THESIS

EFFECTIVENESS OF REHABILITATION TREATMENTS IN REDUCING POST-FIRE EROSION AFTER THE HAYMAN AND SCHOONOVER FIRES, COLORADO FRONT RANGE

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DANIELLA ROUGH ENTITLED “EFFECTIVENESS OF REHABILITATION TREATMENTS IN REDUCING POST-FIRE EROSION AFTER THE HAYMAN AND SCHOONOVER FIRES, COLORADO FRONT RANGE” BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

EFFECTIVENESS OF REHABILITATION TREATMENTS IN REDUCING POST-FIRE EROSION AFTER THE HAYMAN AND SCHOONOVER FIRES, COLORADO FRONT RANGE

A critical environmental concern following high-severity wildfires is the potential for post-fire increases in runoff and erosion. Flooding and sedimentation can pose ecological threats to wildlife habitat and damage human resources such as reservoirs, roads, and structures. Burned area emergency rehabilitation (BAER) treatments are commonly used to reduce these risks, yet few studies have quantified their effectiveness. The primary objective of this study was to evaluate whether scarification with seeding, dry mulch with seeding, aerially-applied hydromulch, ground-applied hydromulch, and polyacrylamide (PAM) treatments significantly reduced erosion after the 2002 Hayman and Schoonover Fires southwest of Denver, Colorado.

The basic design of the study was to compare sediment yields from replicated pairs of treated and control swales from summer 2002 through fall 2004. A variety of other parameters were measured to evaluate causal relationships, including soil texture, slope, aspect, surface cover, precipitation, soil water repellency, and rill density.

The scarification with seeding treatment did not reduce sediment yields relative to the paired controls for any of the three years. The swales treated with aerially-applied hydromulch and dry mulch with seeding reduced sediment yields relative to the controls by more than 90% in the second year, and by 49% and 77% in the third year, respectively.

The ground-applied hydromulch did not significantly reduce sediment yields in any of three years. The wet PAM applied in 2002 reduced sediment yields relative to the controls, but these differences were only significant for the first year. The dry micronized PAM treatment and the wet PAM treatments applied in 2003 and 2004 were ineffective in reducing sediment yields.

The effectiveness of treatments in reducing post-fire erosion was strongly related to the amount of ground cover. The mulch treatments were the most effective because these immediately increased the amount of ground cover. Ground scarification did not increase ground cover and may have increased the erodibility of the top 1-2 cm of soil, as sediment yields from the treated swales were 45% higher than the controls in the first year. The lack of treatment effect from the ground-applied hydromulch was attributed to the poorer slurry formulation. The PAM treatments appeared to be affected by the amount of ash cover as a result of the chemical affinity between the positively charged ash and negatively charged PAM. The soluble cations in ash are necessary for PAM and soil aggregation to occur, but too much ash appeared to intercept PAM and reduce the potential for PAM and soil binding. A laboratory study showed that PAM preferentially binds to ash over mineral soil. The results from this study can help guide future research and management decisions with respect to post-fire rehabilitation treatments.

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1. INTRODUCTION

Many forested areas in the montane western US are dominated by dry ponderosa pine (*Pinus ponderosa*), Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta var. latifolia*), and spruce-fir ecosystems (Romme et al., 2003; Schoennagel et al., 2004). Dendrochronological records from 1600 to present have shown that ponderosa forests in the southwest have historically experienced mixed-severity fire regimes, which include both infrequent high-severity and frequent low-severity fires (Swetnam and Baisan, 1996; Veblen et al., 2000). The fire severity has been well correlated with climatic fluctuations, and widespread high-severity fires have historically occurred around drought years preceded by two to four wet years (Veblen et al., 2000).

The mixed fire regime can result in a patchy landscape from unburned conditions to complete removal of ground cover and tree crowns (Swetnam and Baisan, 1996; Veblen et al., 2000). Typically, ponderosa pine forests in the Colorado Front Range are characterized as having adequate ground cover to protect the soil surface during most high intensity storms. In unburned conditions, most rainfall infiltrates into the soil where the dominant runoff process is sub-surface flow (Dunne and Leopold, 1978). This holds especially true in the arid Colorado Front Range where soil moisture is low and infiltration rates are high (Gary, 1975; Libohova, 2004; U.S.D.A. NRCS, 2005).

