahan and Molitor, 1975; Prosser and Williams, 1998).

Rainfall intensity is important in part because of the positive relationship with raindrop size (Laws and Parsons, 1943). Raindrops hitting the bare soil detach soil particles and disperse soil aggregates (Wischmeier and Smith, 1958). Higher rain intensities also generate more overland flow when the intensities exceed the infiltration rate. The product of kinetic energy times the maximum intensity in 30 minutes (I_{30}) has been found to be a good predictor for soil erosion (Wischmeier and Smith, 1958), and is widely used as an erosivity factor (e. g., Renard *et al.*, 1997). However, a given rainfall intensity at one burned site may cause much more runoff and erosion than the same intensity on other burned areas. Post-fire runoff and erosion were observed in Australia at I_{30} values higher than 7 mm h^{-1}, with a sharp increase at 13 mm h^{-1}, but there was little additional increase in runoff and erosion at a rain intensity of 30 mm h^{-1} (Prosser and Williams, 1998). In Israel, post-fire runoff and erosion were not observed at I_{30} values less than 10 mm h^{-1}; in this environment the antecedent rainfall was very important (Inbar *et al.*, 1998). In the Colorado Front Range an I_{30} of 5 mm h^{-1} produced runoff, and during the first year after burning an I_{30} of 10 mm h^{-1} was considered the threshold for producing flash floods. Storms with a maximum intensity of 90 mm h^{-1} produced major damage to the channel network (Moody and Martin, 2001).

Because the summer convective storms in the Colorado Front Range have high temporal and spatial variability, rainfall simulators can help provide consistent and reliable data. Rainfall simulators allow direct comparisons between different severities, soils, and site characteristics. Rainfall simulators are an important technique in post-fire runoff and erosion studies because studies can be replicated at carefully selected sites to evaluate the importance of different site conditions.

Until this research there have been only a few studies relating high-intensity rainfalls to post-fire runoff and sediment production in the Colorado Front Range for either wild or prescribed fires. Similarly, there are few studies that have related natural rainfall to sediment production rates. In order to study the response of burned areas to natural rainfalls and snowmelt events, a series of hillslope scale plots were used to evaluate sediment production. To quantify the rainfall characteristics a series of recording rain gauges were installed in the field.

1.1.4. Slope length and slope steepness

Slope length and slope steepness are well recognized as influencing overland flow and erosion (Smith and Wischmeier, 1957; Meyer and Monke, 1965; Kilinc and Richardson, 1973). Slope length affects the amount of runoff, whereas slope steepness controls the energy and velocity of overland flow (Meyer, 1976; Thornes, 1980; Fox and Bryan, 1999; Chaplot and Bissonnais, 2000). Runoff on a slope of 40% has twice the velocity of a 10% slope, but doubling the velocity increases the energy of flow by about 4 times (Farmer and Van Haveren, 1971). Higher velocities generate greater shear force, thereby producing more particle detachment and increasing the transport capacity (Fox and Bryan, 1999; Battany and Grismer, 2000). However, some researchers did not find increases in runoff and erosion with increasing slope steepness and slope length, and they suggest that other factors, such as soil type, soil cracking, and ponding, may be important (Bryan, 1979; Evans, 1980; Mah *et al.*, 1992). Similarly, Inbar *et al.* (1998) did not find a clear relationship between slope and runoff or erosion after a forest fire. Shahlaee *et al.* (1991) measured increased runoff and erosion with increasing slope steepness in small plots, but only for high-intensity rain events. At the hillslope scale, post-fire sediment production rates have been related to slope steepness (Hendricks and Johnson, 1944; Wright *et al.*, 1976; Robichaud and Brown, 1999). The applicability of these relationships to the Colorado Front Range is not known. In this study sediment production was measured on 48 hillslopes, and the measured sediment productions rates were related to hillslope contributing area and steepness.

1.1.5. Soil physical properties

Soil physical characteristics influence runoff and erosion rates. Soil erodibility varies with soil texture and percent organic matter because these affect rainsplash and infiltration rates. In general, soils with lower silt contents are less erodible regardless of whether there is more clay or sand. Soils low in organic matter are more prone to erosion (Young, 1976; Morgan 1996). There is not complete agreement over the effects of fire on individual soil properties, but the most accepted changes are that fires destroy the organic matter that binds particles and soil aggregates (Dyrness and Youngberg, 1957; Mataix-Solera *et al.*, 2002) and increase soil erodibility (Durgin, 1985; Giovannini *et al.*, 2001). A fire may also produce a water repellent layer, particularly in coarser soils, and this may reduce the naturally high infiltration rates in forested areas (DeBano, 1981). Very high temperatures may also fuse clays (Dyrness and Youngberg, 1957),

Soil properties after fires are another key topic to study. Forest soils in the Colorado Front Range are typically coarse-textured and have high infiltration rates, but coarser soils are more susceptible to post-fire soil water repellency (DeBano, 1981). The effect of soil texture on post-fire runoff and erosion rates in the Colorado Front Range is a topic that needs further investigation.

1.1.6. Soil water repellency

Soil water repellency is a concern because this can reduce infiltration. Soil water repellency can be found under natural conditions, but this can be greatly enhanced by forest fires (DeBano, 1981). Recent work has shown that burning in the Colorado Front Range can induce a water repellent layer few centimeters below the soil surface (Huffman *et al.*, 2001). Due to its effect on reducing infiltration, many researchers attribute post-fire increases in overland flow and erosion to the water repellent layer. In particular, post-fire water repellency has been related to lower infiltration rates (Robichaud, 2000; Pierson *et al.*, 2001), increases in overland flow (Burch *et al.*, 1989), increased rainsplash (Terry and Shakesby, 1993), and increased rill erosion (Krammes and Osborn, 1969). However, the cause of increased overland flow and erosion has not been rigorously documented in the Colorado Front Range.

One problem in determining the cause of increased runoff after fires is the high variability of soil water repellency in both space and over time (Megahan and Molitor, 1975; Morris and Moses, 1987; Prosser and Williams 1998). Hence some of the tendencies observed at the plot scale are difficult to confirm at the hillslope or watershed scale (Rice and Osborn, 1970; Megahan and Molitor, 1975; Prosser and Williams, 1998).

Because of the variability in soil water repellency and the uncertainty of its effects on runoff and erosion, this work assessed the strength of soil water repellency over time and its effect on runoff and erosion at two different scales in both wild and prescribed fires. Before Huffmann *et al.* (2001) and this research, little information was available on the strength and persistence of soil water repellency. Until the present study there have been no data to quantitatively relate soil water repellency to measured runoff and erosion rates in the Colorado Front Range.

1.2. MODELING POST-FIRE EROSION

All of the factors discussed above can combine to have an interacting or cumulative effect on post-fire increases in runoff and erosion. However, it is important to quantify the effect of each individual factor as well as their combined effect. One way to evaluate the different factors is through models. Surprisingly little effort has been devoted to modeling erosion after fires, but ongoing work includes the Water Erosion Prediction Project (WEPP), which is largely a physically-based model (Elliot and Robichaud, 1998). The SURFERO model is a conceptual model similar to the Revised Universal Soil Loss Equation (Renard *et al.*, 1997), and its contribution was the inclusion of a post-fire hydrophobicity risk index (HYRISK). The model was applied in Colorado, but the authors noted the lack of post-fire erosion data for validation (MacDonald *et al.*, 2000). An analytical hillslope erosion model (HEM) was proposed for use after the Cerro Grande fire in New Mexico. This model can be applied over complex terrain and accounts for both sediment transport and deposition (Wilson *et al.*, 2001), but again it has not been tested due to a lack of field data. Given the complexity and diversity of erosion rates after fires, a major goal of this research was to develop and test models to predict post-fire erosion rates at the hillslope scale in the Colorado Front Range and possibly similar ecoregions.

1.3. PURPOSE AND OBJECTIVES

This research was proposed because of the lack of current data in the Colorado Front Range on the magnitude of post-fire runoff and erosion rates and their recovery over time. There is a corresponding lack of understanding of the main factors causing the observed changes in runoff and erosion after wild and prescribed fires. This information is urgently needed to predict changes in runoff and erosion rates after fires, and design effective rehabilitation treatments. The research is based on the application of artificial rainfalls to small plots, and the study of erosion from natural rainfall and snowmelt events at the hillslope scale using unbounded plots.

The first paper reports on the results of high-intensity rainfall simulations on small plots. Runoff and sediment yields were measured from 26 simulations on three different fires of different ages. The applied rainfall was high intensity because these storms have the greatest impact on runoff and erosion rates, and are therefore of greatest concern. The specific objectives of this paper were to: (1) compare runoff and erosion rates from rainfall simulations on burned sites in the Colorado Front Range; and (2) relate the dependent variables of runoff and erosion to the independent site variables of burn severity, percent cover, soil water repellency, soil moisture, time since burning, and slope. This paper was published in October 2001.

The second paper focuses on sediment production at the hillslope scale from three wildfires and three prescribed fires of different ages. Sediment production rates were measured for two years along with the site characteristics and rainfall inputs. The specific objectives were to: (1) measure post-fire sediment yields at the hillslope scale from both wildfires and prescribed burns; (2) determine the relative erosion rates from summer convective storms and winter frontal storms; (3) measure the change in sediment yields over time as sites recover; (4) evaluate the relative importance of fire severity, rainfall rates, soil water repellency, soil texture, percent ground cover, contributing area, slope, and time since burning on sediment production rates; and (5) develop models to predict post-fire erosion rates in the Colorado Front Range.

The third paper presents the results of a second year of rainfall simulations on small plots. By combining these results with the data from the first paper, it was possible to evaluate changes in runoff and erosion rates over time as well as the factors that control the recovery of runoff and erosion rates after burning. Additional simulations were conducted with a fine mesh to suppress rainsplash, with the expectation that this would result in a better understanding of the underlying erosion processes. The specific objectives were to: (1) determine whether there was a significant difference in runoff and sediment yields between the first and second years after burning; (2) assess the dependence of runoff and sediment yields on burn severity, soil water repellency, soil moisture, percent bare soil, soil texture, and slope; (3) determine the relative influence of rainsplash and sheetwash on sediment yields in high severity sites; and (4) compare the particle-size distribution of the eroded material to the soil texture prior to the simulation.

These three papers provide a unique and valuable understanding of post-fire effects on runoff and erosion at both the plot and hillslope scale. This information can be used directly by resource managers, and it also provides a starting point for future post-fire research in the Colorado Front Range.

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2. POST-FIRE RUNOFF AND EROSION FROM SIMULATED RAINFALL ON SMALL PLOTS, COLORADO FRONT RANGE[1]

2.1. ABSTRACT

Wildfires in the Colorado Front Range are of increasing concern because they can trigger dramatic increases in runoff and erosion. A better understanding of the underlying causes of these increases is needed to predict the effects of future wildfires, estimate runoff and erosion risks from prescribed fires, and design effective post-fire rehabilitation treatments. The objective of this project was to determine whether runoff and sediment yields were significantly related to the site variables of burn severity, percent cover, soil water repellency, soil moisture, time since burning, and slope. To eliminate the variability due to natural rainfall events, we applied an artificial storm of approximately 80 mm h^{-1} on 26 1-m^2 plots in the summer and fall of 2000. The plots were distributed among a June 2000 wildfire, a November 1999 prescribed fire, and a July 1994 wildfire.

For 23 of the 26 plots the ratio of runoff to rainfall exceeded 50%. Nearly all sites exhibited strong natural or fire-induced water repellency, so the runoff ratios were only 15-30% larger for high severity sites in the two more recent fires than for the unburned or low severity plots. The two high severity plots in the 1994 wildfire had very low runoff ratios, and this probably was due to the high soil moisture conditions at the time of the

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simulated rainfall and the resulting reduction in the natural water repellency. Sediment yields from the high-severity sites in the two more recent fires were 16-33 times greater than the unburned and low severity plots. The plots burned at high severity in 1994 yielded only slightly more sediment than the unburned plots. Percent bare soil explained 78% of the variability in sediment yields and the sediment yields from the plots in the 1994 wildfire are consistent with the observed recovery in percent ground cover.

2.2. INTRODUCTION

Undisturbed forested lands are notable for their high infiltration rates, lack of overland flow, and low erosion rates (DeBano, 1981; DeBano 2000a; Hewlett, 1982). Since forests typically grow in wetter areas, forest lands are the primary source of high-quality water in many regions, including Colorado (Dissmeyer, 2000).

Fire is a common disturbance in forest lands. High severity wildfires are of particular concern because they can trigger dramatic changes in runoff and erosion processes that adversely affect water resources. Numerous studies have shown that runoff and erosion rates after widlfires can increase by as much as one to three orders of magnitude (e.g., Helvey, 1980; Morris and Moses, 1987; DeBano *et al.*, 1996; DeBano 2000b, Robichaud *et al.*, 2000).

The effects of fire on runoff and erosion are a major concern in the Front Range of Colorado because the increasing forest density poses a greater risk of wildfire, the proximity of fire-prone ponderosa (*Pinus ponderosa*) and lodgepole (*Pinus contorta*) pine forests to urban areas, and the potential for severe post-fire flooding and erosion (Agnew *et al.*, 1997). The 1996 Buffalo Creek fire was particularly noteworthy, in that high-intensity thunderstorms caused peak flows from small basins to increase from less than 2 $m^3 s^{-1}$ to around 60 $m^3 s^{-1}$ (R. Jarrett, USGS, pers. comm., 2000). Rainsplash, sheetwash, rilling, and channel incision generated tremendous amounts of sediment, and the downstream transport of this sediment temporarily dammed the South Platte River and reduced the capacity of the Strontia Springs Reservoir by approximately one-third. The fire-induced changes in runoff and erosion killed two people and repeatedly destroyed a major highway. The high concentrations of ash and sediment in the runoff from the burned areas have caused severe problems for the water treatment plants that serve the city of Denver (Agnew *et al.*, 1997).

The greater forest density in the Colorado Front Range relative to pre-settlement periods (Veblen and Lorenz, 1991; Mast, 1993) means that similar wildfires will almost certainly occur in the future. Efforts to mitigate the post-fire increases in runoff and erosion are well meaning, but there is a lack of process-based understanding to design effective emergency rehabilitation treatments (Robichaud *et al.*, 2000). Prescribed fires are being used to reduce the risk of wildfires, but there are few quantitative data on the effects of wild and prescribed fires on runoff and surface erosion rates in the Colorado Front Range.

The large changes in runoff after wildfires are commonly ascribed to the development of a water repellent layer at or near the soil surface that restricts infiltration and induces overland flow (DeBano *et al.*, 1970; Scott and Van Wyk, 1990; Shahlaee *et al.*, 1991; Prosser and Williams, 1998; Inbar *et al.*, 1998). The strength of the water-repellent layer is generally believed to increase with increasing fire intensity due to the greater soil heating and consumption of the litter and soil organic matter (Tiedeman *et al.*, 1979; DeBano, 2000b). Though many forest soils are naturally water repellent (DeBano, 1981; Barret and Slaymaker, 1989; Burch *et al.*, 1989), the hydrophobic compounds are not sufficiently concentrated to restrict infiltration over entire hillslopes.

The change from subsurface to overland flow after wildfires can also be facilitated by the loss of the protective litter layer and the potential for rainsplash to cause soil sealing (DeBano 2000b). In high-severity wildfires the organic matter in the soil surface can be consumed, and the resultant loss of aggregate stability can reduce the number of large pores and further reduce the infiltration rate.

The loss of the protective litter layer and the changes in the soil surface can lead to very large increases in soil erosion. After a high severity fire the mineral soil surface is exposed to rainsplash erosion (Inbar *et al.*, 1998), and the reduction in infiltration rates can lead to large amounts of sheetwash and rill erosion. In the case of the Colorado Front Range, Delp (1968) observed relatively low erosion rates after a wildfire, and he emphasized the need for more data on soil erosion rates from high-intensity rainstorms. Morris and Moses (1987) found sediment flux rates on hillslopes to increase by as much as three orders of magnitude after wildfires in ponderosa pine. They attributed this increase to the reduced forest canopy and ground cover, as well as the formation of a water-repellent layer near the soil surface. After the Buffalo Creek fire, Agnew *et al.* (1997) noted that the lack of data and understanding made it difficult to assess the potential for catastrophic flooding and erosion. MacDonald *et al.* (2000) developed a spatially-explicit model to predict post-fire erosion in central and western Colorado, but the reliability of this model is limited by the lack of data for calibration and validation.

More generally, DeBano *et al.* (1996) noted the limited amount of data on the effects of fire in ponderosa pine forests on runoff and water quality.

The effect of wild and prescribed fires on downstream water resources will also depend on the rate at which sites return to pre-disturbance conditions (MacDonald, 2000). Most studies have shown that the greatest increases in runoff and erosion occur within the first 1 or 2 years after burning (Helvey, 1980; Robichaud and Waldrop, 1994; Inbar *et al.*, 1998), although this general pattern can also be altered according to the timing of high-intensity rainfall events (Helvey, 1980). Nearly all studies have shown that soil erosion rates return to background (i.e., pre-disturbance) levels within 3 to 9 years after burning (Robichaud *et al.*, 2000). In the Colorado Front range, several studies have shown that soil erosion rates are similar to undisturbed values 3 to 4 years after burning (Morris and Moses, 1987; Martin and Moody, 2001), but there are few data on the post-fire erosion rates immediately after burning.

Another limitation to measuring the changes in runoff and erosion after a wildfire is the temporal and spatial variability in natural precipitation events. In the Colorado Front Range, high intensity summer convective storms generate the largest flows and the highest erosion rates (Morris and Moses, 1987), and these storms also have the greatest spatial variability.

The use of rainfall simulators can largely obviate the problems of measuring rainfall and comparing sites that are subject to different storm events (Meyer, 1988). By applying consistent amounts of rainfall one can directly compare runoff and erosion from plots with different site characteristics, and statistically evaluate the effect of these site characteristics on runoff and sediment yields. Although the extrapolation of rainfall simulations to larger areas and natural rainstorms is difficult, rainfall simulations are the most predictable and cost-effective means to compare runoff and sediment yields between sites (Meyer, 1988).

Given this background, the objectives of this project were to: (1) compare runoff rates and sediment yields from burned plots in the Colorado Front Range; (2) relate the dependent variables of runoff and sediment yield to the independent site variables of burn severity, percent cover, soil water repellency, soil moisture, time since burning, and slope. A rainfall simulator was used to standardize the storm events on each plot. The overall goal was to measure and understand the effects of fires –both prescribed and wild– on runoff and erosion in the ponderosa and lodgepole pine forest in the Colorado Front Range. This information is urgently needed to predict fire-induced changes in runoff and erosion, assign priorities for fuel treatments, and design effective rehabilitation programs.

2.3. METHODS

2.3.1. Study sites

The study sites were located in three different fires in the northern Colorado Front Range (Figure 1). All three fires were in the fire-prone, mid-elevation zones dominated by ponderosa (*P. ponderosa*) and lodgepole pine (*P. contorta*) (Table 1). The soils are generally classified as sandy loams, and the soil type ranges from Typic Argicryolls to Ustic Haplocryalfs (E. Kelly, Colorado State University, pers. comm., 2001).

The Bobcat fire was a wildfire that burned 4,300-ha in June 2000. Most of the burned area was dominated by ponderosa pine, but there were also small stands of lodgepole pine and Douglas fir.

The Lower Flowers fire was a 300-ha prescribed burn that occurred in November 1999 (Table 1). The burned area was dominated by ponderosa pine with small portions of lodgepole pine. Most of the area was burned at moderate to low severity, although there were some patches of high severity.

The Hourglass fire was the third study site, and this was a wildfire that occurred in July 1994 at a slightly higher elevation where lodgepole pine was dominant (Table 1). This fire burned 516-ha, and most of the burned area was classified as high severity (Omi, 1994).

The study plots within each fire were stratified by burn severity because this is a primary control on post-fire runoff and erosion (DeBano *et al.*, 1996). Burn severity was classified according to the criteria developed by Wells *et al.* (1979) and applied by the USDA Forest Service (1995). In high severity sites the entire organic layer is consumed and there is visible alteration of the structure and color of the surface layer of the mineral soil. In moderate severity sites the entire litter and duff layer is either consumed or charred, but the underlying mineral soil is not visibly altered. In low severity sites the litter and duff layers can be scorched or partly burned, but there is no visible effect on the underlying mineral soil.

2.3.2. Rainfall simulations

A total of 26 rainfall simulations were conducted on 1 m^2 plots in densely-forested areas (Tables 1 and 2). The plots were stratified into three burn severity classes (high, moderate, and low severity or unburned). More simulations were conducted on the two more recent fires and areas burned at high severity because these areas are of greatest concern and possibly have the greatest variability (Table 1). More plots were located in the Bobcat fire because it had better road access and a greater availability of sites burned at high and moderate severity. In the much older Hourglass fire, plots were located only in unburned areas and areas that had been burned at high severity, as we could not reliably identify sites that had burned at moderate or low severity.

At each plot we measured the independent variables of percent cover, slope, surface soil moisture, and soil water repellency. Cover was assessed at 81 points on a 10 x 10 cm^2 grid. Local slope was measured with a clinometer. Mean soil moisture at the time of each simulation was determined gravimetrically (Gardner, 1986) from three 0-5 cm soil samples taken around the perimeter of the plot. Water repellency was assessed by measuring the water drop penetration time (WDPT) (DeBano, 1981) in 1 cm depth increments in three pits around the perimeter of each plot. The mean time for at least three drops of water to be absorbed was determined at each depth; the maximum time of observation was 120 seconds. The measurements of WDPT began at the surface and extended to a depth of 5 cm.

Rainfall was applied with a Purdue-type rainfall simulator and an oscillating nozzle that was usually 2.8-3.0 m above the center of the plot (Meyer and Harmon, 1979; Williams *et al.*, 1995) (Figure 2). For each plot a 1-m^2 metal frame was inserted to a depth of approximately 5 cm, and a metal collection trench was installed at the lower end to collect the runoff. The inside edges were sealed with native soil mixed with a small amount of water and bentonite. Plots were shielded during the simulation to minimize wind effects.

Each simulation consisted of a single 60 min application of rainfall at a constant intensity. The plots were not wetted prior to the simulation because the storm events of greatest concern are the summer convective storms that typically occur when the soil surface is dry. The mean intensity of the applied rainfall was 79 mm h^{-1}, although the range was from 66 to 94 mm h^{-1} (Table 2). The mean rainfall rate of approximately 80 mm h^{-1} was selected because this is comparable to the maximum 1-hour intensities that have been observed in the Front Range. The rate and distribution of rainfall in each simulation was initially assessed from seven rain gauges placed in and around each plot. For most of the simulations a more accurate rainfall rate was determined by covering the plot with a plastic sheet after runoff had ceased, and then measuring the runoff rate while the rainfall simulator was run for an additional 10 minutes.

Runoff rates were measured every minute during the simulation by collecting the runoff for 20-30 seconds and transferring it to a graduated cylinder. We also recorded the time when runoff began and when runoff ceased after the end of the simulation. For each simulation we determined the percent change in the runoff rate over the main part of the runoff hydrograph. Every second runoff sample was collected in a 500 or 1000 mL plastic bottle, weighed and filtered through a pre-weighed 5 μm paper filter. The filters and sediment were dried for 24 hours at 105°C, and weighed to determine the mass of sediment in each water sample. This mass was added to the sum of the filtered samples to obtain the total sediment yield for each plot. Each plot was excavated after the simulation to observe the depth and extent of infiltration. The dependent variables derived from these data included the time to runoff, equilibrium runoff rate, runoff/rainfall ratio, duration of runoff after the simulation stopped, percent change in runoff over the main part of the hydrograph, mean sediment concentration, and total sediment yield.

2.3.3. Statistical analysis

Analysis of variance was used to determine whether there were significant differences in the dependent variables between fires and burn severity classes within fires. If there was a significant difference at $p \leq 0.05$, multiple comparisons (LSMeans) were used to determine which means were significantly different (SAS Institute, Inc., 1999). Simple linear regression was used to assess the relationship between each independent variable and the primary dependent variables.

2.4. RESULTS

2.4.1. Plot characteristics

Most of the rainfall simulations were done in July and August 2000 under very dry conditions (Table 2). Surface soil moisture values were less than 2% for all but one of the 16 simulations on the Bobcat fire. Antecedent moisture conditions were more variable in the other two fires because most of these simulations were done later in the year after natural rains or transient snowmelt. Soil moisture values were less than 10% for the four simulations in high and moderate severity sites in the Lower Flowers fire, and between 10 and 20% for the two simulations in unburned areas. In the case of the Hourglass fire, the surface soil moisture values were greater than 20% for the two simulations in high-severity sites, but less than 10% for the two simulations in unburned sites (Table 2).

Percent ground cover was inversely related to burn severity for the study sites in the two recent fires (Bobcat and Lower Flowers) (Table 2). The high severity plots in these two fires had less than 20% ground cover at the time of the simulations except for the first simulation in the Bobcat fire (Plot 1). This simulation was done only three days after the fire had been controlled, and the plot was in a small depression where ash had accumulated. The other simulations in the Bobcat fire were conducted at least a month after the fire, by which time most of the ash had been removed by wind. The moderate severity plots in these two fires generally had at least 80% cover, whereas the low severity and unburned plots had nearly 100% cover (Table 2). In the older Hourglass fire one of the high severity plots had 79% cover, and the other three plots all had 100% ground cover.

The mean slope of all plots was 26%, and the range was from 15 to 45% (Table 2). There was a significant tendency for percent bare soil to increase with percent slope (R^2=0.28; p=0.005), and this is probably because fire intensity tends to increase as a fire burns upslope.

Ponderosa pine dominated the overstory for the plots in both the Bobcat and Lower Flowers fires, whereas the plots in the Hourglass fire were in lodgepole pine. This difference in vegetation is not believed to have a significant effect on runoff and erosion, as Huffman *et al.* (2001) found no significant differences in natural or fire-induced soil hydrophobicity between these two vegetation types.

The following section will first present the runoff data from the plots in the Bobcat fire, as this fire had the largest sample size and the most consistent site conditions. Runoff from the other two fires will then be compared to the results from Bobcat fire, and the effect of the independent variables will be analyzed using the pooled data from all fires.

2.4.2. Runoff

The observed runoff hydrographs were surprisingly consistent in terms of their overall shape and equilibrium runoff rates (Figure 3). For the high severity sites in the Bobcat fire, runoff generally began within 4 minutes after the beginning of the simulated rainfall (Table 3), and equilibrium runoff was reached within five minutes (e.g., Figure 3a). There was little change in the runoff rate over the remaining 55 minutes of the simulated rainfall (Table 3). For the seven high-severity plots the mean runoff-to-rainfall ratio was 66% with a standard deviation of 8%. The high severity plot with high ash cover had a runoff ratio of 79%, and this value is substantially higher than any of the other plots (Table 3).

The five moderate severity plots in the Bobcat fire produced less runoff than the high severity plots (Figure 4), and the hydrographs from moderate severity plots also had significantly longer rising and recession limbs (Figure 3a and 3b; Table 3). When compared with the high-severity plots, the mean runoff ratio was 58% versus 66%, the mean time to the initiation of runoff was 4.2 minutes versus 2.4 minutes, and the duration of runoff after the end of the simulated rainfall was 8.8 minutes versus 3.5 minutes (Table 3). All of these differences were significant at $p<0.05$.

The four simulations in the Bobcat fire on low severity and unburned sites yielded hydrographs that were not significantly different from the plots burned at moderate severity (Table 3; Figures 3b and 3c). The main difference was that the rate of runoff in some of the low severity and unburned sites tended to increase slowly over the course of the simulation (Figure 3c), but the percent change in the rate of runoff did not vary significantly with burn severity.

The runoff hydrographs from the two high severity plots in the Lower Flowers fire were very similar to the hydrographs from the high severity plots in the Bobcat fire (Table 3; Figures 3a and 3d). At both sites there was a very rapid response to rainfall and relatively constant runoff ratio over the course of the simulation. The recession limbs at Lower Flowers were slightly longer and the runoff ratios slightly less than for the high severity sites in the Bobcat fire, but only the duration of the falling limb was significantly different ($p=0.002$).

The two simulations in Lower Flowers on moderate-severity sites yielded very different results. Plot 6 had a runoff ratio of 63% and a correspondingly rapid hydrograph rise and fall, whereas the other moderate-severity plot (Plot 3) yielded the lowest runoff ratio (32%) and the longest recession limb (12.8 minutes) of all 26 simulations (Table 3; Figure 3e). The low runoff from plot 3 was surprising, since it had 66% ground cover compared with 91% for plot 6, and the surface soil moisture was only slightly higher than plot 6 (9.0% versus 5.4%). Excavation of plot 3 after the simulated rainfall showed that infiltration was occurring over about 90% of the plot. Although the moderate severity plots in Lower Flowers did have lower runoff ratios, longer times to runoff, and longer recession limbs than the high severity plots, the small sample size and high variability meant that none of these differences were statistically significant at $p<0.05$.

The hydrographs from the two unburned plots in Lower Flowers were comparable to the two high severity plots (Table 3; Figures 3d and 3f). For both sets of plots the mean runoff ratio was 61%. The time to runoff and duration of the recession limb for the unburned plots were slightly longer than for the high-severity plots, but none of the runoff characteristics from the unburned plots were significantly different from either the high severity or moderate severity plots.

The two simulations on high severity plots in the 6-year old Hourglass fire yielded a mean runoff ratio of only 36% and a mean falling limb duration of 4.7 minutes (Table 3). In contrast, the two simulations in unburned areas yielded mean runoff ratios of 59% and a mean falling limb duration of 10 minutes. The low runoff ratios from the high severity sites are not surprising since the percent ground cover on these two plots were 79% and 100% (Table 2). As discussed later, the low runoff ratios for the high severity plots may result from the high antecedent soil moisture.

There were no significant differences in the runoff ratios between the Bobcat and Lower Flowers fires when the data were stratified by burn severity (Figure 4). There were also no significant differences in the hydrographs between the three fires for the unburned plots and the low severity plots. The high severity plots in the two more recent fires did have a significantly higher runoff ratio than the high severity plots in the Hourglass fire (Figure 4).

2.4.3. Effect of the site variables on runoff

There were relatively few differences in water repellency with burn severity for either the Bobcat or the Lower Flowers fires (Figures 5a and 5b). The soils were generally most water repellent at 1-2 cm below the surface, and the water repellency declined relatively rapidly below about 3 cm. These results are consistent with a much more detailed study of soil hydrophobicity in the same areas (Huffman *et al.*, 2001).

In the older Hourglass fire, the sites burned at high severity showed no evidence of water repellency, whereas there was a moderate to weak water repellency at all depths in the unburned sites (Figure 5c). These results are confounded by the fact that water repellency in the high severity sites was assessed later in the fall after a series of storms had increased the ambient soil moisture to 20% or more (Table 2). Other studies (e.g., Doerr and Thomas, 2000; Huffman *et al.*, 2001) have shown that soils lose their water repellency at these higher soil moisture values.

The runoff ratio for all sites increased with increasing water repellency, as indicated by the WDPT at 2 cm ($R^2 = 0.38$; $p=0.0008$) (Figure 6a). If only the high severity sites were considered, the R^2 between soil WDPT and runoff ratios increases from 38% to 81%. There was also a highly significant decline in the runoff ratio with increasing soil moisture for the high severity sites ($R^2=0.71$; $p=0.001$), but this relationship is largely due to the two Hourglass plots with high soil moistures and low runoff ratios (Figure 6b). The runoff ratio in the moderate severity plots also declined with increasing soil moisture, but this was significant only at $p=0.09$ (Figure 6b). Soil moisture had little effect on runoff ratios for the unburned plots.

There was a tendency for the WDPT to increase with decreasing soil moisture (R^2=0.26; p=0.009). Runoff ratios were not significantly related to either percent slope or percent bare soil.

2.4.4. Sediment yields

The overall pattern of the sedigraphs was surprisingly consistent, as in nearly all cases there was an initial sharp rise in sediment concentrations shortly after the onset of runoff (Figure 7). Sediment concentrations usually fell sharply after this initial peak, and sediment concentrations were flat or slowly declining over the remaining 50 minutes of simulated rainfall (Figure 7). In the high severity plots peak sediment concentrations ranged up to 90 g L^{-1}, and the sediment concentrations at the end of the simulations were at least 30 g L^{-1}. In the low severity and unburned plots peak sediment concentrations were less than 10 g L^{-1}, and the concentrations over the rest of the simulation were less than 5 g L^{-1} (Figure 7c and 7f).

The mean sediment yield for the high severity plots in the Bobcat fire was 1,280 g, or nearly seven times the mean sediment yield of 179 g for the plots burned at moderate severity (Table 4; Figure 8), and this difference was highly significant (p<0.0001). The mean sediment yield for the low severity and unburned plots was only 80 g, or half the measured value from the moderate severity plots, and this difference was statistically different at p=0.03. The observed differences in sediment yields were slightly greater than the differences in sediment concentrations because the high severity plots had an equilibrium runoff rate that averaged 27% more than the moderate severity plots (Table 3). The high severity plot in the Bobcat fire that had the highest runoff ratio and a high ash cover (Bobcat 1) yielded 41% less sediment than the mean from the other six high severity plots and this suggests that sediment yields are not a simple function of runoff rate. The first three simulations listed in Table 4 have substantially lower sediment concentrations because more of the eroded sediment was deposited in the runoff trough.

The overall pattern of sediment yields from the plots in the Lower Flowers fire were very similar to the Bobcat fire (Table 4; Figure 8). The mean sediment yield in the two high severity sites was 850 g and the mean sediment yield for the plots burned at moderate severity was 111 g. The two unburned plots yielded only 26 g of sediment, or 3% of the mean sediment yields from the high-severity plots. As in the case of the Bobcat fire, the difference in sediment yields between the high and moderate severity plots was also significant (p=0.03), but the difference in sediment yields between the moderate severity and unburned plots was not significant.

Sediment yields from all four simulations in the Hourglass fire were generally similar to the sediment yields from the low-severity and unburned plots in the Bobcat and Lower Flowers fires (Table 4; Figure 8). The average sediment yield for the two plots burned at high severity was 52 g, but the plot with 79% ground cover and a higher runoff ratio produced almost seven times as much sediment as the plot with 100% ground cover and a lower runoff ratio. The two unburned plots in the Hourglass fire produced only 21 and 23 g of sediment. Although the mean sediment yield from the high severity plots in the Hourglass fire was twice the mean sediment yield from the unburned plots, this difference was not significant owing to the small sample size and variability in sediment yields from the high severity plots.

The comparisons of sediment yields between fires showed no statistical differences in sediment yields between the Bobcat and Lower Flowers fires when stratified by burn severity (Figure 8). However, sediment yields from the high severity sites in these two fires were significantly different than the high severity sites in the Hourglass fire (Figure 8). There were no significant differences in sediment yields between the three fires for the low severity and unburned sites.

2.4.5. Effect of site variables on sediment yields

Water repellency was highly correlated with increasing sediment yields for the plots burned at high severity (R^2=0.43; p=0.03) (Figure 9a). The other two burn severity classes did not have a significant relationship between water repellency and sediment yields. Similarly, soil moisture was inversely related to sediment yields for plots burned at high severity (R^2=0.43; p=0.03), whereas there was no significant relationship between soil moisture and sediment yields for either of the other two burn severity classes (Figure 9b). The high correlations for the high severity plots are largely due to the fact that the two high severity plots in the Hourglass fire had very low sediment yields, high antecedent soil moisture values, and no water repellency.

Percent bare soil was strongly correlated with increasing sediment yields when all the data were pooled ((R^2=0.78; $p<0.0001$), and this was due primarily to the fact that the high severity sites had little cover and high sediment yields (Figure 9c). Increasing slope was significantly associated with increasing sediment yields when all the data were pooled, and slope explained 43% of the variation in sediment yields. As noted earlier, the steeper plots were generally burned at high severity. Since slope was not significantly correlated with sediment yield when the data were stratified by burn severity, the relationship between burn severity and slope is largely responsible for the significant increase in sediment yields with increasing slope.

2.5. DISCUSSION

2.5.1. Runoff rates

High fire severities are generally believed to induce stronger hydrophobic layers (DeBano, 1981), so areas burned at high severity should have lower infiltration rates than areas burned at moderate or low severities. Although few studies have evaluated soil water repellency, infiltration, and runoff rates in ponderosa or lodgepole pine forests after burning, infiltration rates were reduced by 62% in ponderosa pine sites in Arizona that had burned at high severity (Campbell *et al.*, 1977). Zwolinski (1971) found that ponderosa pine sites burned at high and low severity had much lower infiltration than unburned sites in the first summer after burning.

In contrast, our results showed only relatively small differences in the runoff/rainfall ratio after stratifying by burn severity. The mean runoff ratios for the high severity plots in the Bobcat fire were only about 13% greater than the mean runoff ratio for the plots burned at moderate severity, and 20% greater than the mean runoff ratio for the unburned plots and plots burned at low severity (Figure 4). The differences in runoff with burn severity were less consistent for the other two fires.

One possible reason for the small differences in runoff rates with burn severity is the relatively high intensity of the simulated rainfall. The mean rainfall intensity was 79 mm h^{-1}, and in 23 of the 26 plots runoff was more than 50% of the applied rainfall. Even in the unburned plots the mean runoff ratio was 58%. If evaporation losses are assumed to be negligible, the hydrographs from the unburned plots indicate that the equilibrium infiltration rate under undisturbed conditions is only around 20-35 mm h^{-1}. If the unburned plots have a runoff ratio of 50% when they are subjected to a high intensity simulated rain, it is not possible to see a dramatic increase in runoff ratios from the burned plots.

The small differences in runoff observed in our study are in contrast to the results of other rainfall simulator studies in burned areas. Simanton *et al.* (1990) used rainfall rates of 65 mm h^{-1} and collected four times as much runoff from sagebrush sites burned at high severity as compared to unburned sites or sites burned at low severity. Robichaud and Waldrop (1994) applied 100 mm h^{-1} to forested sites in the southern U.S. and generated ten times as much runoff from high severity sites as compared to sites burned at low severity. It seems that the small differences in runoff with burn severity in our study are due primarily to the high runoff rates from our unburned or low severity sites relative to other researchers (e.g., Shahlaee *et al.*, 1991).

Both our field observations and the water drop penetration data suggest that water repellency, both natural and fire-induced, may be one cause of the high runoff rates. Figures 5a and 5b indicate that the soils were water repellent at 1-3 cm below the surface in all sites in the Bobcat and Lower Flowers fires, regardless of burn severity. Robichaud and Hungerford (2000) also found that forest soils were water repellent under dry conditions in unburned areas as well as after burning. In southeastern Australia the runoff increased by 5-15% under dry conditions in eucalyptus forest due to natural soil water repellency (Burch *et al.*, 1989), and Pierson *et al.* (2001) found that unburned intercanopy areas in shrublands generated more runoff than intercanopy areas that had been burned.

In the case of the Hourglass fire, the unburned sites had weak water repellency to a depth of at least 5 cm, whereas there was no water repellency in the sites burned at high severity (Figure 5c). The lack of any water repellency in the high severity sites in the Hourglass fire can be attributed to the fact that the soil moisture content at these sites was more than 20% (Table 2). Other studies have shown that natural and fire-induced water repellency is not present at such high soil moisture levels, making the soils much more wettable than under dry conditions (Shahlaee *et al.*, 1991; Doerr and Thomas, 2000; Huffman *et al.*, 2001). The high soil moisture content and corresponding lack of water repellency is probably why the two high severity sites in the Hourglass fire had a mean runoff ratio of only 36%. Our excavation of the simulations confirmed that the wetting front had penetrated several centimeters in approximately 90% of the plot area.

The shape of the hydrographs observed in our study also suggested a relatively strong water repellency layer under dry conditions in both the burned and unburned plots. If the soils are not water repellent the infiltration rate should decrease and the runoff rate should increase due to the progressively smaller role of the capillary forces (Hillel, 1998). On the other hand, an increase in infiltration and decrease in runoff during the simulation would suggest a progressive wetting and breakdown of a water-repellent layer. Because most of the simulations showed nearly constant runoff after the first 5-10 min, this suggests that the natural or fire induced water repellency remained effective throughout the simulated rainfall event. Our excavation of the plots after each simulation also showed that in nearly all cases the soils were dry immediately below the surface, and in most plots the wetting front had penetrated more than a few centimeters in only a few locations. These observations also showed that most sites had a relatively strong water-repellent layer at or near the surface. Because there was no consistent relationship between percent cover and the runoff ratio, soil sealing does not appear to be an important process, except in the case of the first plot on the Bobcat fire where there was a high ash cover. The implication is that water repellency and antecedent soil moisture are the primary controls on the amount of runoff from our simulated rainfall.

2.5.2. Effect of burn severity and water repellency on sediment yields

The differences in sediment yields with burn severity were much larger than the differences in runoff, and the measured sediment yields were generally more consistent than the runoff ratios when stratified by fire and burn severity (Table 4; Figure 8). Mean sediment yields from the high severity plots in the Bobcat and Lower Flowers fires were respectively 7.1 and 7.7 times greater than the sediment yields from the plots burned at moderate severity. The mean sediment yields from the moderate severity plots in these two fires were 2.2 and 4.3 times greater than the mean sediment yields from the low severity and unburned plots (Table 4). This means that the high severity plots in the Bobcat fire produced 16.0 times as much sediment as the low severity and unburned plots, and the high severity sites in the Lower Flowers fire produced 32.7 times as much sediment as the unburned plots.

The mean sediment yield of 1,280 g m^{-2} from the nine recently-burned, high-severity plots in this study is higher than the values reported in other studies. In the southeastern U.S. simulated rainfall rates of 101.6 mm h^{-1} produced 60 g m^{-2} from small plots (Shahlaee *et al.*, 1991), whereas Robichaud and Waldrop (1994) measured sediment yields of 139 g m^{-2} as a result of applying 100 mm h^{-1} of simulated rainfall for 30 minutes on plots burned at high severity. Given the shorter simulation period used by Robichaud and Waldrop, the latter value is actually quite comparable to our measured sediment yields. In sagebrush communities Simanton *et al.* (1990) found that high severity sites produced five times as much sediment as unburned sites. Prosser (1990) and Inbar *et al.* (1998) found erosion rates under natural rainstorms to increase by 2-3 orders of magnitude in high-severity sites relative to unburned conditions.

The large increase in erosion rates with increasing burn severity is most commonly ascribed to the loss of ground cover and the increase in runoff due to soil water repellency (Osborn, 1954; Morris and Moses, 1987; Inbar *et al.*, 1998). In our study percent ground cover accounted for 78% of the observed variability in sediment yields (Figure 9c). Comparable plots that produced less runoff but had less percent cover still produced more sediment (e.g. Lower Flowers plot 3 versus plot 6). Because burn severity had a large and significant effect on sediment yields but only a small effect on runoff ratios, the large differences in sediment yields with burn severity should be attributed primarily to the differences in ground cover rather than the differences in runoff, water repellency, or antecedent soil moisture.

2.5.3. Erosion recovery rates

Our results suggest that the recovery of ground cover is the most important factor in reducing post-fire erosion rates over time, at least for the plot scale addressed in this study. The two high-severity plots in the Hourglass fire had burned 6 years prior to our rainfall simulations, and the percent ground cover on these two plots was 79% and 100%, respectively. The high-severity plot in the Hourglass fire with 79% ground cover produced nearly 4.5 times as much sediment as the plot with 100% ground cover. The mean sediment yield from these two plots was only 6.6% of the sediment yields from the high-severity plots in the more recent Bobcat and Lower Flowers fires; percent ground cover in the latter sites was less than 20% in all but one plot (Table 2). These comparisons indicate that the lower sediment yields from the high severity sites in the Hourglass fire are due to the increase in ground cover over the 6 years since burning. Preliminary results from a study of emergency rehabilitation treatments on the Bobcat fire show that mulched sites produce substantially less sediment than unmulched sites, and this again emphasizes the importance of surface cover on erosion rates.

The observed reduction in erosion rates over time is consistent with most other studies. Erosion rates from high-severity sites in the nearby Buffalo Creek fire declined to background levels within three years (Martin and Moody, 2001). Studies in other areas have also shown that erosion rates decline to background levels within 3 to 9 years after burning (Martin and Moody, 2001). In the case of the Hourglass fire, the mean erosion rate from the two high-severity plots is still twice the erosion rate of the unburned plots (Table 4). Since the simulations on these two plots were conducted under wet antecedent conditions that may have depressed the runoff rate and there was a substantial difference in sediment yields between the two high severity plots, we cannot conclusively state whether erosion rates in the Hourglass fire have completely recovered to background levels.

2.5.4. Representativeness and scale effects

The plot-scale data show a 17- to 33-fold increase in erosion from the recently burned, high severity plots relative to low severity or unburned plots. In absolute terms, the erosion rate from the high severity plots averages 1,280 g m^{-2} or 13 Mg ha^{-1}. This value is greater than the erosion rates observed in most other studies in ponderosa pine in the first year after burning (see review in Robichaud *et al.*, 2000), but much lower than the erosion rates from mixed conifer forests in Arizona (Hendricks and Johnson, 1944) or ponderosa pine and Douglas-fir stands in Idaho (Megahan and Molitor, 1975).

The sediment yields from our plots may be low in absolute terms because the plots used for the rainfall simulation were only 1 m long, so rainsplash and sheetwash were the primary erosion processes (Mutchler *et al.*, 1988). In the high severity plots the plot edges and rain gauges were coated with soil particles to a height of at least 15 cm at the end of the simulations. During the simulations most of the plot was generating runoff and sheetflow and there was little evidence of rill erosion.

Both field studies and process-based models suggest that plots must be at least several meters long before rill erosion becomes an important erosion process (Mutchler *et al.*, 1988). The research underlying the WEPP model suggests that rill erosion is the dominant process at the hillslope scale (Nearing *et al.*, 1989). The absence of rill erosion in our study indicates that our sediment yields per unit area would probably increase if the same rainfall event were to be applied on longer plots. The increasing importance of rill erosion at larger scales might also affect the relative importance of the different site factors; slope, for example, might become a more significant factor than is currently suggested by our plot-scale data.

The representativeness of our erosion rates are also affected by the amount and intensity of the simulated rainfall. The mean simulated rainfall rate of 79 mm h^{-1} is larger than the estimated 100-yr, 1-hour storm of 56 mm h^{-1} (Miller *et al.*, 1973), but comparable to the largest storm events that have been observed in the area. In 1976, for example, 75 mm h^{-1} fell for approximately 3 hours in the same general area as the Bobcat fire, and in 1997 89 mm $h^{-1}$of rain fell in 1 h in Fort Collins. On 16 August 2000 a convective storm over the Bobcat fire dropped 61 mm of rainfall with a peak 1 h intensity of 29 mm. After the Buffalo Creek fire in 1996 a summer convective storm produced 63 mm of rain in two hours, and this triggered severe flooding and erosion (Agnew *et al.*, 1997). These data indicate that our simulated storm event has a high recurrence interval but is not unrealistic for the Colorado Front Range.

The mean rainfall erosivity from our simulations is approximately 1790 MJ mm ha^{-1} h^{-1}, which is approximately five times the estimated average annual rainfall erosivity of 340 MJ mm ha^{-1} h^{-1} (Renard *et al.*, 1997). The rainfall energy from a 10-yr storm event in the area of the Bobcat Fire is nearly 700 MJ mm ha^{-1} h^{-1}, or close to 40% of the rainfall erosivity used in our simulations. These calculated rainfall erosivities assume that our simulated rainfall has a kinetic energy that is similar to natural rainstorms with the same intensity, and this assumption is supported by the work of Meyer and Harmon (1979). Because both the rainfall rate and our calculated rainfall erosivities show that our simulations represent relatively extreme storm events, one might expect correspondingly high erosion rates per unit area. The severely burned plots did generate 16-32 times more sediment than low severity/unburned plots, and the measured erosion rate of 1,280 g m^{-2}

seems to be a high number, but we also need to consider that this erosion rate is based on the absence of rill erosion.

Any effort to extrapolate our results to a larges scale will require an explicit consideration of the shift in erosion processes from rainsplash and sheet erosion at the plot scale to rill erosion at the hillslope scale. The problems of identifying a representative storm event and changing erosion processes with increasing spatial scale mean that the measured erosion rates should be regarded more as more of an index of relative differences than absolute values that can be extrapolated to entire hillslopes or drainage basins. Larger- scale simulations and repeated measurements over time are needed to help determine the extent to which these results can be used to predict the effects of future fires and to design effective post-fire rehabilitation treatments.

2.6. CONCLUSIONS

Runoff rates from simulated rainfall on plots that had been recently burned at high severity were only slightly greater than from plots burned at moderate severity. Runoff rates from moderate severity sites were not significantly different from plots burned at low severity or unburned plots. Both natural and fire-induced water repellency were present 1-3 cm below the surface in the Bobcat and Lower Flowers fires and this, together with the high intensity of the applied rainfall, may explain the small differences in runoff with burn severity. The two high severity plots in the Hourglass fire produced the least runoff, and this is probably due to the wet antecedent conditions and corresponding lack of water repellency. Percent ground cover and slope had little influence on runoff rates.

Burn severity had a very large effect on sediment production in the two recent fires. The high-severity plots in the Bobcat and Lower Flowers fires produced almost eight times as much sediment as the plots burned at moderate severity, and 16-33 times as much sediment as the low severity and unburned plots. The mean sediment yield from the two plots burned at high severity in the Hourglass fire was only twice the sediment yield from the unburned plots, and this suggests that erosion rates decline to near-background levels within six years after burning. Sediment yields were most strongly correlated with the percent bare soil (R^2=0.78), and only weakly correlated with the amount of runoff or percent slope. The mean sediment yield from plots recently burned at high severity was approximately 1.3 kg m^{-2}. This value is considered relatively high as compared to other studies, even with the absence of rill erosion.

Rainsplash and sheetwash were the dominant erosion processes at the scale of our rainfall simulations. The strong relationship between percent ground cover and sediment yields suggests that the decline in erosion rates to pre-burn conditions results primarily from the increase in ground cover. Because runoff and erosion rates depend more on burn severity than the type of fire, fire managers should minimize the area burned at high severity in prescribed fires. Post-fire rehabilitation techniques should focus on maximizing the amount of ground cover. Studies at the hillslope and catchment scale are needed to evaluate the changes in erosion rates and processes with increasing scale.

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Table 1. Characteristics of each fire and number of simulations by fire severity.

Fire	Type	Date burned	Area (ha)	Primary vegetation type	Elevation (m)	Number of simulations			Totals
						High severity	Moderate severity	Low severity or unburned	
Bobcat	Wildfire	June 2000	4,289	Ponderosa pine	1670-2580	7	5	4	16
Lower Flowers	Prescribed fire	Nov. 1999	300	Ponderosa pine	2530-2940	2	2	2	6
Hourglass	Wildfire	July 1994	516	Lodgepole pine	2590-2930	2	0	2	4
					Totals	11	7	8	26

Table 2. Plot characteristics, date of rainfall simulation, and soil moisture at the time of the simulation by fire and fire severity.

Fire	Plot number	Fire Severity	Date of Simulation	Ground cover (%)	Slope (%)	Soil moisture (%)
Bobcat	1	High	June 23	92*	24	1.0
Bobcat	2	High	July 20	11	25	1.0
Bobcat	3	High	July 21	10	22	1.0
Bobcat	4	High	July 24	8	38	1.0
Bobcat	5	High	July 25	17	45	1.0
Bobcat	15	High	Aug. 15	15	25	1.5
Bobcat	16	High	Oct. 31	6	40	9.4
			Mean	**23**	**31**	**2.3**
Bobcat	6	Moderate	Aug. 02	79	32	1.7
Bobcat	7	Moderate	Aug. 03	88	23	1.5
Bobcat	8	Moderate	Aug. 04	95	24	1.6
Bobcat	9	Moderate	Aug. 07	90	21	1.1
Bobcat	14	Moderate	Aug. 14	90	16	1.7
			Mean	**88**	**23**	**1.5**
Bobcat	11	Low	Aug. 09	99	21	1.4
Bobcat	13	Low	Aug. 11	100	22	1.6
Bobcat	10	Unburned	Aug. 08	98	23	1.2
Bobcat	12	Unburned	Aug. 10	100	23	1.8
			Mean	**99**	**22**	**1.5**
Lower Flowers	1	High	Aug. 16	9	26	1.0
Lower Flowers	2	High	Aug. 18	1	30	9.5
			Mean	**5**	**28**	**5.3**
Lower Flowers	3	Moderate	Aug. 26	66	25	9.0
Lower Flowers	6	Moderate	Oct. 19	91	19	5.4
			Mean	**79**	**22**	**7.2**
Lower Flowers	4	Unburned	Oct. 14	100	18	19.1
Lower Flowers	5	Unburned	Oct. 17	100	15	10.1
			Mean	**100**	**17**	**14.6**
Hourglass	1	High	Sep. 02	79	30	20.7
Hourglass	2	High	Sep. 02	100	36	27.4
			Mean	**90**	**33**	**24.1**
Hourglass	3	Unburned	Sep. 19	100	21	3.3
Hourglass	4	Unburned	Oct. 03	100	28	8.3
			Mean	**100**	**25**	**5.8**

* Most of the ground cover was ash

Table 3. Runoff data for each simulation by fire and fire severity.

Fire	Plot number	Fire severity	Application rate (mm h^{-1})	Equilibrium runoff (mm h^{-1})	Runoff/ rainfall ratio (%)	Time to initial runoff (min:s)	Duration of runoff after sprinkling (min:s)
Bobcat	1	High	93	80	79	2:50	2:50
Bobcat	2	High	85	60	66	3:25	3:45
Bobcat	3	High	84	60	70	2:05	2:30
Bobcat	4	High	82	55	64	1:55	3:20
Bobcat	5	High	86	54	61	1:46	3:15
Bobcat	15	High	76	50	54	4:05	4:30
Bobcat	16	High	94	66	68	4:00	4:00
		Mean	**86**	**61**	**66**	**2:26**	**3:27**
Bobcat	6	Moderate	76	44	55	4:35	7:53
Bobcat	7	Moderate	80	55	63	4:55	10:00
Bobcat	8	Moderate	78	52	62	2:57	9:25
Bobcat	9	Moderate	73	39	50	4:03	8:35
Bobcat	14	Moderate	79	52	61	4:30	8:13
		Mean	**77**	**48**	**58**	**4:12**	**8:49**
Bobcat	11	Low	80	51	58	3:00	8:10
Bobcat	13	Low	79	44	50	2:43	9:30
Bobcat	10	Unburned	74	48	58	6:00	13:10
Bobcat	12	Unburned	78	44	52	2:50	8:40
		Mean	**78**	**47**	**55**	**3:38**	**9:52**
Lower Flowers	1	High	78	50	62	2:25	8:26
Lower Flowers	2	High	85	53	60	1:30	5:30
		Mean	**82**	**52**	**61**	**1:57**	**6:58**
Lower Flowers	3	Moderate	80	27	32	3:00	12:48
Lower Flowers	6	Moderate	75	50	63	2:52	8:30
		Mean	**77**	**39**	**48**	**2:56**	**10:39**
Lower Flowers	4	Unburned	77	42	59	3:26	7:30
Lower Flowers	5	Unburned	66	48	62	2:52	7:35
		Mean	**71**	**45**	**61**	**3:09**	**7:32**
Hourglass	1	High	75	34	43	1:40	5:00
Hourglass	2	High	80	24	28	5:15	4:20
		Mean	**77**	**29**	**36**	**3:27**	**4:40**
Hourglass	3	Unburned	63	42	64	3:20	12:03
Hourglass	4	Unburned	80	46	54	2:48	8:00
		Mean	**72**	**44**	**59**	**3:04**	**10:01**

Table 4. Sediment yields and sediment concentrations for each plot by fire and fire severity.

Fire	Plot number	Fire severity	Total sediment (g)	Sediment concentration (g L-1)
Bobcat	1	High	804	11.0
Bobcat	2	High	1100	19.3
Bobcat	3	High	1030	17.6
Bobcat	4	High	1690	32.3
Bobcat	5	High	1570	30.1
Bobcat	15	High	1040	25.5
Bobcat	16	High	1750	28.6
Mean			**1280**	**23.5**
Bobcat	6	Moderate	223	5.4
Bobcat	7	Moderate	279	5.6
Bobcat	8	Moderate	173	3.6
Bobcat	9	Moderate	86	2.4
Bobcat	14	Moderate	133	2.8
Mean			**179**	**4.0**
Bobcat	13	Low	59	1.5
Bobcat	11	Low	122	2.6
Bobcat	12	Unburned	55	1.4
Bobcat	10	Unburned	85	2.0
Mean			**80**	**1.9**
Lower Flowers	1	High	590	12.3
Lower Flowers	2	High	1110	21.9
Mean			**850**	**17.1**
Lower Flowers	3	Moderate	131	5.1
Lower Flowers	6	Moderate	90	1.9
Mean			**111**	**3.5**
Lower Flowers	4	Unburned	37	0.4
Lower Flowers	5	Unburned	14	0.8
Mean			**26**	**0.6**
Hourglass	1	High	86	2.6
Hourglass	2	High	19	0.9
Mean			**52**	**1.7**
Hourglass	3	Unburned	21	0.5
Hourglass	4	Unburned	23	0.5
Mean			**22**	**0.5**

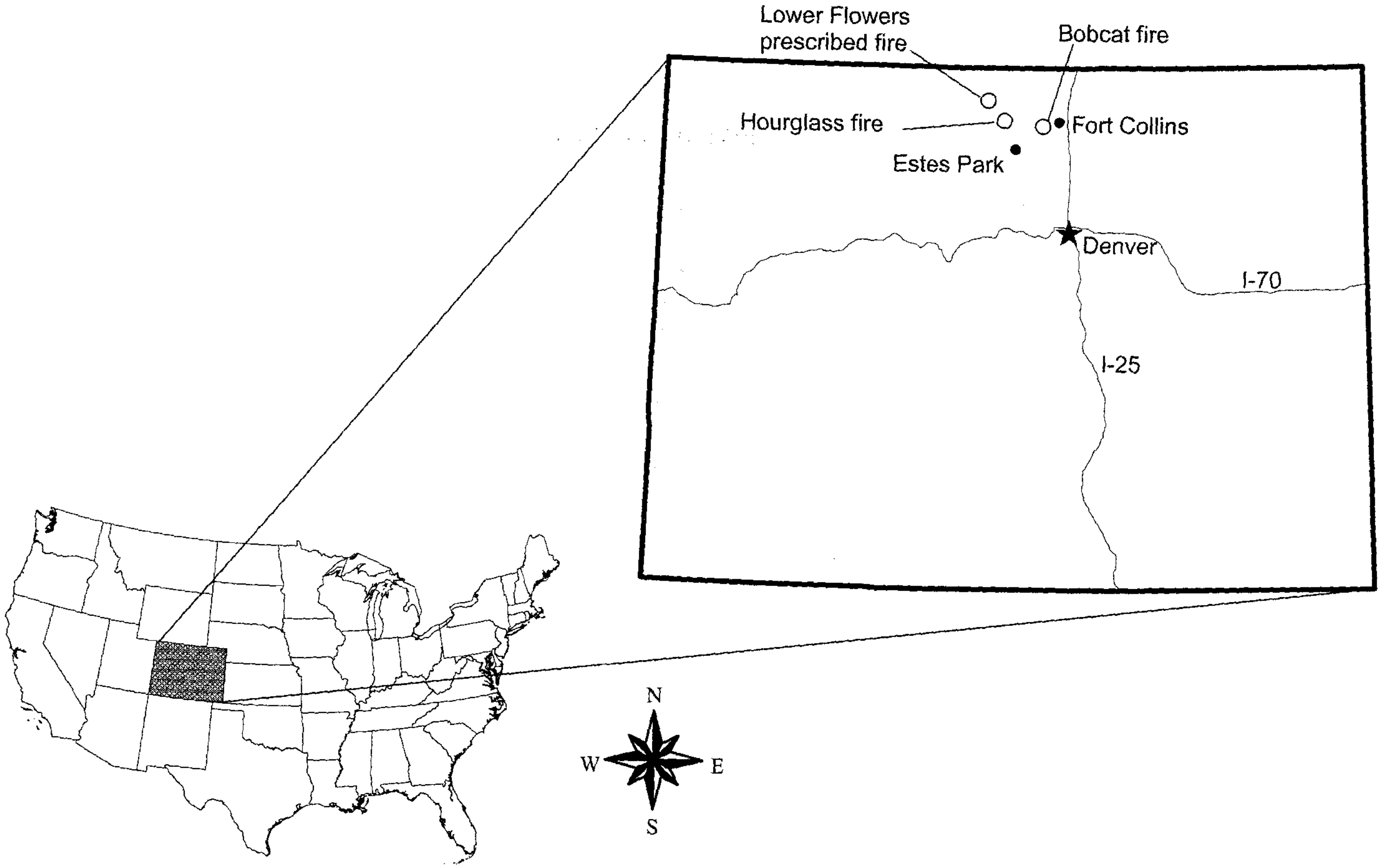

Figure 1. Location of the three fires used in this study.

Figure 2. Photograph of the rainfall simulator and runoff plot on a high-severity site in the Bobcat fire.

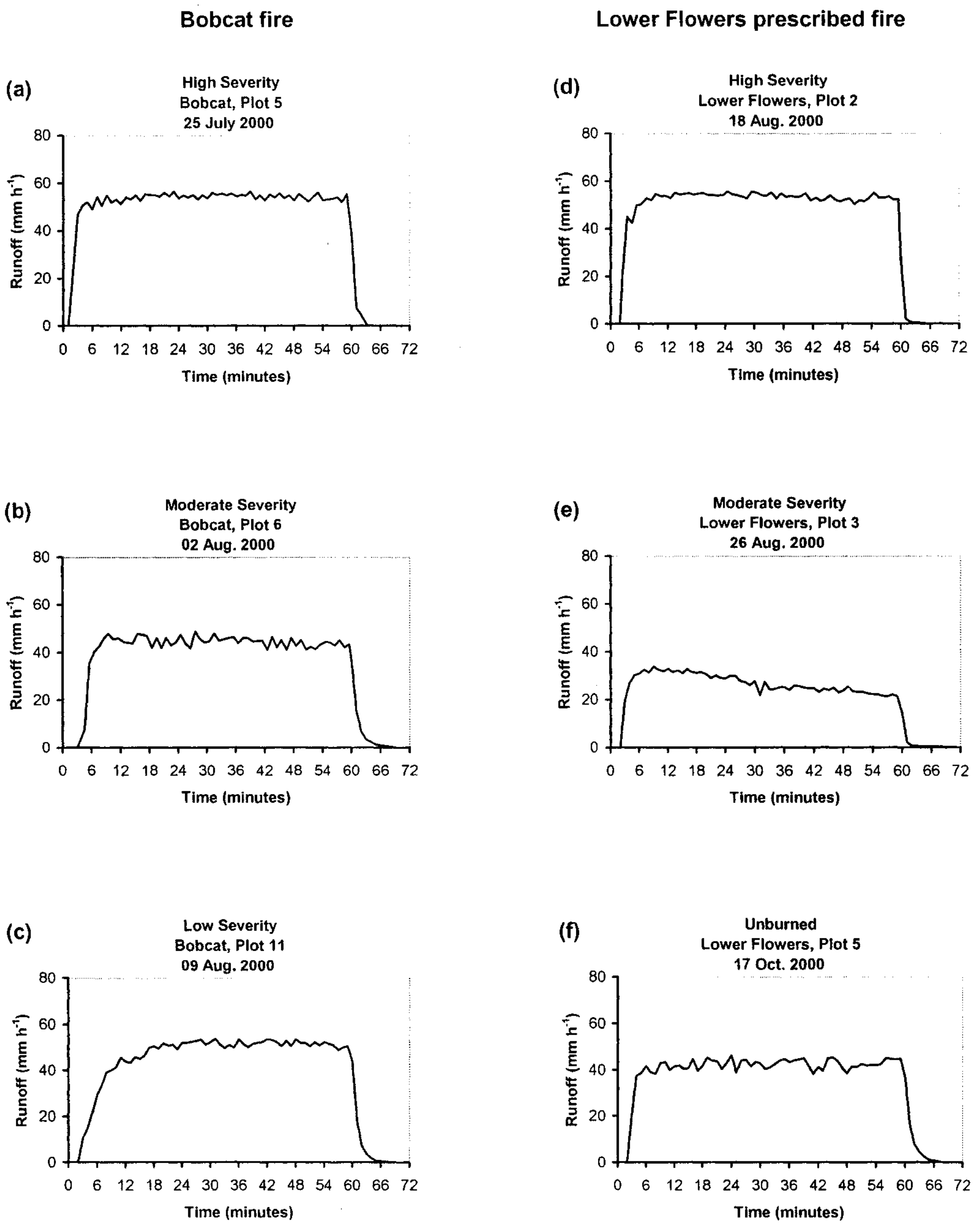

Figure 3. Typical runoff hydrographs from the: Bobcat wildfire (a-c) and Lower Flowers prescribed fire (d-f) for different severities. Rainfall was applied from 0 to 60 min at a rate of 66-94 mm h^{-1}.

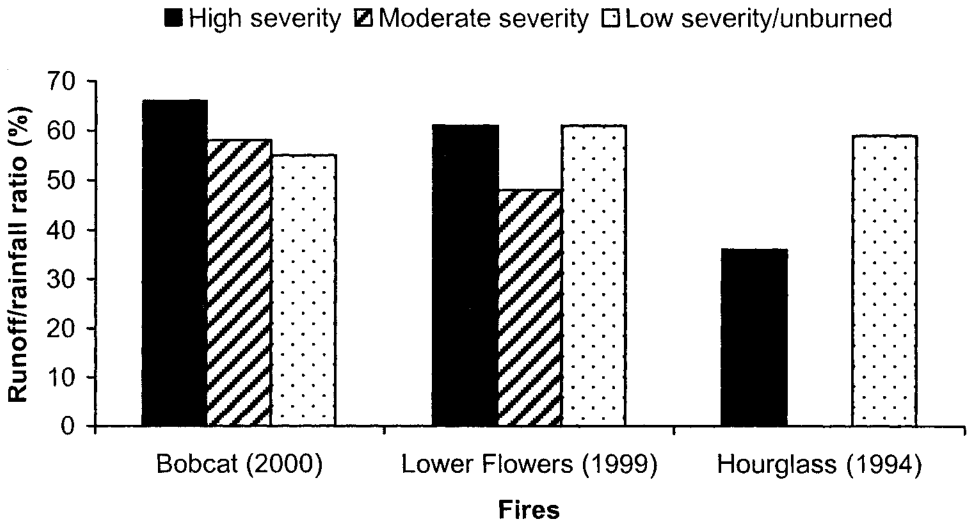

Figure 4. Mean runoff/rainfall ratios by fire and fire severity.

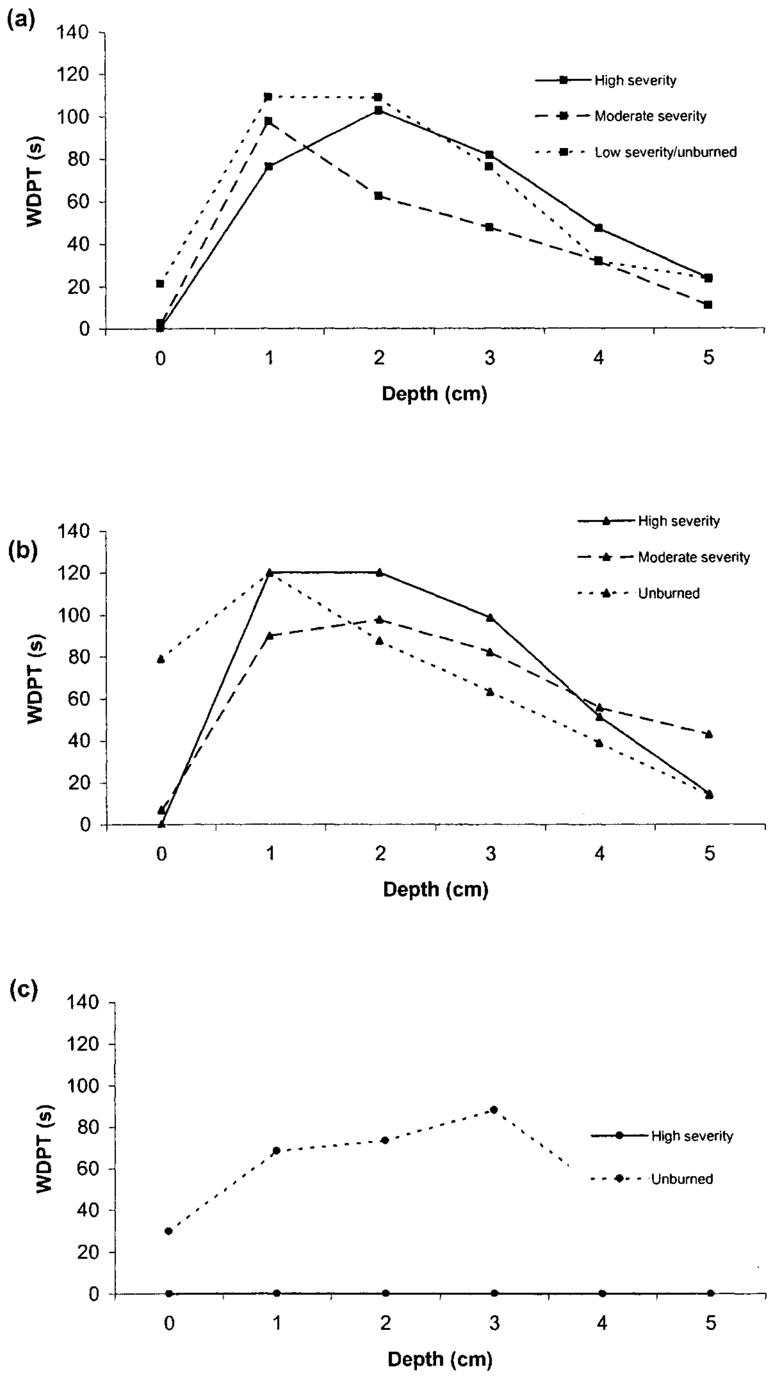

Figure 5. Water repellency from the soil surface to a depth of 5 cm as indicated by the water drop penetration time for the: (a) Bobcat wildfire (b) Lower Flowers prescribed fire, and (c) Hourglass wildfire. Zero depth represents the surface of the soil or litter if present. The persistence of several water drops at each depth was measured for a maximum of 120 s.

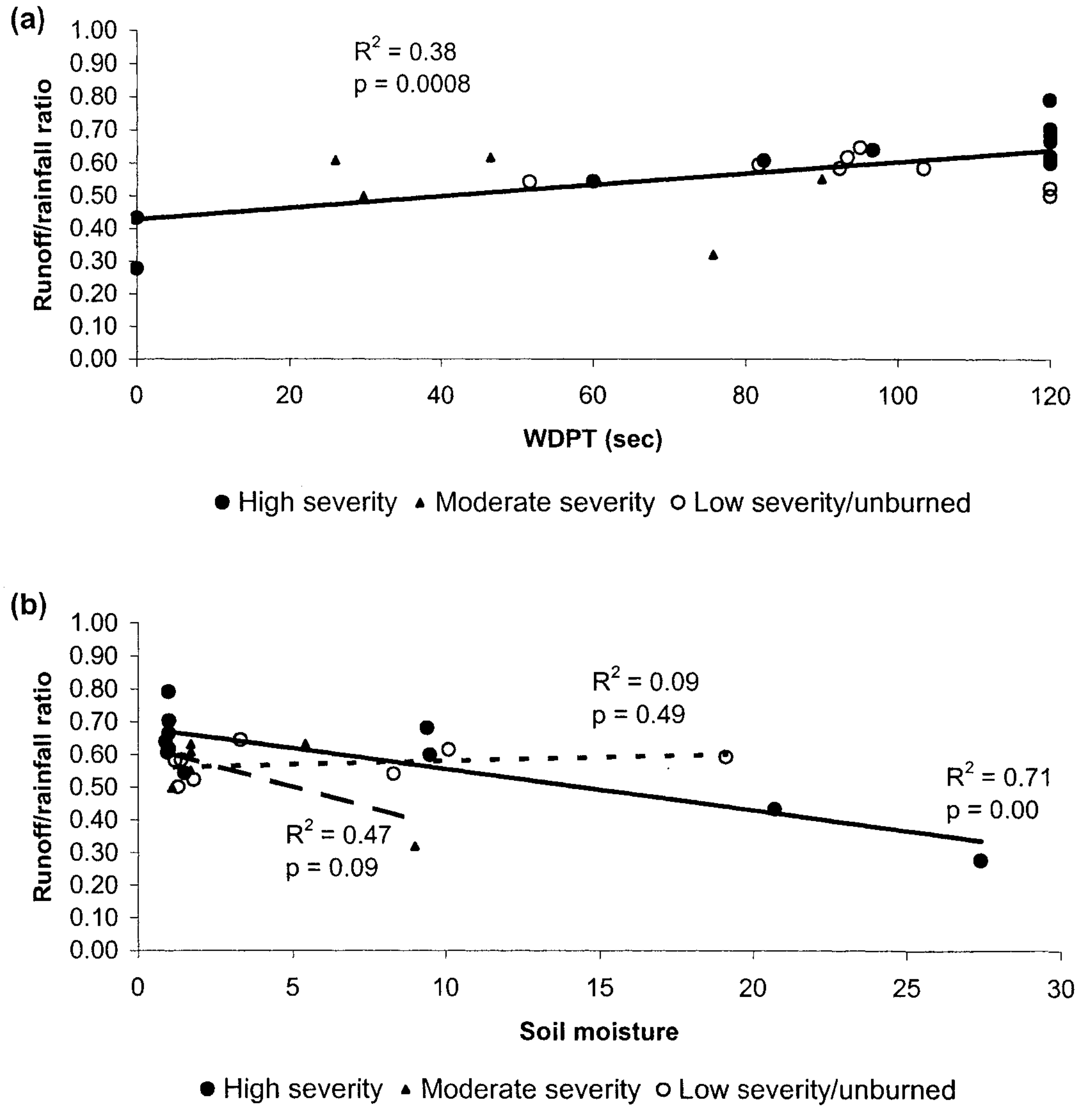

Figure 6. Relationship between the runoff/rainfall ratio and: (a) mean WDPT at 2 cm, and (b) percent soil moisture.

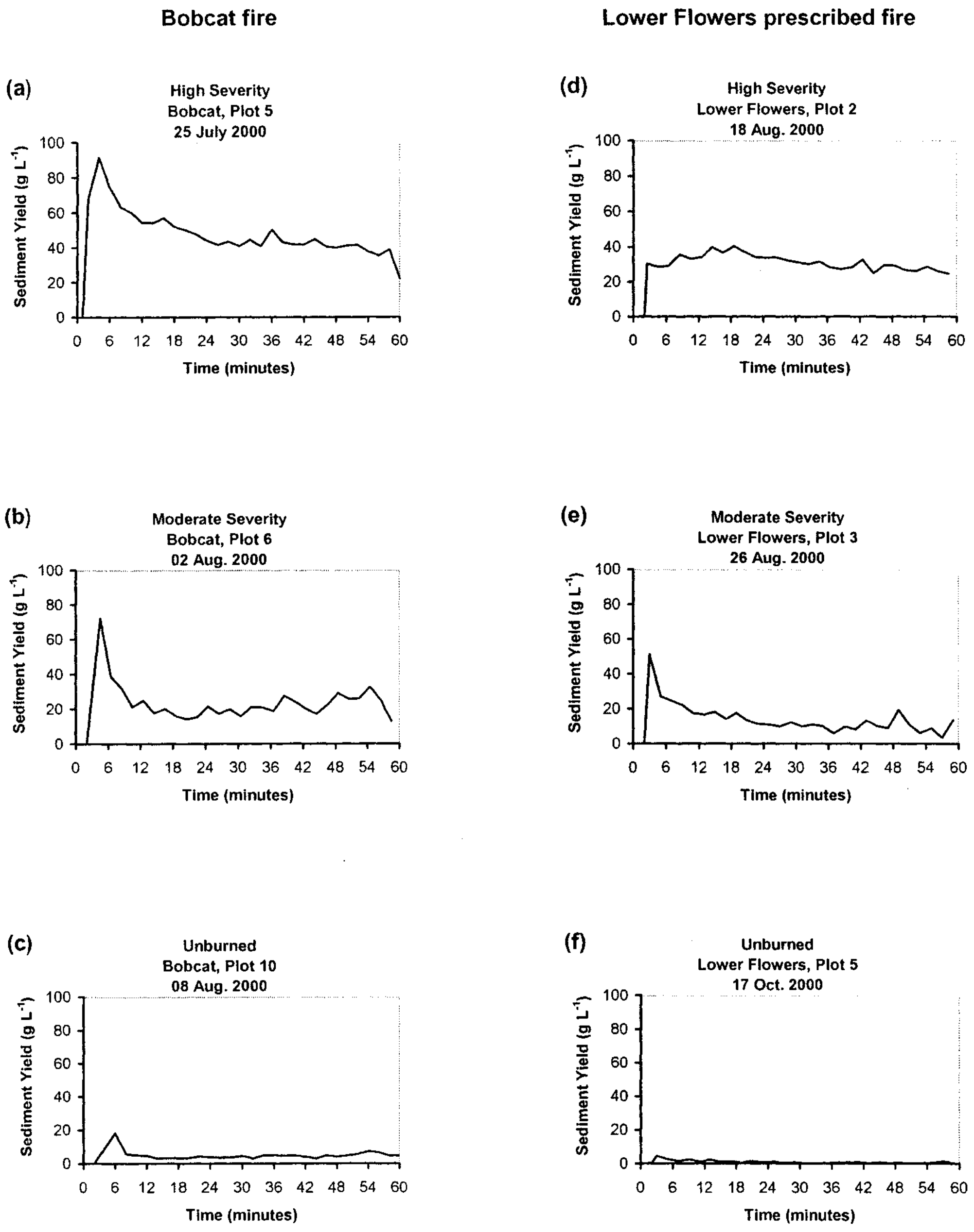

Figure 7. Typical sedigraphs from the: Bobcat wildfire (a-c) and Lower Flowers prescribed fire (d-f) for different severities. Rainfall was applied for time 0 to 60 min at a rate of 66-94 mm h^{-1}.

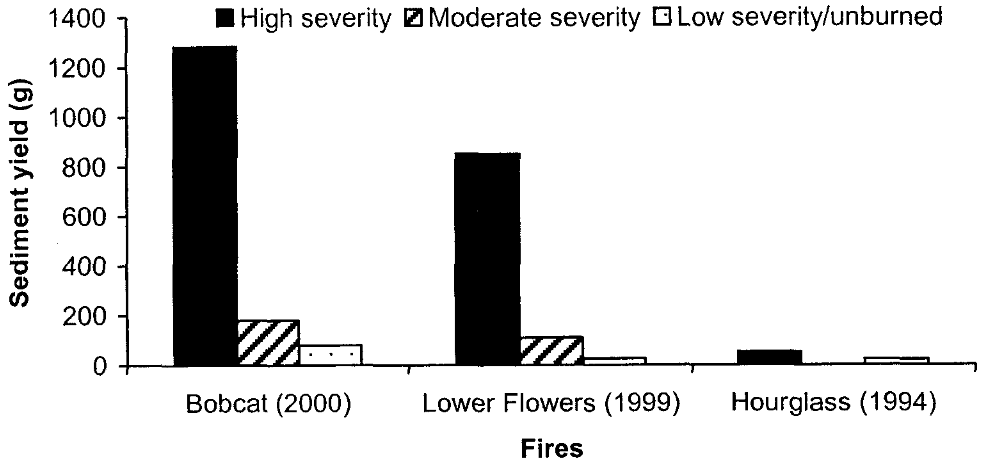

Figure 8. Mean sediment yields by fire and burn severity.

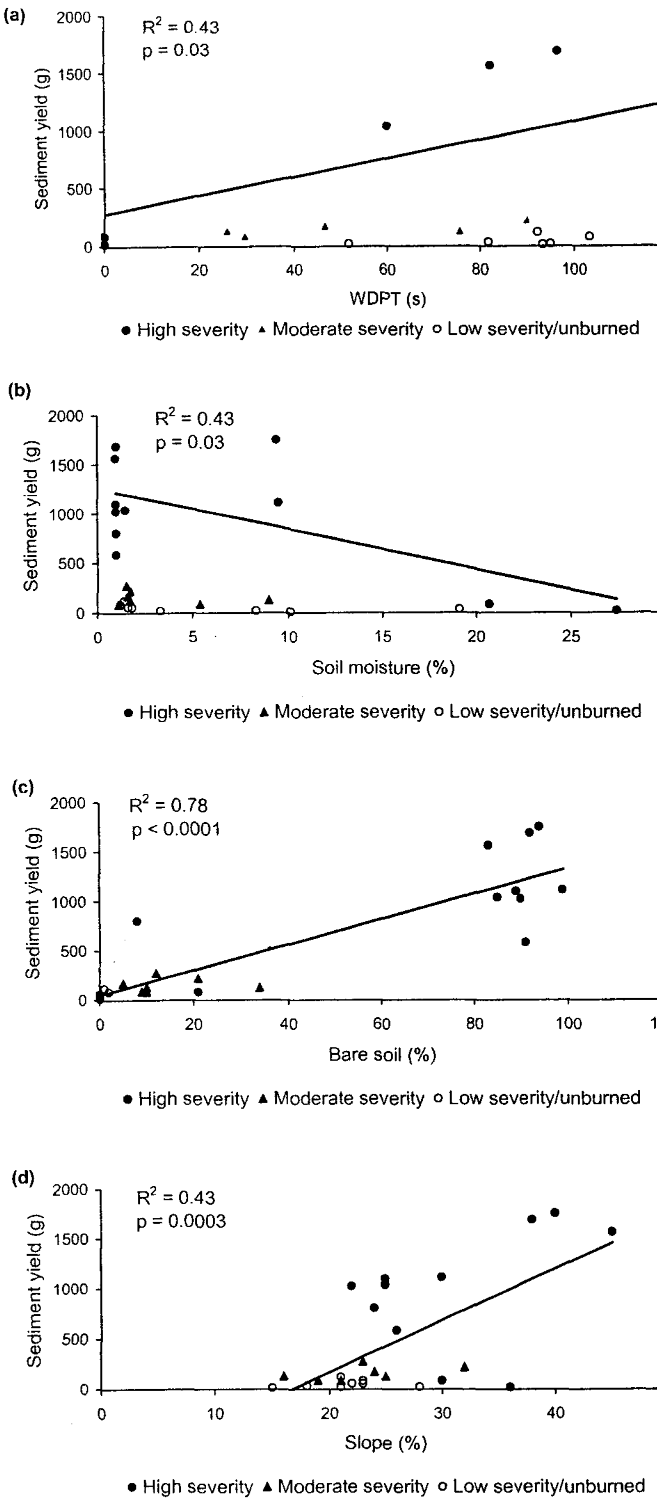

Figure 9. Relationship between sediment yields for each plot and: (a) mean WDPT at 1 cm, (b) percent soil moisture, (c) percent bare soil, and (d) slope. The regression lines and statistics in (a) and (b) are only for the high severity line.

3. MEASUREMENT AND PREDICTION OF POST-FIRE EROSION RATES AT THE HILLSLOPE SCALE, COLORADO FRONT RANGE

3.1. ABSTRACT

Post-fire sediment production and prediction are of great concern because of the potential risk to property and aquatic ecosystems. The objectives of this project were to: 1) measure post-fire sediment yields at the hillslope scale from wildfires and prescribed burns; 2) compare erosion rates from summer rainfall and winter snowmelt events; 3) determine the effect of fire severity, rainfall, soil water repellency, soil texture, ground cover, contributing area, slope, time since burning, and hillslope topography on sediment production rates; and 4) develop empirical models to predict post-fire erosion rates.

Forty-eight sediment fences were used to measure sediment production rates on six fires of varying ages in the Colorado Front Range from late spring 2000 through fall 2001. Sediment production rates from sites burned at high severity in the Bobcat wildfire exceeded 10 Mg ha^{-1} yr^{-1}, whereas sediment production rates from high severity sites in prescribed fires were only 0.1-4 Mg ha^{-1} yr^{-1}. The high severity sites in the Bobcat wildfire produced nearly 200 times as much sediment per unit area as moderate severity sites. The mixture of rain and snowmelt during the following winter produced less than 27% of the total annual sediment load. Sediment production rates from swales or small drainages produced 2-3 times more sediment than planar hillslopes. Data from older fires indicated that sediment production rates from high severity sites were still significantly

higher three years after burning than sites burned at low severity. Four to six years may be required for sediment production rates in high severity areas to decline to the values measured from sites burned at low severity.

The main factors affecting erosion rates were fire severity, percent bare soil, rainfall erosivity, soil water repellency, and soil particle size. In the recent fires, sediment production depended on rainfall intensity and percent bare soil, while for the older fires sediment production rates depended primarily on percent bare soil, regardless of rainfall intensity. A series of empirical prediction models yielded R^2 values from 0.77 for a five-parameter model to 0.62 a simpler two-parameter model. Validation against other sites yielded similar R^2 values of 0.61, but the smallest least square error was for the three-parameter model using percent bare soil, fire severity, and rainfall erosivity.

3.2. INTRODUCTION

Most large wildfires in forested areas include areas burned at high severity because they occur under very dry conditions with high fuel loadings. Erosion rates in forested areas typically increase by several orders of magnitude after a wildfire because of the loss of surface cover and change in runoff processes (Inbar *et al.*, 1998; Robichaud *et al.*, 2000; Benavides-Solorio and MacDonald, 2001; Hufmann *et al.*, 2001). Severe flooding, erosion, and downstream sedimentation were observed after the 1996 Buffalo Creek fire in the Colorado Front Range (Moody and Martin, 2001). There is evidence that fire suppression and reduced grazing has increased forest density in ponderosa pine ecosystems in the Colorado Front Range, and this has increased the likelihood of high-severity wildfires (Brown *et al.*, 1999; Kaufmann *et al.*, 2000a; Kaufmann *et al.*, 2000b;

Kaufmann *et al.*, 2001; Huckaby *et al.*, 2001). The number and size of recent, high-severity fires in the Colorado Front Range support this hypothesis.