Fire suppression over the last few decades has led to unnatural fuel accumulations in many forested areas in the western US, especially in the ponderosa pine forests in the southern Rocky Mountains. The build-up of "ladder" fuels, more continuous canopy coverage, and climate change have shifted the historic fire regime to more low-frequency, high-severity fires (Schoennagel et al., 2004; Westerling et al., 2006). High-severity wildfires can result in the complete removal of vegetation and litter, and volatilization of organic matter in the soil, which leads to the development of a fire-induced water repellent layer at or near the soil surface (DeBano, 1981, 2000; Shakesby et al., 2000). The water repellent layer can impede infiltration, causing an increase in overland flow (Scott and Van Wyk, 1990). During high-intensity storms, the newly exposed mineral soil is subject to rainsplash and soil sealing, which also decrease infiltration and lead to sheetwash and rill erosion (Campbell et al., 1977; Shainberg et al., 1990; DeBano, 1998, 2000). The rates of runoff and erosion on the severely burned soil can be orders of magnitude greater than unburned conditions (Morris and Moses, 1987; Moody and Martin, 2001; Shakesby and Doerr, 2006). Typically, the largest increases in runoff and erosion following high-severity wildfires occur during the first and second storm seasons after a wildfire (DeBano et al., 1996, 1998; Robichaud and Brown, 1999; Benavides-Solorio and MacDonald, 2005; Kunze and Stednick, 2006).

The combination of widespread high-severity fires in the last century and expanding urban development into wildland areas has increased the potential for domestic water supplies and other resources to be adversely impacted by fires. These concerns have brought the issue of post-fire runoff and erosion to the forefront of environmental concerns (Schoennagel et al., 2004). After the 1996 Buffalo Creek Fire, severe flooding and sedimentation resulted in the destruction of four houses and other downstream structures, the deaths of two people, and the deposition of over 350,000 m^3 of sediment into the Strontia Springs Reservoir. Over $4.2 million was spent on fire suppression and emergency rehabilitation treatments after the Buffalo Creek fire (Agnew et al., 1997; Martin, 2000; Moody and Martin, 2001; CUSP, 2007).

Burned area emergency rehabilitation (BAER) treatments are commonly applied by land managers after high-severity fires to reduce the magnitude of downstream impacts from increased runoff and erosion (Miles et al., 1989; Robichaud et al., 2000). Typical treatments include the application of grass seed with or without ground scarification, felling burned trees across the slope to act as dams for water and sediment (contour log erosion barriers), and the application of mulch. While the use of these treatments is widespread, there have been few rigorous studies on the effectiveness of these techniques (MacDonald, 1989; Miles et al., 1989; Robichaud et al., 2000).

The few studies that have researched the effectiveness of post-fire rehabilitation treatments generally found mulch treatments to be highly effective, seeding treatments to be effective in some areas but not others, and contour felling treatments to be effective for a few storms before their capacity is exceeded (Bautista et al, 1996; Badía and Martí, 2000; Robichaud et al., 2000; Dean, 2001; Wagenbrenner et al., 2006). The major shortfalls of these studies have been small sample sizes, minimal or no geomorphological data, no storm-specific data, and the lack of a paired design to more rigorously compare treated and control plots. Replicated field-scale studies are hindered by the large masses of sediment that need to be quantified.

This study measured hillslope-scale (0.07 to 0.7 ha) sediment yields because this is the smallest scale relevant to managers that was still logistically feasible. Natural variability was minimized and the ability to detect significant differences was increased by using a paired design with swales that were similar in location, contributing areas, slopes, aspects, soil types, and burn severities.

The results of this study are presented in two chapters. Chapter 2 summarizes a three-year study that monitored the effectiveness of four BAER treatments in reducing post-fire erosion after the 2002 Hayman Fire. The treatments monitored included hand scarification in combination with seeding, manually-applied straw mulch with seeding, and ground- and aerially-applied hydromulch. After the Hayman Fire these treatments were applied by the US Forest Service to approximately 12,000 ha at a cost of over $16.5 million (Robichaud et al., 2003).

Chapter 3 presents data on the effectiveness of an alternative rehabilitation treatment, polyacrylamide (PAM). PAM is a soil binding agent which aggregates soil particles to reduce erodibility and increase infiltration. Anionic PAM has been used extensively in agricultural applications with considerable success in reducing erosion from furrow irrigation (Sojka and Lentz, 1997; Sojka et al., 2000). After the Hayman Fire the Denver Water Board applied wet PAM to 360 hectares of land around the Cheesman Reservoir that burned at high-severity (Kennedy, 2003). This study evaluated the effectiveness of a similar wet PAM treatment to reduce post-fire erosion after the Schoonover Fire. Six pairs of treated and control swales were used to monitor sediment yields for dry PAM, a single PAM application, and multiple PAM application treatments.