Even though large increases in sediment production can occur after wildfires, earlier studies in the Colorado Front Range often found low erosion rates. A high severity wildfire in August 1966 had little or no effect on infiltration rates, organic matter, porosity, or bulk densities when compared to unburned conditions (Kilinc, 1968). The small changes after the fire can be attributed in part to the low rainfall intensities, as the maximum 30-minute intensity observed after the fire was only 11 mm h^{-1}. Morris and Moses (1987) presented a more comprehensive study of post-fire erosion rates in the Colorado Front Range. They used small Gerlach traps to measure erosion, and sediment flux rates from high severity sites was found to be three orders of magnitude higher than from unburned sites. They associated the higher sediment fluxes with the loss of ground cover and fire-induced soil water repellency, but they did not rigorously measure rainfall intensity, percent bare soil, or soil water repellency. A more recent study showed that high rainfall intensities caused very large amounts of erosion after a high severity wildfire southwest of Denver, Colorado (Moody and Martin, 2001). In this case an estimated 80% of the erosion came from channel incision in low-order drainages. However, these studies lacked data from multiple plots at the hillslope scale and specific data on the site characteristics that might control the effect of fires on erosion rates. Such data are needed to better understand the magnitude of erosion after forest fires and the factors controlling post-fire sediment production rates.

Studies outside the Colorado Front Range have suggested that the key factors controlling post-fire runoff and erosion rates are fire severity, percent bare soil, rainfall intensity, soil water repellency, soil texture, and slope (Inbar *et al.*, 1998). Benavides-Solorio and MacDonald (2001) used a rainfall simulator to quantify the role of these factors in small (1 m^2) plots in the Colorado Front Range (Chapter 2), but there is still a lack of data and understanding at the hillslope scale.

Several authors have defined the first two rainy seasons as the critical period for flooding and sedimentation after fires (Robichaud *et al.*, 2000; Inbar *et al.*, 1998), but the reasons for the decreasing risk over time are not completely understood or well documented. Key factors may include the breakdown of post-fire soil water repellency and the increase of vegetation cover.

This study was proposed because of the lack of information on post-fire erosion rates from different fire severities in fires of different ages in ponderosa and lodgepole pine ecosystems (DeBano *et al.*, 1996; DeBano, 2000). The main goal was to measure post-fire erosion rates in the Colorado Front Range and assess the causes of the observed variability between fires, between sites, and over time. The specific objectives were to: (1) measure post-fire sediment yields at the hillslope scale from both wildfires and prescribed burns; (2) determine the relative erosion rates from summer convective storms and winter frontal storms; (3) measure the decline in sediment yields over time as sites recover; (4) evaluate the relative importance of fire severity, rainfall rates, soil water repellency, soil texture, percent ground cover, contributing area, slope, time since burning, and hillslope topography on sediment production rates; and (5) develop models to predict post-fire erosion rates in the Colorado Front Range.

3.3. METHODS

3.3.1. Study sites

Six fires in the Northern Colorado Front Range were selected for this study (Figure 1, Table 1). Five fires were in the more fire-prone mid-elevation zones dominated by ponderosa (*Pinus ponderosa*) and lodgepole pine (*Pinus contorta*), while the highest elevation fire (Bear Tracks) included areas dominated by subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) (Table 1). In general, soils are derived from coarse granitic rocks, sandstones, limestones, and quartzite (Gary, 1975). Soil textures are sandy loams and loamy sands, and the soil type ranges from Typic Argicryolls to Ustic Haplocryalfs (E. Kelly, Colorado State University, pers. comm., 2001).

The primary study site was the Bobcat fire, which burned 4,300 ha in June 2000 (Table 1). Most of the burned area was dominated by ponderosa pine, but there were also small stands of lodgepole pine and Douglas-fir (*Pseudotsuga menziesii*). Aerial photographs indicated that approximately 45% of the area burned at high severity, 25% at moderate severity, and 30% at low severity (USDA Forest Service, 2000). The study plots within the Bobcat fire were in two locations: Bobcat and Jug Gulch in the western part of the fire, and Green Ridge on the eastern edge of the fire.

The Lower Flowers and Dadd Bennett prescribed fires burned 300 and 200 ha in November 1999 and January 2000, respectively. The burned areas were dominated by ponderosa pine with small inclusions of lodgepole pine. Most of the area burned at moderate to low severity, although there were a few patches of high severity.

The Bear Tracks wildfire occurred in June 1998 and burned 196 ha at 2,740 m to 3,050 m (Table 1). The dominant trees were subalpine fir, Engelmann spruce, and lodgepole pine. Field reconnaissance indicated that approximately 30% of the area burned at high severity, 30% at moderate severity, and 40% at low severity.

The Crosier fire was the oldest prescribed burn, and this occurred in September 1998. It burned around 1,000 ha of ponderosa pine and lodgepole pine (Table 1), and some areas burned at high severity. The elevation range is from 2160 m to 2580 m.

The Hourglass wildfire was the oldest fire, as this occurred in July 1994. This fire was at an elevation of 2,590 m to 2,930 m, and lodgepole pine was the dominant forest type (Table 1). The fire burned 516 ha, and most of the burned area was classified as high severity (Omi, 1994).

The study plots within each fire were stratified by burn severity because the condition of the litter and soil after burning is a primary control on post-fire runoff and erosion rates (DeBano *et al.*, 1996). Burn severity was classified qualitatively according to the criteria developed by Wells *et al.* (1979) and applied by the USDA Forest Service (1995). In high severity sites the entire organic layer is consumed and there is visible alteration of the structure and color of the surface layer of the mineral soil. In moderate severity sites the entire litter and duff layer is either consumed or charred, but the underlying mineral soil is not visibly altered. In low severity sites the litter and duff or layers are scorched but not altered over their entire depth, and there is no visible effect on the underlying mineral soil.

3.3.2. Sediment fences

Forty-eight sediment fences were constructed in fall 1999 and spring-summer 2000 (Table 1). The sediment fences were established on both planar hillslopes and in small swales. The swales were defined by convergent slopes and, in some cases, evidence of concentrated flow or very small headwater channels. The mean contributing area of the sediment fences was 1,250 m^2, and the range was from 190 to 6,630 m^2. There was no significant difference in contributing area between the fences on planar hillslopes and the fences in swales. Fences were preferentially placed in areas burned at high severity because these areas were expected to have the highest post-fire erosion rates and are therefore of greatest concern.

The sediment fences were installed transverse to the slope. The center of each fence was lower than the edges, as this prevented the flow of water and sediment around the edges of the fence. The sediment fences were built with 1.2-m wide filter fabric supported by 1.3-m rebar driven approximately 50 cm into the ground (Figure 2). The filter fabric was attached to the rebar with twisted wire, and the remaining fabric was spread in front of the fence to form an apron and facilitate the identification and removal of the captured sediment. The leading edge of the fabric was secured to the mineral soil surface with wire staples 15 cm long and 5 cm wide (Figure 2). The average fence length was 8 m, and the capacity of each fence was about 2,000-2,500 kg of wet soil. Details of the methods for constructing the fences can be viewed at http://www.fs.fed.us/institute/middle_east/platte_pics/silt_fence.htm. In some sites a second fence was installed to increase the sediment storage capacity.

The sediment collected in each fence was periodically removed and weighed with a portable hanging scale to the nearest ¼ kg. Samples were taken each time the sediment was removed to determine percent moisture, percent organic matter, and the particle-size distribution as described below. The data were grouped into two summer rain periods (June-October 2000 and 2001, respectively) and one winter period with mixed rain and snow (November 2000 to May 2001). Over the study period excessive sediment loads overtopped 7 fences in summer 2000 and 6 fences in summer 2001.

Percent ground cover, local slope, soil water repellency, and contributing area were measured for each sediment fence. Percent ground cover was measured each year in mid to late summer using a systematic point count of approximately 100 points. Each point was classified as bare soil, vegetation, moss, rocks, litter, or woody debris. The hillslope or swale axis gradient was measured with a clinometer.

Soil water repellency was assessed at six locations at 1-cm intervals to a depth of 5 cm using the water drop penetration time (WDPT) (Debano, 1981). Soils are classified as strongly water repellent if the water drops remain for more than 40 seconds, moderately water repellent if the drops remain for 10-40 seconds, and not water repellent if the drops remain for less than 10 seconds (USDA Forest Service, 1995). In this study the maximum time recorded was 120 s. Soil water repellency was measured under as dry conditions as possible in summer 2000 and summer 2001.

The contributing area was determined by walking the perimeter with a Trimble GeoExplorer II. For most analyses the sediment yields were normalized by the contributing area. Twelve other sediment fences were established in severely burned areas in the Bobcat fire as part of another study (Wagenbrenner, 2003), and these data were used to validate the models developed in the study reported here.

3.3.3. Precipitation

Average annual precipitation in the Colorado Front Range generally increases with elevation, and the values for the different study sites range from about 380 to 500 mm yr^{-1}. Precipitation comes mostly as rain in late spring and summer, and as snow from about November to April or May (Gary, 1975). At the Manitou Experimental Forest, which has an elevation of 2,360 m, the mean annual precipitation is about 400 mm, and around 60% of this falls as rain between June and October (Gary, 1985). At the Fraser Experimental Forest, which is at an elevation of 2,743 m, the average annual precipitation is 573 mm and more than 60% of this falls as snow (Alexander *et al.*, 1985).

Recording rain gages were installed near each set of sediment fences except at the Bear Tracks fire. Data from five gages were available for the Bobcat fire as compared to two gages for the Dadd Bennett fire and one gage each for the Crosier, Hourglass, and Lower Flowers fires. Rainfall data were collected from June to October. Rainfall data from the gage at Crosier Mountain were used for the Bear Tracks fire because this was the closest gage and it was at a higher elevation than other nearby sites. The resolution of most gages was 0.2 mm, but the easternmost gage in the Bobcat wildfire only had a resolution of 1 mm.

Storms were considered separate events if one hour passed with no rainfall. The kinetic energy for each storm greater than 5 mm was calculated by

$$E_m = 0.29\,[1 - 0.72\exp(-0.05\,I_m)] \qquad (1)$$

where E_m is the kinetic energy in MJ ha^{-1} mm^{-1} per storm, and I is the intensity in mm h^{-1} (Renard *et al.*, 1997). The total erosivity for the period from June to October was calculated by

$$R = \Sigma E\ I_{30} \qquad (2)$$

where R is the rainfall erosivity in MJ ha^{-1} mm^{-1} h^{-1} for the period June to October, E is the kinetic energy per storm, and I_{30} is the maximum 30-minute rainfall intensity per storm (Renard *et al.*, 1997).

3.3.4. Soil texture

Three soil samples were collected from a depth of 0-5 cm in the contributing area of each sediment fence. These samples were combined and two sub-samples were dried and sieved to determine the mass greater than 2 mm. The organic matter in the fraction smaller than 2 mm was removed by burning for 4 h at 400 ^{0}C (Ben-Dor and Banin, 1989; Cambardella *et al.*, 2001) and mixing with hydrogen peroxide (Gee and Bauder, 1986). Soil texture was then assessed by the hydrometer method (Gee and Bauder, 1986). The data from sieving and hydrometer analysis were combined to determine the D_{95}, D_{84}, D_{75}, D_{50}, and D_{16} in both millimeter and phi classes (Scott, 2000). Each time a sediment fence was emptied two sediment samples were collected, and the same procedures were used to determine percent organic matter and the particle-size distribution.

3.3.5. Statistical analysis

One-way ANOVA was used to determine if there were significant differences at $p \leq 0.05$ in the logarithm of sediment production rates between fires for each year, by hillslope position (i.e., planar or swale), and between the textures of the soil and the eroded sediment. If there was a significant difference, multiple comparisons through least square means (LSmeans) were used to determine the significant differences by fire severity and between fires (SAS Institute, 1999). The sediment production data were log transformed prior to these analyses to obtain a normal distribution (Ott and Longnecker, 2001).

Simple linear regression was used to assess the relationship between each independent variable and sediment production. Several multivariate procedures were used to determine the relationship between sediment production and the independent variables, and these included forward, backward, and stepwise regression using the REG procedure (SAS Institute, 1999). The GLM (General Linear Model) procedure was also used because this considers both categorical and continuous variables. Models were selected by maximizing the R^2 value for the set of variables being considered, and each variable had to be significant at $p \leq 0.05$ to be included.

Data from twelve sediment fences on high severity sites in the Bobcat fire (Wagenbrenner, 2003) were used for model testing and validation. The predicted values for each model were graphically compared against the validation data, and a R^2 was calculated for the regression between the observed and predicted data. The fit of each model was evaluated by calculating the sum of the squared errors (LS) by equation 3

$$LS = \Sigma \left(Y_{obs} - Y_{pred}\right)^2 \tag{3}$$

where Y_{obs} are the untransformed sediment yields from the independent data set, and Y_{pred} are the predicted sediment yields from the model being tested (DeCoursey *et al.*, 1982; Sorooshian and Gupta, 1995).

For each model the standard error of the prediction (SEP) was also calculated, as this normalizes the square root of the sum of the squared errors by the number of observations minus the number of parameters used in the model (Salas and Smith, 1999), as shown in equation 4:

$$\mathrm{SEP} = \frac{\sqrt{\Sigma}\,(Y_{obs} - Y_{pred})^2}{n - p} \qquad (4)$$

In this equation n is the number of observations, and p is the number of parameters in the model being tested.

3.4. RESULTS

3.4.1. Precipitation

Summer precipitation at the different studies ranged from 115 mm to 219 mm in 2000, and from 117 mm to 252 mm in 2001. Both the Crosier Mountain and the Bobcat sites generally had more rainfall in 2001 than in 2000 (Table 2). Nearly 90% of the storms were small events with less than 5 mm of rainfall, and field observations showed that these storms produced little or no runoff and erosion. Typically there were 6-10 storms each summer with at least 5 mm of rainfall, and most sites had a similar number of storms with at least 5 mm of rainfall in 2000 and 2001. The two exceptions were Lower Flowers, which had 6 large storms in 2001 as opposed to 15 large storms in 2000, and Crosier Mountain, which had 10 large storms in 2000 compared to 13 large storms in 2001 (Table 2).

Average 30-minute intensities for the large storms ranged from 6.2 mm h^{-1} to 18 mm h^{-1}, the maximum 30-minute intensities were usually less than 30 mm h^{-1}, but there were two storms with maximum 30-minute intensities of 60-70 mm h^{-1}. Rainfall erosivities for a summer ranged from 63 MJ-mm ha^{-1} h^{-1} to 891 MJ-mm ha^{-1} h^{-1}. For every site except Dadd Bennett the rainfall erosivity was greater in 2001 than in 2000 (Table 2). The largest increases were at Lower Flowers where the rainfall erosivity was four times greater in 2001 than in 2000, and Crosier Mountain, which had almost seven times more rainfall erosivity in 2001 than in 2000. Most of the erosivity resulted from only 3 or 4 high-intensity storms, and these generally occurred in August.

3.4.2. Soils

The soils at all sites had from 60-80% sand and no more than 5% clay (Figure 3). The Bobcat wildfire was divided into two areas because the plots at Green Ridge had coarser soils than the plots at Bobcat Gulch and Jug Gulch (Figure 3). The difference between areas was highly significant for sand and silt ($p<0.001$) and significant for clay ($p<0.05$).

At the soil surface there was little evidence of water repellency except for the moderate severity sites in the Bobcat fire (Table 3). In summer 2000 the soils in the high severity sites in the Bobcat, Lower Flowers, and Bear Tracks fires were all strongly water repellent at 1-2 cm below the surface. The sites burned at moderate severity in the Bobcat and Lower Flowers fires also had strong water repellency at 1-2 cm in summer 2000. The high severity sites in the older Crosier Mountain and Hourglass fires generally had moderate or no water repellency. At all sites there was progressively less water repellency at 3, 4, and 5 cm. Comparisons between years generally showed weaker soil water repellency in summer 2001 than in summer 2000 except for the 1-3 cm depths in the Bobcat fire.

The data for sites burned at low severity were not as clear or consistent as the data for sites burned at high and moderate severities (Table 3). Soil water repellency was observed primarily at depths of 1-2 cm, and was generally absent at the soil surface and depths of 3 or more cm. The measured soil water repellency was similar or weaker in 2001 as compared to 2000 for the Dadd Bennett, Bear Tracks, and Lower Flowers fires. In contrast, the low severity sites in the Bobcat fire were more water repellent in 2001 than in 2000, and this may be due to drier soil conditions at the time the soils were tested (Huffman and MacDonald, in preparation). The much older Hourglass fire showed little evidence of soil water repellency at any depth or severity.

3.4.3. Percent cover

The percent bare soil for high severity sites in 2000 ranged from 27% to 92% (Table 4; Figure 4a). The most recent burns had the highest percent bare soil, and the mean value for high severity sites was 92% for the Bobcat fire, 68% for the Bear Tracks fire, and 62% for the Lower Flowers prescribed fire (Figure 4a). Less bare soil was observed at Lower Flowers because the fire did not completely burn the tree canopies and the post-fire needle fall covered 23% of the surface. The sites burned at high severity in the 1994 Hourglass fire had only 27% bare soil in 2000.

In sites burned at moderate severity the percent bare soil in 2000 was around 50% for the Bobcat, Lower Flowers, and Dadd Bennett fires, whereas the Crosier Mountain and Hourglass fires respectively had 36% and 38% bare soil (Figure 4a). Rocks generally accounted for 10% to 25% of the ground cover in each fire except the Bobcat fire, where less than 10% of the surface was covered by clasts larger than 2 mm (Table 4). The percent live vegetation in 2000 was less than 5% in the recent Bobcat, Lower Flowers, and Dadd Bennett fires, regardless of fire severity. The percent live vegetation ranged from 14% to 55% for the other fires, with the highest values occurring in the three older fires (Crosier Mountain, Bear Tracks, and Hourglass).

The percent bare soil declined from 2000 to 2001 for all fires and all severities (Figure 4; Table 4). As might be expected, the high severity sites in the recent fires had the highest percentages of bare soil in 2001, and these ranged from 41% in the Lower Flowers and Bear Tracks fires to 62% for the Bobcat fire. These values represent a relative decline of about 35% from summer 2000. For high severity sites in the Crosier Mountain fire the percent bare soil decreased from 48% to 20%, whereas the decrease in the much older Hourglass fire was only from 27% to 19%. The main reason for these changes was the increase in live vegetation (Table 4).

The percent bare soil in sites that recently burned at moderate severity declined by 20-30% between summer 2000 and summer 2001, and there was a corresponding increase in percent live vegetation (Table 4; Figure 4b). Similarly, the percent bare soil in the one low severity site in the Bobcat fire declined from 50% in 2000 to 17% in 2001. The low severity sites in the other fires had no more than 28% bare soil in 2000. Hence the absolute decline in percent bare soil in the low severity sites was no more than 10% from 2000 to 2001, and the increase in percent live vegetation was no greater than 11%.

Needlefall and residual litter were particularly important in the low and moderate severity sites in the Bobcat, Lower Flowers, Dadd Bennett, and Crosier fires, as these covered from 15% to 68% of the ground surface (Table 4). This generally was progressively less litter with increasing fire severity and less litter in wildfires because the fire consumed more of the tree canopies.

Percent bare soil showed a significant, non-linear decline with time since burning when the data from both years were stratified by fire severity (Figure 5). The effect of time since burning was strongest for sites burned at high severity ($R^2=0.81$; $p<0.0001$), weakest for sites burned at moderate severity ($R^2=0.33$; $p=0.005$), and intermediate for sites burned at low severity ($R^2=0.60$; $p=0.0004$) (Figure 5). The poorer relationship for moderate severity sites is largely due to the relatively high amount of bare soil in the older Hourglass wildfire.

3.4.4. Slope, contributing area, and aspect

Most of the contributing areas had slopes of 25-45% (Table 5). The overall mean was 31% and the range was from 13% to 55%. Mean slopes were similar for all fire severities, as the average slopes were 31% for high severity sites, 30% for moderate severity sites, and 34% for low severity sites.

The mean contributing area for the 48 sediment fences was 1,250 m^2, and the range was from 190 m^2 to 6,600 m^2 (Table 5). The mean contributing area was 1,300 m^2 for high severity sites and 1,600 m^2 for moderate severity sites. The eight fences in sites burned at low severity had a mean contributing area of only 660 m^2.

The aspect of the sediment fences was largely controlled by the aspects of each fire and the location of the access roads. The sediment fences were located in all aspects, but almost 70% had a southeast, north, or northeast aspect (Table 5).

3.4.5. Sediment production

The wide range of contributing areas suggested that the sediment yields first had to be normalized by area in order to be comparable. The effect of area on sediment yields was evaluated for summer 2000 and summer 2001 for those fences and fires that produced the most sediment, and where there were at least four sediment fences in the same severity class.

For 2000 the high severity sites from the Bobcat and Bear Tracks wildfires had a positive relationship between area and sediment yields ($R^2=0.66$; $p<0.0001$; Figure 6a). Similar results were obtained for the data from moderate severity sites from all fires ($R^2=0.66$; $p=0.002$; Figure 6b). For 2001 the high severity sites from Bobcat and Bear Tracks also showed an increase in sediment yields with increasing area ($R^2=0.51$; $p=0.002$; Figure 6c). Given these results, most of the subsequent data are presented in terms of sediment per unit area.

In summer 2000 the highest sediment production rates were in sites burned at high severity, especially in the most recent wildfires and prescribed burns (Table 6; Figure 7a). Mean sediment production rates from high severity sites were 0.76 kg m^{-2} for the Bobcat fire, 0.20 kg m^{-2} for the Bear Tracks fire, and 0.081 kg m^{-2} for the Lower Flowers prescribed fire. Much lower sediment production rates were measured in the older Crosier Mountain prescribed fire and the 1994 Hourglass wildfire (0.0059 kg m^{-2} and 0.0023 kg m^{-2}, respectively).

Moderate severity sites produced much less sediment per unit area except for the Dadd Bennett prescribed burn. Sediment yields from moderate severity sites in the Dadd

Bennett prescribed fire were 0.067 kg m^{-2} as compared to 0.017 kg m^{-2} for the Bobcat wildfire and 0.013 kg m^{-2} for the Lower Flowers prescribed fire (Table 6). Again the older Crosier Mountain and Hourglass fires had much lower values of 0.00056 kg m^{-2} and 0.0038 kg m^{-2}, respectively.

In most cases the lowest sediment production rates were from those areas that burned at low severity. The measured values for low severity sites in summer 2000 ranged from 0.0025 kg m^{-2} to 0.037 kg m^{-2}, with the higher values coming from the more recent fires (Table 6).

These data show that fire severity was an important control on sediment production rates in summer 2000, particularly in the more recent wildfires (Table 6; Figure 7a). In the Bobcat fire there was a 40-fold difference in sediment production between the high severity sites and both the moderate and low severity sites, and this difference was significant at $p<0.0001$. Similarly, the high severity sites in the Bear Tracks wildfire produced about 40 times more sediment than the low severity sites, but the small sample size and high variability meant that this difference was significant only at $p=0.06$. For summer 2000 there were no significant differences in sediment production rates with fire severity for any of the three prescribed fires or the oldest wildfire (Hourglass), although sediment production rates from high severity sites at Lower Flowers were marginally significant relative to moderate severity sites ($p=0.07$).

The mixture of frontal rainstorms and snowmelt from November 2000 to May 2001 generated much less sediment than the summer rainstorms. On average the sediment generated over this period varied from 10% to 27% of the total sediment generated from June 2000 to late May 2001 (Table 6). Other than the Crosier Mountain prescribed fire, the older fires generated a higher proportion of their total sediment yields in the snowmelt season.

The overall pattern and magnitude of sediment production rates in summer 2001 was similar to summer 2000 (Figure 7), especially after considering the differences in rainfall erosivity. There was more absolute variability in sediment yields in 2001, especially for the high severity sites in the Bobcat and Bear Tracks fires (Table 6). The high severity sites generally had the highest sediment production rates, and the mean values for high severity sites were 0.98 kg m^{-2} for the Bobcat fire, 0.56 kg m^{-2} for Bear Tracks, and 0.37 kg m^{-2} for Lower Flowers (Table 6, Figure 7b). High severity sites at the Crosier Mountain prescribed fire and the Hourglass fire yielded just 0.025 kg m^{-2} and 0.0014 kg m^{-2}, respectively.

Moderate and low severity sites produced less sediment in summer 2001 than summer 2000 (Table 6). The only exception was the Lower Flowers prescribed fire, where the three severity classes all had roughly similar sediment production rates that were substantially higher than the values measured in summer 2000 (Figure 7). Except for Lower Flowers, the sediment production rates for moderate and low severity were always less than 0.005 kg m^{-2}. One-way ANOVA showed that there were no significant differences in sediment production rates between summer 2000 and summer 2001 when the data were stratified by fire and fire severity except for the moderate severity sites at Lower Flowers ($p=0.04$) (Table 6; Figure 7b).

Sediment production rates in summer 2001 were strongly significantly different by fire severity for the Bobcat, Bear Tracks, and Crosier Mountain fires. At Bobcat the high severity sites produced 180 times more sediment than moderate severity sites and

120 times more sediment than the low severity site. Similarly, the high severity sites in the Bear Tracks fire produced 130 times more sediment per unit area than the low severity sites ($p=0.01$). At Crosier Mountain there was a 50-fold difference between the high and moderate severity sites, but the absolute values were very small. These differences were larger in summer 2001 than summer 2000, and this is due to the higher sediment production rates in high severity sites as well as the lower sediment production rates in moderate and low severity sites. There were no significant differences in sediment production rates by fire severity for the Lower Flowers, Dadd Bennett, and Hourglass fires.

Comparisons between fires showed that in summer 2000 the high severity sites in the Bobcat fire produced 9 times more sediment than the Lower Flowers prescribed fire, 4 times more sediment than the Bear Tracks wildfire, 130 times more sediment than the Crosier Mountain prescribed fire, and 330 times more sediment than the Hourglass wildfire (Table 6; Figure 7a). Each of these differences was significant at $p<0.05$. In summer 2001 there were no significant differences between the high severity sites at the Bobcat, Lower Flowers, and Bear Tracks fires because the sediment production rates were substantially higher at Lower Flowers and Bear Tracks relative to summer 2000. However, the high severity sites at the Bobcat fire produced 40 times more sediment per unit area than the Crosier Mountain prescribed fire ($p<0.0001$) and 700 times more sediment than the Hourglass fire ($p<0.0001$) (Table 6; Figure 7b).

When the data for all fires and years were pooled, there was an exponential decline in sediment production rates over time for each severity class (Figure 8). The relationship between time since burning and sediment production was highly significant for high severity sites ($R^2=0.65$; $p<0.0001$), but much weaker for the combination of moderate and low severity sites ($R^2=0.15$; $p=0.02$) (Figure 8). The strong relationship for high severity sites is due in part to the low sediment production rates from the much older Hourglass fire, but excluding the Hourglass data still yielded an R^2 of 0.20 ($p=0.001$). The moderate and low severity sites were pooled because the regression equations for these two severity classes were very similar and not statistically different.

3.4.6. Effect of percent bare soil

Percent bare soil is highly correlated with the logarithm of sediment production for summer 2000 and summer 2001 (Figures 9a, b). In each case the R^2 is approximately 0.65 and the relationship is significant at $p<0.0001$ (Figures 9a, b). The slope of the regression is 51% steeper in 2001 than in 2000, indicating a higher erosion rate for a given percent cover in 2001 than in 2000. This difference is significant at $p=0.01$, and it probably is due to the higher erosion rates resulting from the higher rainfall erosivities experienced in 2001.

3.4.7. Effect of hillslope position

Some of the observed variability in sediment production is due to hillslope position. When normalized by rainfall erosivity, the swales generally produced more sediment than planar hillslopes, but these differences were only significant for the sites with the highest sediment yields. For high severity sites in the Bobcat wildfire, the sediment production rate in swales averaged 1.12 kg m^{-2} in summer 2000, whereas the planar hillslopes averaged only 0.53 kg m^{-2} ($p=0.01$). In summer 2001 the swales again produced twice as much sediment as the planar hillslopes (1.53 kg m^{-2} vs. 0.64 kg m^{-2}), and this difference was significant at p=0.04 (Figure 10).

At Bear Tracks the fences in swales recorded 8 times more sediment per unit area in summer 2000 than the fences on planar slopes, but this difference was not significant (p=0.09). Similarly there was a 4-fold difference in sediment production between the swales and planar hillslopes at the Bear Tracks fire in 2001, but again the difference was not significant (p=0.35). At Crosier Mountain the hillslope sites produced more sediment per unit area than the swales in both 2000 and 2001, but the sediment production rates were very low and the differences were not significant.

3.4.8. Effect of soil water repellency

In both 2000 and 2001 the logarithm of sediment production increased with increasing soil water repellency. For summer 2000 the overall R^2 was 0.20 (p=0.001), and for 2001 the R^2 was slightly higher at 0.23 (p=0.001). High severity sites largely controlled the trends for each year, and the R^2 values for just high severity sites were 0.34 for summer 2000 and 0.44 for summer 2001 ($p<0.001$ in each case). Within high severity sites the trend was largely controlled by the older Hourglass wildfire, as these sites had little soil water repellency and very low sediment production rates. When the data from the high severity sites in the Hourglass fire were excluded, there no longer was a significant relationship between soil water repellency and sediment production for the sites burned at high severity.

3.4.9. Effect of rainfall erosivity

The mean erosivity for all fires increased from 250 MJ-mm ha^{-1} h^{-1} in summer 2000 to 405 MJ-mm ha^{-1} h^{-1} in summer 2001, or 62% (Table 2). When all the data were pooled, rainfall erosivity was not significantly related to sediment production for either summer 2000 or summer 2001. However, rainfall erosivity was strongly related to sediment production on a storm-by-storm basis for the high severity sites in the Bobcat fire in summer 2001, which was the largest and most complete data set from any of the six fires used in this study. Rainfall erosivity explained about 50% of the variability in sediment production for both swales and planar hillslopes (Figure 10). As expected, the slope of the regression in 2001 was steeper for the swales than the planar hillslopes because of the higher sediment production rates. The comparison of the regression lines from planar hillslopes in 2000 and 2001 showed that the steepest regression line was in 2000, and this is probably due to the smaller range of rainfall erosivities in summer 2000. The steeper slope in 2000 also may indicate that more sediment was readily available for transport in summer 2000, which was immediately after the Bobcat fire, than in summer 2001.

3.4.10. Effect of soil particle size

Soil texture parameters, such as percent sand, silt, or clay were not significant related to sediment production rates. Different percentiles of the entire particle-size distribution were also tested against sediment production rates, and the parameters representing the fine fraction (D_{16}, D_{25}, and D_{50}) showed little or no relationship with sediment production rates. However, the parameters at the coarse end of the particle-size distribution were inversely related to the log of sediment production at $p<0.0001$. For the D_{75}, D_{84}, and D_{95} the R^2 ranged from 0.16 to 0.18, indicating that sediment production rates tended to decline with increasing size of the larger particles. Presumably this relationship is due to the difficulty of detaching and entraining these larger particles as well as their ability to protect other smaller particles against rainsplash, sheetwash, and rill erosion.

3.4.11. Particle-size distribution of the eroded sediment

Analysis of the particle-size distribution of the sediment collected from the hillslope and fences showed some interesting differences and trends with respect to fire severity, hillslope position, and rainfall erosivity. Comparisons of the eroded sediment from high and moderate severity sites will use the data from sediment fences in Bobcat Gulch and Jug Gulch for summer 2000, as this is the most complete data set. In 2001 most of the material collected from moderate severity sites was organic matter, so there was not enough mineral material to conduct a particle-size analysis. Figure 11a shows that there were no significant differences in soil texture between the high and moderate severity sites.

The sediment collected from the fences in high severity sites was significantly coarser than the original soil. On average, the sediment collected was 71% sand as compared to 62% sand in the contributing area, and there was only 26% percent silt in the eroded sediment as compared to 34% in the soils. These differences were significant at $p<0.01$. There was no difference in percent clay between the soils and the sediment collected in the fences, and this indicates that the coarser texture of the eroded sediment was not simply due to a lower trapping efficiency for smaller particles. On the other hand, the limited number of samples from sites burned at moderate severity suggest that the eroded sediment was finer than the original soil, and this also indicates that the sediment fences were effective in capturing both the coarse and the fine sediment.

Comparisons between severities showed that the sediment eroded from high severity sites generally was coarser than the sediment from sites burned at moderate severity. The sediment collected from high severity sites had 71% sand versus 57% for moderate severity sites (p=0.06), and the respective values for silt were 36% in high severity sites versus 26% in moderate severity sites (p=0.10). Clay sized particles accounted for 3% of the mineral mass collected from high severity sites as compared to 6% for the moderate severity sites, and this difference was significant at p=0.04 (Figure 11b).

In both 2000 and 2001 the sediment eroded from the swales had significantly more sand and significantly less silt than the sediment eroded from the planar hillslopes (Figure 12). For this analysis the data from 2001 were included because the high severity sites produced enough mineral sediment to determine the particle-size distribution.

In both summer 2000 and 2001 the eroded sediment also tended to become coarser over the summer for most of the sediment fences at the Bobcat fire. This coarsening was confounded by the tendency for the collected sediment to coarsen with increasing rainfall erosivity. For the pooled data from Bobcat and Jug Gulch in 2001, the percent sand increased with increasing erosivity for both swales (R^2=0.24; p=0.15) and planar hillslopes (R^2=0.26; p=0.089), and the percent silt decreased in both swales (R^2=0.23; p=0.11) and planar hillslopes (R^2=0.29; p=0.10).

3.4.12. Modeling post-fire sediment production

A wide variety of models can be developed for predicting post-fire sediment production depending on the data available and the modeling goals. Initial efforts to develop sediment prediction models for absolute (kilograms) and normalized (kg m^{-2}) sediment production rates yielded poor results. Residual plots indicated that the sediment production rates had to be log transformed to be normally distributed.

The best multivariate model for predicting normalized sediment production rates used four continuous variables and one discrete variable. The discrete variable was fire severity and the four continuous variables were percent bare soil, rainfall erosivity, soil water repellency at 1 cm, and soil particle size D_{84}. For the overall model the R^2 was 0.77, and all five variables were significant at $p<0.01$ (Model 1, Tables 7 and 8; Figure 13a). Soil texture, slope, time since burning, and hillslope position were not significant predictive variables. Eliminating the data from fences that overtopped in 2000 and 2001 had little effect on the model structure or coefficients. Similarly, excluding the data from the Bear Tracks wildfire, which lacked on-site rainfall data, had little effect. Hence the entire data set was used for model development.

Validation of the complete model (Model 1, Table 7 and 8) was not possible because neither particle size data nor soil water repellency data were available for the 12 other sediment fences in the Bobcat fire. Hence these two variables were excluded and a second model was developed for validation so-called "constrained model". This model used one discrete (fire severity) and three continuous variables (percent bare soil, rainfall erosivity, and time since burning) to predict sediment production rates (Tables 7 and 8).

The overall model R^2 was 0.73 (Figure 13b) as compared to 0.77 for the complete model, and the root mean square error increased from 0.54 for the complete model to 0.58 (Tables 7 and 8). This model explained 61% of the variation in the validation data set, but tended to underpredict at high sediment production rates (Figure 14a). The least square error (LS) was 9.49 and the standard error of the prediction (SEP) was 0.34.

A series of progressively simpler models were developed to determine whether these could be used to estimate post-fire erosion rates. The best 3-parameter model (model 3) used fire severity, percent bare soil, and erosivity as the predictive variables, and the resulting R^2 was 0.70 (Figure 13c) as compared to 0.77 for the complete model. The root mean square error increased from 0.54 to 0.61 (Tables 7 and 8). Validation yielded a similar fit (R^2=0.61; Figure 14b) as the constrained model. The 3-parameter model tended to underpredict at smaller sediment production rates but performed better than the constrained model when sediment production rates exceeded 0.5 kg m^{-2} (Figure 14b). This model has lower LS of 8.86 and lower SEP of 0.30 as compared to model 2, indicating slightly better fit.

The best 2-parameter model dropped the categorical variable of fire severity and used only the continuous variables of percent bare soil and rainfall erosivity (Model 4) (Tables 7 and 8). The R^2 dropped to 0.65, and the root mean square increased to 0.65 (Figure 13d). Validation yielded a similar R^2 as the other two models and a similar tendency as model 2 with respect to underpredicting low sediment production rates (Figure 14c). This model has the largest LS of 10.18, and intermediate SEP of 0.32.

3.5. DISCUSSION

3.5.1. Controls on sediment production

Fire severity is one of the important factors controlling post-fire soil erosion rates. Fire severity has a direct effect on the amount of bare soil as well as soil water repellency. These two factors combine to reduce infiltration rates and increase the amount and velocity of overland flow. The problem is that fire severity is a qualitative, categorical index of the magnitude of these changes. Fire severity is useful because it can be readily inferred from aerial photographs of burned areas. The results from this study showed that, at least for the first two years after burning, sediment production rates were up to 180 times greater in high severity sites than sites burned at moderate or low severity.

Percent ground cover is a better index of erosion than fire severity because it is a continuous variable. Percent ground cover is important because it reduces the detachment and dispersal of soil by raindrop impact (Osborn, 1953) and retards surface runoff (McNabb and Swanson, 1990). The reverse of percent cover is percent bare soil, and in this study sediment production rates in both 2000 and 2001 were strongly related to the percent bare soil (Figure 9). The highest sediment production rates were from recently-burned, high severity sites that had at least 40-60% bare soil. Morris and Moses (1987) found that erosion flux rates in the Colorado Front Range were greatest when bare soil was at least 85-95%.

After a fire ground cover will recover over time. The results from this study showed a decline in percent bare soil in the second year after burning. The percent bare soil in high severity sites was still from 40% to 80%, and the observed increase in ground cover generally did not greatly reduce erosion rates from high severity sites in the recent fires. It is believed that ground cover at high severity sites was not effective in the recent burns for two reasons: 1) field observations suggest that the annual herbs with single stems did not provide much protection against sediment detachment and transport; and 2) the rainfall erosivity increased by 62% compared to the first year. Other studies indicate that ground cover has to be higher than 70% to be effective (Singer and Blackard, 1978; Evans, 1980). Under high intensity rains, such as those generated by a rainfall simulator, the percent cover may have to be at least 80% to reduce erosion rates (Marcos *et al.*, 2000; Benavides-Solorio and MacDonald, 2001).

At moderate and low severity sites in the Lower Flowers prescribed fire, sediment production rates in summer 2001 were 0.36 kg m^{-2}, despite having 70-85% ground cover. This erosion rate was of comparable to the erosion from high severity sites (Figure 7b). Much of the ground cover was ponderosa pine needles, especially in low severity sites, but rill erosion appeared to be the dominant erosion process. Pannkuk *et al.* (2000) demonstrated that a 40-70% cover of ponderosa pine needles did not prevent rill formation when subjected to simulated rainfall of 34 mm h^{-1} plus additional overland flow. The lack of protection was due to the poor contact of the curved pine needles with the soil and the observations that the needles did not slow the overland flow. In contrast, the 80% ground cover at high severity sites in the older Hourglass fire was very effective at reducing erosion under a relatively high erosivity of 250 MJ-mm ha^{-1} h^{-1} because there was 20% moss as well as annual herbs, grass, woody debris, and woody plants. Moss may be particularly effective because it covers the soil, absorbs the raindrop impact, allows infiltration, and greatly reduces the velocity of overland flow.

Soil erosion is a mechanical process that requires energy, and most of the energy to detach particles is provided by raindrop impact (Wischmeier and Smith, 1958). The best prediction of rainfall energy is the rainfall erosivity, which is the kinetic energy times the maximum 30-minute intensity (I_{30}) (Wischmeier and Smith, 1958; Renard *et al.*, 1997). In this study rainfall erosivity was an important control on sediment production, particularly in the high severity sites with less than 40% ground cover. When the ground cover exceeded 70%, sediment production rates drastically decreased, and rainfall erosivity was not an important control.

The average annual erosivity for the study area is about 340 MJ-mm ha^{-1} h^{-1} (Renard *et al.*, 1997), but in 2000 most sites had erosivities below this value (mean=247 MJ-mm ha^{-1} h^{-1}). The main exception was the Dadd Bennett prescribed fire, where the erosivity was over 800 MJ-mm ha^{-1} h^{-1}, and this was mostly due to one storm. The high erosivity at Dadd Bennett resulted in comparatively high erosion rates from moderate and low severity sites (Figure 7a). In the second year the mean erosivity was 400 MJ-mm ha^{-1} h^{-1}, or 18% above the estimated annual mean. As a result most sites showed an increase in sediment production. At Crosier Mountain, the erosivity in 2000 was over 600 MJ-mm ha^{-1} h^{-1} as compared to just 90 MJ-mm ha^{-1} h^{-1} in 2000, and the sediment production from high severity sites was four times higher in 2001 than in 2000. At Lower Flowers the erosivity in 2001 was 890 MJ-mm ha^{-1} h^{-1}, or four times higher than in 2000. This caused sediment production rates to increase by 17 times in moderate severity sites and 10 times in low severity sites. The rainfall erosivities at Dadd Bennett, Crosier Mountain, and Lower Flowers can be considered high but not extreme, as the 10-year storm event for the Bobcat fire area has an estimated erosivity of 680 MJ-mm ha^{-1} h^{-1}

(Renard *et al.*, 1997). These results suggests that much higher post-fire erosion rates could occur under more extreme storm events, especially from high severity sites in the first two years after burning.

The snowmelt season produced much less sediment, and this is probably because snomelt and frontal storms have less kinetic energy. Renard *et al.* (1997) indicate that the winter period (November-May) accounts for only 10% of the total erosivity in the northern Colorado Front Range, and this proportion is consistent with the sediment production data reported here.

3.5.2. Sediment yield from prescribed fires vs. wildfires

The two recent wildfires (Bobcat and Bear Tracks) yielded more sediment than the two recent prescribed burns (Lower Flowers and Dadd Bennett). This difference probably results from two reasons. First, the high severity areas in the wildfires were more consistent and widespread than in the prescribed fires. As a consequence there was more bare soil area in wildfires than prescribed fires. Sheetwash and rill erosion rates increase with increasing percent bare soil, and the detached particles can travel further in wildfires due to the size and continuity of the areas burned at high severity. In prescribed fires there is a much more patchy distribution of fire severity. The runoff and sediment generated in a high severity patch are likely to be absorbed or attenuated in adjacent moderate or low severity sites because of the higher infiltration capacity and greater surface roughness.

Second, there was little or no needle cover in high severity sites in recent wildfires because the entire canopy had been consumed. In contrast, the high severity sites in the prescribed fires had some cover from needle fall from the burned trees as well as from adjacent unburned or less severely burned areas. This cover would immediately help protect the soil surface from rainsplash, and the data show that sediment yields decline rapidly with increasing percent cover (Figure 9a).

3.5.3. Influence of topographic position on sheetwash and rill erosion

Data from the Bobcat and Bear Tracks fires indicated that swales produced 2 or 3 times more sediment per unit area than planar hillslopes. Slope position was not important in the general model, largely because the data were so variable and other factors, such as percent cover and rainfall erosivity, were so dominant. In addition to producing more sediment, the material eroded from the swales was coarser than the material from the planar hillslopes. This difference in the size of the eroded material is probably due to the difference in the depth and velocity of overland flow. Overland flow on planar hillslopes will be in the form of sheetflow. Overland flow in swales will be concentrated into rills, and therefore have more energy to detach and transport larger particles.

Field observations in the Bobcat fire indicate that the granitic soils were more susceptible to rill erosion, whereas sheetwash dominated in the paramicaceous soils (Soil Survey Staff, 1999). Although a single property cannot indicate the susceptibility of a soil to rilling, soil aggregation and shear strength may be the most important factors (Bryan, 2000). Granitic soils generally have less aggregation and shear strength than paramicaceous soils (Soil Survey Staff, 1999), and this may explain the higher rate of rilling. More erosion control efforts may be needed in granitic soils because they lack of aggregation results in a greater susceptibility to rill erosion and higher erosion rates per unit area. Coarser soils also may produce sediment for longer periods because the low water holding capacity inhibits vegetative regrowth.