The results of these two studies provide useful data on the effectiveness of several commonly applied BAER treatments and an alternative treatment that has not been previously evaluated for post-fire conditions. The greatest value of this thesis is the large number of treatments that were evaluated in the same environment, which allowed for direct comparisons between treatments with minimal environmental variability. The results help to understand the relative importance of the underlying physical factors that control the effectiveness of a treatment, but the absolute results should only be extrapolated to similar environments in the Colorado Front Range. The findings will provide useful information for cost-benefit analyses and the future formulation and selection of different BAER treatments.

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2. EFFECTIVENESS OF POST-FIRE REHABILITATION TREATMENTS AFTER THE HAYMAN FIRE, COLORADO FRONT RANGE

2.1. ABSTRACT

Post-fire runoff and erosion are often of concern following high-severity wildfires. To reduce runoff and erosion, burned area emergency rehabilitation (BAER) treatments are often applied, yet few studies have quantified their efficacy. The primary objective of this study was to evaluate whether four different treatments--scarification with seeding, aerially-applied hydromulch, ground-applied hydromulch, and dry mulch with seeding--reduced post-fire erosion in a ponderosa pine dominated forest burned at high severity during the 2002 Hayman Fire.

The basic design was to compare sediment yields from replicated pairs of treated and control swales from summer 2002 through summer 2004. The scarification with seeding treatment did not increase live vegetative cover or reduce sediment yields relative to the paired controls for any of the three years. The three mulch treatments reduced sediment yields in summer 2002 by more than 99%, but these reductions were not statistically significant. The swales treated with ground-applied hydromulch had significantly higher ground cover than the controls in 2002 and spring 2003, but not from fall 2003 to fall 2004. The ground-hydromulch did not reduce sediment yields in either summer 2003 or summer 2004. Conversely, aerially-applied hydromulch and dry mulch with seeding treatments significantly reduced sediment yields by greater than 90% in the second year, and by 49% and 77% in the third year, respectively. These two treatments

had significantly higher ground cover than the controls for the first 1.5 and 2 years after burning, respectively.

The primary controls on treatment effectiveness are the amount of ground cover and time since burning. The mulch treatments were the most effective because these immediately increased the amount of ground cover. The scarification with seeding treatment was not effective because it did not provide additional ground cover, and may have increased soil erodibility.

2.2. INTRODUCTION

High-severity wildfires in the Colorado Front Range have become a concern over the last decade as a result of fire suppression and the associated increases in fire size and severity (Veblen and Lorenz, 1991; Schoennagel et al., 2004). Larger-scale, high-severity wildfires can lead to increased rates of runoff and erosion that are orders of magnitude greater than unburned conditions (Morris and Moses, 1987; Moody and Martin, 2001; Shakesby and Doerr, 2006). Expanding urban development and the magnitude of high-severity fires in the last century have increased the potential for natural and human resources to be adversely impacted by wildfires.

The increases in runoff and erosion are typically attributed to the loss of ground cover and organic matter, and the development of a fire-induced water repellent layer at or near the soil surface (DeBano, 1981, 2000; Shakesby et al., 2000). The water repellent layer results from volatilization and remobilization of aliphatic compounds, and this can impede infiltration and increase overland flow (Scott and Van Wyk, 1990). During high-intensity rain events, newly exposed bare mineral soil is subject to rainsplash and soil sealing, which also decrease infiltration and lead to increased rates of sheetwash and rill erosion (Campbell et al., 1977; Shainberg et al., 1990; DeBano, 1998, 2000). Typically, the largest increases in runoff and erosion occur during the first and second storm seasons after a wildfire (DeBano et al., 1996, 1998; Robichaud and Brown, 1999; Benavides-Solorio and MacDonald, 2005; Kunze and Stednick, 2006).

After high-severity wildfires, land managers commonly apply burned area emergency rehabilitation (BAER) treatments to reduce the magnitude of the increases in runoff and erosion (Miles et al., 1989; Robichaud et al., 2000). Typical treatments include the application of grass seed with or without ground scarification, felling burned trees across the slope to act as dams for water and sediment (contour log erosion barriers), and the application of mulch. While the use of these treatments is widespread, there have been few rigorous studies on the effectiveness of these techniques (MacDonald, 1989; Miles et al., 1989; Bautista et al., 1996; Robichaud et al., 2000; Dean, 2001).

In the case of the Bobcat Fire west of Fort Collins, Colorado, over $600,000 was spent on post-fire rehabilitation treatments. Wagenbrenner and others (2006) monitored the effectiveness of these treatments in reducing hillslope-scale erosion for four years after the fire. The results showed that mulching significantly reduced erosion rates by greater than 95% for three of the years monitored. Contour felling treatments significantly reduced erosion rates after small storms. Seeding had no effect on erosion rates for any of the years monitored. A study in northeastern Spain showed that burned plots with dry mulch with seeding produced two to three times less sediment than the control plots for two different soil types (Badía and Martí, 2000). The effectiveness of mulching in burned areas is consistent with studies in other disturbed areas, such as construction sites and reclaimed mined lands (Meyer et al., 1970; Goldman et al., 1986; Benik et al., 2003). However, the disadvantages of mulching after forest fires include the logistics of applying mulch in unroaded areas, keeping the mulch in place on steeper slopes or areas subjected to high winds, the limited availability of mulch after large fires, the addition of unnatural litter into otherwise pristine watersheds, and the potential introduction of exotic species and noxious weeds (Weeks and Colter, 1952; Foltz and Dooley, 2003; Kruse et al., 2004). Surface runoff beneath the mulch also can reduce the potential effectiveness of mulching as erosion can occur below the layer of elevated surface roughness (Kramer and Meyer, 1969; Foster et al., 1982).

In June 2002 the Hayman Fire burned 56,000 ha of ponderosa pine (*Pinus ponderosa*) dominated forest, 50 km southwest of Denver, Colorado. Approximately 19,000 ha or 35% of the total area was burned at high-severity (U.S.D.A. Forest Service, 2003). The subsequent flooding, erosion, and deposition of fine ash and sediment created a considerable threat to the water supply for the 2.5 million residents in the Denver metropolitan area (Robichaud et al., 2003). About $16.5 million was spent after the Hayman Fire to apply BAER treatments to over 18,000 ha (Robichaud et al., 2003). Treatments included ground- and aerially-applied hydromulch (1,250 ha), manually- and aerially-applied straw mulch (6,300 ha), and seeding in combination with mechanical or hand scarification (5,300 ha) (Robichaud et al., 2003). The primary goal of this study was to monitor the effectiveness of these treatments in facilitating vegetative regrowth and reducing post-fire erosion.

2.2.1. Study Objectives

The specific objectives of the study were to: (1) compare sediment yields by treatment between treated and untreated swales burned at high severity, (2) monitor changes in sediment yields by treatment over time, (3) determine if any of the treatments increased the amount of vegetative cover over time, and (4) relate the observed sediment yields to key site variables in order to explain any observed differences in sediment yields between treatments. These results should provide valuable information regarding future management decisions involving BAER treatment selection and application methods.

2.3. SITE DESCRIPTION AND METHODS

2.3.1. Site Description

The study site is in the northern portion of the Hayman Fire about 50 km southwest of Denver, Colorado. The Hayman Fire burned nearly 56,000 ha in June and July 2002 (Figure 2.1). The majority of the burned area was in the Pike-San Isabel National Forest, and over 50% of the burned area was classified as moderate to high severity. All of the study swales are in Upper Saloon Gulch and Upper Brush Creek, which are in the northeastern corner of the burned area (Figure 2.1). Elevations range from 2,200 to 2,400 m, and prior to burning the predominant vegetation was ponderosa pine (*Pinus ponderosa*).

Soils are derived from the Pikes Peak granite, which weathers to a soil dominated by coarse sand and gravel (Moore, 1992; U.S.D.A. NRCS, 2005). The two primary soil types are Sphinx (sandy-skeletal, mixed, frigid, shallow Typic Ustorthents) and Legault (sandy-skeletal, paramicaceous, shallow Typic Cryorthents) (U.S.D.A. NRCS, 2005).

These soils drain quickly (5-15 cm hr^{-1}) and have very low available water capacity (0.03-0.07 cm cm^{-1}) (U.S.D.A. NRCS, 2005b). Hillslope gradients range from 5-80%. Runoff and erosion potential are moderate to severe, depending on slope and depth to bedrock (U.S.D.A. NRCS, 2005). Annual interrill erosion rates are typically around 0.0 to 0.28 Mg ha^{-1} (Moody and Martin, 2001).