In the Buffalo Creek fire of the Colorado Front Range, rill and channel erosion accounted for an estimated 86% of the total sediment yield (Moody and Martin, 2001). The high erosion rates and extensive channel incision after the Buffalo Creek fire probably resulted from the lack of soil aggregation high rainfall intensities over the burned area, and resulting high rates of overland flow.

Field observations during two rainstorms in the Bobcat fire indicated that overland flow can rapidly occur in response to intense rainfalls. A maximum sediment concentration of 58,000 mg L^{-1} was measured from a series of grab samples taken on 10 August 2001 from a swale (sediment fence 8) in the Bobcat fire. Such high sediment concentrations confirm that swales and small drainages are a major concern and probably need special attention in post-fire rehabilitation efforts. Further research is needed to evaluate the relative importance of sheetwash versus rilling in post-fire erosion, the differences in erosion rates with respect to slope position, soil type, and the processes responsible for any observed differences.

3.5.4. Model and scale effects

The various predictive models are important because they can help land managers assess post-fire erosion risks and direct post-fire rehabilitation efforts to those areas with the greatest erosion risk. Quantitative analyses are needed to improve our understanding of the various controlling factors, and by implication the processes that control post-fire runoff and erosion rates.

The most complete model did not include soil texture or slope. Soil texture may have been omitted because all sites had relatively similar, coarse-textured soils. Slopes was not important even though it has been found to be important in other erosion studies (Kilinc and Richardon, 1973; McCool *et al.*, 1987; Fox and Bryan, 1999), and is included in most models (e.g., Renard *et al.*, 1997). As in the case of soil texture, the range of slopes tested in this study was limited, as most of the plots had slopes of 25-45%. The interaction of area times slope was strongly and significantly correlated with sediment production, but the statistical analysis suggests that sediment production is controlled more by area than slope. Area was not included because the sediment production values were already normalized by area.

The most useful predictive models are probably models 2 and 3. because they have better fit and adjust better to the independent data. Model 2 used fire severity, percent bare soil, rainfall erosivity, and time since burning in the model 2. Each of these variables is easily obtained except percent bare soil, and this can be estimated or calculated as a function of fire severity and time since burning (Figure 5). These two models had only slightly lower R^2 values than the complete model and comparable root mean square errors. The validation process showed that the predictions converged with the observed data at higher erosion rates (Figure 14a, b), and these are the erosion rates of most concern to resource managers. Managers and natural resource specialists are less likely to have spatially explicit data on soil water repellency, and/or the soil particle-size distribution, so model 1 (complete model) may be more useful for researchers.

The primary limitation of empirical models, such as the ones developed here, is that they only can be used for similar conditions. Hence the models developed here should only be applied in the central Rocky Mountains where the soils are loamy sands or sandy loams and most of the erosion occurs as a result of convective rain storms. The models are also subject to the limitations of the field data. In particular, the highest rainfall erosivities at 600-900 MJ-mm ha^{-1} h^{-1} were not experienced on the most recent wildfire. Another possible limitation is that slope was not explicitly included in the models even though other erosion studies have identified slope as a key variable. Nevertheless, the models developed here should be applicable for the commonly observed slope range of approximately 20-45%.

3.5.5. Scale considerations

Sediment values from sites recently burned at high severity were about 10 Mg ha^{-1} yr^{-1}. This is similar to the mean value of 13 Mg ha^{-1} for 1 m^2 plots subjected to a 75 mm h^{-1} artificial storm (Benavides-Solorio and MacDonald, 2001). If the sediment production rates from the hillslope and small plots are normalized by rainfall, the high severity hillslope sites in the Bobcat wildfire produced 74 kg ha^{-1} mm^{-1}, whereas the small plots subjected to simulated rainfall produced 150 kg ha^{-1} mm^{-1}.

The measured sediment production rate of 10 Mg ha^{-1} yr^{-1} is high relative to the maximum value of 2.5 Mg ha^{-1} yr^{-1} measured from similar sediment fences in a mixed fir and ponderosa pine forest (Robichaud and Brown, 1999). Morris and Moses (1987) reported a sediment production rate of less than 1.2 Mg ha^{-1} yr^{-1} for burned sites in the Colorado Front Range if a slope length of 150 m is assumed. However 10 Mg ha^{-1} yr^{-1} is low compared to the estimated sediment yields of up to 68 Mg ha^{-1} yr^{-1} from high intensity storms after the Buffalo Creek fire (Moody and Martin, 2001).

Another key issue is whether the sediment generated at the hillslope scale will reach the channel network and thereby affect downstream resources. Most of the sediment eroded from hillslopes and swales can probably be delivered to channels if a storm has high intensity and sufficient duration. At the Buffalo Creek fire high-intensity storms produced considerable amounts of sediment and channel incision, and most of the sediment came from the channel network (Moody and Martin, 2001).

3.6. CONCLUSIONS

The highest mean sediment production rates were 10 Mg ha^{-1} yr, and this was from the high severity sites in Bobcat wildfire in the second summer after burning. The high severity sites in the Bobcat wildfire produced up to 185 times more sediment than moderate severity sites. High severity sites in wildfires produced at least 2.5 times more sediment than corresponding sites in prescribed fires of similar age. These results indicate that sites burned at high severity in wildfires represent the greatest erosion risk and should therefore be the focus of emergency. Future prescribed fires should minimize the areas of high severity.

Sediment production rates from high severity sites were still high three summers after the 1998 Bear Tracks wildfire. On the other hand, sediment production rates from high severity sites in the 1994 Hourglass wildfire were comparable to low severity sites in the more recent fires. These results indicate that post-fire erosion rates in the Colorado Front Range should largely recover within 4 to 6 years after burning.

The mixture of frontal rainstorms and snowmelt from November 2000 to May 2001 generated over 10% to 27% of the total sediment produced, from June 2000 to May 2001. The proportion of the total erosion that occurred in the summer was generally higher in the more recent fires and lower in the older fires.

Fire severity was a primary control on sediment production, especially in the most recent wildfires. Percent ground cover was the single most important variable in explaining sediment production. In the first year after burning sites that had 80% to nearly 100% bare soil generated the highest sediment yields, whereas the maximum sediment yields during the second year came from sites with 40% to 80% bare soil. The increase 17-28% in live vegetation at high severity sites did not greatly reduce erosion rates in the second year after burning.

Rainfall erosivity was related to erosion rates when the percent bare soil was between 40% to 100%, and this relationship was strongest at around 70-100% bare soil. Field observations indicate that annual herbs with single stems were not effective in reducing erosion rates, especially when rill erosion was occurring. Ground cover values greater than 80% were particularly effective in reducing soil erosion.

Sediment production significatively increased with increasing soil water repellency, particularly in high severity sites, but the R^2 values were relatively low. Soil water repellency was generally stronger at 1 and 2 cm below the surface in the more recent fires.

Sediment production rates tended to decrease with increasing values of the soil particle-size parameters like D_{75}, D_{84}, and D_{95}. Sediment production rates were not related to percent sand, silt, or clay, or the values of D_{16}, D_{25}, or D_{50}.

Multivariate analysis confirmed that fire severity, percent bare soil, rainfall erosivity, soil water repellency, and soil particle size were the most important controls on sediment production. The recommended models for predictive purposes are model 2, which includes fire severity, percent bare soil, rainfall erosivity, and time since burning, and model 3.

Sediment fences in swales yielded 2 to 3 times more sediment than comparable sediment fences in planar hillslopes. This suggests that proportionately more effort should be devoted to reducing erosion in areas where runoff is concentrated and rills are likely to develop.

The high sediment production rates measured in this study confirm the importance of post-fire erosion in the Colorado Front Range, particularly from sites burned at high severity. The high post-fire erosion rates are due in part to the natural characteristics such as coarse-textured and poorly aggregated soils, steep slopes, and high-intensity summer rain storms.

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Table 1. Study sites and number of sediment fences by site and fire severity.

						Number of sediment fences			
Fire	**Type**	**Date burned**	**Area (ha)**	**Primary vegetation type**	**Elevation range (m)**	**High severity**	**Moderate severity**	**Low severity or unburned**	**Totals**
Bobcat	Wildfire	June 2000	4,289	Ponderosa pine	1670-2580	13	2	1	16
Lower Flowers	Prescribed fire	Nov. 1999	300	Ponderosa pine	2530-2940	4	4	2	10
Dadd Bennett	Prescribed fire	Jan. 2000	200	Ponderosa pine	2100-2730	0	3	2	5
Bear Tracks	Wildfire	June 1998	196	Subalpine fir Engelmann spruce Lodgepole pine	2740-3050	3	0	2	5
Crosier Mt.	Prescribed fire	Sept. 1998	1,011	Ponderosa pine Lodgepole pine	2160-2580	4	1	0	5
Hourglass	Wildfire	July 1994	516	Lodgepole pine	2590-2930	5	1	1	7
					Totals	29	11	8	48

Table 2. Precipitation for each fire in summer 2000 and 2001.

								Storms larger than 5 mm								
Fire	**Rain gauge**	**Period of data**		**Total rainfall (mm)**		**Total number of *rain events***		***Number of storms***		**Maximum I_{30} (*mm h*$^{-1}$)**		**Average I_{30} (*mm h*$^{-1}$)**		**Erosivity (*MJ-mm ha*$^{-1}$ *h*$^{-1}$)**		
		2000	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**Total**
Bobcat	Snowtop	Jun 26-Oct 31	Jun 1-Oct 31	150	201	73	97	9	9	17.6	26.0	12.6	14.0	220	303	523
	Galuchie	Jun 26-Oct 31	Jun 3-Oct 31	129	179	67	103	8	10	17.6	26.8	12.9	11.7	193	271	464
	Green Ridge	Jul 7-Oct 31	Jun 3-Oct 31	115	117	56	46	6	6	12.0	18.0	7.0	11.3	63	137	200
Dadd Bennett	Mom Gulch	Jun 8-Oct 31	Jun 3-Oct 31	173	172	84	117	9	9	70.6	33.0	14.3	10.5	812	369	1181
Lower Flowers	Lower F.	Jun 7-Oct 31	Jun 2-Oct 31	219	177	97	113	15	6	22.4	61.0	9.2	18.0	226	891	1117
Crosier	Crosier	Jun 9-Oct 31	Jun 12-Oct 31	159	252	83	95	10	13	12.8	27.2	6.2	16.7	90	608	698
Hourglass	Pingree Park	Jun 7-Oct 31	Jun 7-Oct 31	171	168	102	121	9	9	19.2	23.6	9.5	12.4	144	253	397

Table 3. Mean soil water repellency in seconds by fire, fire severity, soil depth, and year. The values in parentheses are the standard deviation. - indicates that no sediment fence was installed for this severity.

		Number of sediment	WDPT at surface (s)		WDPT at 1 cm (s)		WDPT at 2 cm (s)		WDPT at 3 cm (sec)		WDPT at 4 cm (s)		WDPT at 5 cm (s)	
Fire	**Severity**	**fences**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**
Bobcat	High	13	2 (4)	0	63 (31)	78 (41)	54 (28)	78 (40)	30 (16)	35 (40)	16 (9)	14 (17)	11 (8)	4 (11)
	Moderate	2	45 (51)	0	81 (37)	120 (0)	68 (40)	110 (14)	53 (39)	80 (57)	41 (27)	30 (14)	24 (23)	7 (4)
	Low	1	4	0	23	120	21	100	4	10	2	10	3	0
Lower Flowers	High	4	2 (2)	0	78 (39)	53 (26)	63 (33)	43 (5)	28 (6)	0	10 (3)	0	13 (25)	0
	Moderate	4	0.5 (1)	0	63 (34)	38 (33)	55 (31)	40 (37)	23 (18)	10 (20)	5 (5)	0	1 (3)	0
	Low	2	0	0	15 (21)	15 (21)	60 (85)	20 (28)	25 (35)	0	5 (7)	0	0	0
Dadd Bennett	High	0	-	-	-	-	-	-	-	-	-	-	-	-
	Moderate	3	0	0	23 (6)	10 (17)	57 (25)	10 (17)	27 (15)	0	8 (3)	0	0	0
	Low	2	0	0	85 (21)	90 (14)	85 (7)	40 (14)	31 (16)	0	8 (4)	0	0	0
Crosier	High	4	5 (5)	0	26 (36)	8 (15)	51 (26)	30 (22)	30 (31)	3 (5)	17 (19)	0	11 (12)	0
	Moderate	1	0	0	32	0	56	0	73	0	41	0	24	0
	Low	0	-	-	-	-	-	-	-	-	-	-	-	-
Bear Tracks	High	3	12 (8)	2 (3)	100 (20)	63 (21)	113 (12)	37 (12)	50 (10)	8 (3)	14 (5)	3 (3)	3 (3)	0
	Moderate	0	-	-	-	-	-	-	-	-	-	-	-	-
	Low	2	0	0	50 (14)	13 (4)	30 (14)	5 (0)	8 (4)	0	2 (2)	0	0	0
Hourglass	High	5	0	0	0	2 (3)	16 (16)	2 (3)	2 (2)	0	0	0	0	0
	Moderate	1	0	0	0	0	0	0	0	0	0	0	0	0
	Low	1	10	0	50	0	20	0	5	0	0	0	0	0

Table 4. Percent cover by fire, fire severity, and year. - indicates that no sediment fence was installed for this severity.

		Number of sediment	Percent bare soil		Percent litter		Percent rocks		Percent woody debris		Percent live vegetation	
Fire	**Severity**	**fences**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**
Bobcat	High	13	92	62	1	3	6	6	1	3	0	25
	Moderate	2	52	21	43	43	4	6	1	1	0	30
	Low	1	50	17	45	68	0	0	5	1	0	14
Lower Flowers	High	4	62	41	23	31	10	9	4	2	1	17
	Moderate	4	51	29	25	27	16	18	4	3	4	23
	Low	2	21	16	55	62	13	6	8	4	3	12
Dadd Bennett	High	0	-	-	-	-	-	-	-	-	-	-
	Moderate	3	56	25	22	15	16	19	4	2	2	40
	Low	2	28	18	43	49	25	22	4	2	0	9
Crosier	High	4	48	20	4	3	23	18	3	2	22	56
	Moderate	1	36	7	21	24	14	8	3	4	26	57
	Low	0	-	-	-	-	-	-	-	-	-	-
Bear Tracks	High	3	68	41	1	3	10	12	7	17	14	28
	Moderate	0	-	-	-	-	-	-	-	-	-	-
	Low	2	25	19	9	10	13	7	10	10	43	54
Hourglass	High	5	27	19	3	4	22	20	9	10	38	47
	Moderate	1	38	30	2	4	4	2	1	2	55	63
	Low	1	3	1	19	24	23	18	16	18	39	40

Table 5. Characteristics of each sediment fence with mean values by fire and fire severity. - indicates that no sediment fence was installed for this severity.

							Sediment production			
Fire	Number	Fire severity	Hillslope position	Slope (%)	Aspect	Contributing area (m^2)	Rain 2000 (kg)	Snowmelt 2000-01 (kg)	Rain 2001 (kg)	Year(s) overtopped
Bobcat	1	high	swale	27	E	1300	2243	7	2193	2000, 2001
	2	high	planar	25	NE	1600	766	2	211	
	3	high	planar	30	NE	1700	770	2	648	
	4	high	swale	28	E	1800	998	2	1526	2000, 2001
	5	moderate	swale	27	SW	2400	73	4	3	
	6	high	planar	28	NE	1400	599	37	680	
	7	low	planar	26	NE	280	6	4	2	
	8	high	swale	30	N	3800	3342	215	3843	2000, 2001
	9	high	planar	42	N	1900	965	40	578	
	10	high	planar	39	N	1200	758	50	707	
	11	moderate	planar	29	N	590	3	2	6	
	12	high	swale	32	E	1100	1013	139	1620	2000, 2001
	13	high	planar	27	SW	520	238	43	180	
	14	high	planar	28	SW	690	209	75	421	
	15	high	swale	33	SW	490	723	126	1276	
	16	high	planar	43	NW	190	197	80	444	
	Means	**High**		**32**		**1400**	**986**	**63**	**1102**	
		Moderate		**28**		**1500**	**38**	**3**	**4**	
		Low		**26**		**280**	**6**	**4**	**2**	
Lower Flowers	17	high	planar	28	SE	1000	220	8	497	2001
	18	high	planar	32	SE	940	40	14	47	
	19	moderate	planar	36	SE	390	3	3	36	
	20	moderate	planar	26	SE	320	1	3	4	
	21	moderate	planar	27	SE	390	9	5	111	
	22	high	planar	30	SE	710	20	18	373	
	23	low	planar	26	SE	600	36	7	431	
	24	high	planar	18	SE	1100	41	9	467	
	25	moderate	planar	24	SE	1100	18	3	501	
	26	low	planar	18	E	360	5	4	1	
	Means	**High**		**27**		**950**	**80**	**12**	**346**	
		Moderate		**28**		**540**	**8**	**4**	**163**	
		Low		**22**		**480**	**21**	**5**	**216**	
Dadd Bennett	27	moderate	swale	22	NE	6600	374	2	3	2000
	28	moderate	planar	33	E	730	92	3	4	
	29	moderate	swale	42	E	2500	365	3	112	2000
	30	low	planar	55	SW	450	30	25	5	
	31	low	planar	37	W	590	40	31	6	
	Means	**High**		**-**		**-**	**-**	**-**	**-**	
		Moderate		**32**		**3300**	**277**	**3**	**40**	
		Low		**46**		**520**	**35**	**28**	**6**	
Crosier Mountain	32	high	swale	32	N	1600	2	0.4	21	
	33	high	planar	32	N	520	4	0.5	10	
	34	moderate	swale	26	N	1800	1	0.1	1	
	35	high	planar	43	NE	560	5	0.5	28	
	36	high	planar	44	N	880	5	0.6	16	
	Means	**High**		**38**		**890**	**4**	**0.5**	**19**	
		Moderate		**26**		**1800**	**1**	**0.1**	**1**	
		Low		**-**		**-**	**-**	**-**	**-**	
Bear Tracks	37	high	planar	27	SE	710	24	14	124	
	38	high	swale	42	E	1300	337	89	696	2000, 2001
	39	high	swale	27	NE	740	225	79	706	
	40	low	planar	35	SE	670	6	5	5	
	41	low	planar	37	SE	1900	1	1	2	
	Means	**High**		**32**		**910**	**195**	**60**	**508**	
		Moderate		**-**		**-**	**-**	**-**	**-**	
		Low		**36**		**1300**	**4**	**3**	**4**	
Hourglass	42	high	swale	13	N	1900	3	0.1	6	
	43	high	planar	15	N	3500	3	0.1	2	
	44	high	swale	30	NW	880	4	0.3	2	
	45	high	swale	45	NW	950	3	0.3	1	
	46	high	swale	32	NE	1610	2	0.1	1	
	47	moderate	swale	33	NE	1100	4	2	2	
	48	low	planar	34	NE	400	1	0.4	1	
	Means	**High**		**27**		**1800**	**3**	**0.3**	**2**	
		Moderate		**33**		**1100**	**4**	**2**	**2**	
		Low		**34**		**400**	**1**	**0.4**	**1**	

Table 6. Mean sediment production for rain season 2000, snow season 2000-2001, and rain season 2001 by fire and fire severity. Values in parentheses are standard deviations. - indicates that no sediment fence was installed for this severity.

			Sediment production		
Fire	**Fire severity**	**Number of sediment fences**	**Rain season 2000 (kg m^{-2})**	**Snow season 2000-2001 (kg m^{-2})**	**Rain season 2001 (kg m^{-2})**
Bobcat	High	13	0.76 (0.44)	0.12 (0.24)	0.98 (0.80)
	Moderate	2	0.017 (0.018)	0.0024 (0.0014)	0.0053 (0.0060)
	Low	1	0.019	0.014	0.0084
Lower Flowers	High	4	0.081 (0.092)	0.014 (0.0082)	0.37 (0.22)
	Moderate	4	0.013 (0.0091)	0.008 (0.0046)	0.22 (0.20)
	Low	2	0.037 (0.032)	0.011 (0.0010)	0.36 (0.50)
Dadd Bennett	High	0	-	-	-
	Moderate	3	0.11 (0.046)	0.0016 (0.0016)	0.017 (0.024)
	Low	2	0.067 (0.00059)	0.054 (0.0024)	0.011 (0.0011)
Crosier Mountain	High	4	0.0059 (0.0034)	0.00071 (0.00033)	0.025 (0.017)
	Moderate	1	0.00056	0.00007	0.00052
	Low	0	-	-	-
Bear Tracks	High	3	0.20 (0.15)	0.065 (0.044)	0.56 (0.39)
	Moderate	0	-	-	-
	Low	2	0.0049 (0.0062)	0.0040 (0.0049)	0.0042 (0.0045)
Hourglass	High	5	0.0023 (0.0016)	0.00023 (0.0012)	0.0014 (0.00019)
	Moderate	1	0.0038	0.0019	0.0014
	Low	1	0.0025	0.0010	0.0013

Table 7. Statistics for the four models developed to predict post-fire sediment production rates at the hillslope scale for the Northern Colorado Front Range. The dependent variable is the logarithm of sediment production per unit area (kg m^{-2}). D_{84} refers to the diameter of soil particles at 84% of the cumulative distribution using a phi scale.

Model 1		**Model 2**		**Model 3**		**Model 4**	
Complete model		**Constrained model for validation**		**Simplified 3-parameter model**		**Simplified 2-parameter model**	
Variable	p-value	Variable	p-value	Variable	p-value	Variable	p-value
Fire severity	<0.0001	Fire severity	<0.0001	Fire severity	0.0012	Percent bare soil	<0.0001
Percent bare soil	<0.0001	Percent bare soil	<0.0001	Percent bare soil	<0.0001	Rainfall erosivity	<0.0001
Rainfall erosivity	<0.0001	Rainfall erosivity	<0.0001	Rainfall erosivity	<0.0001		
Water repellency at 1 cm	0.0016	Time since burning	0.0018				
D_{84}	0.0131						
Overall model	<0.0001	Overall model	<0.0001	Overall model	<0.0001	Overall model	<0.0001
R^2	0.77	R^2	0.73	R^2	0.70	R^2	0.65
Root mean square error	0.54	Root mean square error	0.58	Root mean square error	0.61	Root mean square error	0.65

Table 8. Regression equations for the four models developed in this study and the R^2 relative to the validation data. E is total sediment yield from June-October in kg m^{-2}, BAR is percent bare soil, R is the rainfall erosivity from June-October in MJ-mm ha^{-1} h^{-1}, WR_1 is the soil water repellency in seconds at a depth of 1 cm, TSB is the time since burning in years, and D_{84} is the diameter in phi units for the size of the 84th percentile of the soil in the contributing area.

						Validation		
Model	**Model number**	**n**	**Fire severity**	**Regression equation**	**Model R^2**	**R^2**	**Least square error (LS)**	**Standard error of the prediction (SEP)**
Complete model	1	96	High	$Log_{10}E= -3.303 + 0.02832BAR + 0.001954R + 0.005039WR_1 + 0.1363P_{84}$	0.78	Not validated		
			Moderate	$Log_{10}E= -3.977 + 0.02832BAR + 0.001954R + 0.005039WR1 + 0.1363P_{84}$				
			Low	$Log_{10}E= -3.515 + 0.02832BAR + 0.001954R + 0.005039WR1 + 0.1363P_{84}$				
Constrained model for validation	2	96	High	$Log_{10}E= -2.528 + 0.02470BAR + 0.001634R - 0.01192TSB$	0.73	0.61	9.49	0.34
			Moderate	$Log_{10}E= -3.320 + 0.02470BAR + 0.001634R - 0.01192TSB$				
			Low	$Log_{10}E= -2.839 + 0.02470BAR + 0.001634R - 0.01192TSB$				
Simplified 3-parameter model	3	96	High	$Log_{10}E= -3.525 + 0.03490BAR + 0.001934R$	0.70	0.61	8.86	0.30
			Moderate	$Log_{10}E= -4.103 + 0.03490BAR + 0.001934R$				
			Low	$Log_{10}E= -3.507 + 0.03490BAR + 0.001934R$				
Simplified 2-parameter model	4	96	All pooled	Log10E= -3.631 + 0.03576BAR + 0.001754R	0.62	0.61	10.18	0.32

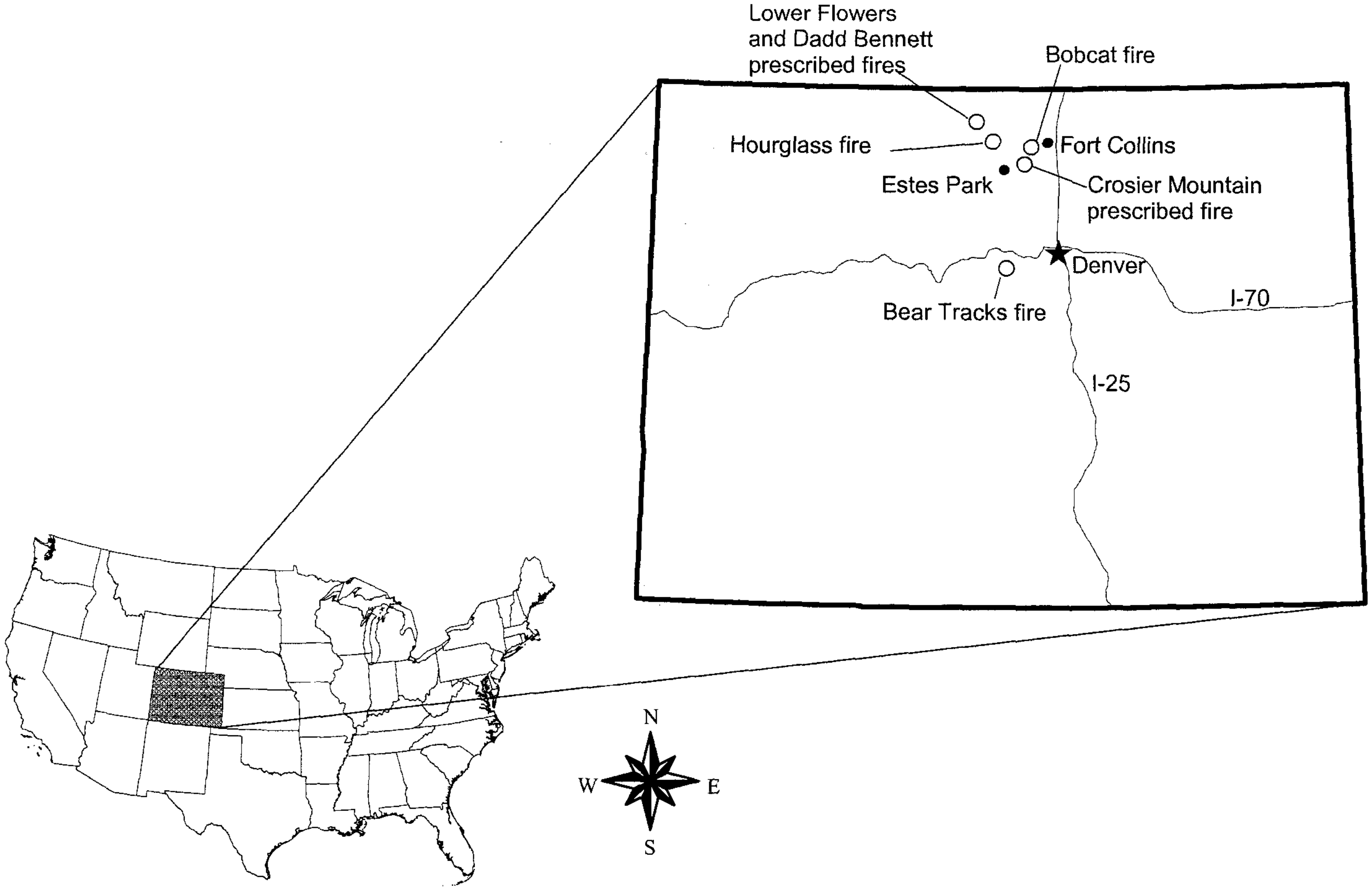


Figure 1. Location of the six fires used in this study.

Figure 2. Sediment fence on a planar hillslope in an area burned at high severity in the Bobcat wildfire. Picture was taken in summer 2001, approximately 14 months after burning.

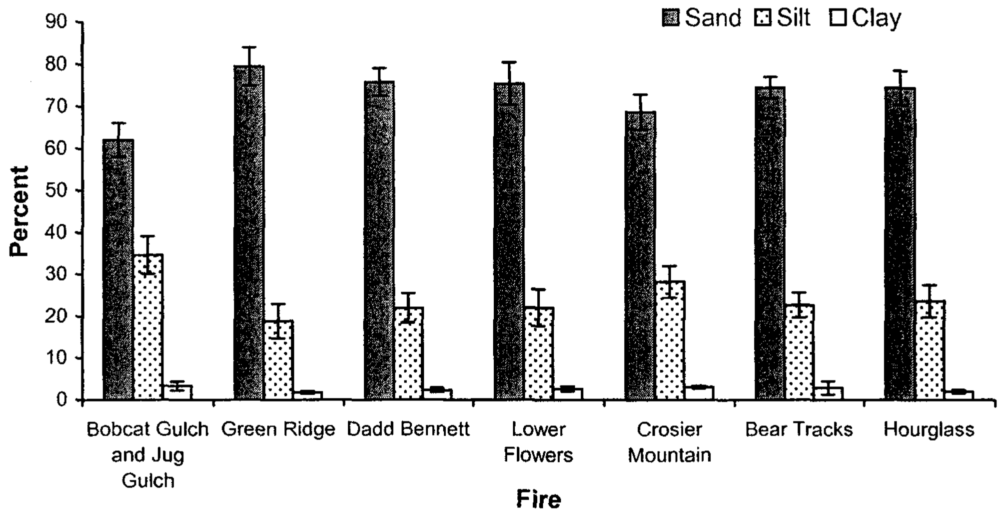
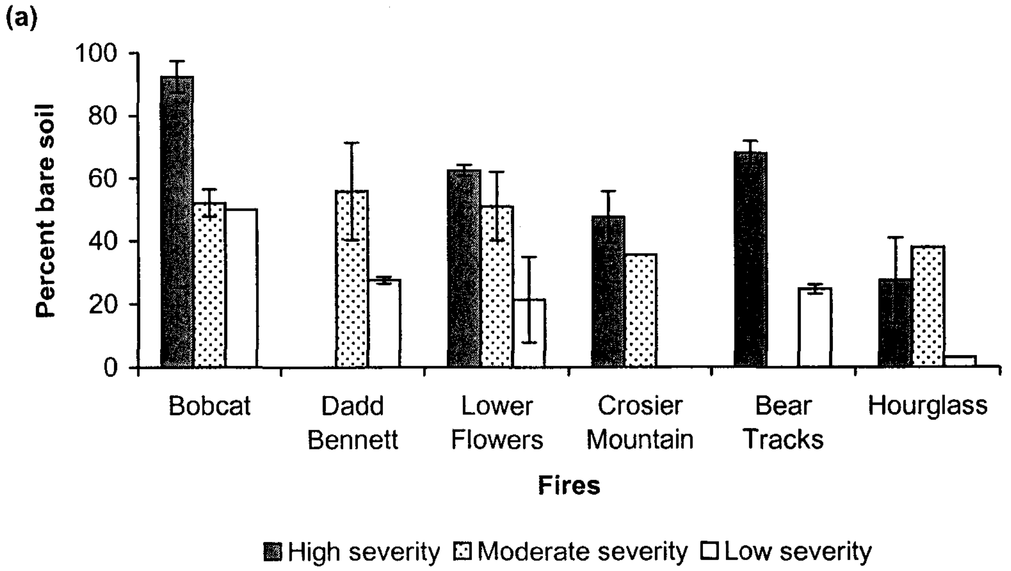


Figure 3. Mean soil texture for each fire. Bars represent represent one standard deviation.



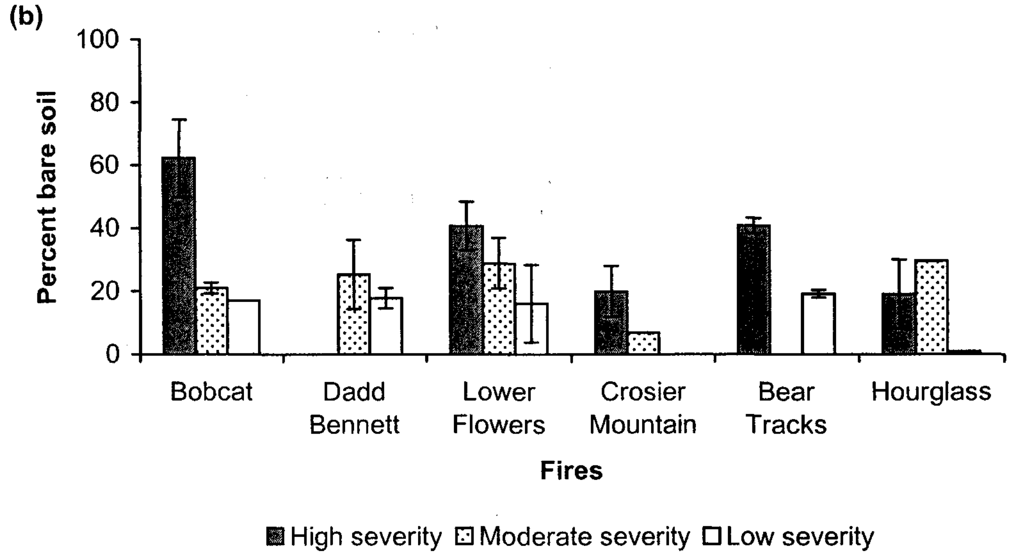


Figure 4. Percent bare soil by fire by fire and fire severity for: (a) 2000, and (b) 2001. Bars represent one standard deviation.

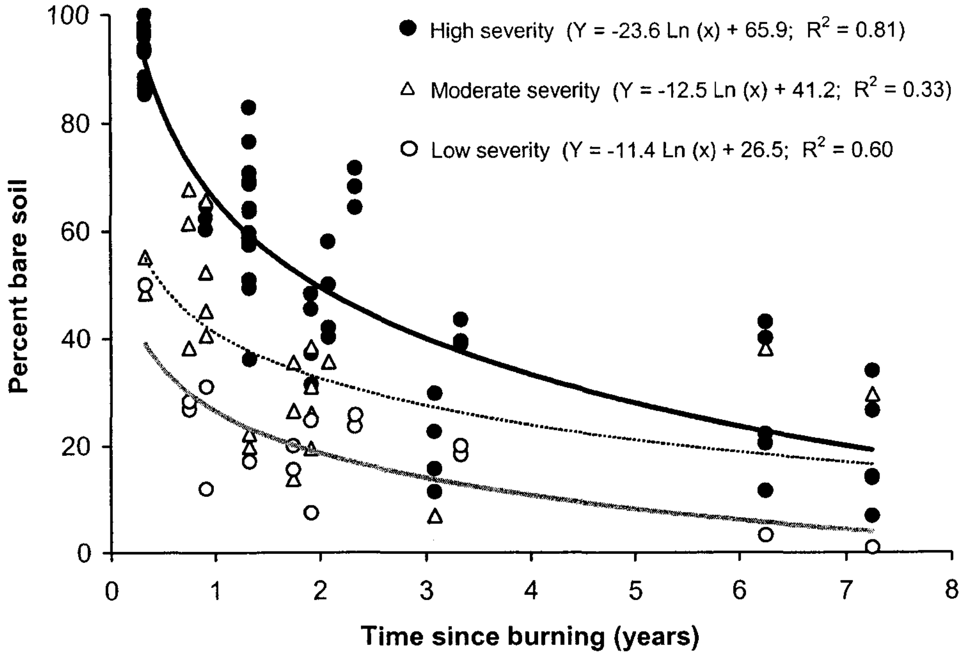


Figure 5. Relationship between percent bare soil and time since burning by fire severity. The solid line represents sites burned at high severity, the dashed line represents sites burned at moderate severity, and the solid gray line represents sites burned at low severity.

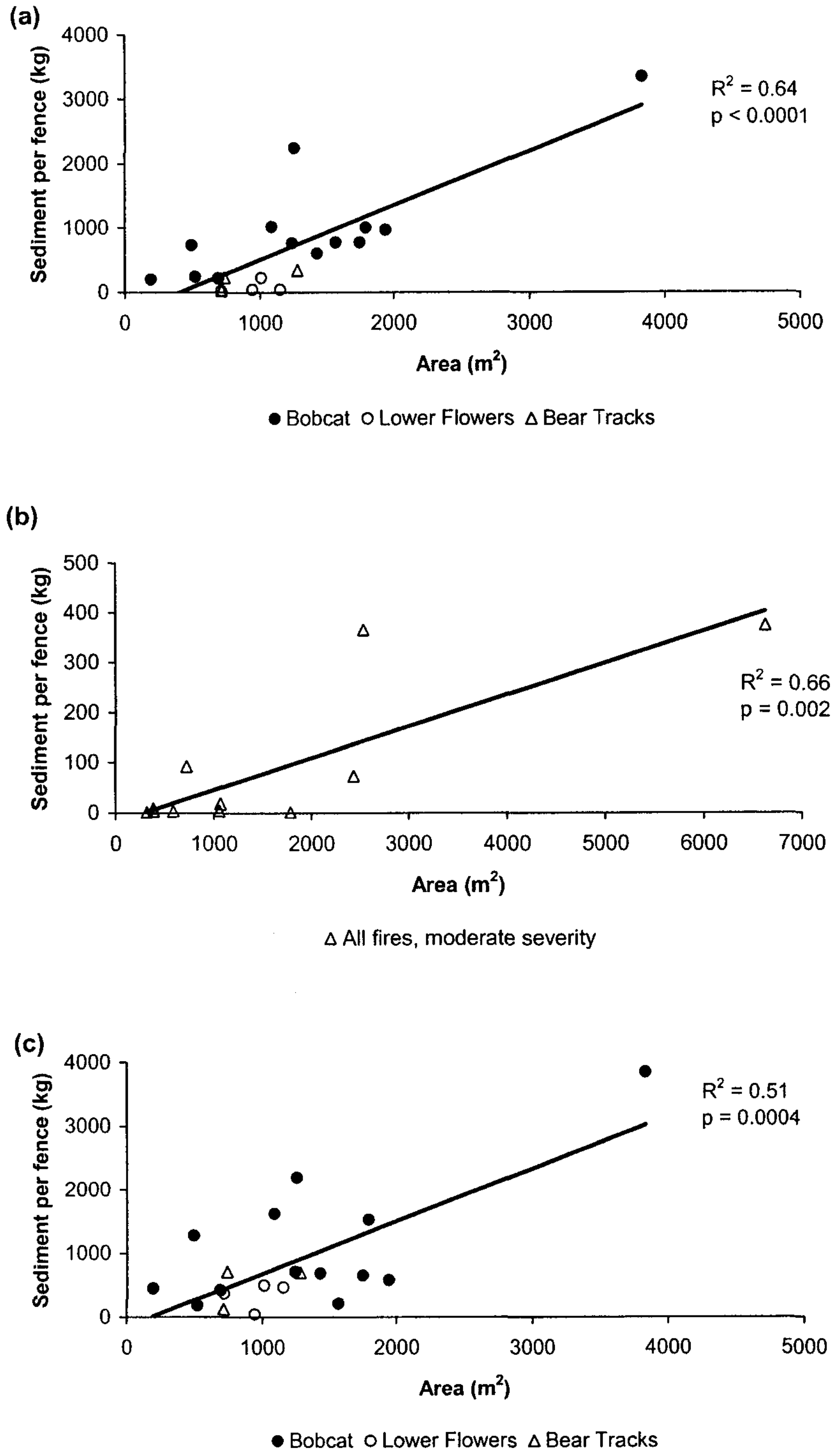
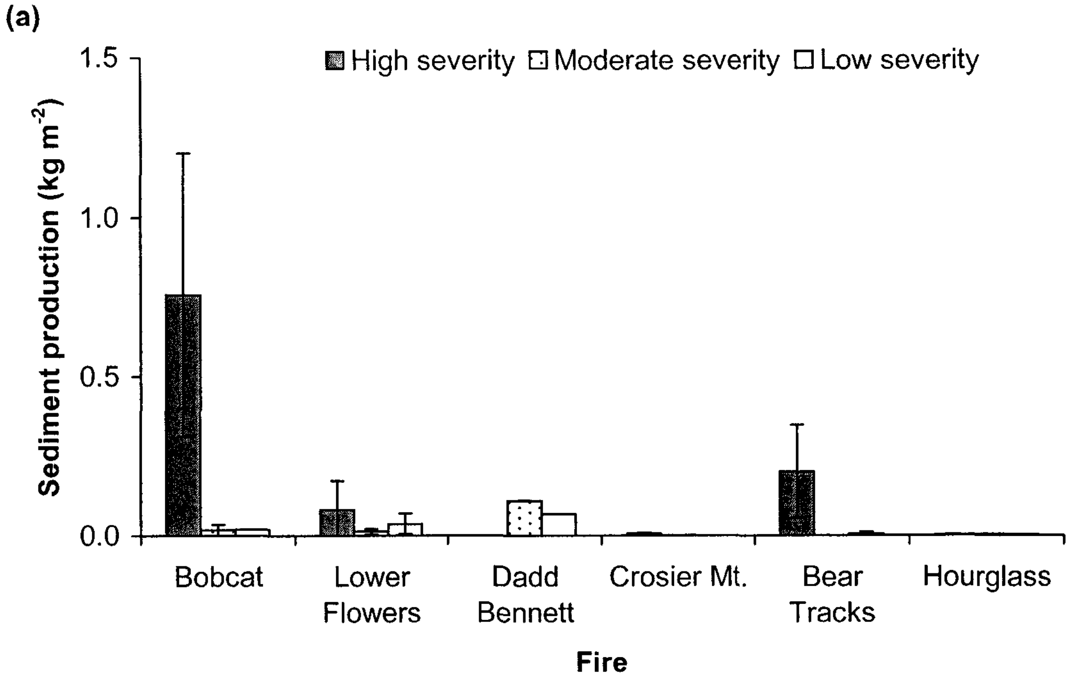


Figure 6. Relationship between area and total sediment production for: (a) high severity sites in the Bobcat, Lower Flowers, and Bear Tracks fires for summer 2000; (b) moderate severity sites for all fires for summer 2000; and (c) high severity sites in the Bobcat, Lower Flowers, and Bear Tracks fires for summer 2001.



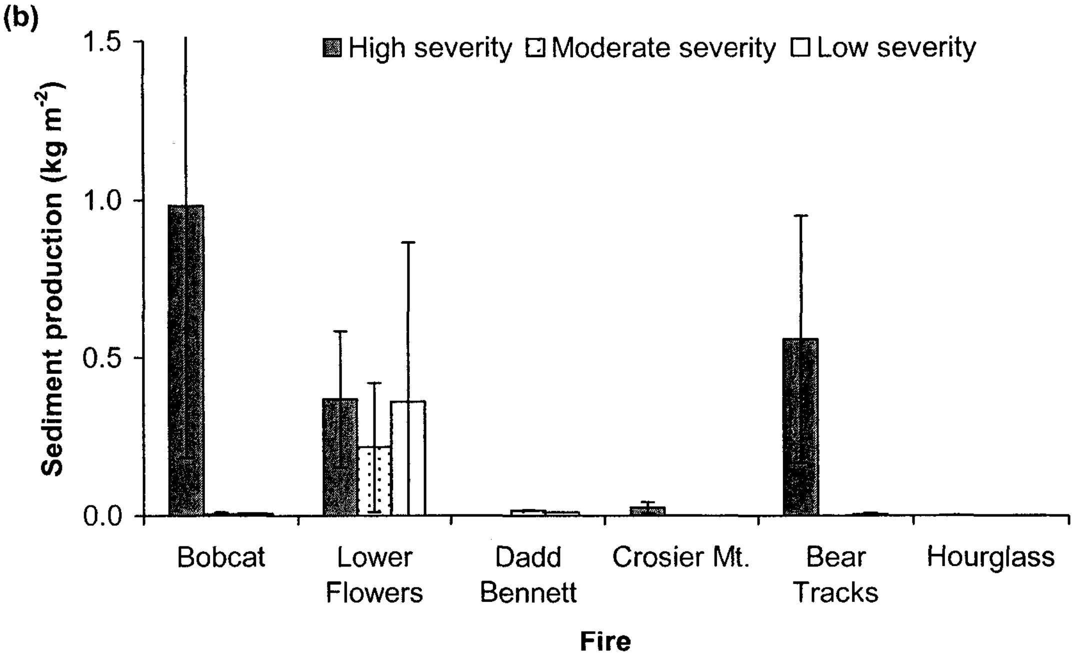


Figure 7. Sediment production per unit area by fire and fire severity for (a) June-October 2000, and (b) June-October 2001. Bars represent one standard deviation.

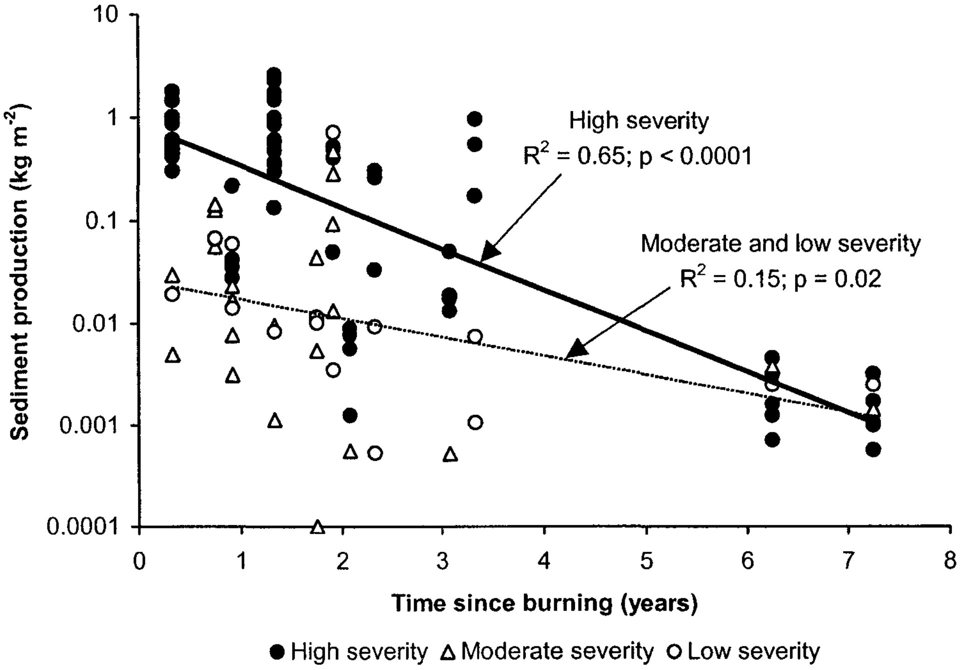
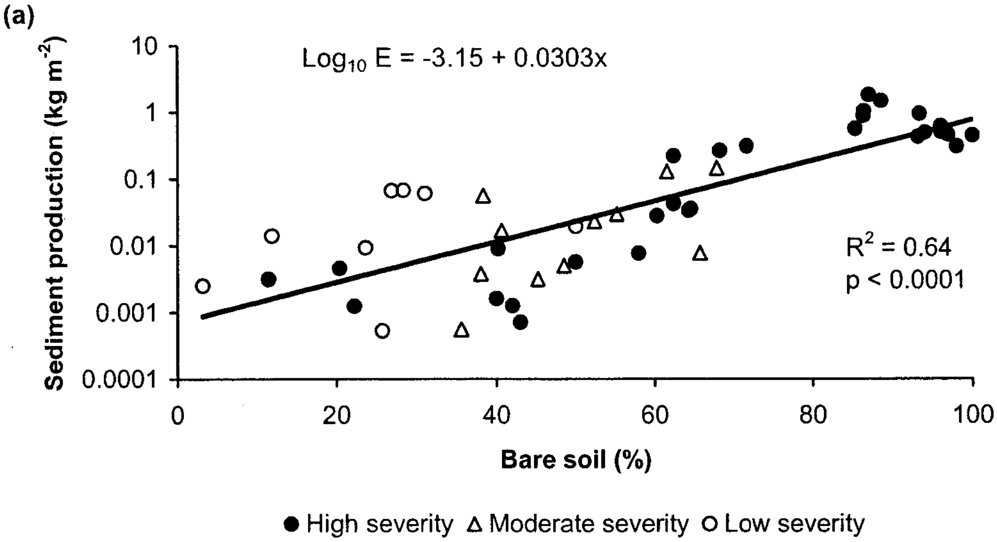


Figure 8. Relationship between sediment production and time since burning by fire severity for summer 2000 and 2001. The solid line represents sites burned at high severity and the dashed line represents the sites burned at moderate and low severity.



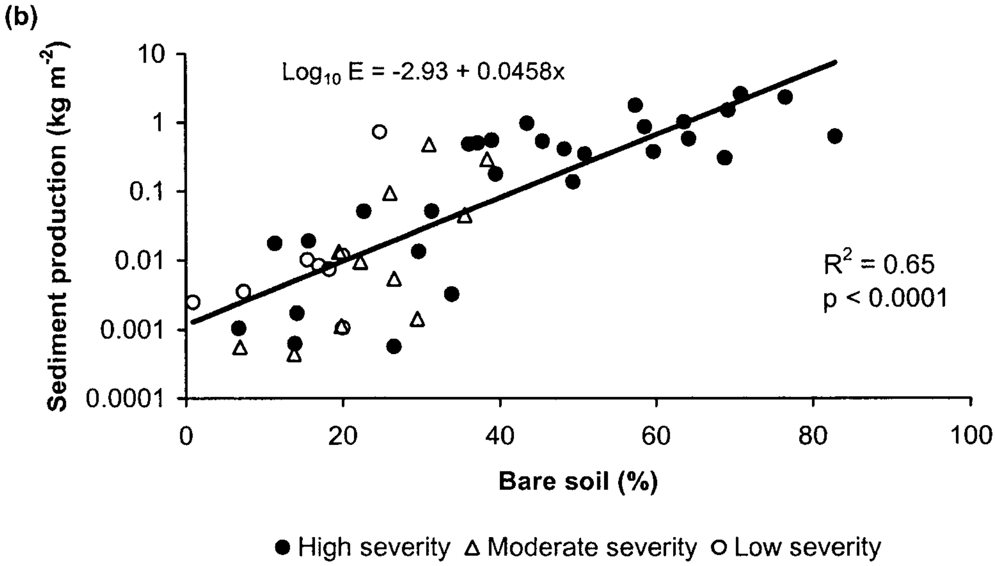


Figure 9. Sediment production versus percent bare soil for: (a) summer 2000, and (b) summer 2001. E is the total sediment yield from June to October in kg m^{-2}, and the slope of the lines in the two figures is significantly different (p=0.01).

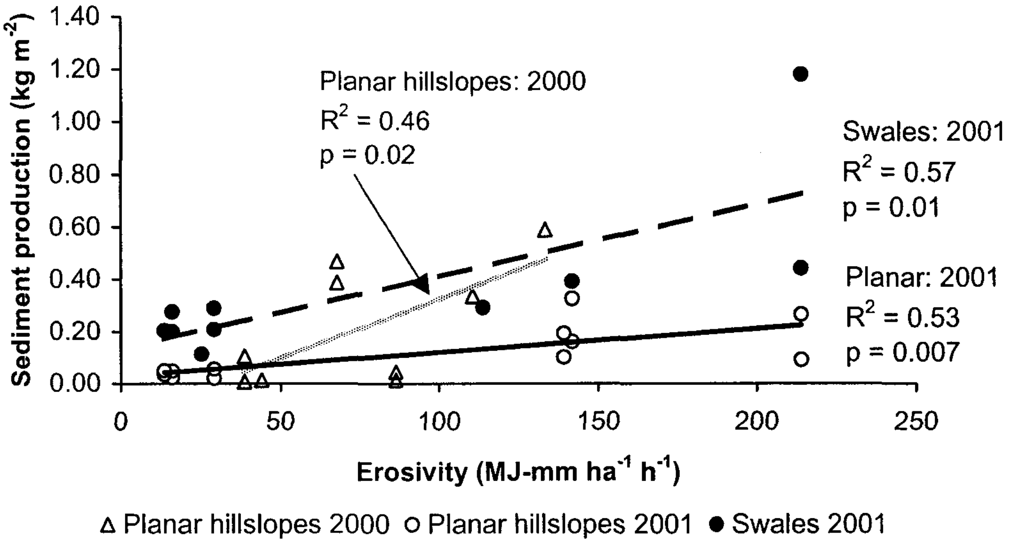


Figure 10. Relationship between rainfall erosivity and sediment production by hillslope position for individual storms from Bobcat Gulch and Jug Gulch at Bobcat fire. The gray line represents planar hillslopes in 2000, the solid black line represents planar hillslopes in 2001, and the dashed line represents the swales in 2001.

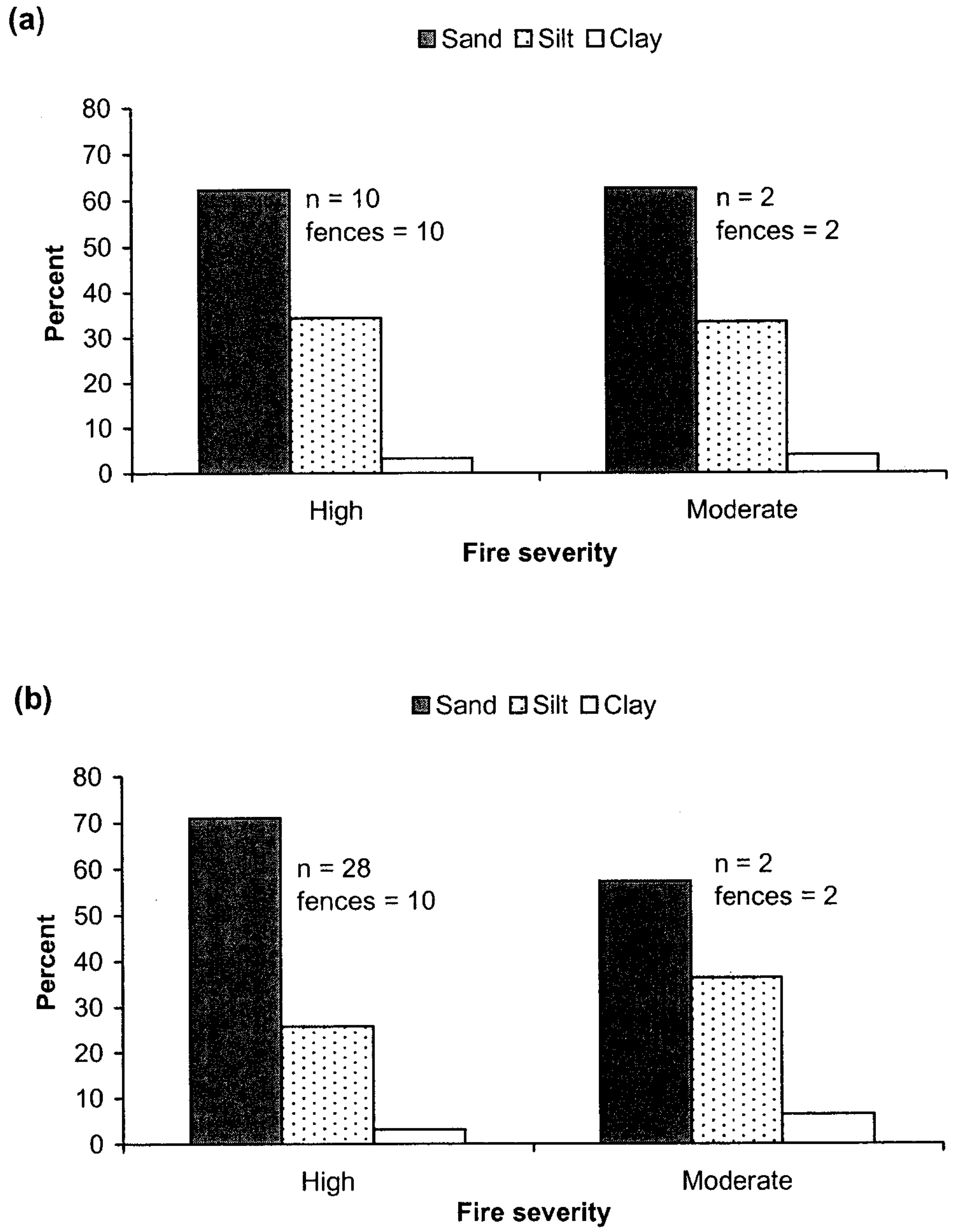


Figure 11. Mean percent sand, silt, and clay for high and moderate severity sites at Bobcat Gulch and Jug Gulch in summer 2000 for: (a) soils, and (b) eroded sediment.

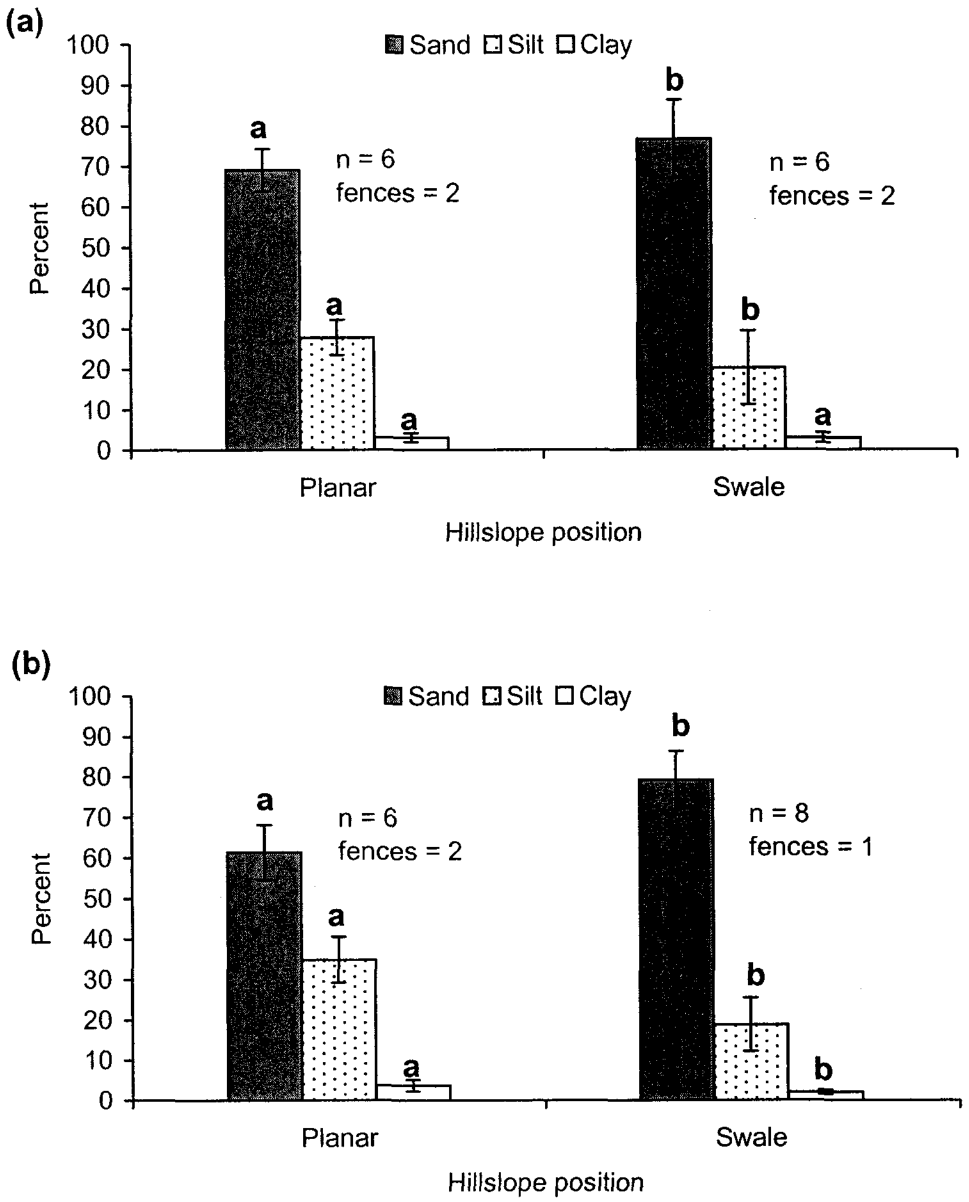


Figure 12. Particle-size distribution of the eroded sediment from planar and swale fences in summer 2001 for: (a) Bobcat Gulch and (b) Jug Gulch. Different letters indicate that the differences between planar hillslopes and swales are significant at $p < 0.05$.

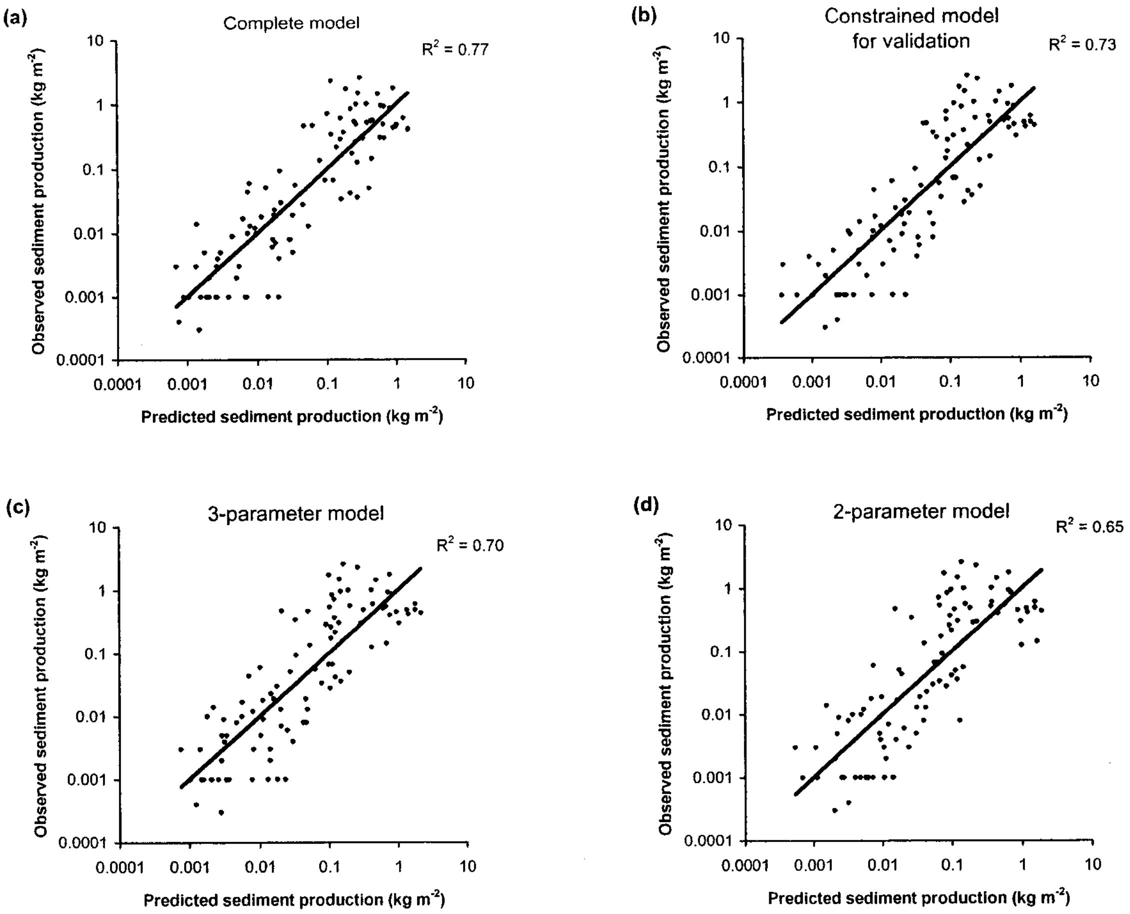
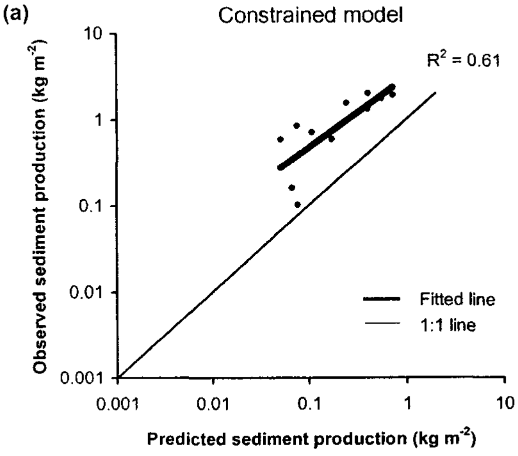
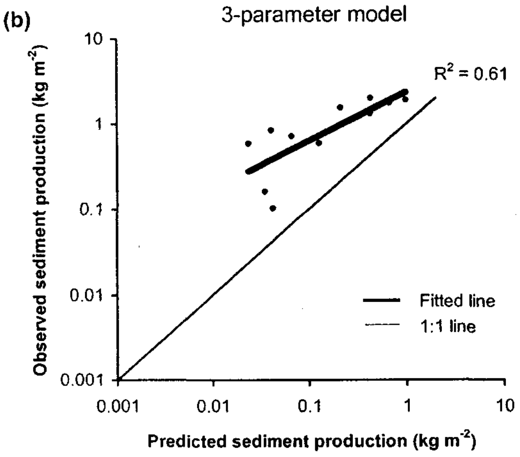


Figure 13. Regression analysis for the observed and predicted sediment production values for: (a) complete model, (b) constrained model for validation, (c) 3-parameter model, and (d) 2-parameter model.





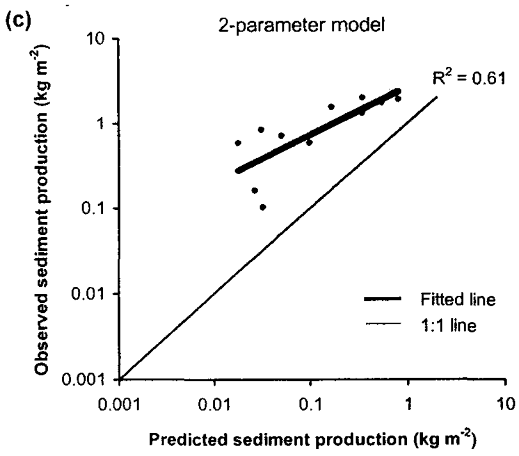


Figure 14. Validation of three different models using an independent set of data for: (a) constrained model, (b) 3-parameter model, and (c) 2-parameter model.

4. USE OF A RAINFALL SIMULATOR TO EVALUATE POST-FIRE RUNOFF AND EROSION RATES OVER TIME, COLORADO FRONT RANGE

4.1. ABSTRACT

There is an urgent need to better understand the persistence of increased runoff and sediment yields after wildfires, and the key controls on recovery rates. This information can help evaluate risk and design mitigation practices. This project was designed to: (1) determine whether there is a significant difference in runoff and sediment yields between the first and second years after burning, (2) assess the dependence of runoff and sediment yields on burn severity, soil water repellency, soil moisture, percent cover, soil texture, and slope; (3) determine the relative importance of rainsplash versus sheetwash erosion in high severity sites, and (4) assess erosion processes by comparing the particle-size distribution of the eroded material to the underlying soil.

Simulated rainfall was applied on twenty-six 1-m^2 plots for one hour at a mean rate of 75 mm h^{-1}. The simulations were conducted in summer 2001 on the Bobcat wildfire and the Lower Flowers prescribed fire in the Colorado Front Range, and the results were compared to the data collected in summer 2000 (Benavides-Solorio and MacDonald, 2001). For high severity sites in the Bobcat wildfire the runoff/rainfall ratio decreased from 66% in the first summer after burning to 46% in summer 2001. For the Lower Flowers prescribed fire, the mean runoff/rainfall ratios in high severity sites decreased from 61% to 52%. Post-fire soil water repellency was the main control on runoff/rainfall ratios.

The mean sediment yield for high-severity sites at the Bobcat wildfire was 1,200 g m^{-2} in the second year after burning and this was not significantly different from the first year. High severity sites produced 7 times more sediment than plots burned at moderate severity, and 27 times more sediment than the low severity and unburned plots. At the Lower Flowers prescribed fire sediment yields from high severity sites decreased from 850 g m^{-2} in 2000 to 350 g m^{-2} in 2001.

Multivariate analysis of both years of data showed that the primary factors affecting sediment yields were percent bare soil, percent silt, and the runoff/rainfall ratio. In 2000 the percent sand increased and the amount of silt and clay decreased over the course of the simulations, and in the high severity sites the eroded material was often finer than the soil matrix. In the second year the eroded material was similar to the soil matrix and there were no clear trends in the particle size distributions over time. Suppressing rainsplash reduced sediment yields by 14-44%.

The results indicate a continuing risk for increased runoff and sediment yields from high intensity storms in areas burned at high severity. Prescribed fires and areas burned at low severity pose much less risk to affect downstream areas.

4.2. INTRODUCTION

By removing vegetation and altering soil surface conditions, forest fires can greatly increase runoff and erosion rates. Runoff following fires is often many times greater than from comparable undisturbed sites (Scott and Van Wyk 1990; Scott 1993;

Inbar *et al.*, 1998). Sediment yields from sites burned at high severity can increase by several orders of magnitude relative to undisturbed areas or areas burned at low severity (Inbar *et al.*, 1998).

The problem is that changes in runoff and erosion are spatially variable and therefore difficult to predict at a watershed scale. Measurements at the watershed scale can provide information about overall or average changes, but it is difficult to relate the observed changes to the factors that might be causing those changes. In contrast, studies at smaller scales can better identify the processes and controlling factors in runoff and sediment production. Rainfall simulators allow a much more controlled study than is possible with natural rainfall events, especially given the uncertainty and spatial variability of summer convective storms in the Colorado Front Range. Applying a specified rainfall is important because rainfall intensity is a strong control on runoff rates (Haan *et al.*, 1994) and sediment production (Renard *et al.*, 1997). In the Colorado Front Range low intensity rainfalls did not produce much erosion after a severe fire in spruce-fir and lodgepole pine forests (Striffler and Mogren, 1971), whereas high-intensity storms caused very large increases in runoff and sediment yields after a 1996 fire (Moody and Martin, 2001a).

Fire severity is another important control on runoff and erosion rates, as this affects the amount of ground cover and other important properties (Wells *et al.,* 1979; DeBano *et al.*, 1998). In areas burned at high severity, the complete loss of the litter and organic matter at the soil surface can lead to soil sealing and greatly increase the soil erodibility (Dyrness and Youngberg, 1957; Durgin, 1985; Garcia-Oliva *et al.*, 1999). Decreases in infiltration can be related to the formation of a post-fire water repellent layer

(Burch *et al.*, 1989; Robichaud, 2000; DeBano, 2000; Shakesby *et al.,* 2000). Another factor contributing to the observed increase in post-fire erosion rates is the increase in kinetic energy from both raindrop impact and overland flow (Wischmeier and Smith, 1958; Evans, 1980; Meyer, 1981). Overland flow can be either thin laminar flow (Meyer, 1981) or concentrated flow in rills or gullies (Thornes, 1980). Rills and gullies are indicators of serious surface erosion and can have much higher erosion rates than interrill areas (Foster, 1982). The magnitude of the changes in runoff and erosion also are affected by the magnitude of subsequent rainfall events.

The most dramatic changes in runoff and erosion occur in the first year or two after burning (Brown, 1972; DeByle and Packer, 1972; Campbell *et al.,* 1977; Scott and Van Wyk, 1990; Keller *et al.,* 1997; Inbar *et al.,* 1998; Prosser and Williams, 1998; Cerda, 1998; Robichaud and Brown, 1999; Pierson *et al.*, 2001). In a few cases significant post-fire increases in runoff can persist for up to six years (Helvey, 1980).

Some factors influencing the recovery rate of runoff and erosion are the weakening of post-fire soil water repellency and increasing ground cover (Cerda, 1998; Inbar *et al.*, 1998). Low sediment yields were measured from high-intensity rainfall simulations in a hardwood forest, and this result was attributed to the protection given by the residual of 1-3 cm of root mat after burning (Shahlaee *et al.*, 1991). Morris and Moses (1987) also recognized that increasing ground cover reduced sediment yields after fires in the Colorado Front Range.

Rainfall simulations are particularly useful for studying runoff and erosion processes in short-duration, high-intensity storms. Rainfall simulations on small plots in the first season (2000) after burning found that runoff/rainfall ratios in high severity sites were only 15-25% larger than for low severity and unburned sites (Benavides-Solorio and MacDonald, 2001). Simulations on high severity sites in the 6-year old Hourglass fire yielded very low runoff ratios. Higher runoff/rainfall ratios were associated with stronger soil water repellency and lower soil moisture values. Sediment yields from the high severity sites in the recent fires averaged 1,280 g m^{-2}, and were 16-30 times larger than the sediment yields from low severity and unburned sites. Percent bare soil explained about 80% of the variability in sediment yields. Other factors affecting sediment yields included soil water repellency and soil moisture (Benavides-Solorio and MacDonald, 2001).

To better understand the changes in runoff and erosion over time, a second year of rainfall simulations were conducted on the Bobcat wildfire and Lower Flowers prescribed fire. The objectives were: (1) determine whether there is a significant decline in runoff and sediment yields between the first and second years after burning; (2) assess the dependence of runoff and sediment yields on burn severity, soil water repellency, soil moisture, percent cover, soil texture, and slope; (3) determine the relative importance of rainsplash versus sheetwash erosion in high severity sites; and (4) compare the particle-size distributions of the eroded material to the native soil.

4.3. METHODS

4.3.1. Study sites

The study sites were on the Bobcat wildfire and Lower Flowers prescribed fire in the northern Colorado Front Range. Both fires were in the fire-prone, mid-elevation zones dominated by ponderosa pine (*Pinus ponderosa*) and lodgepole pine (*Pinus* *contorta*) (Figure 1). The Bobcat fire burned 4,300 ha in June 2000 (Table 1). The burned area was dominated by ponderosa pine, but there were also small stands of lodgepole pine and Douglas fir. Approximately 45% of the burned area was classified as high severity, 25% as moderate severity, and 30% as low severity (USDA Forest Service, 2000).

The Lower Flowers fire was a 300 ha prescribed burn that took place in November 1999 (Table 1). The burned area was dominated by ponderosa pine with small portions of lodgepole pine. Most of the area was burned at moderate to low severity, although there were some small (less than 0.1 ha) patches of high severity.

The second year of rainfall simulations were conducted close to the sites used in the first year. Simulations were not continued on the 1994 Hourglass fire because the low runoff rates and sediment yields measured in summer 2000 suggest that this site had already largely recovered to pre-burn conditions.

The study plots within each fire were stratified by burn severity because the condition of the litter and soil after burning is a primary control on post-fire runoff and erosion rates (DeBano *et al.*, 1996). Burn severity was classified following the criteria developed by Wells *et al.* (1979) and applied by the USDA Forest Service (1995). High severity sites are characterized by complete consumption of the organic layer and visible alteration of the structure and color of the uppermost layer of the mineral soil. In moderate severity sites, the litter and duff layer is either consumed or charred, but the underlying mineral soil is not visibly altered. In low severity sites, the litter and duff layers are scorched but not altered over their entire depth, and there is no visible effect on the underlying mineral soil.

4.3.2. Rainfall simulations

Twenty-six rainfall simulations were conducted in 2001 on 1 m^2 plots in densely forested areas (Table 1). More simulations were conducted on areas burned at high severity because these areas are of greatest concern and generally have the greatest variability in absolute terms. More plots were located in the Bobcat fire because it had better road access and hence a greater availability of sites burned at high and moderate severity.

Rainfall was applied to each plot with a Purdue-type rainfall simulator using an oscillating nozzle that was typically set at 2.9-3.0 m above the center of the plot (Meyer and Harmon, 1979; Neibling *et al.*, 1981; Williams *et al.*, 1995) (Figure 2). For each plot a 1 m^2 metal frame was inserted to a depth of approximately 5 cm, and a metal trough was installed at the lower edge to collect the runoff (Figure 3). The inside edges were sealed with native soil mixed with a small amount of water and bentonite.

Each simulation consisted of a single 60-minute application of rainfall at a constant intensity. The plots were not wetted prior to the simulation because the storm events of greatest concern are the summer convective storms that often occur under dry antecedent (on dry soil) conditions. The mean intensity of the applied rainfall was 75 mm hr^{-1}, although the rate ranged from 68 to 84 mm hr^{-1}. This mean rainfall rate was selected because it is comparable to the maximum 1-hour intensities that occur in the Front Range (Miller *et al.*, 1973; Moody and Martin, 2001a). The rate and distribution of rainfall in each simulation was initially assessed using seven rain gauges placed around the perimeter of the plot. For most of the simulations a more accurate rainfall rate was determined by covering the plot at the end of the simulation with a plastic sheet and measuring the runoff rate while the rainfall simulator was run for an additional ten minutes.

Runoff rates were measured every minute during the simulation by collecting the runoff for 30 seconds and transferring it to a graduated cylinder. Every second runoff sample was kept in a 500 or 1000 mL plastic bottle. The sample bottles were weighed to determine the amount of runoff, and then the sample was put through a 5 μm paper filter to trap the sediment. The filters and sediment were dried at 105 °C for 24 hours or until a constant weight was obtained. The mass of sediment was calculated from the difference between the initial weight of the filter paper and the weight of the filter paper plus sediment. The sediment was scraped from the filter and composited as necessary for particle-size analysis using the hydrometer method (Gee and Bauder, 1986). Any sediment remaining in the runoff trough after the simulation was also collected, dried, and weighed to determine the total sediment yield. The particle-size distribution of this sediment was also determined. After each simulation the surface of the plot was excavated to observe the depth and extent of infiltration. The dependent variables derived from these data included the time to runoff, equilibrium runoff rate, runoff/rainfall ratio, duration of runoff after the simulation stopped, mean sediment concentration, and total sediment yield.

The measured independent variables for each plot included percent cover, slope, soil water repellency, antecedent surface soil moisture, and soil particle-size distribution. Percent cover was assessed by placing a 10 x 10 cm grid over the plot and classifying the cover as live vegetation, rock, litter, woody debris, pine cones, or bare soil at each of the 81 points where the grid lines crossed. Plot slope was measured with a clinometer.

Soil water repellency was assessed by measuring the water drop penetration time (WDPT) (DeBano, 1981) in three pits around the perimeter of each plot. At each pit the time for at least three drops of water to infiltrate was measured at the surface and each 1-cm increment to a depth of 5 cm. The maximum time of observation was 120 seconds. Because soil water repellency at the surface could affect the amount of runoff and erosion, soil water repellency measurements began at the surface of the organic layer for the unburned and low severity plots, and at the top of the ash layer in the plots burned at moderate or high severity.

Antecedent soil moisture was determined gravimetrically (Gardner, 1986) from three soil samples taken at a depth of 0-5 cm from around the perimeter of the plot. The three samples were homogenized and separated into two replicate samples. The fraction coarser than 2 mm was determined by sieving, and the texture of the fraction finer than 2 mm was determined using the hydrometer method (Gee and Bauder, 1986). Organic matter larger than 2 mm was removed manually. The fraction smaller than 2 mm was heated to 450 °C for 4-5 hours to remove the organic matter (Ben-Dor and Banin, 1989; Cambardella *et al.*, 2001). Concentrated hydrogen peroxide was then added to eliminate the residual aggregation of soil particles due to organic matter (Gee and Bauder, 1986). Similarly, the particle-size distribution of the sediment obtained from the trough and runoff samples was determined when at least 40-50 g of sediment were available.

One simulation in each fire was stopped before the end of 60 minutes because the nozzle clogged and produced an uneven rainfall distribution. Plot 3 on the Bobcat wildfire was stopped at 51 minutes, and plot 3 at Lower Flowers was stopped at 47 minutes (Table 4). Since the other plots showed relative little change in runoff and erosion rates in the last 15 minutes of the simulation, the data from these two plots were simply extrapolated to 60 minutes.

Three of the simulations on high severity sites in the Bobcat wildfire were used to determine runoff and erosion rates when rainsplash was eliminated. For these simulations a 1 mm mesh screen was suspended 5 cm above the surface. Because the screen absorbed the kinetic energy of the raindrops and the simulated rainfall only dripped through, overland flow was the primary source of energy for soil detachment and transport. The data from each of these three plots were compared to a similar control plot to yield three pairwise comparions.

4.3.3. Statistical analysis

The runoff data were normally distributed and no transformations were needed. For sediment yields a lognormal transformation was needed to normalize the data. One-way ANOVA and t-tests were used to determine significant differences in pairwise comparisons between fires and between years at $p \leq 0.05$. The effect of fire severity was assessed by general linear models (GLM) (SAS, 1999). Multiple comparisons through least squares means (LSmeans) were used to determine which means were significantly different. The LSmeans were adjusted by Tukey-Kramer, which can be used for unequal sample size and controls for a maximum experimentwise error rate (SAS, 1999; Ott and Longnecker, 2001).

Simple linear regression was used to assess the relationship between each independent variable and the different dependent variables related to runoff and sediment yields. Forward, backward, and stepwise regressions were used to assess the multivariate relationships between runoff, sediment yields, and the independent variables of rain intensity, runoff/rainfall ratios, total runoff, percent bare soil, time since burning, soil water repellency, soil texture, soil moisture, and slope. The best model was chosen by the combination of high R^2 and low Mallows' Cp (Ott and Longnecker, 2001). Each of the variables included in the resulting models was significant at $p \leq 0.05$.

4.4. RESULTS

4.4.1. Plot characteristics

The second year of rainfall simulations were done under the driest conditions possible, but the Bobcat sites were generally wetter in the summer of 2001 than in summer 2000. The mean soil moisture values for the Bobcat simulations in 2001 were 8% for high severity sites, 11% for the moderate severity sites, and 6% for the low severity and unburned sites (Table 2). The corresponding mean values in 2000 were all 1-2%.

In contrast, soil moisture values at Lower Flowers were lower in 2001 than in 2000. In 2001 the mean soil moisture values in high, moderate, and low severity and unburned sites were 6%, 5%, and 4%, respectively (Table 2). In 2000 the mean soil moisture values for these same severity classes were 15%, 24%, and 6%.

The amount and type of percent ground cover in 2001 was similar in both fires (Table 2; Figure 4). In each fire the amount of ground cover was inversely related to fire severity, although there was considerable variability within both the high and low severity classes. Low severity sites also had high variability. In the Bobcat fire, the mean percent cover in high severity sites was 22% and the range was from 0 to 50%. After removing one outlier, the mean percent bare soil was 89% in 2000 and 78% in

2001. Most of the change from 2000 to 2001 can be attributed to the 16% increase in live vegetation (Figure 4a). The mean percent bare soil in the moderate and low severity/unburned sites was only 12% and 1%, respectively.

For high severity sites in the Lower Flowers fire, the percent bare soil averaged 73% (Table 2) as compared to 95% in 2000. In contrast to the Bobcat fire, most of the cover on these plots was provided by litter rather than vegetative regrowth, as the prescribed fire generally did not consume the canopy and there was substantial needle cast (Figure 4b). The percent bare soil in the moderate and low severity/unburned sites at Lower Flowers averaged 21% and 5%, respectively, and these values were similar to the values measured in summer 2000.

Soil water repellency was strongest at 1-3 cm below the surface at both sites (Figure 5). Water drop penetration times were generally longer at Lower Flowers, and this is probably due to the higher fuel loadings, slower rate of fire spread, and lower soil moisture values (Huffman *et al.*, 2001). There was surprisingly little difference in soil water repellency with fire severity, and this may be partly due to the relatively rapid weakening of the post-fire water repellency, especially in high severity sites (Huffman and MacDonald, in preparation). When compared to data from summer 2000, the soil water repellency was substantially weaker in the high severity sites at Lower Flowers, but was slightly stronger in moderate severity sites (Figure 4b). When compared to summer 2000, the measured soil water repellency in the Bobcat fire was much weaker for all three severities, with the largest decreases being in the sites burned at high and moderate severity.

The mean slope for all plots in year 2001 was 21% as compared to 25% in 2000 (Table 2). In general, slopes decreased slightly with decreasing burn severity, but the mean slope for each severity class was very similar between fires.

4.4.2. Runoff

The runoff hydrographs were consistent in their overall shape as they generally showed a rapid initial increase in runoff, a long period of equilibrium runoff, and a rapid decline once rainfall ceased (Figure 6). In most cases, the runoff rate was relatively constant after about 5-10 minutes, but in a few cases the runoff slightly decreased (e.g., Figure 6d) or increased over time (e.g., Figure 6c).

The runoff rates observed in 2001 were more variable than in 2000, particularly in the case of the Bobcat fire. The equilibrium runoff rates for high severity sites in the Bobcat fire ranged from 21 mm h^{-1} to 58 mm h^{-1}, with a mean of 39 mm h^{-1} (Table 3). The mean runoff/rainfall ratio in high severity sites in the Bobcat fire was 46% in 2001 as compared to 66% in 2000, but the range in 2001 was from 27% to 67%. The time to initial runoff was typically around 150 s, but this varied from 80 s to 230 s. The duration of runoff after the simulation ceased averaged 190 s with a range of 160-240 s. (Table 3).

The equilibrium runoff rate for the moderate severity plots in the Bobcat fire was 34 mm h^{-1}, or 13% less than the high severity sites (Table 3). The runoff/rainfall ratio of 40% also was 13% less than the high severity plots. On average, the plots burned at moderate severity took 46% longer to produce runoff, and produced runoff for 32% longer once the simulated rainfall ceased (Table 3).

In the low severity and unburned plots the equilibrium runoff rate was only 28 mm h^{-1}, and the average runoff/rainfall ratio of 36% also was lower than in the plots burned at high and moderate severity (Table 3). The time to initial runoff was slightly less than for the moderate severity sites, whereas the duration of runoff after the rainfall ceased was 305 s, or 21% longer than for the plots burned at moderate severity. For the Bobcat fire in 2001 there were no significant differences in any of these runoff variables with fire severity.

The runoff data were not as variable at Lower Flowers, and there were some surprisingly patterns in the runoff characteristics with fire severity. The plots burned at moderate severity produced slightly more runoff than either of the other two severity classes, while the runoff rates for the low severity/unburned sites were similar to the sites burned at high severity (Table 3). For each severity class there was more runoff than from the corresponding sites in the Bobcat fire.

The time to initial runoff at Lower Flowers followed the same pattern as the equilibrium runoff values, with the moderate severity sites having the shortest time to runoff (170 s) and the low severity/unburned sites having the longest (205 s). The duration of runoff after the cessation of the rainfall was generally longer than at Bobcat, and the largest values were in the moderate and low severity/unburned classes (Table 3). The smaller sample sizes and variability between plots meant that there were no statistically significant differences between severities for any of the runoff parameters measured at Lower Flowers. Comparisons between the Bobcat and Lower Flowers sites by severity were generally not significant except for the difference in runoff rates for moderate severity sites (p=0.02).