2.3.2. Study Design and Treatment Applications

Sediment yields were measured from 28 zero-order basins ("swales"). For the purpose of this study, a swale is defined as a converging area that concentrates overland flow. Most of the swales used in this study had sediment fences installed in summer 2001, prior to the Hayman Fire, in order to assess the effects of a proposed thinning treatment (Libohova, 2004). The contributing areas of the 24 original swales ranged from 700 m^2 to 8,800 m^2, and they had no defined channel prior to burning. There was no measurable sediment production from any of these swales between 8 June 2001 (when the sediment fences were installed) and 8 June 2002, immediately before the Hayman Fire.

In the present study four BAER treatments were evaluated and there were four replicates per treatment. Three treatments were evaluated using a paired swale design, where the swales within each pair had similar slopes, aspects, and contributing areas. One swale from each pair was randomly selected and treated, and the other swale was left as a control. The three treatments that used this design were: (1) scarification with seeding; (2) ground-applied hydromulch ("ground hydromulch"); and (3) dry mulch with seeding ("dry mulch"). The aerially-applied hydromulch treatment ("aerial hydromulch") did not use a paired design because the helicopters could not treat individual swales, so the controls for this treatment were the four closest untreated swales. These control swales were 100-900 m away from the four treated swales (Figure 2.1).

Scarification with Seeding

The scarification with seeding treatment was applied on 6 August 2002. Scarification can potentially break up the water repellent layer and increase surface roughness. This can potentially increase infiltration and provide surface roughness to trap sediment and retain the seeds on the hillslope until germination can occur (Cipra et al., 2003; Robichaud et al., 2003).

The hand scarification was done by dragging a 0.3-m wide McLeod with 9-cm long metal tines along the contour. In each swale a series of three adjacent parallel lines were raked approximately 0.3 m apart from one another to make 1.5-m wide strips, consistent with methods used by the U.S. Forest Service (K. Kanaan, 2002, pers. comm.). The spacing between these strips should range from approximately 3 m on 30-40% slopes to 6 m on 20-30% slopes.

Following scarification, seeds were manually applied over the scarification lines using a rotary spreader. The target seed density was 280 seeds m^{-2}, or approximately 84 kg ha^{-1}. The certified weed-free seed mix consisted of 70% spring oats (*Avena sativa*) and 30% winter triticale (*x Triticosecale rimpaui*). The depth of the scarification was measured on each treated swale with a ruler at seven random locations within the scarified strips. The seed density was measured in seven 0.09 m^2 plots at random locations within the scarified strips.

Dry Mulch

The dry mulch treatment was applied by U.S.D.A. Forest Service fire crews on 14 August 2002. Prior to mulching, seeds were manually applied to the entire swale using the same rotary seed spreader, seed mixture, and target density as the scarification with seeding treatment. Following seeding, dry straw mulch was spread over the surface at a target application rate of 2.24 Mg ha^{-1}.

Ground Hydromulch

The ground hydromulch was sprayed from vehicles on 28 September 2002. The hydromulch was applied as a water-based slurry at 47,000 L ha^{-1}, and this included 2.2 Mg ha^{-1} of whole wood fiber mulch, 110 kg ha^{-1} guar tackifier, and a 84 kg ha^{-1} seed mixture of 70% spring barley (*Hordeum vulgare*) and 30% winter triticale (*x Triticosecale rimpaui*). The maximum spray distance from the roads was 90 m.

Aerial Hydromulch

The aerial hydromulch treatment was applied by helicopter in 0.45 Mg drops over a period of two weeks in late August 2002. The hydromulch was applied as a water-based slurry at 38,000 L ha^{-1}, and this included the same seed mixture as the ground hydromulch at a rate of 81 kg ha^{-1}, 2.0 Mg ha^{-1} of hemlock wood fiber mulch, 81 kg ha^{-1} guar tackifier, and 11 kg ha^{-1} of a soil binding agent polyacrylamide (PAM).

2.3.3. Plot Characterization

A series of plot characteristics were measured to ensure comparability between sites and better understand the potential causes of any differences or trends in sediment yields. The variables measured in each swale included the contributing area, slope, aspect, soil texture, surface cover (ground cover and bare soil), rill density, and soil water repellency.

The contributing area of each swale was measured in July 2002 using a high resolution Trimble global positioning system (GPS) with a 3 m horizontal root mean squared [HRMS] accuracy. Axis and side slopes were measured with a clinometer. Aspect was measured with a compass adjusted for magnetic declination.