4.4.3. Effect of soil water repellency, soil moisture, percent bare soil, and slope on runoff ratios

Runoff/rainfall ratios significantly increased with increasing soil water repellency (Figure 7a). This relationship was significant for the pooled 2001 data at depths of 1, 2 and 3 cm (R^2=0.35, p=0.003; R^2=0.23, p=0.019; and R^2=0.20, p=0.03; respectively), although the WDPT at 1 cm had the strongest relationship. Stratifying the data by fire severity increased the R^2 for the WDPT at 1 cm to 50% for high severity sites (p=0.03) and 91% for moderate severity sites (p<0.001) (Figure 7b). For the low severity and unburned sites there was no significant relationship between runoff/rainfall ratios and the WDPT at any depth.

Antecedent soil moisture was not significantly related to runoff/rainfall ratios when the 2001 data were pooled. After stratifying by severity, runoff/rainfall ratios significantly increased with increasing soil moisture for high severity sites (R^2=0.47; p=0.04), and decreased with increasing soil moisture for sites burned at moderate severity (R^2=0.88; p=0.002) (Figure 8a). This apparent contradiction can be explained by the fact that water repellency was not significantly related to soil moisture in the high severity sites, whereas soil water repellency significantly declined with increasing soil moisture in moderate severity sites (R^2=0.82; p=0.005) (Figure 8b). Recent work suggests that soil water repellency is more readily eliminated by higher soil moisture values in sites burned at moderate severity than in sites burned at high severity (Huffman and MacDonald, in preparation).

For sites burned at high severity, the rainfall/runoff ratio significantly increased with increasing percent bare soil (R^2=0.45; p=0.05) (Figure 9a). This relationship can be explained by the relatively rapid decrease in soil water repellency in high severity sites with increasing percent ground cover (R^2=0.50; p=0.03) (Figure 9b). Because most of the cover in sites burned at high severity is from vegetative regrowth, this implies that vegetative regrowth may be and indicator in the reduction of postfire soil water repellency.

4.4.4. Comparisons between years and analysis of the pooled data from 2000 and 2001

Runoff/rainfall ratios decreased at the Bobcat fire from 2000 to 2001 (Figure 10a). The mean runoff/rainfall ratios for high severity sites decreased from 66% in 2000 to 46% in 2001, or a decline of 30% (p=0.02). Similarly, the mean values for moderate severity sites decreased from 58% in 2000 to 40% in 2001, or 31% (p=0.02). The mean runoff/rainfall ratio in low severity/unburned sites decreased from 55% in 2000 to 36% in 2001 (Figure 10a), but this was not significant (p=0.14) due to the high variability between plots.

At Lower Flowers the mean runoff/rainfall ratio in high severity sites decreased from 61% in 2000 to 53% in 2001, but this was not significant (Figure 10b). The other two severities showed small but insignificant increases in runoff/rainfall ratios from 2000 to 2001 (Figure 10b).

When the data from both years were pooled, soil water repellency was positively and significant correlated with runoff/rainfall ratios (R^2=0.27, p=0.0003) (Figure 11a). This relationship was substantially stronger in high severity sites than the entire data set (R^2=0.69, $p<0.0001$) (Figure 11a). For both the pooled data and the high severity sites the strongest relationship was with the WDPT at 2 cm. The moderate severity sites also showed a strong relationship between soil water repellency and the runoff/rainfall ratio, but in these sites the relationship was strongest at 1 cm (R^2=0.61, p=0.001). The low severity/unburned sites did not have a significant relationship between runoff/rainfall ratios and the WDPT at any depth.

Runoff/rainfall ratios were not related to percent bare soil for either the pooled data or high severity sites, but the lack of a relationship is largely due to one outlier (Figure 11b). The outlier is from a simulation on a high severity site in July 2000, and the plot was in a slight depression with a relatively deep layer of wind-deposited ash. This resulted in a high runoff/rainfall ratio but a very low percent bare soil. When this outlier was removed, runoff/rainfall ratios in high severity sites significantly increased with increasing percent bare soil (R^2=0.56, p=0.0006) (Figure 11b).

Rainfall intensity was not significantly related to runoff/rainfall ratios for the pooled data, but the high severity sites tended to have a higher runoff/rainfall ratio with increasing rainfall application rates (R^2=0.35, p=0.01). There was no relationship between the rainfall application rate and runoff/rainfall ratios for either the moderate severity sites or the low severity/unburned sites. Runoff/rainfall ratios were not significantly correlated with slope or antecedent soil moisture for either the pooled data or the data when stratified by fire severity.

Multivariate analysis indicated that soil water repellency was the only significant variable for explaining runoff/rainfall ratios, and this was true for both the pooled data and the high severity sites. However, the R^2 was only 0.27 suggesting that other factors are involved. Univariate analyses showed that infiltration rates on each plot were controlled by same factors as the runoff/rainfall ratios. Similarly, multivariate analysis showed that only the soil water repellency was significantly related to infiltration rates.

4.4.5. Sediment yields

Most sedigraphs showed a consistent pattern of a sharp rise in sediment concentrations almost immediately after runoff began (Figure 12). In all cases peak sediment concentrations occurred between 3 and 7 minutes after rainfall began. After the peak there typically was a sharp decrease in sediment concentrations, and in most cases the sediment concentrations stabilized 4-8 minutes after the peak (e.g., Figure 12). In some cases the sediment concentrations declined over a much larger period of time (Figure 12a), and for three simulations on high severity sites there was not a clear sedigraph pattern because much of the sediment was trapped in the trough.

For high severity sites in the Bobcat fire, the peak sediment concentrations varied from 30 to more than 100 g L^{-1}. Sediment concentrations generally stabilized at about 20-40 g L^{-1}, and the overall mean sediment concentration for high severity sites was 32 g L^{-1}.

Peak sediment concentrations for moderate severity sites on the Bobcat fire were around 15 g L^{-1}, and then declined to a stable value of about 5 g L^{-1} (Figure 12b). The mean sediment concentration in the moderate severity sites was only 6.3 g L^{-1} or 20% of the value from high severity sites (Table 4). The mean sediment concentration for the plot burned at low severity was 3.9 g L^{-1} or 6% of the mean from high severity sites, while the mean from the three unburned plots was only 1.2 g L^{-1} or less than 4% of the mean value from the high severity plots (Table 4).

Although the sedigraphs at Lower Flowers had a similar shape to the sedigraphs from the Bobcat fire (Figure 12), the mean peak sediment concentration for high severity sites was 22.7 g L^{-1}, or 30% less the corresponding value from the Bobcat fire. The mean sediment concentration from high severity sites was 9.3 g L^{-1}, or just 28% of the mean sediment concentration from high severity sites in the Bobcat fire (Table 4).

The moderate severity sites at Lower Flowers had peak values of less than 10 g L^{-1} and a mean sediment concentration of 3.1 g L^{-1} (Table 4). Low severity and unburned sites had a mean concentration of 0.9 g L^{-1}. The mean sediment concentrations for both the moderate and low severity/unburned sites at Lower Flowers were slightly less than half of the corresponding values from the Bobcat fire.

Sediment yields followed the same patterns as the mean sediment concentrations because the amount of runoff was relatively similar. However, the variation in sediment yields tended to be greater than the variation in sediment concentrations because sediment yields tended to increase with increasing runoff. Thus the mean sediment yield from high severity sites in the Bobcat fire was 1,228 g m^{-2}, but the standard deviation was 860 g m^{-2} (Table 4; Figure 13). The moderate severity sites in the Bobcat fire had a mean sediment yield of 177 g m^{-2} or 14% of the value from high severity sites, although the standard deviation for these sites was only 7 g m^{-2}. The sediment yield from the low severity site in the Bobcat fire was 98% g m^{-2} or 8% of the value from high severity sites. The unburned sites produced only 27 g m^{-2}, or 2% of the value from high severity sites (Table 4). The 7-fold difference between high and moderate severity sites in the Bobcat fire was highly significant ($p=0.005$), as was the 3-fold difference between the moderate severity and the low severity/unburned sites ($p=0.01$).

At Lower Flowers the mean sediment yield from the high severity sites was 389 g m^{-2}, or 32% of the mean value from high severity plots on the Bobcat fire (Figure 13; Table 4). For moderate severity sites the mean value was 139 g m^{-2}, or 36% of the value from high severity sites, and this difference was significant at p=0.02. The mean sediment yield from low severity and unburned sites at Lower Flowers was 34 g m^{-2} (Table 4), and the 4-fold difference between moderate and low severity/unburned sites was significant at p=0.004.

The mean sediment yield from high severity sites in the Bobcat fire was three times the value from the corresponding sites at Lower Flowers, but this difference was only marginally significant (p=0.05) due to the high variability between plots (Table 4; Figure 13). For the other two severity classes the sediment yields from the Bobcat fire were about 30% higher than at Lower Flowers, but the small sample size and variability between plots meant that neither of these differences was statistically significant.

4.4.6. Effect of soil water repellency, antecedent soil moisture, percent bare soil, percent silt, runoff/rainfall ratios, and slope on sediment yield

The relationship between soil water repellency at 2 cm and sediment yields was significant for the sites burned at high severity (R^2=0.51; p=0.03) (Figure 14a). If only the six simulations on high severity sites in the Bobcat fire are considered, the R^2 increases to 91% (p=0.003) (Figure 14a). The relationship between soil water repellency and sediment yields was not significant when the data from all severities was pooled.

Antecedent soil moisture was significantly related to sediment yields from high severity sites (R^2=0.48; p=0.04) (Figure 14b), but not when all the data were pooled. The higher sediment yields with increasing soil moisture result in part from the higher runoff rates in high severity sites with increasing soil moisture (Figure 8a).

The variable most strongly related to sediment yields was percent bare soil. This nonlinear relationship was highly significant for the pooled data (R^2=0.79; $p<0.0001$) (Figure 14c) and for high severity sites (R^2=0.61; p=0.01).

Percent silt was slightly related to sediment yields (R^2=0.20; $p<0.003$) for the pooled 2001 data, and highly correlated to sediment yields from the high severity sites (R^2=0.77; $p<0.002$) (Figure 14d). The poor relationship for the pooled 2001 data is probably due to the much stronger effect of percent cover in reducing sediment yields from moderate severity and low severity/unburned sites.

Runoff/rainfall ratios were not related to sediment yields when the 2001 data were pooled. For high severity sites the runoff/rainfall ratios were positively correlated with sediment yields (R^2=0.28), but this relationship was significant only at p=0.14.

Sediment yields also increased with increasing slope (R^2=0.23, p=0.02). As discussed in Benavides-Solorio and MacDonald (2001), this relationship largely results from the fact that the steeper slopes tended to burn at high severity.

4.4.7. Comparisons between years and analysis of the pooled data from 2000 to 2001

Comparisons between 2000 and 2001 showed little evidence of a decline in sediment production rates from the Bobcat fire for any of the three severity classes (Figure 15a). In high severity sites the mean sediment yields were 1,280 g m^{-2} in 2000 and 1,228 g m^{-2} in 2001, or a decline of only 4%. The mean sediment yield for moderate severity sites were nearly identical —179 g m^{-2} in 2000 and 177 g m^{-2} in 2001. The highest relative difference was for the low severity and unburned sites, where the mean sediment yield declined from 80 g m^{-2} in 2000 to 45 g m^{-2} in 2001, but this difference was not statistically significant (Figure 15a).

At Lower Flowers there was more evidence for a decline in sediment yields over time in the sites burned at high severity, but not for the other two severity classes (Figure 15b). For the high severity sites the mean sediment yield declined from 850 g m^{-2} in 2000 to 389 g m^{-2} in 2001, or about 54%. However, the small sample sizes and high variability in 2000 meant that this difference was not significant ($p=0.14$). Sediment yields slightly increased in the moderate severity sites, but this was not statistically significant despite the relatively low variability. Sediment yields in the low severity and unburned sites were about 30 g m^{-2} in both years (Figure 15b).

When the data from both years were pooled, the log-transformed sediment yields were highly correlated with percent bare soil ($R^2=0.75$, $p<0.0001$). When stratified by fire severity, the high severity sites had a surprisingly poor relationship between sediment yields and percent bare soil ($R^2=0.25$, $p=0.04$), and this was largely due to the outlier with high ash cover and a high sediment yield. When this point was removed, the relationship between sediment yields and percent bare soil slightly improved for the pooled data ($R^2=0.81$, $p<0.0001$) and greatly improved for high severity sites ($R^2=0.55$, $p=0.0007$) (Figure 16a). The other two severity classes did not show a significant relationship between sediment yields and percent bare soil.

Slope was significantly correlated with sediment production for the complete data set ($R^2=0.41$, $p<0.0001$) because the steeper plots generally burned at high severity (Figure 16b). For high severity sites the relationship between sediment yield and slope was only significant at $p=0.07$ ($R^2=0.19$). The other two severity classes showed no relationship between slope and sediment yields.

The intensity of the simulated rainfall was significantly related to sediment production for the pooled data (R^2=0.29, p=0.0002), but not when the data were stratified by fire severity (Figure 16c). The soil water repellency values at the different depths were not significantly related to sediment yields for the pooled data. However, the soil water repellency at 2 cm was significantly related to sediment yields for the high severity sites (R^2=0.25, p=0.03). Antecedent soil moisture was not significantly related to sediment production for either the pooled data or any of the severity classes.

The percent of silt in the soils was not related to sediment yields for the pooled data, but percent silt was strongly related to sediment yields for the high severity sites (R^2=0.65, $p<0.0001$) (Figure 16d).

Multivariate analyses based on both years of data —including the 1994 Hourglass fire— selected percent bare soil, percent silt, and the runoff/rainfall ratio as the three significant variables for predicting the log of sediment production (R^2=0.83). Considering only high severity sites, the antecedent soil moisture was also included, these four variables explained 94% of the variation in the log-transformed sediment production. If the data from the Hourglass fire were removed from the analysis of the high severity sites, the R^2 dropped to 0.80 and the only significant variables were percent silt and the runoff/rainfall ratios.

The variables selected in the multivariate analyses provide some useful insight into the controlling processes. The dominance of percent bare soil emphasizes the importance of protecting the ground surface and slowing overland flow. Sit-sized particles are more easily eroded, and the percent silt may represent the availability of easily-eroded soil particles. Runoff/rainfall ratios probably represent the shear stress of the overland flow and the energy available for sediment transport.

4.4.8. Effect of rainsplash and sheetwash on sediment production

The paired plots used to analyze the effect of rainsplash on runoff and sediment production had similar slopes and percent bare soil, but the three pairs differed in the amount of ash cover (Table 5). Pair 1 had 1-2 cm of ash covering almost the entire plot; pair 2 had no ash cover; and pair 3 had 60% ash cover. There were some differences within pairs in the antecedent soil moisture, soil water repellency, and applied rainfall, and in some cases these differences confounded the results. In pairs 1 and 3 the antecedent moisture in the treated plots was only 5% as compared to 12-14% in the control plots (Table 5). Soil water repellency values were very similar in the first two pairs, but in the third pair the soil in the control plot was less water repellent than the soil in the treated plot. The applied rainfall was very similar for the first pair, but in the other two pairs the rainfall rates in the control plots were 19% and 13% higher than in the treated plots (Table 5).

Comparisons of the runoff hydrographs from the treated and control plots showed no consistent pattern in the time to initial runoff or the equilibrium runoff rate, even after accounting for the differences in the applied rainfall (Table 5). However, the runoff/rainfall ratios were substantially higher in the treated plots in pairs 1 and 3 after accounting for differences in the applied rainfall (Table 5).

Within each pair sediment concentrations and the total sediment yield was higher in the control plot that the treated plot (Table 6). The first pair had the highest sediment production rates (Table 6), and the sedigraphs show a sharp rise in sediment production with a peak concentration of nearly 120 g L^{-1} in the control plot and 90 g L^{-1} in the plot without rainsplash (Figure 17a). There was a gradual recession until the sediment concentrations dropped to 40 g L^{-1} in the control plot and less than 10 g L^{-1} in the treated plot. The second pair showed a similar pattern to that of the control plot, but the sediment concentrations were much lower (Figure 17b). For the third pair about 50% of the initial sediment from the control plot was trapped in the runoff trough (Figure 17c), and this is why the initial sediment concentrations in the control plot were so low and the later values were so variable.

The sediment yields from the three treated plots were respectively 74%, 47%, and 76% of the values from the control plots (Table 6). When the sediment yields were normalized by rainfall the sediment yield from the treated plots were 14-44% less than the sediment yields from the control plots (Table 6). This normalized difference in erosion can be interpreted as the amount of erosion due to rainsplash. The greatest difference in sediment production was for pair two, and this was the pair with no ash cover. The other pairs had from 60-90% ash cover and substantially smaller difference in sediment production when rainsplash was suppressed.

4.4.9. Soil particle size analysis

The particle-size data obtained from the soil samples were initially stratified by fire, fire severity, and year. However, there were no differences in the soils within a given fire by fire severity or year. Hence the data from each fire were pooled.

For the Bobcat fire the mean soil texture for the fraction finer than 2 mm was 67% sand, 30% silt, and 3% clay, although the sites burned at moderate severity did tend to have slightly less sand and slightly more silt and clay (Figure 18). The soils at Lower

Flowers were slightly coarser than the soils in the Bobcat fire, as the overall mean values for the fine fraction were 76% sand, 21% silt, and 3% clay (Figure 18). The individual soil samples were all classified as either sandy loams or loamy sands.

The particle-size distribution of the sediment eroded from the Bobcat sites showed some differences from the original soil. In the first summer after burning, the sediment eroded from the high severity sites had significantly less sand and significantly more silt and clay than the original soil (Figure 19a). Similar differences were observed in 2000 in the moderate severity sites, but these differences were not statistically significant (Figure 19b). In 2001 there were no significant differences in the particle-size distribution between the native soil and the eroded sediment from the high severity sites or the moderate severity sites (Figure 19). Comparisons between years showed no significant differences in the texture of the eroded sediment. However, there was a general tendency for the eroded sediment from both high and moderate severity sites to had more silt and less sand in 2000 as compared to 2001 (Figure 19).

At Lower Flowers the particle-size distributions were nearly identical for the native soil and the sediment eroded from high severity sites from both 2000 and 2001. There also were no apparent trends between years. In contrast, the eroded sediment from moderate severity sites had a lower percentage of sand than the native soil in both 2000 and 2001 ($p=0.06$ and 0.03, respectively) (Figure 20a). Compared to the native soil, the sediment eroded from sites burned at moderate severity also had significantly more silt in 2000 ($p=0.055$) and more clay in 2001 ($p<0.001$). As in high severity sites, there was a same tendency for the sediment eroded from the moderate severity sites to be coarser in the second year after burning as compared to the first year, but this difference between years was not statiscally significant.

The amount of silt in the native soil was strongly correlated with sediment yields for high severity plots (R^2=0.65) and this was significant at $p<0.001$ (Figure 16d). Sediment yields also increased with increasing percent silt for the moderate severity sites (R^2=0.43; p=0.01), but the slope of this relationship was much lower than for the high severity sites (Figure 16d).

Changes in texture were also observed at the scale of a single simulation. Figure 21 shows the percent sand, silt, and clay for two high severity sites in the Bobcat fire in 2000. The soils at these two sites were a sandy loam and a loamy sand, respectively. In each case the percent sand increased over the simulation while the percent silt decreased (Figure 21). The initial concentration of silt in the second plot (plot 16) was more than twice the value of the native soil, and the percent sand in the initial runoff was only 35%, or about half of the value in the native soil (Figure 21b). In both simulations the texture of the eroded sediment seemed to stabilize, but the sediment eroded from plot 15 was always substantially finer than the native soil (Figure 21b).

In 2001 the eroded sediment generally did not show much of a trend in the particle-size distributions over time. In some cases the initial sediment pulse was finer than the native soil, but after 10-15 minutes the particle-size distribution stabilized and the texture of the eroded sediment was generally similar to the native soil.

4.5. DISCUSSION

4.5.1. Runoff in relation to fire severity

The literature clearly indicates that sites burned at high severity produce much more runoff than comparable unburned areas (Campbell *et al.*, 1977; Scott, 1990; Inbar *et al.*, 1998). However, our simulations on the Bobcat fire showed that runoff/rainfall ratios from high severity sites were only 20% greater than for the low severity/unburned sites in 2000 and only 27% greater in 2001 (Figure 10a). At Lower Flowers there was not much difference in the runoff/rainfall ratios with fire severity (Figure 10b). At Lower Flowers the moderate severity sites had the highest runoff/rainfall ratios, and this may have been caused by the stronger soil water repellency in the moderate severity sites relative to the high severity sites (Figure 10b). In contrast, Robichaud and Waldrop (1994) found that runoff/rainfall ratios in high severity sites were nearly 5 times higher than the ratios from low severity sites. Sites burned at high severity in a ponderosa pine forest in New Mexico yielded 110% more runoff than unburned sites (Johansen *et al.*, 2001). Sagebrush/juniper sites burned at high intensity produced 4 times more runoff than sites burned at low severity (Simanton *et al.*, 1990).

The high intensity of the simulated rainfall and the relatively high runoff rates from the low severity/unburned plots are probably the primary reasons for the small differences in runoff with fire severity. In the Bobcat fire the runoff/rainfall ratios from low severity and unburned plots were 55% in 2000 and 36% in 2001. These values are high relative to other studies. For example, an applied rainfall of 100 mm h^{-1} on low severity plots in a mixed hardwood-pine forest yielded only 9% runoff (Robichaud and Waldrop, 1994). In a ponderosa pine forest in Northern New Mexico, the runoff/rainfall ratio was 20% for unburned 30 m^2 plots when 60 mm h^{-1} was applied (Johansen *et al.*, 2001).

The high intensity of the simulated rainfall probably exceeded the infiltration rate in the low severity and unburned sites. Particularly in the burned sites, the high intensity of the applied rainfall will increase the amount of rainsplash and overland flow. Small particles will clog the soil pores and cause soil sealing, which further increases the amount of surface runoff (Fox and Bissonnais, 1998). Rainfall intensities greater than 10 mm h^{-1} exceeded the infiltration rate on severely-burned areas after the Buffalo Creek fire near Denver (Moody and Martin, 2001b)

In 2000 there was a tendency for the soil water repellency to decrease with increasing soil moisture, at least for the sites burned at moderate severity (Figure 10b). The relationship between soil moisture and soil water repellency was not as clear in 2001. The poor relationship may be due to weakening of post-fire water repellency and the use of an average soil moisture from 0 to 5 cm depth. Differences in soil color with depth suggest that there were variations in the soil water content in the top 5 cm of the soil in the study plots, and Cerda (1998) documented that the mean water content from 0-2 cm varied from the mean water content at 4-6 cm by 7% to 15%. This suggests that it would be better to take samples for determining soil moisture at intervals of 1-2 cm instead of from 0-5 cm.

4.5.2. Sediment yields: controlling and influencing factors

In contrast to runoff, sediment yields were strongly related to fire severity. The mean sediment yields for high severity sites at Bobcat and Lower Flowers in 2001 were 1,228 g m^{-2} and 390 g m^{-2}, respectively, and these values are high relative to other studies. For example, the mean sediment yield in high severity sites in a hardwood forest was 139 g m^{-2} when 100 mm h^{-1} of rain was applied for 30 minutes (Robichaud and Waldrop, 1994). High severity sites in ponderosa pine had a mean sediment yield of 460 g m^{-2} when subjected to a rainfall rate of 60 mm h^{-1} for 120 minutes (Johansen *et al.*, 2001). In Georgia, an applied rainfall of 102 mm h^{-1} for 30 minutes produced only 65 g m^{-2} in a burned hardwood and pine forest (Shahlaee *et al.*, 1991). Sagebrush sites burned at high severity yielded only 31 g m^{-2} when rainfall was applied at 85 mm h^{-1} for 60 minutes (Pierson *et al.*, 2001). These comparisons suggest a higher erosion risk from burned sites in the Colorado Front Range than other areas.

Percent bare soil appears to be the primary control on sediment production, as this explained 81% of the variability in sediment production. However, percent bare soil was not the best predictor of sediment yields in high severity sites in the recent fires because these sites all had similar amounts of bare soil. For these sites percent silt and the runoff/rainfall ratio were the key variables related to sediment yields. The increase in sediment production with increasing silt content is consistent with other studies (e.g., Young, 1976; Morgan 1996). The influence of percent silt in high severity sites indicate that soil texture and the ash cover need to be evaluated in future studies. The runoff/rainfall ratio is important because this refers to is directly related to the amount of overland flow and hence the shear stress and transport capacity (Evans, 1980).

An important issue for resource managers is the persistence of the increased runoff and erosion risk after wild and prescribed fires. The data from this study suggest that the factors controlling the decline in runoff and sediment production over time may differ with fire severity. Both soil water repellency and ground cover must recover, as the first increases runoff and the second provides resistance to particle detachment by reducing rainsplash and soil sealing as well as reducing flow velocities (Foster, 1982).

Nevertheless, the data from the second year of simulations showed a decline in soil water repellency and runoff/rainfall ratios (i.e., higher infiltration rates), but these declines did not significantly reduce sediment yields from the plots burned at high severity. Apparently the increase in percent cover in high severity sites in the Bobcat fire from 11% in 2000 (removing one outlier) to 22% in 2001 was not enough to provide protection against rainsplash and sheetwash. The erosion rates from moderate severity sites were always much lower than the high severity sites despite the stronger soil water repellency, and this difference in erosion rates is almost certainly due to the higher percent ground cover in the plots burned at moderate severity. The implication is that soil water repellency and the loss of cover work together to increase runoff, while percent silt, soil water repellency, runoff/rainfall ratios, and the loss of cover are all important controls on sediment production in the first two years after a fire. As the percent cover increases beyond 20% or so it becomes the dominant control on erosion rates. Soil water repellency was not selected as a significant variable for predicting sediment yields, but since this was the variable most closely related to runoff/rainfall ratios, soil water repellency can indirectly affect sediment yields. When rill erosion is present, other processes and factors may be important with respect to reducing erosion rates over time.

The variability in sediment production rates from the high severity sites in the Bobcat fire was greater in the second year than the first year. The greater variability in 2001 may be attributed to the uneven breakdown of soil water repellency, irregular presence of ash on the soil surface, and differences in the amount of vegetative regrowth.

This increase in variability, when combined with the shift in controlling processes, suggest that it may be progressively more difficult to predict post-fire erosion rates two or more years after burning than in the first year after fire.

The general tendency in both fires was for the eroded material to be finer than the native soils in the first year after burning. Both fires also showed a tendency for the eroded material to become coarser over time, and this trend has been observed in other erosion studies (Young and Onstad, 1978; Poesen and Savat, 1980; Durnford and King, 1993; Fullen *et al.*, 1996) as well as post-fire studies (Morris and Moses, 1987; Martin and Moody, 2001). In the second year the eroded sediment was similar to the soil matrix or slightly coarser. This coarsening of the eroded material is probably due to the initial removal of the finer particles and resultant armoring of the surface layer. The coarser particles in the upper layer effectively shield the finer particles underneath (Foltz, 1993).

The coarsening of the eroded sediment over time was also observed in individual simulations. Since this coarsening was most pronounced in the first year after burning, it appears that the erosion of fine sediment is supply-limited.

The coarsening of the soil surface and the consistency of sediment yields over time indicates that the erosion of sand-sized particles is transport limited (Durnford and King, 1993). Miller and Baharuddin, (1987) found that after runoff rates stabilize, the rate of soil loss is determined by the detachment rate. These results suggest that when there is readily available material like ash and silt, these particles can be easily removed by the initial rainfall. Once the finer material has been removed, the remaining coarse material makes up a higher proportion of the eroded sediment. Higher rainfall intensities or more concentrated overland flow may be needed to detach and transport the remaining material.

4.5.3. Effect of rainsplash on sediment yields

Soil erosion by water requires both particle detachment and transport. The main surface erosion processes are rainsplash, interrill, rill, and gully erosion (Meyer, 1976; Foster 1982). In the small (1 m^2) plots used in this study the main processes that can be studied are rainsplash and interrill erosion.

High severity fires greatly increase the amount of material that can be detached and transported. Soil organic matter binds smaller particles into aggregates, and when the organic matter is lost by burning the particles are more easily detached (Durgin, 1985). The resulting non-cohesive mixture of ash and mineral particles is easily transported (Young, 1976), and the sediment yield will depend on the transport capacity of the flow (Bryan, 2000). Under these conditions the availability of loose particles and the transport capacity will be more important than detachment by rainsplash.

The data presented here support this view, as the suppression of rainsplash in high severity plots reduced sediment yields by only 14% to 44% (Table 6). The suppression of rainsplash had the greatest effect on the plot with no ash cover, and less effect on the plots with more ash and loose material. The plot with the highest ash cover also had a sediment yield that was 50% higher than any other plot (2,700 g m^{-2}). These results suggest that the ability of overland flow to transport loose particles is more important than rainsplash detachment. Erosion rates from unpaved roads may be limited by the same factors as severely-burned areas, and a recent study showed that rainsplash contributed just 38-45% of the total sediment yield. Rainsplash was less important when loose soil was readily available (Ziegler *et al.*, 2000).

These observations help explain why sediment yields from the high severity sites in the Lower Flowers prescribed fire recovered more rapidly than sediment yields from high severity sites in the Bobcat wildfire. At Lower Flowers the soils were coarser and there was much less ash cover than in the Bobcat fire, so there was less fine sediment available for transport. The greater ash cover and finer soils in the Bobcat fire provided a large supply of more easily transportable particles.

4.5.4. Representativeness and scale effects

Although we found only small differences in runoff with fire severity, large changes in runoff have been observed after high severity fires at the watershed scale (Campbell *et al.*, 1977; Scott and Van Wyk, 1990; Inbar *et al.*, 1998; Moody and Martin, 2001b). On bare hillslopes, such as those burned at high severity, the surface runoff can easily reach the drainage network. On hillslopes burned at moderate and low severity the residual surface roughness will help slow overland flow and allow more infiltration. In areas with a patchy distribution of burn severity, some of the runoff from high severity sites may infiltrate in downslope areas that burned at lower severity.

Field observations from the 3.9 km^2 Jug Gulch watershed in the Bobcat fire support the idea of higher runoff rates at the catchment scale in areas burned at high severity. Fifty-five percent of the Jug Gulch watershed burned at high severity. Peak streamflows of 0.8 and 1.7 $m^3 s^{-1} km^{-2}$ were observed after short-duration storms with maximum intensities of 18 mm hr^{-1} and 32 mm hr^{-1}, respectively (Kunze and Stednick, 2002). The adjacent Spruce Gulch watershed was mostly unburned or burned at low severity, and little or no runoff was produced on this watershed from rainfall intensities of 14 mm hr^{-1} and 21 mm hr^{-1}.

If runoff data from this study is extrapolated to the watershed scale, a rainfall intensity of 75-90 mm h^{-1} should generate peak flows of 20-30 m^3 s^{-1} km^{-2}. After the Buffalo Creek fire southwest of Denver, a storm of 90 mm h^{-1} produced peak flows of 24 m^3 s^{-1} km^{-2} in the 27 km^2 Spring Creek watershed (Moody and Martin, 2001a). Since the Spring Creek watershed had similar vegetation as the Bobcat fire and coarse-textured soils, this comparison suggests that the runoff rates derived from rainfall simulations may be applied to severely burned areas subjected to high intensity storms. A similar extrapolation for low severity and unburned plots is not possible because the highest rainfall intensity on the Spruce Gulch catchment was only 37% of the rainfall intensity applied with the rainfall simulator.

When normalized by rainfall, the sediment yields measured in this study are high relative to other studies that have conducted rainfall simulations after forest fires. In the Bobcat wildfire the high severity sites had mean sediment yields of 150 kg ha^{-1} mm^{-1} in 2000 and 158 kg ha^{-1} mm^{-1} in 2001. Sediment yields from high severity sites in the Lower Flowers prescribed fire in 2000 and 2001were 103 and 51 kg ha^{-1} mm^{-1}, respectively. For low severity and unburned sites the mean sediment yields from both fires were 10 kg ha^{-1} mm^{-1} in 2000 and 6 kg ha^{-1} mm^{-1} in 2001.

Sediment yields were around 113 kg ha^{-1} mm^{-1} for 30 m^2 plots in a ponderosa pine forest in New Mexico that had been burned at high severity (Johansen, 2001). The same study reported sediment yields of 2-4 kg ha^{-1} mm^{-1} in unburned areas. The maximum sediment yield from small plots in a mixed hardwood and pine forest burned at high severity was 68 kg ha^{-1} mm^{-1}, while low severity sites yielded only 2 kg ha^{-1} mm^{-1} (Robichaud and Waldrop, 1994). High severity sites in hardwood and pine forest yielded a maximum 3.8 kg ha^{-1} mm^{-1} (Shahlaee, 1991). The results indicate high erosion risk from high intensity rains in the Colorado Front Range.

Sediment yields per unit area typically decrease with increasing area (Walling, 1983), and for the Bobcat fire it is possible to compare sediment yields across different spatial scales. The small plots produced 150 kg ha^{-1} mm^{-1} in 2000 and 158 kg ha^{-1} mm^{-1} in 2001. Sediment production rates at the hillslope scale for sites burned at high severity were 61 kg ha^{-1} mm^{-1} in 2000 and 74 kg ha^{-1} mm^{-1} in 2001 (Chapter 3). The estimated sediment yield from the 3.9 km^2 Jug Gulch catchment was 10 kg ha^{-1} mm^{-1}, or about 7% of the value measured from small plots. Although more watershed scale data are needed, these comparisons can help managers to estimate the proportion of sediment eroded from severily burned areas that might reach the main channels and adversely impact downstream resources.

The results from this study, when combined with previous work (Benavides-Solorio and MacDonald, 2001), suggest that the high severity plots in the Bobcat fire are probably far from recovery in terms of sediment yields. The mean value of 158 kg ha^{-1} mm^{-1} in 2001 is still more than 20 times greater than the mean value of 7 kg ha^{-1} mm^{-1} for high severity sites in the 1994 Hourglass fire. The sediment yields from high severity plots in the Lower Flowers prescribed fire averaged 51 kg ha^{-1} mm^{-1} in 2001, or about 7 times the value from the Hourglass fire. This, plus the 54% decline in sediment yields at Lower Flowers from 2000 to 2001, suggests that recovery is further advanced at Lower

Flowers than the Bobcat fire site. Continuation of the simulations is critical to accurately determining the time scale to recovery and the factors that control the rate of recovery.

4.6. CONCLUSIONS

Mean runoff/rainfall ratios at the Bobcat fire in the second year after burning were 46% in sites burned at high severity, 40% in sites burned at moderate severity and 36% in low severity/unburned sites, but these differences were not significant due to the high variability between plots. At Lower Flowers the mean runoff/rainfall ratios ranged from 53% to 63% and were not related significantly to fire severity. The higher runoff/rainfall ratios at Lower Flowers are at least partially due to the stronger soil water repellency relative to sites in the Bobcat fire.

Runoff/rainfall ratios generally declined from 2000 to 2001. The runoff/rainfall ratios for high severity sites in the Bobcat wildfire decreased from 66% to 46%, and the runoff/rainfall ratios for high severity sites in the Lower Flowers prescribed fire decreased from 61% to 52%. Runoff rainfall ratios in the moderate severity and low severity/unburned sites also decreased in the case of the Bobcat fire, but not at Lower Flowers.

Univariate analysis of the data from 2000 and 2001 showed that the runoff/rainfall ratios for high severity sites were significantly related to soil water repellency, percent bare soil, and rainfall intensity. Multivariate analyses on both years of data indicated that soil water repellency was the only variable that helped explain runoff/rainfall ratios for the entire data set and for high severity sites.

Sediment yields in 2001 varied significantly with fire severity in both the Bobcat wildfire and Lower Flowers prescribed fire. High severity sites in the Bobcat fire had a mean sediment yield of 1,230 g m^{-2} as compared to 177 g m^{-2} in moderate severity sites and only 45 g m^{-2} in low severity/unburned sites. High severity sites in the Lower Flowers prescribed fire had a mean sediment yield of 389 g m^{-2} as compared to 139 g m^{-2} from moderate severity sites and 34 g m^{-2} from low severity/unburned plots.

When stratified by fire and fire severity, there was no significant difference in sediment yields between 2000 and 2001. When the data from both years were pooled, sediment yields were highly correlated with percent bare soil (R^2=0.81). Percent silt and runoff/rainfall ratios were also significantly related to sediment yields using univariate analyses. Soil water repellency was poorly related to sediment yields, even though the soil water repellency was related to runoff/rainfall ratios. Multivariate analysis showed that percent bare soil, percent silt, and the runoff/rainfall ratio could explain 83% of the variability in the log-transformed sediment yield.

Sediment yields were reduced by 14-44% when rainsplash was supressed. The suppression of rainsplash had a greater effect when there was more cover by fine ash. These results suggest that the hydraulic forces caused by sheetflow are more important than rainsplash.

Although runoff rates were lower in the second year after burning for high severity sites on the Bobcat fire, this did not significantly reduce sediment yields. In high severity sites, both water repellency and ground cover must recover, because the first increases runoff and the second protects against detachment by rainsplash and offers resistance to overland flow and sediment transport. For the high severity sites on the

Bobcat fire, the mean percent cover only increased from 11% in 2000 to 22% in 2001, and this was not enough to reduce sediment yields. Sediment yields from moderate severity sites are more dependent on the amount of ground cover than soil water repellency. When rill erosion is present, other processes and factors may be important.

The sediment eroded from the plots in 2000 was generally finer than the native soils, indicating selective entrainment and transport. Comparisons between years indicate a coarsening of the eroded material over time. Similarly, particle-size data from individual simulations suggest a coarsening of the eroded material relative to the initial runoff. These trends suggest that the erosion of silt and clay are supply-limited, whereas the erosion of sand-sized particles is transport limited.

The results show that high intensity storms can cause very high rates of runoff and sediment production from recently-burned areas. Efforts to increase groundcover may reduce post-fire erosion rates, but this cover must be present for at least two years because these was still very little vegetative recovery in high severity sites by the second summer after burning.

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Table 1. Characteristics of each fire and number of simulations in 2001 and 2000 by fire severity.

						Number of simulations (2001/2000)			
Fire	**Type**	**Date burned**	**Area (ha)**	**Primary vegetation type**	**Elevation (m)**	**High severity**	**Moderate severity**	**Low severity or unburned**	**Totals (2001/2000)**
Bobcat	Wildfire	June 2000	4,289	Ponderosa pine	1670-2580	9 / 7	4 / 5	4 / 4	17 / 16
Lower Flowers	Prescribed burn	Nov. 1999	300	Ponderosa pine	2530-2940	3 / 2	3 / 2	3 / 2	9 / 6
					Totals	12 / 9	7 / 7	7 / 6	26 / 22

Table 2. Plot characteristics, date of rainfall simulation, and soil moisture at the time of the simulation by fire and burn severity. Ground cover is 100 minus the percent bare soil.

Fire	Plot number	Fire severity	Date of simulation	Ground cover (%)	Slope (%)	Soil moisture (%)
Bobcat	1	High	June 28	19	27	14.0
Bobcat	2	High	July 3	36	23	3.5
Bobcat	3	High	July 6	19	20	3.3
Bobcat	4	High	July 10	50	26	3.2
Bobcat	10	High	Sept. 20	6	38	10.3
Bobcat	12	High	Sept. 25	0	21	11.5
Mean				**22**	**26**	**7.6**
Bobcat	7	Moderate	July 19	81	14	17.6
Bobcat	8	Moderate	Aug. 7	91	17	7.6
Bobcat	9	Moderate	Aug. 15	90	20	13.0
Bobcat	11	Moderate	Sept. 22	89	19	7.8
Mean				**88**	**18**	**11.5**
Bobcat	13	Low	Sep. 27	98	20	4.0
Bobcat	5	Unburned	July 12	100	15	7.2
Bobcat	6	Unburned	July 18	100	18	7.2
Bobcat	14	Unburned	Sept. 29	100	15	4.2
Mean				**99**	**17**	**5.7**
Lower Flowers	1	High	Oct. 2	33	27	7.4
Lower Flowers	2	High	Oct. 4	29	25	4.9
Lower Flowers	3	High	Oct. 9	20	22	5.0
Mean				**27**	**25**	**5.8**
Lower Flowers	4	Moderate	Oct. 11	81	27	5.0
Lower Flowers	5	Moderate	Oct. 12	75	22	5.3
Lower Flowers	7	Moderate	Oct. 17	79	15	5.5
Mean				**79**	**21**	**5.3**
Lower Flowers	6	Low	Oct. 16	86	15	3.0
Lower Flowers	8	Unburned	Oct. 18	100	20	5.4
Lower Flowers	9	Unburned	Oct. 22	98	24	3.7
Mean				**95**	**20**	**4.0**

Table 3. Runoff data for each simulation by fire and fire severity.

Fire	Plot number	Fire severity	Application rate (mm h^{-1})	Equilibrium runoff rate (mm h^{-1})	Runoff/ rainfall ratio (%)	Time to initial runoff (s)	Duration of runoff after sprinkling ceased (s)
Bobcat	1	High	84	52	58	148	160
Bobcat	2	High	75	21	27	150	180
Bobcat	3	High	84	26	30	147	NA
Bobcat	4	High	64	26	35	230	240
Bobcat	10	High	83	58	67	80	190
Bobcat	12	High	76	49	59	180	180
Mean			**78**	**39**	**46**	**156**	**190**
Bobcat	7	Moderate	79	22	24	220	180
Bobcat	8	Moderate	69	35	47	210	240
Bobcat	9	Moderate	79	35	41	210	210
Bobcat	11	Moderate	77	41	48	270	375
Mean			**76**	**34**	**40**	**228**	**251**
Bobcat	13	Low	69	28	37	240	240
Bobcat	5	Unburned	76	42	51	223	373
Bobcat	6	Unburned	76	11	13	175	190
Bobcat	14	Unburned	71	33	43	180	420
Mean			**73**	**28**	**36**	**205**	**306**
Lower Flowers	1	High	82	38	43	240	255
Lower Flowers	2	High	73	42	53	180	280
Lower Flowers	3	High	76	52	63	150	NA
Mean			**77**	**44**	**53**	**190**	**268**
Lower Flowers	4	Moderate	72	53	70	150	450
Lower Flowers	5	Moderate	76	49	62	150	360
Lower Flowers	7	Moderate	70	44	58	210	330
Mean			**73**	**48**	**63**	**170**	**380**
Lower Flowers	6	Low	68	46	63	210	480
Lower Flowers	8	Unburned	68	36	50	210	390
Lower Flowers	9	Unburned	76	40	50	195	250
Mean			**71**	**41**	**54**	**205**	**373**

NA indicates that the simulated rainfall was stopped at approximately 50 minutes because of a clogged nozzle.

Table 4. Sediment yields and sediment concentrations for each plot by fire and fire severity.

Fire	**Plot number**	**Fire severity**	**Total sediment (g)**	**Sediment concentration ($g\ L^{-1}$)**
Bobcat	1	High	1162	23.9
Bobcat	2	High	488	23.9
Bobcat	3	High	703	27.8
Bobcat	4	High	551	24.1
Bobcat	10	High	1793	32.4
Bobcat	12	High	2673	60.0
Mean			**1228**	**32.0**
Bobcat	7	Moderate	181	9.8
Bobcat	8	Moderate	173	5.3
Bobcat	9	Moderate	169	5.3
Bobcat	11	Moderate	184	5.0
Mean			**177**	**6.3**
Bobcat	13	Low	98	3.9
Bobcat	5	Unburned	49	1.3
Bobcat	6	Unburned	19	1.8
Bobcat	14	Unburned	13	0.4
Mean			**45**	**1.9**
Lower Flowers	1	High	242	6.9
Lower Flowers	2	High	395	10.3
Lower Flowers	3	High	530	10.8
Mean			**389**	**9.3**
Lower Flowers	4	Moderate	113	2.3
Lower Flowers	5	Moderate	166	3.6
Lower Flowers	7	Moderate	140	3.5
Mean			**139**	**3.1**
Lower Flowers	6	Low	38	0.9
Lower Flowers	8	Unburned	22	0.7
Lower Flowers	9	Unburned	43	1.1
Mean			**34**	**0.9**

Table 5. Plot characteristics, rainfall application rates, and runoff characteristics for the paired plots with rainsplash (control) and where rainsplash was supressed by a fine mesh (treated).

Pair	Treatment	Site	Slope (%)	Bare soil (%)	Ash cover (%)	Soil moisture (%)	Average WDPT at 1 cm (s)	Average WDPT at 2 cm (s)	Rainfall rate (mm h^{-1})	Time to initial runoff (s)	Equilibrium runoff rate (mm h^{-1})	Runoff/ rainfall ratio (%)
1	Control	12	21	100	90	11.5	80	120	75.7	3:00	48.8	59.0
	Treated	1a	20	100	90	5.0	81	120	78.1	3:30	59.1	69.4
2	Control	10	38	94	0	10.3	120	90	83.4	1:20	57.8	66.9
	Treated	2a	40	95	0	9.3	120	103	69.8	1:47	47.9	66.6
3	Control	1	27	81	60	14.0	26	48	84.1	2:28	51.6	57.9
	Treated	3a	24	94	60	5.4	117	120	74.6	1:35	58.8	74.5

Table 6. Sediment yields for rainfall simulation plots with rainsplash (control) and without rainsplash (treated). Percent erosion from rainsplash was calculated from the difference in sediment yields per millimeter of precipitation.

Pair	**Treatment**	**Site No.**	**Mean sediment concentration ($g\ L^{-1}$)**	**Sediment yield ($g\ m^{-2}$)**	**Sediment yield per unit rainfall ($g\ m^{-2}\ mm^{-1}$)**	**Percent erosion from rainsplash**
1	Control	12	60.0	2673	35.3	28
	Treated	1a	36.3	1976	25.3	
2	Control	10	32.4	1793	21.5	44
	Treated	2a	18.1	844	12.1	
3	Control	1	23.9	1162	13.8	14
	Treated	3a	15.8	886	11.9	

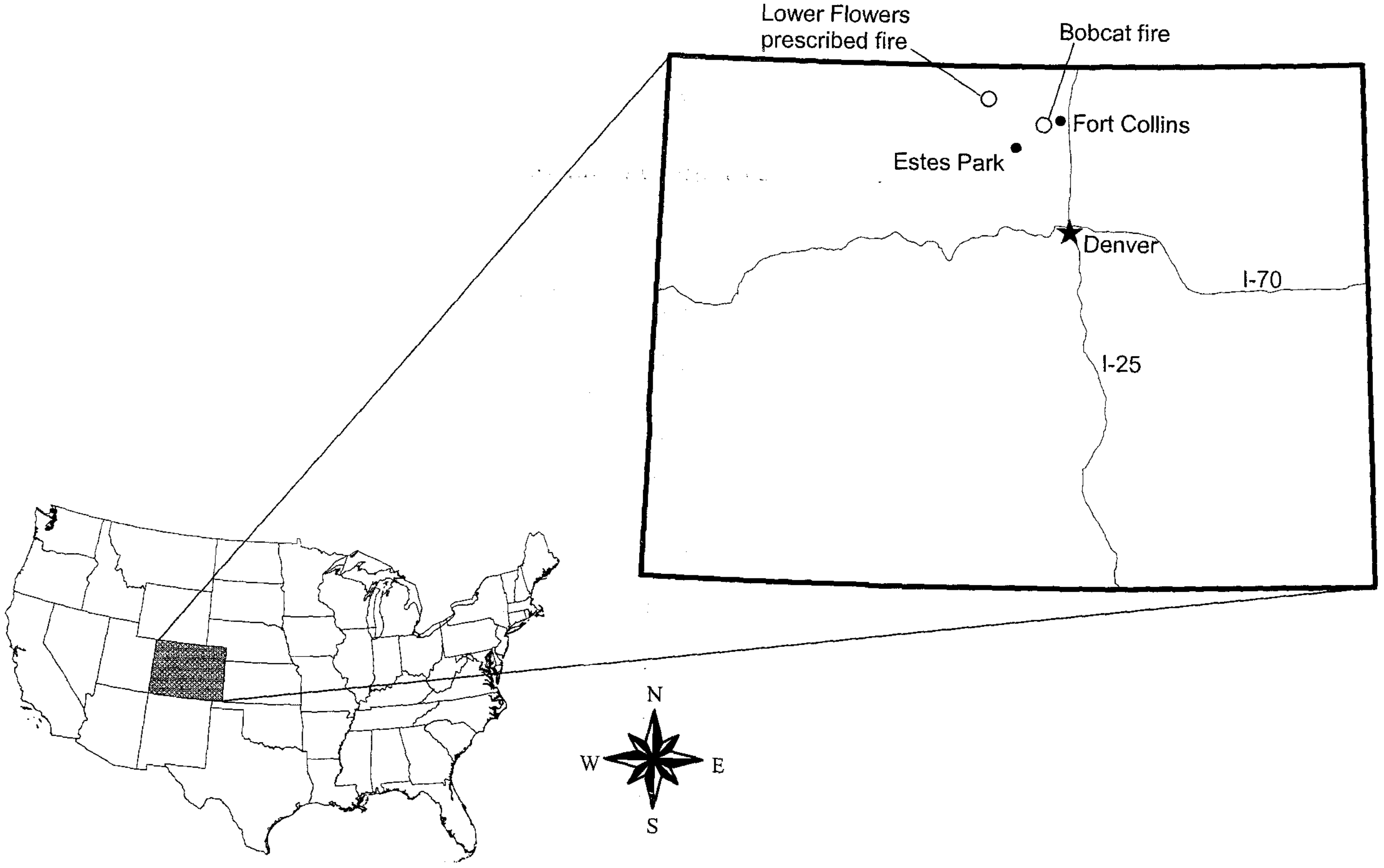


Figure 1. Location of the two fires used in this study.

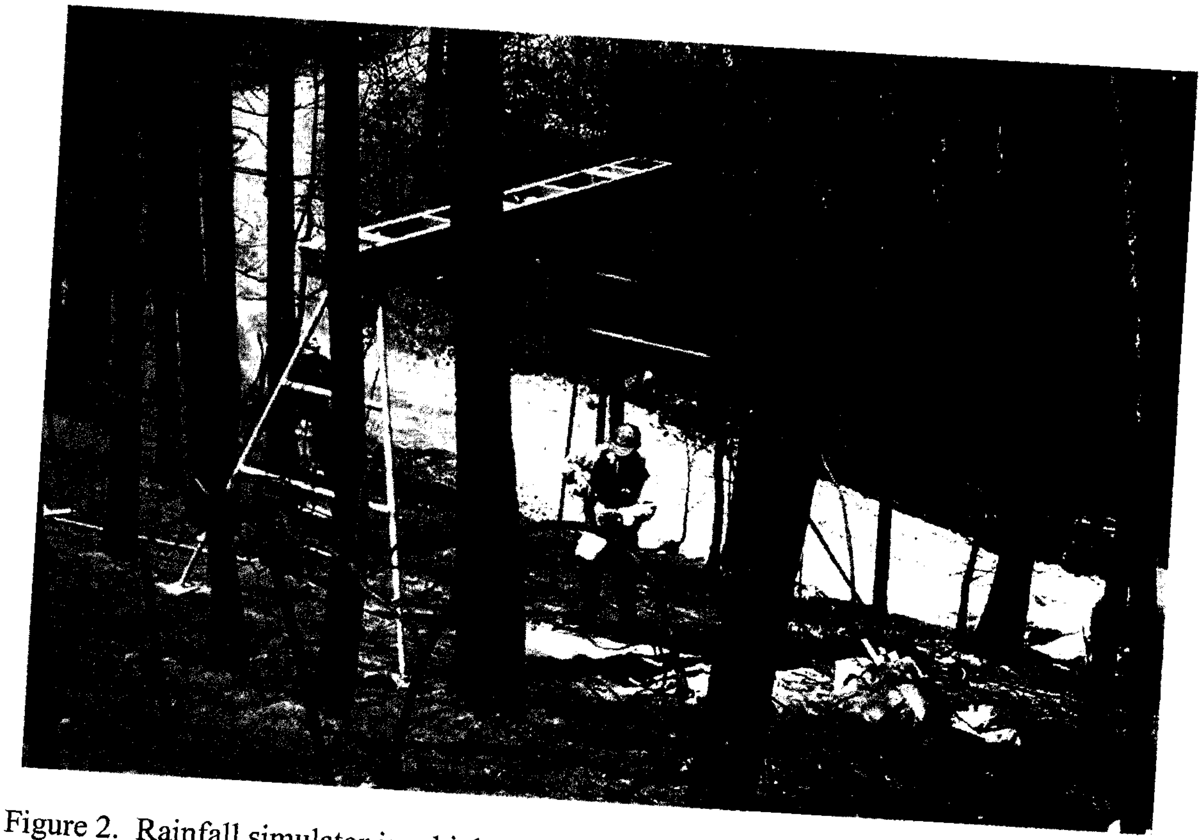


Figure 2. Rainfall simulator in a high severity site.

Figure 3. Picture of the frame used to isolate each 1 m^2 plot and the trough used to collect runoff.

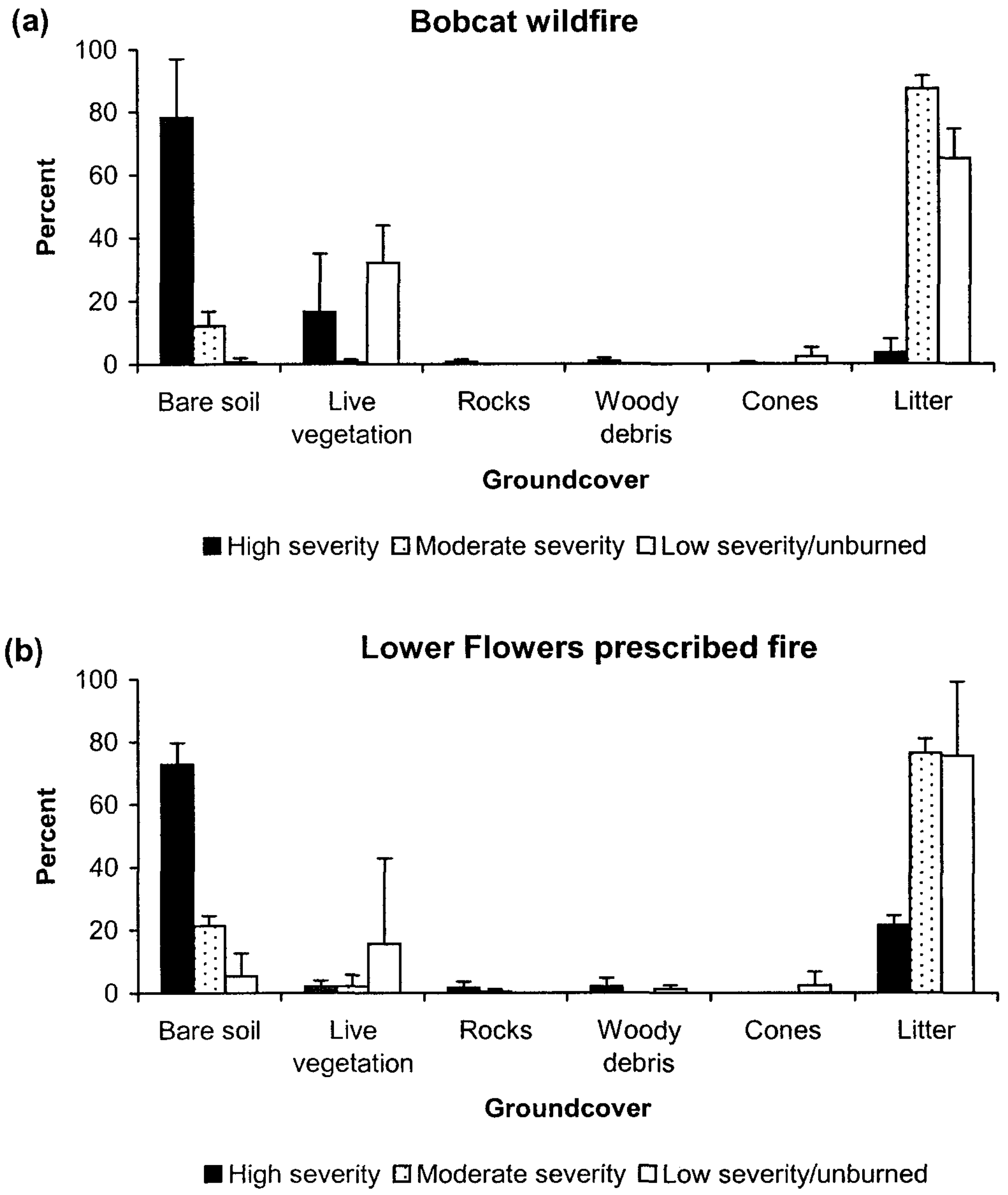


Figure 4. Percent cover by fire severity for: (a) Bobcat wildfire, and (b) Lower Flowers prescribed fire. Bars represent one standard deviation.

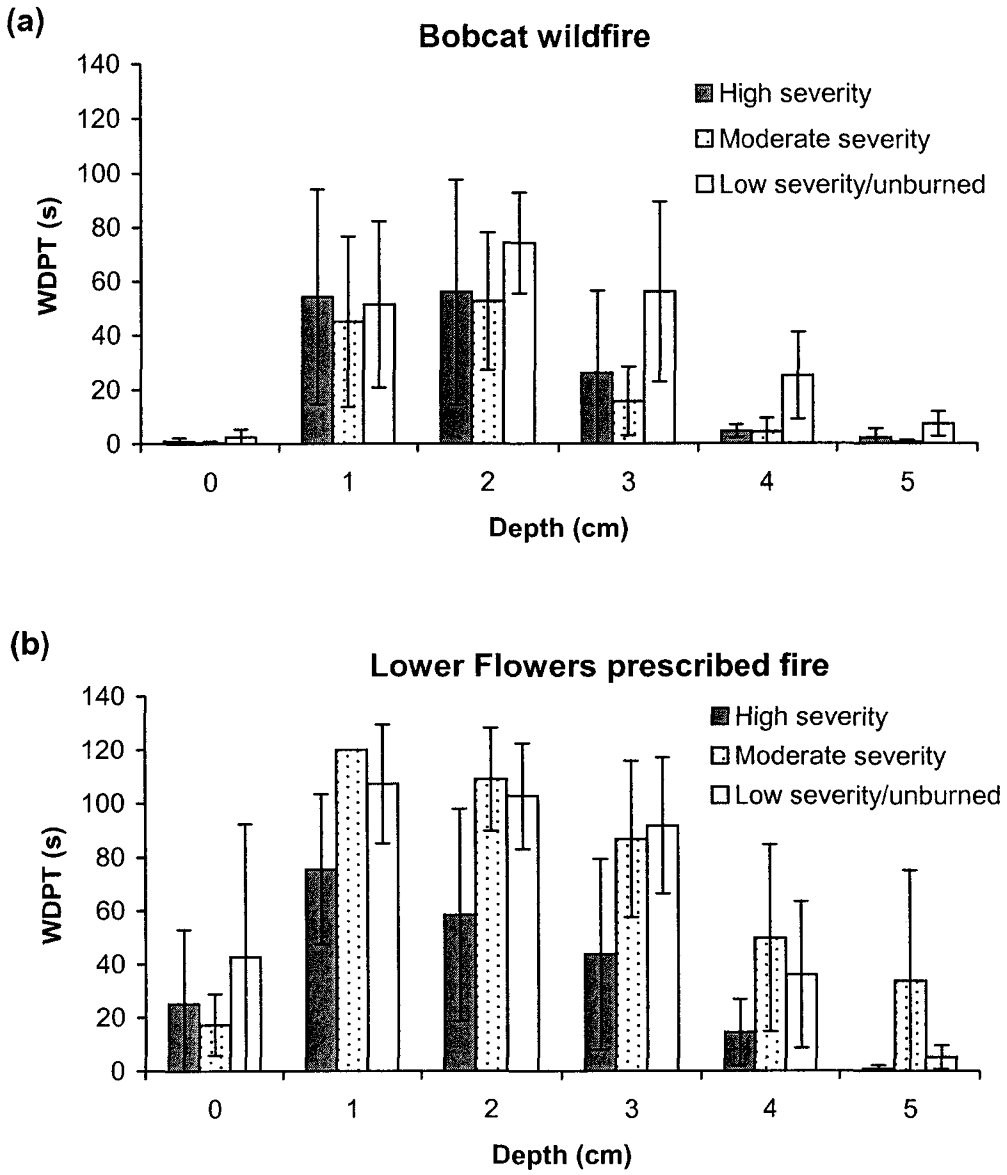


Figure 5. Water repellency from the surface to a depth of 5 cm as indicated by the water drop penetration time for: (a) Bobcat wildfire, and (b) Lower Flowers prescribed fire. Bars respresent one standard deviation.

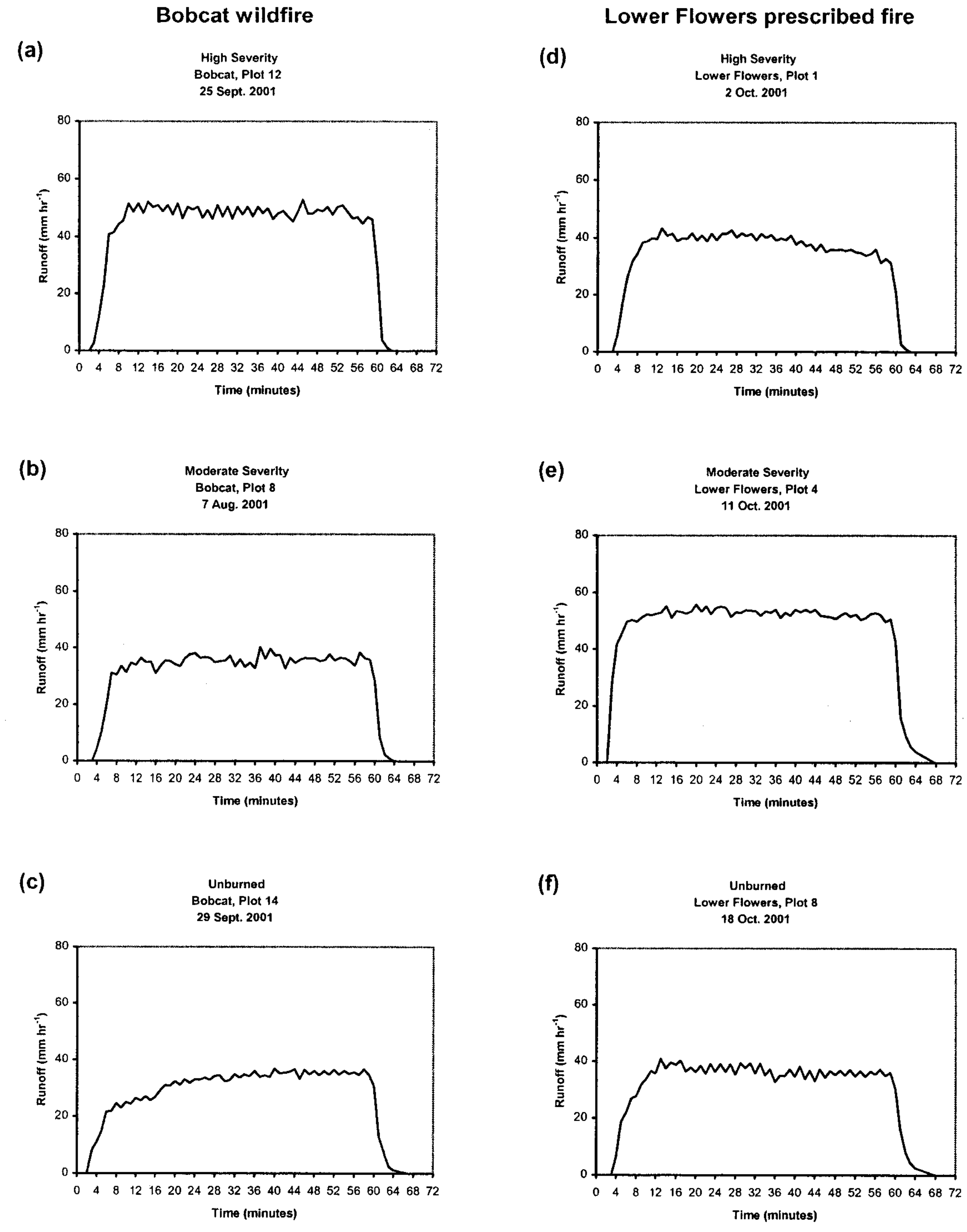


Figure 6. Runoff hydrographs from the Bobcat wildfire (a-c) and Lower Flowers prescribed fire (d-f) for different severities. Rainfall was applied from 0 to 60 minutes at a rate of 68-84 mm h^{-1}.

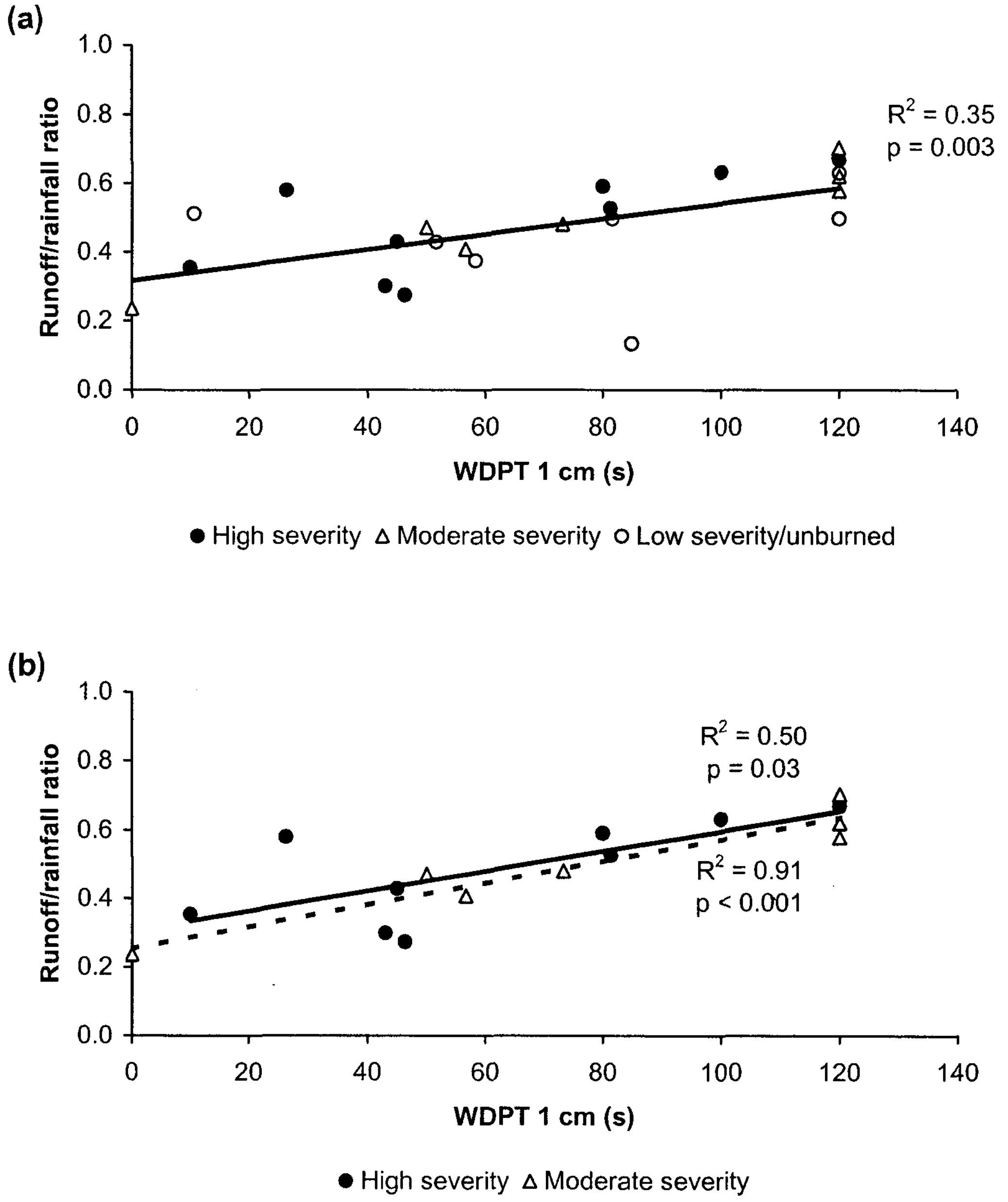


Figure 7. Relationship between the runoff/rainfall ratio and: (a) mean WDPT at 1 cm for all 2001 data, and (b) mean WDPT at 1 cm for sites burned at high severity (solid line) and moderate severity (dashed line).

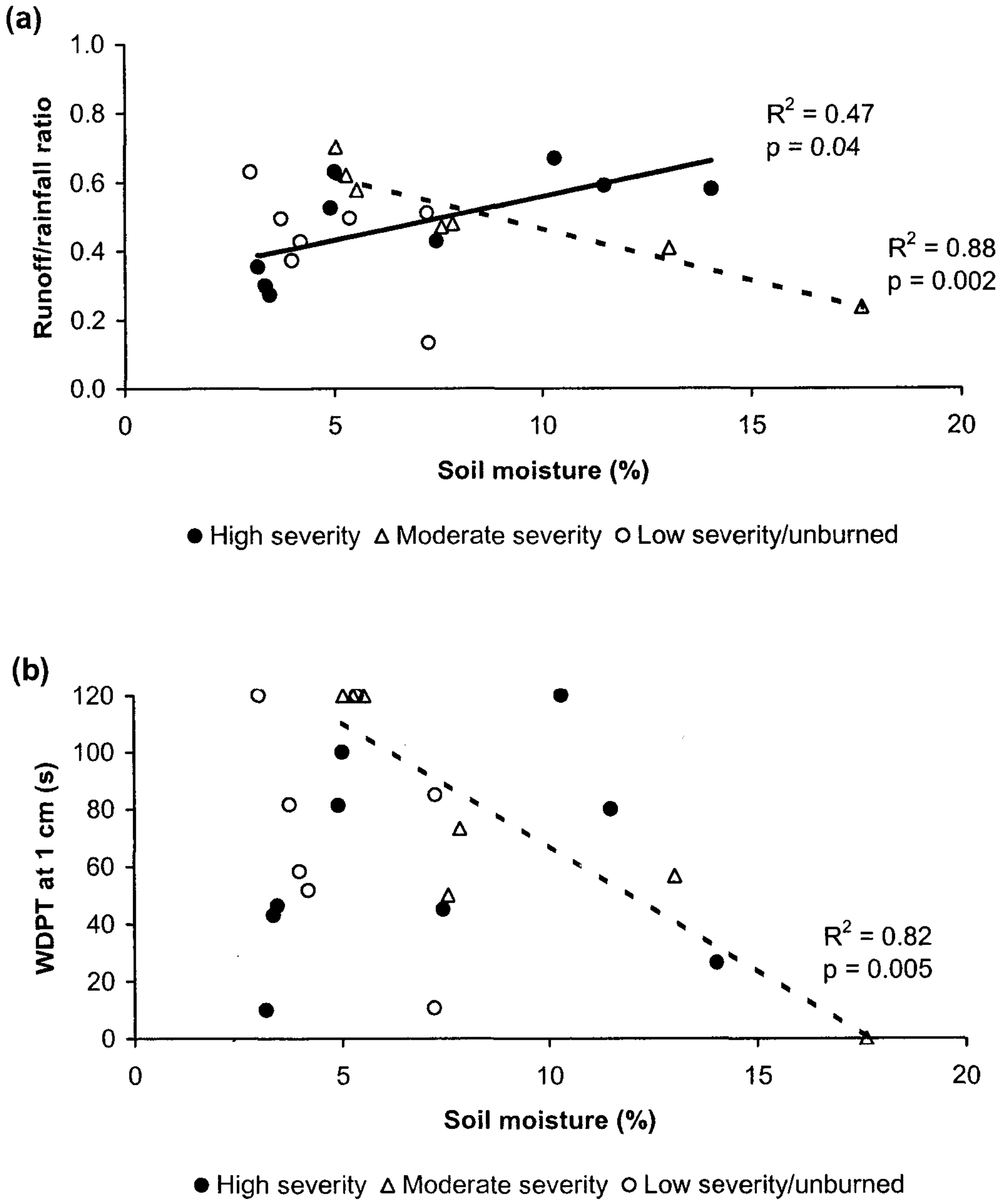


Figure 8. Relationship between: (a) soil moisture and runoff/rainfall ratio, and (b) soil moisture and WDPT at 1 cm. The solid line in (a) represents high severity sites, and the dashed line in each plot represents moderate severity sites.

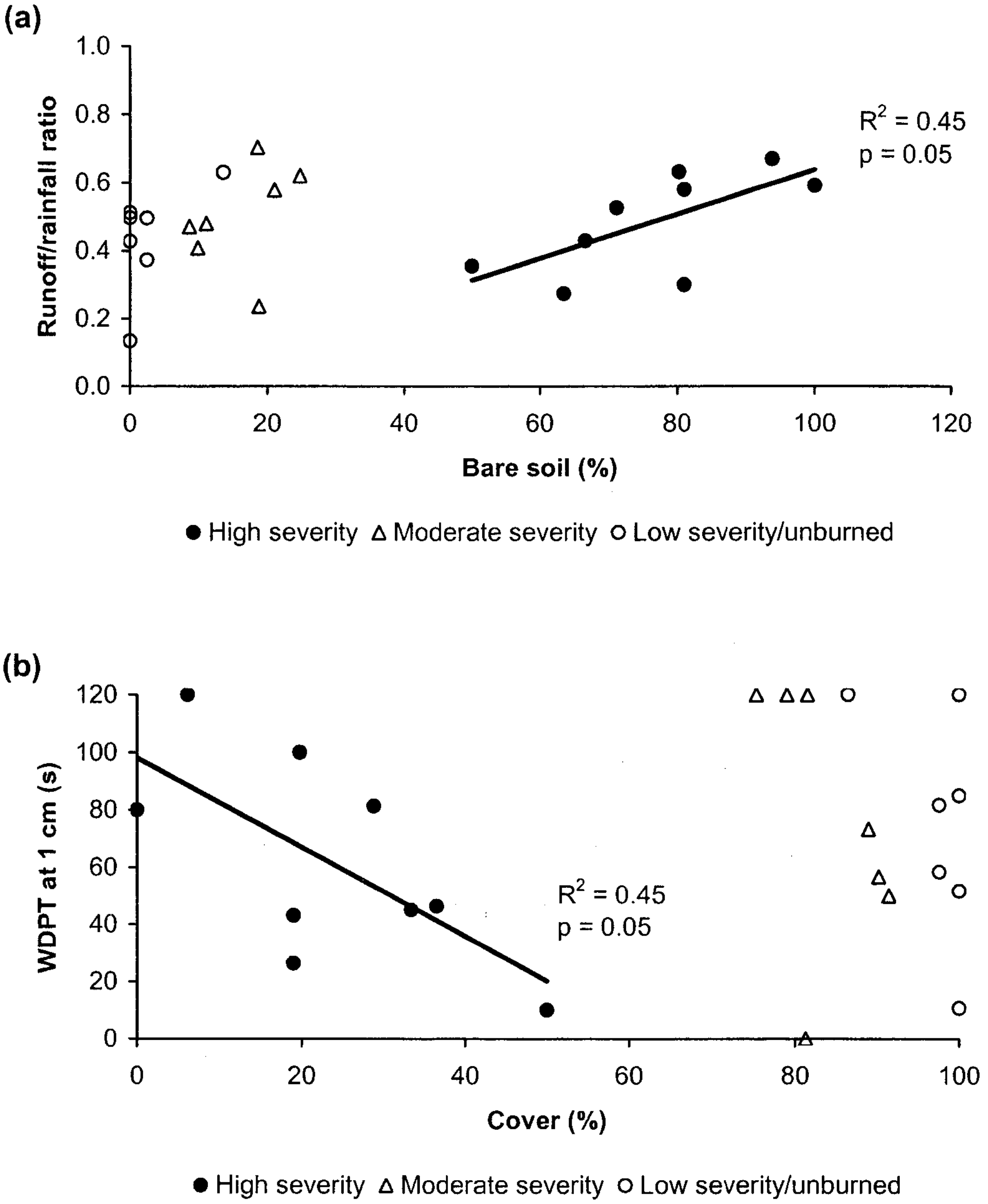


Figure 9. Relationship between: (a) percent bare soil and runoff/rainfall ratio, and (b) percent cover and WDPT at 1 cm. The solid line and statistics are for the sites burned at high severity.

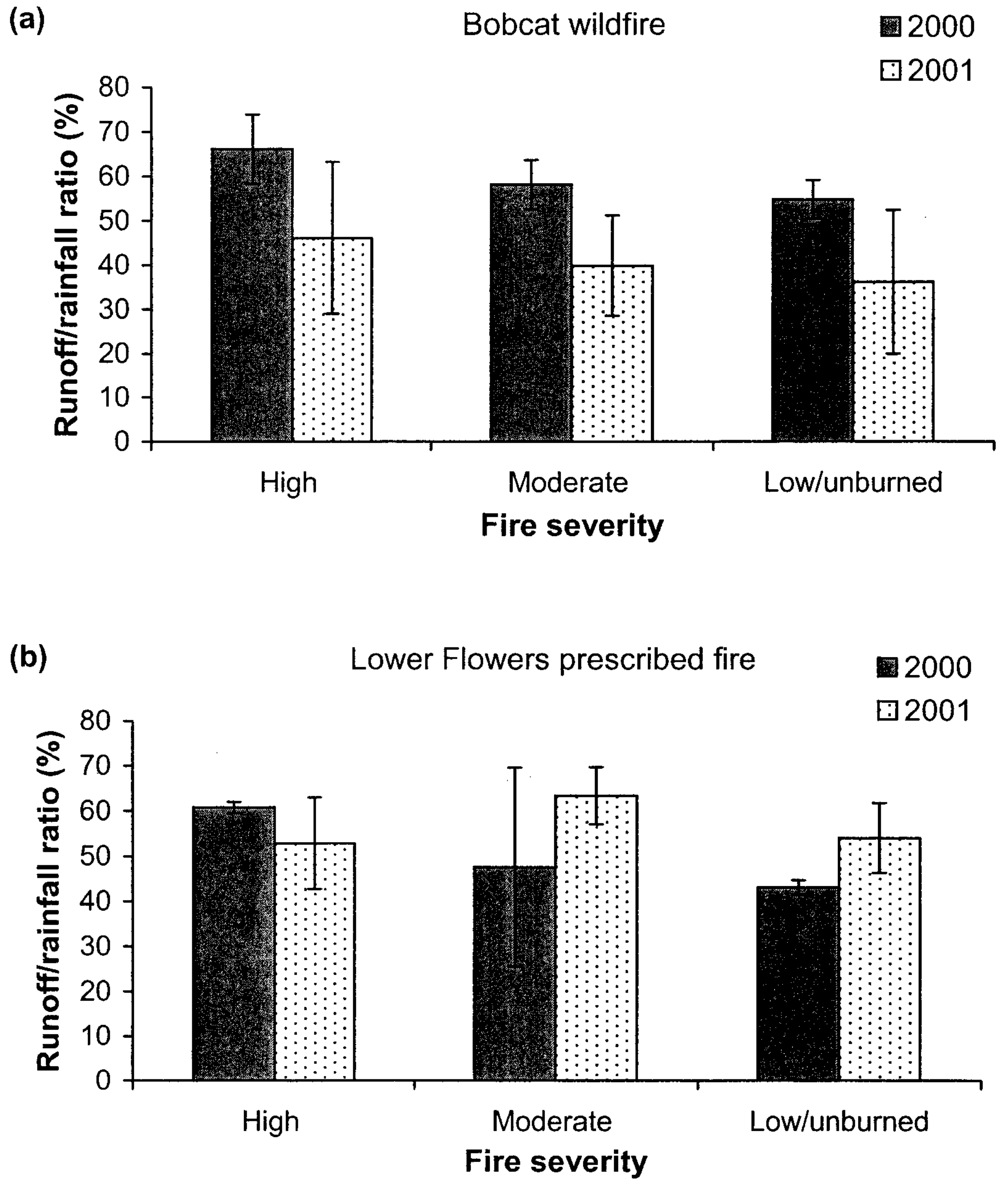


Figure 10. Runoff/rainfall ratios by year and fire severity for: a) Bobcat wildfire, and b) Lower Flowers prescribed fire. Bars represent one standard deviation.

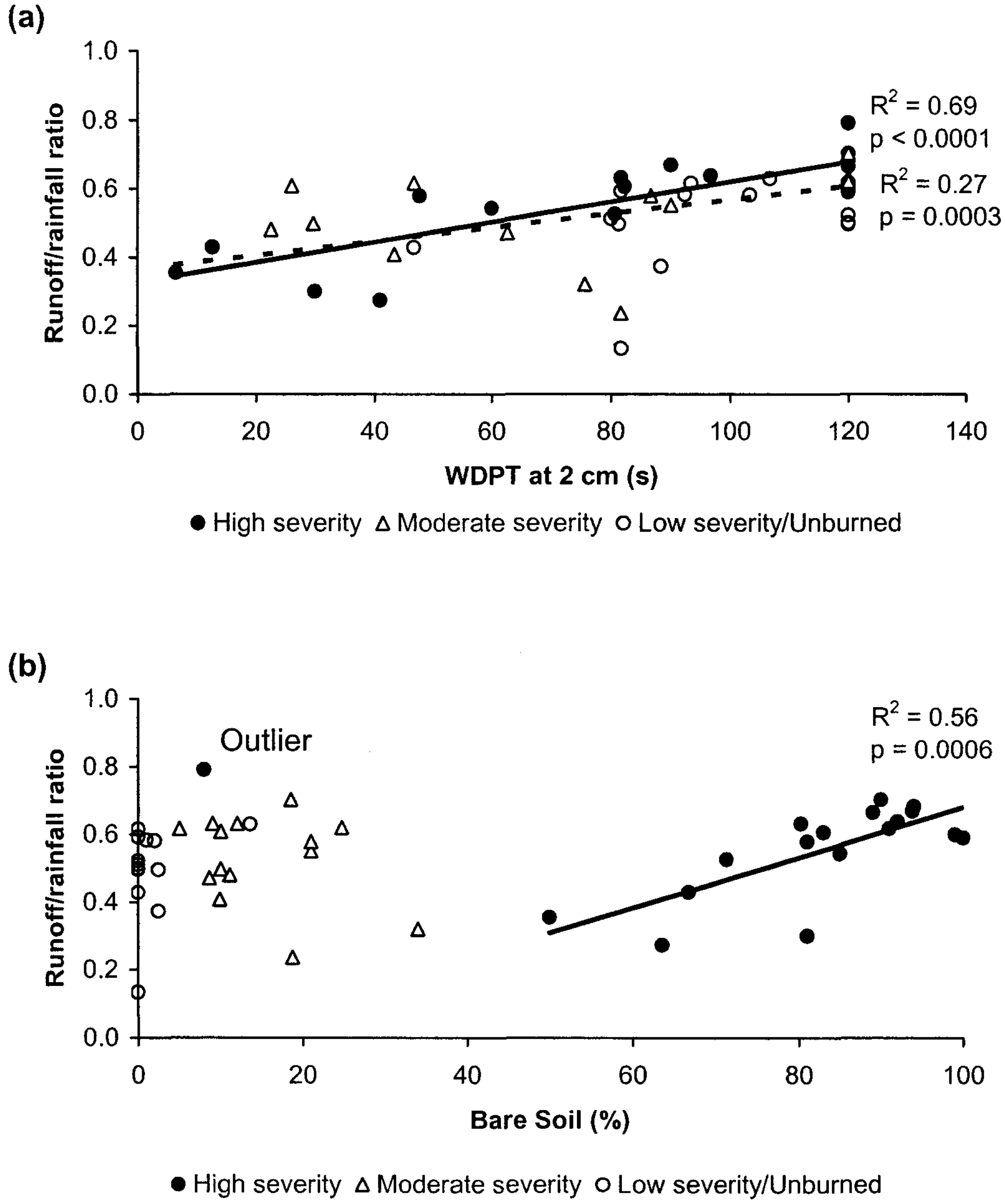


Figure 11. Relationship between the runoff/rainfall ratio and: (a) mean WDPT at 2 cm for pooled data from both years, and (b) percent bare soil for high severity sites. The dashed line in (a) represents all sites and the solid lines in (a) and (b) represent only the high severity sites.

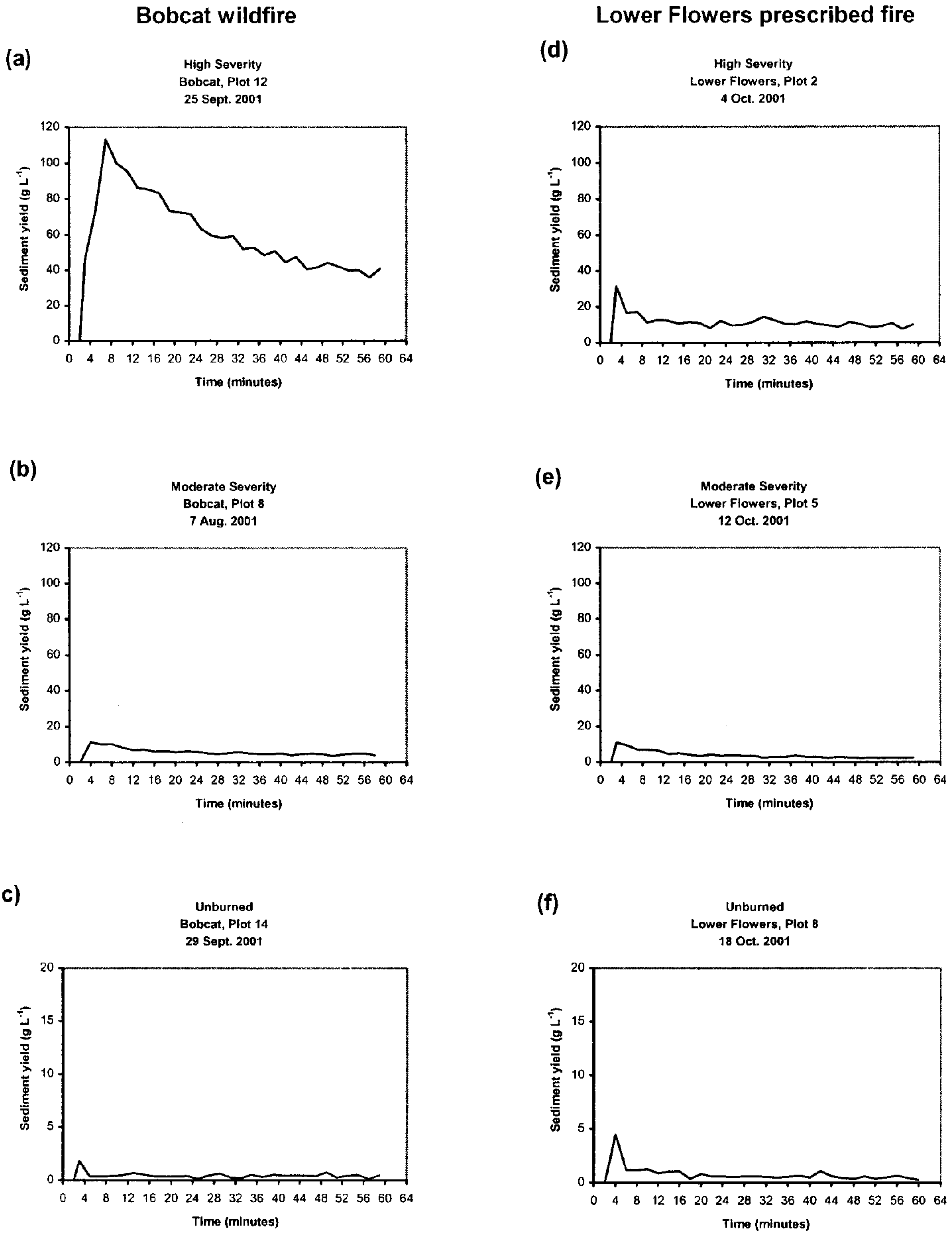


Figure 12. Sedigraphs from the Bobcat wildfire (a-c) and Lower Flowers prescribed fire (d-f) for different fire severities. Rainfall was applied from 0 to 60 minutes at a rate of 68-84 mm h^{-1}.

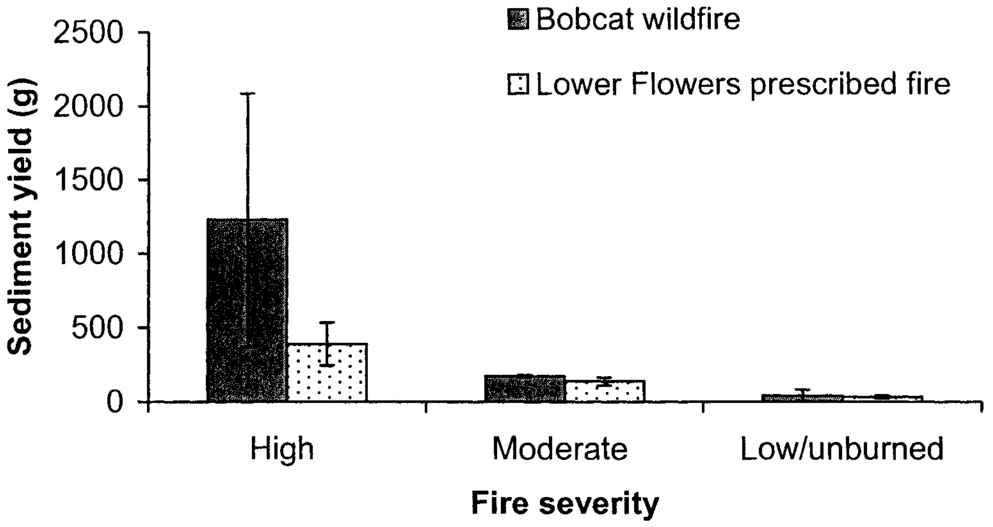


Figure 13. Sediment yields in 2001 by fire severity and fire. Bars represent one standard deviation.

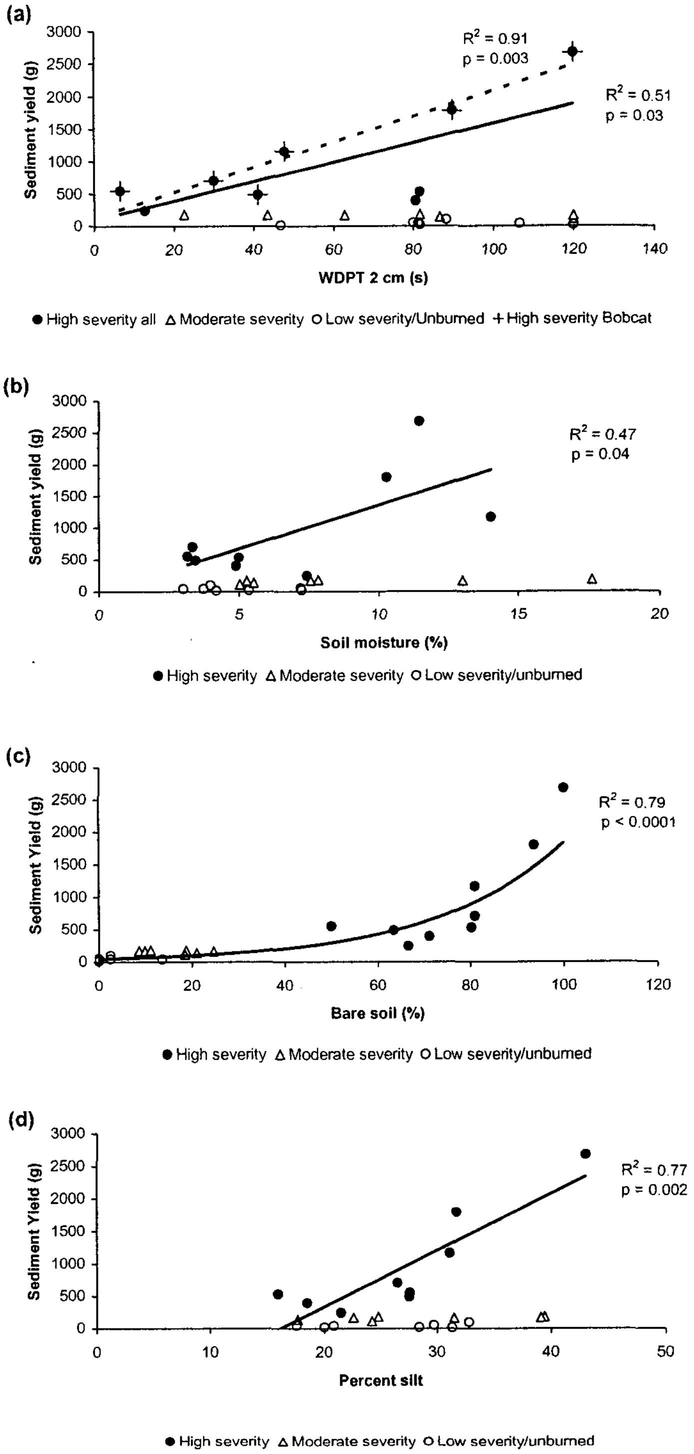


Figure 14. Relationship between sediment yields in 2001 and: (a) mean WDPT at 2 cm, (b) percent soil moisture, (c) percent bare soil, and (d) percent silt. The solid lines in (a), (b) and (d) are only for high severity sites, and the dashed line in (a) is only for the high severity plots from the Bobcat fire. The solid line in (c) is for all the data from 2001.

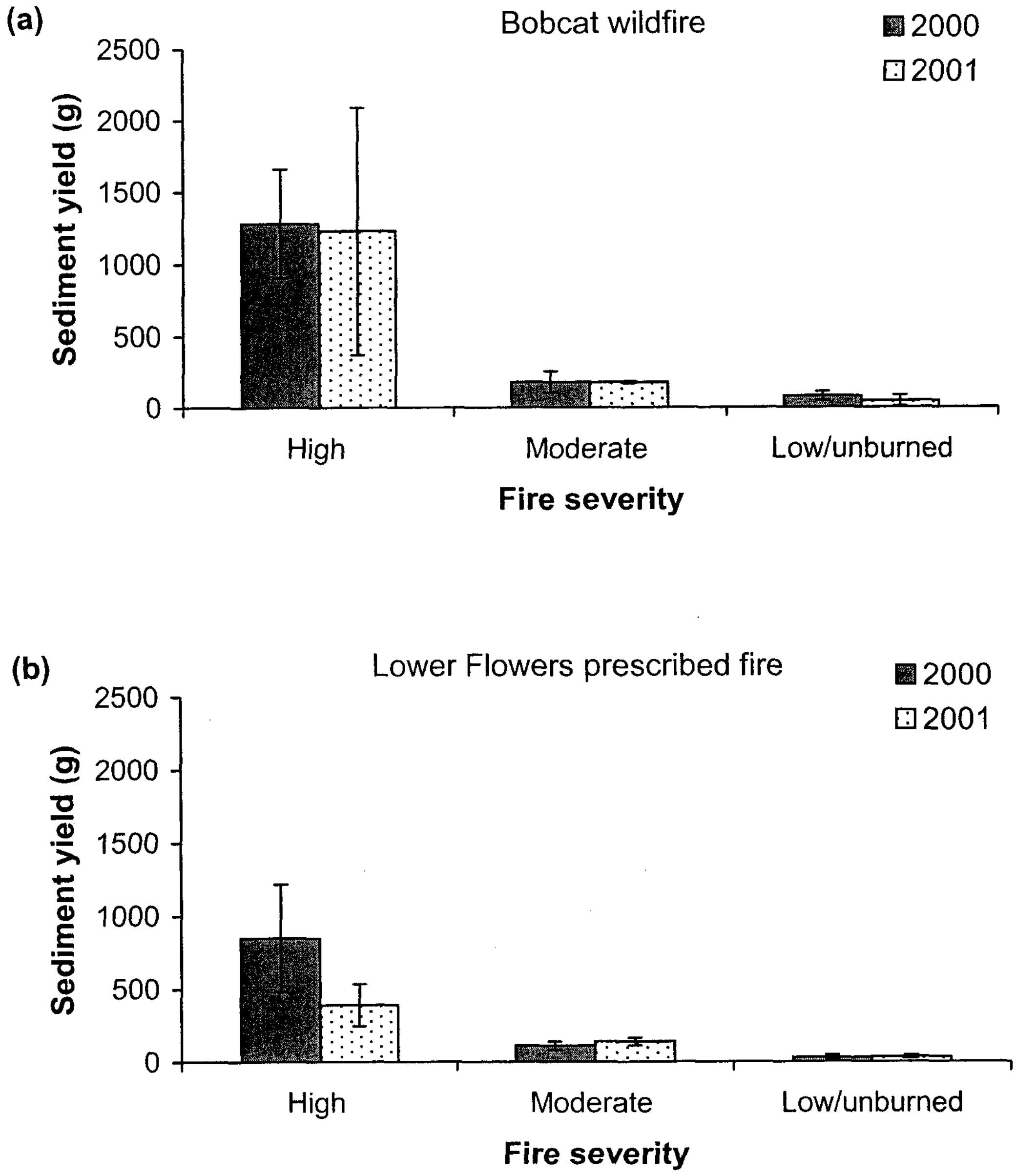


Figure 15. Sediment yields in 2000 and 2001 by fire severity for: a) Bobcat wildfire and b) Lower Flowers prescribed fire. Bars represent one standard deviation.

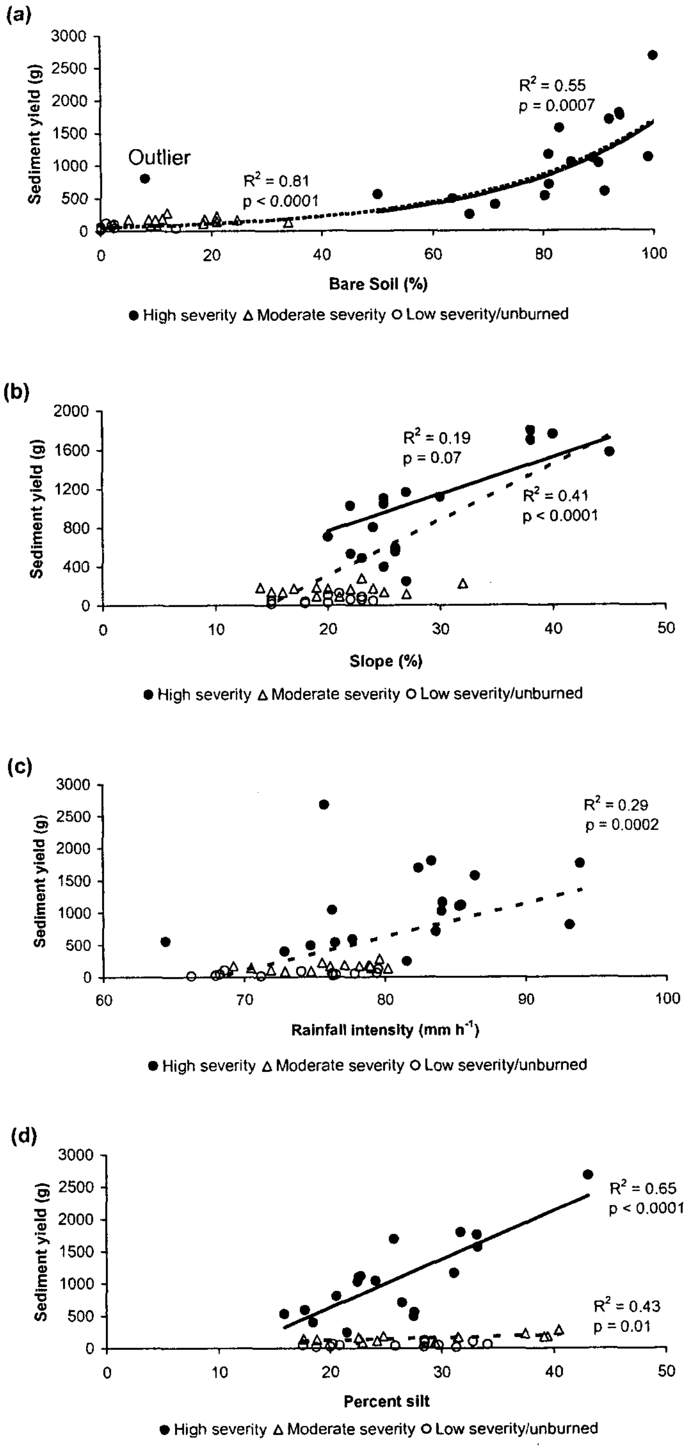


Figure 16. Relationships between the sediment yields from 2000 and 2001 and: (a) percent bare soil, (b) slope, (c) rainfall intensity, and (d) percent silt. The solid lines and statistics are for high severity sites, and the dashed lines and statistics are for the entire data set. The outlier is excluded from the regression shown in (a).

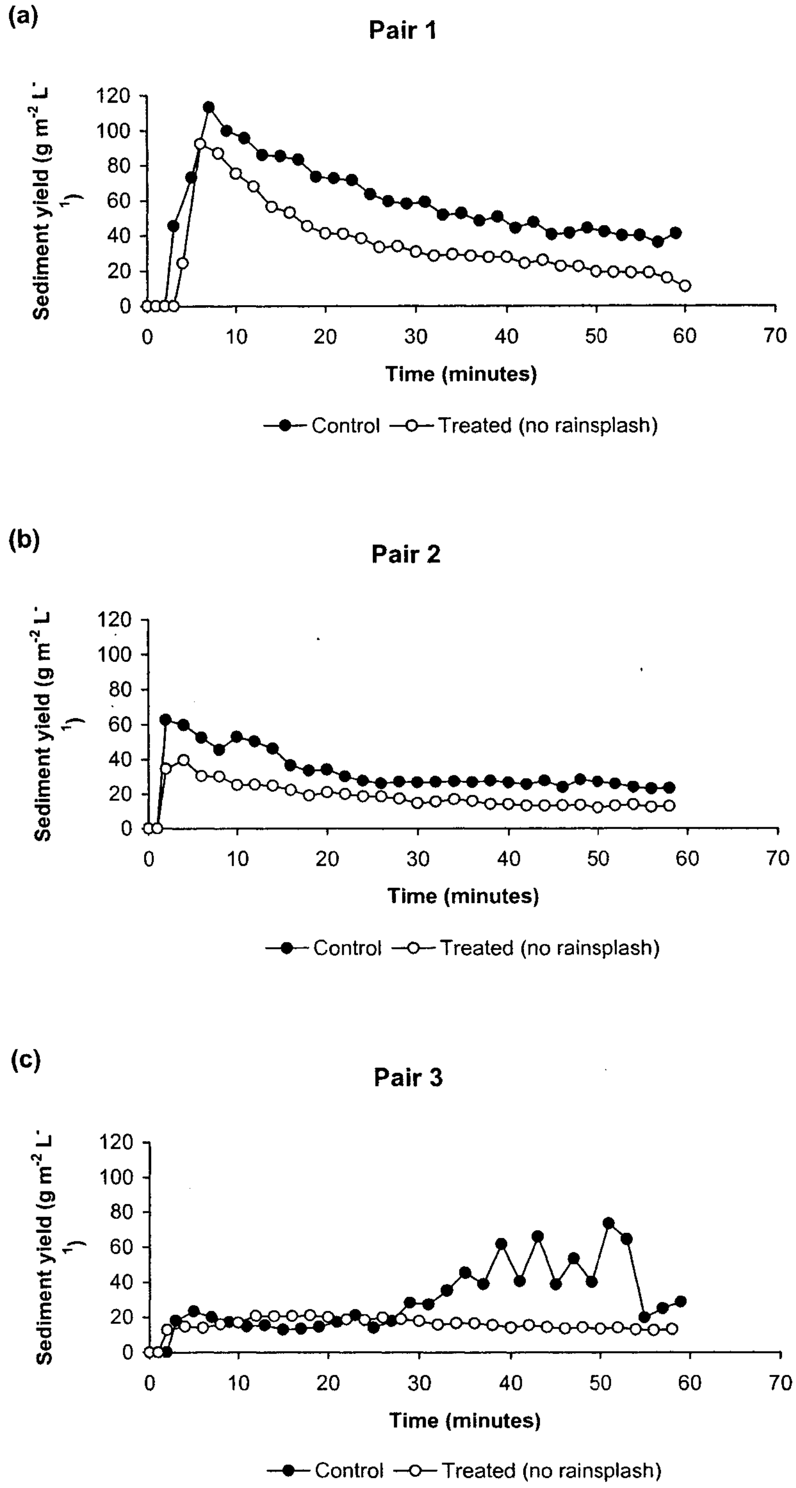


Figure 17. Sediment concentrations over time for three pairs of plots on sites burned at high severity in the Bobcat fire. Pair 1 had extensive ash cover, pair 2 had no ash cover, and pair 3 had about 60% ash cover.

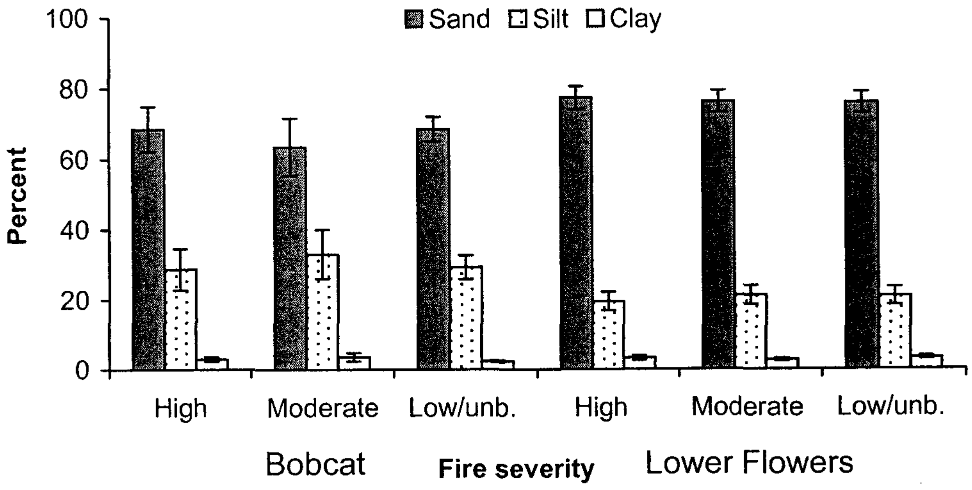
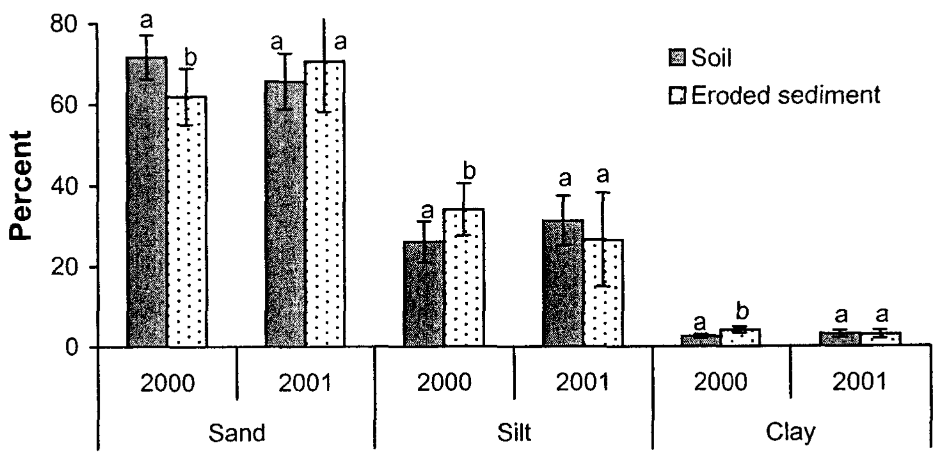


Figure 18. Mean percent sand, silt, and clay for the surface soil (0-5 cm) by fire severity for the Bobcat fire and Lower Flowers prescribed fire. Bars represent one standard deviation.

(a) **High severity sites**



(b) **Moderate severity sites**

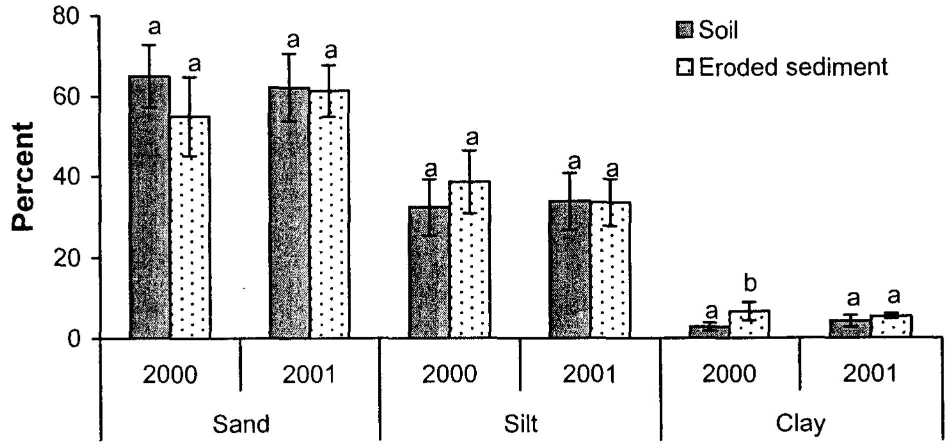
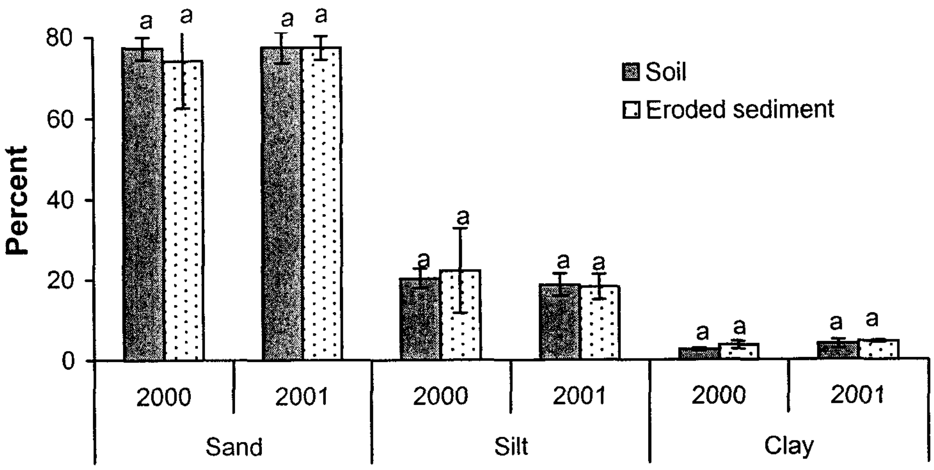


Figure 19. Percent sand, silt, and clay for the surface soil (0-5 cm) and the eroded sediment in 2000 and 2001 for the Bobcat fire for: (a) high severity sites and (b) moderate severity sites. Different letters indicate significant differences in that fraction for that year. Bars represent one standard deviation.

(a) **High severity sites**



(b) **Moderate severity sites**

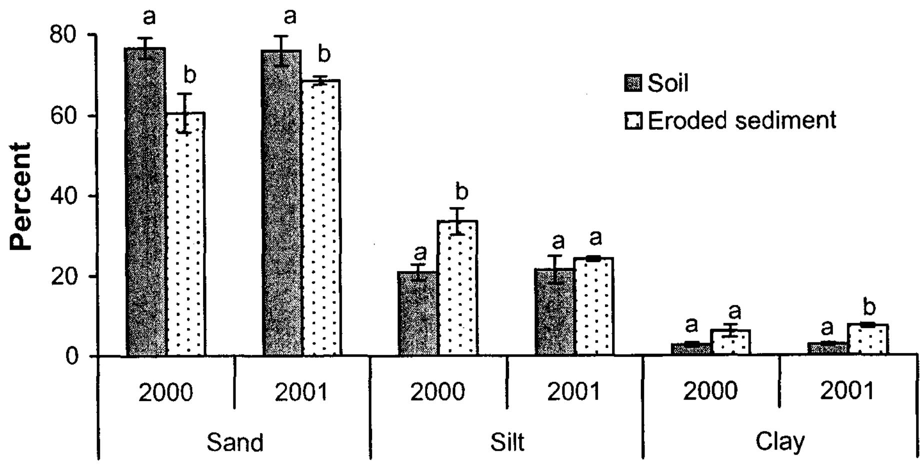


Figure 20. Percent sand, silt, and clay for the surface soil (0-5 cm) and the eroded sediment in 2000 and 2001 for the Lower Flowers prescribed fire for: (a) high severity sites and (b) moderate severity sites. Different letters indicate significant differences in that fraction for that year. Bars represent one standard deviation.

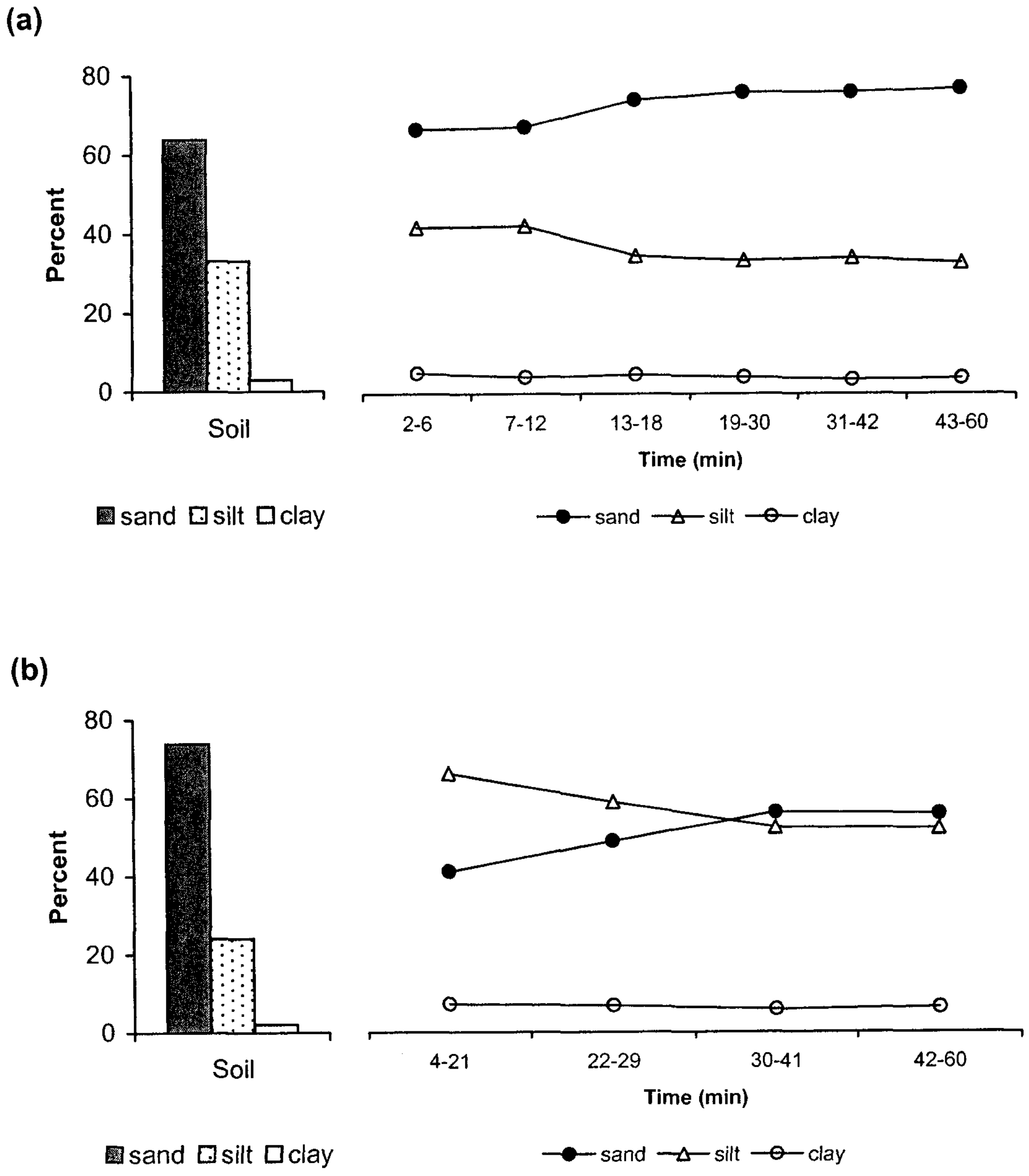


Figure 21. Particle-size distribution of the native soil and the eroded sediment over the course of a single simulation on two high severity plots in the Bobcat fire in 2000. Plot 16 (a) had little ash cover and plot 15 (b) had a high percentage of ash cover.

5. CONCLUSIONS AND FUTURE RESEARCH

Wildfires are important in the Colorado Front Range because they can cause dramatic changes in water quality and aquatic ecosystems. The results from this research quantify the changes in runoff and erosion from both wild and prescribed fires of different ages at both the small plot and hillslope scale. By simultaneously measuring a series of site variables and relating these back to the observed runoff and erosion rates, one can better understand the underlying causal factors. The results will help predict erosion rates from prescribed fires or wildfires, and may lead to the development of better post-fire rehabilitation treatments. The measured runoff and erosion rates also can be used to test other models. Finally, the results will help guide future research on post-fire runoff and erosion processes.

5.1. SMALL PLOTS

For the small plots in the Bobcat fire, the runoff/rainfall ratios exceeded 50% in the first summer (2000) after burning for most plots and fire severities. Runoff rates in high severity sites were only slightly higher than in sites burned at moderate severity or low severity/unburned sites. Runoff/rainfall ratios increased with soil water repellency and decreased with soil moisture. Soil water repellency was mainly fire-induced, but because it was a dry year soil water repellency was also found in low severity and unburned sites.

In the second summer (2001) after burning the runoff/rainfall ratio decreased to 46% in high severity sites. In the second year the high severity sites in the Bobcat fire had runoff/rainfall ratios 28% higher than the low severity/unburned sites. In some cases the Lower Flowers prescribed burn had higher runoff ratios than the Bobcat wildfire, and this resulted mainly from the stronger soil water repellency.

The runoff/rainfall ratios were correlated to soil water repellency for both years of data and all burn severities from both fires (R^2=0.27; p=0.0003). Multivariate analysis of the complete data set showed that soil water repellency was the only significant explanatory variable for runoff/rainfall ratios. The runoff/rainfall ratios observed in each year were higher than the values reported for most other rainfall simulator studies in burned areas.

Fire severity had a much larger effect on sediment production than did runoff. Simulations in 2000 and 2001 in areas burned at high severity yielded 30 times more sediment than simulations in low severity and unburned plots. The mean sediment yield from high severity sites in the Bobcat wildfire was very similar for summer 2000 and summer 2001. The mean value of 1.2 kg m^{-2} was 3 times larger than high severity sites in the Lower Flowers prescribed burn. High severity sites always produced more sediment than sites burned at moderate or low severity.

When the two years of data were pooled, the three factors controlling sediment yields were percent bare soil, percent silt, and the runoff/rainfall ratio (R^2=0.83). The data indicate that the erosion risk after wildfires remained high in the second year after burning for sites burned at high severity, whereas the erosion risk was substantially reduced in the prescribed fire despite similar runoff/rainfall ratios. Sites at Lower

Flowers also produced less sediment in 2001 than the sites in the Bobcat even when the plots had similar percent cover. This difference in erosion rates is probably due to the presence of more readily-available sediment in the wildfire relative to the prescribed fire.

Particle-size analyses of the eroded sediment suggest a decrease in percent fines over time, and this may be due to an armoring of the soil surface. Simulations with reduced raindrop energy indicate that the kinetic energy of sheetflow is more important for sediment production than the energy due to rainsplash. The role of sheetwash was greatest when highly erodible materials, such as ash, are readily available on the soil surface. Slope steepness was not an important factor for either runoff/rainfall ratios or sediment production, and this resulted from the relatively small range of slopes for the sites burned at high severity.

5.2. HILLSLOPE PLOTS

Sediment production rates were monitored for two years on 48 plots located in six different fires of varying ages. The average sediment yield at the hillslope scale from high severity sites in the Bobcat fire was 1.0 kg m^{-2}, and this is similar to the 1.2-1.3 kg m^{-2} measured from the small plots. Fire severity had a large effect on sediment production, as the high severity sites in the Bobcat fire produced about 75 times more sediment than moderate severity sites. As in the case of the small plots, percent bare soil was highly correlated with sediment yields (R^2=0.65). Rainfall produced erosion when the percent bare soil was 40% or more, but the highest sediment yields were generated when there was at least 70% bare soil. The amount of regrowth in the second year after burning was not enough to substantially reduce erosion rates. At Lower Flowers prescribed fire there were no significant differences between severities in the second year after burning due to the high variability between plots, much higher rainfall erosivity, and increased rill erosion on all plots.

The plots in convergent areas or swales produced 2-3 times more sediment per unit area than the plots on planar hillslopes. The combination of this results and field observations indicate that rill erosion produces more sediment than sheetwash erosion, but the relative importance of these two processes cannot be precisely quantified from the results of this study.

Soil texture was not a primary control on sediment production. The lack of any relationship with texture may stem from the fact that all the soils were coarse-textured and therefore had relatively little variability. Similarly, slope was not significant because the slopes only varied from 25% to 45%, and the effect of slope was small relative to the effect of percent cover.

Multivariate models with 2-5 independent variables were developed for users with different levels of information, and the R^2 for these ranged from 0.65 to 0.77. The key variables for predicting sediment production rates at the hillslope scale were fire severity, percent bare soil, and rainfall erosivity. Soil water repellency, hillslope position, soil particle size, and time since burning were important in some cases, and they could be used as surrogate variables given the relationships developed in this study. The multivariate models for predicting hillslope erosion rates had an R^2 of 0.61 when the models were validated with an independent data set.

Erosion from swales and small drainages can be an important source of runoff and sediment. Since much of this material can reach the main drainages, post-fire rehabilitation treatments have to protect the swales and put obstacles in the main drainages to reduce flow velocity and channel scour. The data from both the small plots and hillslope scale showed that sediment production was highly correlated with percent bare soil. The data from small plots suggest that increasing ground cover reduces sediment production, and in these plots sheetwash erosion is the dominant erosion process. However, for rill erosion the type of ground cover is also important. To effectively reduce rill erosion, ground cover must be present over almost the entire soil surface and the cover must have good contact with the soil surface.

These results indicate that sediment production from prescribed fires can be minimized by minimizing the area burned at high severity. If the crowns are not burned, the needlefall and residual soil organic matter will help protect the soil from rainsplash and sheetwash but not from rill erosion.

5.3. FUTURE RESEARCH

The results from the small plots and hillslopes indicate a high risk of surface erosion after high-severity fires in the Colorado Front Range. Future research needs to focus on both field data collection and the generation of additional empirical or physically-based models. These models can help determine relative erosion risks, and thereby guide the selection and implementation of post-fire rehabilitation treatments. Future research should address include soil water repellency, rainfall intensity, the validity of hillslope plots, soil properties, erosion processes, and model development and testing. The specific research needs with respect to each of these topics are discussed in the following sections.

5.3.1. Soil water repellency

Soil water repellency is an important control on runoff rates and, to a lesser degree, on sediment production. Because post-fire water repellency is highly variable in space and over time, more research is needed to quantify the soil water repellency in different fires over a sequence of storms. This research and previous work (Huffman and MacDonald, in preparation) suggests that soil water repellency is weakened or largely eliminated with increasing soil moisture, and this relationship needs to be investigated in more detail. In particular soil moisture must be measured at the same depth as soil water repellency so that the effect of soil water moisture at each depth can be more rigorously associated with the measured soil water repellency.

Soil water repellency in the small plots in 2001 was weaker and more variable than in 2000. The reasons for the decline in soil water repellency over time are not well understood. An understanding of the factors that control the breakdown of post-fire water repellency can help identify practices that might facilitate the recovery to pre-fire infiltration rates.

Most of the hydrographs from the small plots had constant runoff rates once runoff began. This suggests that the soil water repellency did not change over the duration of the rainfall simulation. Additional parameters particularly the depth and velocity of overland flow, should be measured in the field and related to the strength and depth of soil water repellency. Measured flow depths and velocities are needed to parameterize or calibrate more physically-based runoff and erosion models.

5.3.2. Artificial and natural rainfall

This study found only small differences in runoff/rainfall ratios between burn severities. The rainfall was applied at a relatively high intensity and approximately the same intensity was applied to all plots. The high runoff/rainfall ratios may be explained by the presence of soil water repellency and possible soil sealing. Soil water repellency produces an impermeable layer, while soil sealing clogs the pores that transmit water. Both processes act to reduce infiltration rates and thereby increase runoff/rainfall ratios. More research is needed to determine the relative importance of each process over time and how each varies with respect to fire severity.

Sediment yields from both artificial and natural rain events increased with increasing rainfall intensity, but the studies presented here were not designed to rigorously evaluate the relationship between sediment production and rainfall intensity. Rainfall simulations at lower intensities are needed to determine the variations in runoff/rainfall ratios and sediment yields with rainfall intensity. This could be done by using two different intensities during the same simulation (e.g., a lower intensity for the first 30 minutes followed by a higher intensity in the second 30 minutes).

It would also be of interest to conduct some simulations where the rainfall intensity decreases over time, as natural storms sometimes have a high initial intensity that decreases over time. This pattern of simulated rainfall might produce smaller amounts of runoff and sediment because the infiltration rate may increase over time.

Simulations with varying rainfall intensities should provide a better understanding of post-fire runoff and erosion processes and the effects of particular storm patterns on runoff and erosion rates.

On a regional scale, a better map of rainfall depths, durations, and frequencies is needed for the Colorado Front Range. These data and the resulting rainfall erosivities could improve erosion modeling and risk assessment. A better knowledge of specific storms might improve BAER assessments and the selection of treatments.

5.3.3. Assessment of sediment trapping efficiency and runoff at the hillslope scale

The trap efficiency of sediment fences can exceed 90% when collecting the sediment on either a storm-by-storm or a seasonal basis (Robichaud *et al.*, 2001). One limitation is the need to accurately determine the contributing area of a particular sediment fence. Robichaud and Brown (2002) suggest that fences can be used for contributing areas from 15 m^2 to nearly 2,000 m^2, but they also recognize that sediment fences may overtop as occurred in this study. To confirm the trapping efficiency a series of plots should be installed on burned hillslopes with different contributing areas, and each plot should have a series of sediment fences to capture the eroded sediment. The plots should be installed on both planar hillslopes and in swales, and the fences should all be emptied on a storm-by-storm basis. The amount and particle-size distribution of the sediment in each successive fence can be used to assess the trap efficiency as a function of the magnitude of a rain event and the contributing area.

Another need is to quantify the amount of overland flow at the hillslope scale. A control structure, like a flume or V-notch weir, can be used to quantify runoff rates from selected hillslope plots. Because the contributing areas are relatively small, the control structure can be relatively inexpensive. Immediately below the structure one or more fences will be needed to collect the sediment that passes trough the flume or over the weir. These data are needed to relate sediment production to runoff rates, and thereby better understand the mechanics of sediment detachment and transport. Data on runoff rates are also needed to help assess the trapping efficiency of sediment fences.

5.3.4. Soil properties

Aggregate stability and the percentage of soil aggregates were not measured in this study. Since the soils were noncohesive these parameters were not believed to be important. However, field observations indicated that soil aggregates were present in low severity and unburned sites. The presence and stability of aggregates can increase shear strength and thereby reduce erosion rates. Several studies suggest that fires increase soil erodibility (Durgin, 1985; Giovannini *et al.*, 2000), but a determination of the shear strength and aggregate stability (Bryan, 2000) in unburned sites and sites burned at different severities can help assess the effects of fire on soil erodibility and soil sealing. Better information on fire-induced soil erodibility and soil sealing may improve our predictions of post-fire runoff and erosion rates, and lead to the design of better post-fire rehabilitation treatments.

5.3.5. Erosion processes

Another important topic for further research is the effect of spatial scale on runoff and erosion. With increasing scale one would expect an increase in infiltration, a shift from sheetwash to rill erosion, and a decrease in sediment yields (Foster, 1982). As first step rainfall simulations should be conducted on plots several meters long where the flow can become concentrated in microchannels or rills (Haan *et al.*, 1994). The results can be compared to the data from 1 m^2 plots where concentrated flow is less prevalent (Mutchler *et al.*, 1988).

At the hillslope scale this study documented higher erosion rates in swales than on planar hillslopes. However, the rainfall simulations indicated that sheetwash is more important than rainsplash. Moody and Martin (2001) found that rill erosion is the dominant source of sediment after the Buffalo Creek wildfire in the Colorado Front Range. However, field observations in the Bobcat fire indicate that high rainfall intensities did not produce rill erosion at some sites while in other sites low-intensity storms produced rill erosion. More intensive studies are needed in the Colorado Front Range to determine and predict the relative balance between rill and interrill erosion, and the relative influence of soil and topographic factors on rill versus interril erosion.

5.3.6. Modeling

The empirical models generated in this study predict erosion at the hillslope scale, and these should be compared to other erosion models such as RUSLE (Renard *et al.*, 1997), WEPP (Elliot and Robichaud, 1998), and SURFERO (MacDonald *et al.*, 2000). The erosion rates measured in this study should help to calibrate or validate each of these models. Similarly, the data from the small plots can be used to calibrate more physically-based models, such as KINEROS2 (Smith *et al.*, 1995), to determine if these could then be applied over larger scales.

Future progress will require more detailed field measurements (e.g., runoff velocity, flow depth, and surface roughness) and quantifying the relative importance of rill versus interrill erosion in different sites. These data are needed to develop and calibrate more physically-based models. The integration of field studies and modeling should result in better predictions of post-fire erosion risks and improvements in the design of post-fire rehabilitation treatments.

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