Surface cover was measured at 100 to 150 points in each swale using a systematic point count along five to ten transects with random origins (Parker, 1951). At each point the surface cover was classified as ash, bare soil, live vegetation, trees, litter/duff, woody debris (>1 cm in diameter), logs (>10 cm diameter), or rocks (>5 cm secondary axis). The first cover count was conducted in July 2002, and these were repeated in spring and fall of 2003 and 2004 to represent the beginning and end of each growing season. Additional cover counts were conducted immediately after the application of dry mulch, aerial hydromulch, and ground hydromulch to determine the change in ground cover caused by the treatments. Cover counts also were conducted in spring and fall 2004 on four swales that had been treated with an aerial application of dry mulch ("aerial dry mulch") in August 2002 at approximately the same time as the hand-applied dry mulch. These surface cover measurements were taken in order to compare the amount of mulch cover between the ground-based and aerial applications of dry mulch, and to evaluate the representativeness of the hand-applied treatment relative to the larger-scale aerial application.

Soil samples were collected from a depth of 0-5 cm from the top, bottom, and primary channel of each swale. Each sample was approximately 1 kg and represented a composite of ten randomly selected locations within the specified area. Samples were homogenized and sieved to determine the percent of coarse material (>2.0 mm) coarse to very coarse sand (0.50 to 2.0 mm), medium sand (0.25 to 0.50 mm), very fine to fine sand (0.063 to 0.25 mm), and clay/silt (<0.053 mm). Percent organic matter was determined by incinerating the samples for 6 hours at 400°C and determining the difference in weights pre- and post- incineration (Cambardella et al., 2001).

Rill density was measured in fall 2003 and fall 2004 to determine the effect of the treatments on rill formation, and to determine whether rill density was related to sediment yields. Rills were defined as incised channels caused by surface runoff that were small enough (less than 10 cm) to be smoothed out by normal tillage. Rill densities were calculated by counting the number of rills on five to ten 1-m wide transects across each swale. The only incised channels in the swales that were not included in the rill density measurements were the primary axis channels.

Soil water repellency was measured in summer 2002, 2003, and 2004 on the untreated burned swales (36 sampling pits), and in 2003 and 2004 on the treated swales (48 sampling pits or 12 per treatment). Measurements were made at depths of 0, 3, 6, 9, and 12 cm below the soil surface at randomly selected locations in the top, middle, and bottom of each swale. The critical surface tension (CST) test was used, which quantifies the wettability of a surface using different concentrations of ethanol in water (Letey, 1969). Solutions of 0% ethanol (CST=72.75 dynes cm^{-1}), 1% (69.50 dynes cm^{-1}), 3% (63.01 dynes cm^{-1}), 5% (56.37 dynes cm^{-1}), 9% (51.03 dynes cm^{-1}), 14% (46.06 dynes cm^{-1}), 19% (41.50 dynes cm^{-1}), 24% (36.95 dynes cm^{-1}), 34% (33.24 dynes cm^{-1}), and 48% (30.10 dynes cm^{-1}) were used to determine CST. Starting with pure water progressively higher concentrations of ethanol were applied in succession until infiltration of multiple drops occurred within 5 seconds. No water repellency was present when the 0% ethanol solution infiltrated into the soil within 5 seconds, while higher concentrations (lower CST) represented stronger soil water repellency. For comparative purposes, CST was also measured in Trumbull, an unburned area approximately 5 km away from the study sites. Measurements were taken from 39 sampling pits in summer 2002 at depths of 0, 3, 6, and 9 cm using the same sampling technique as described above (Libohova, 2004).

2.3.4. Precipitation

Precipitation was measured using three tipping-bucket rain gauges with a resolution of either 0.2 mm or 0.25 mm. The southernmost gauge (USG South) was located on the south fork of Upper Saloon Gulch, and this was installed in June 2001 (Figure 2.1). The other two gauges were in the north fork of Upper Saloon Gulch. The middle of the three gauges (USG North) was installed in August 2002, and the gauge on the north end of the study area (USG North 2) was installed in June 2003. All swales were within 700 m of a rain gauge. The gauges were cleaned and data were downloaded at least once every two months.

Previous studies on post-fire erosion in the Colorado Front Range have found that nearly all of the post-fire sediment production occurs during the summer thunderstorm season between 1 May and 31 October (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006). To include all potential sediment-producing storms, rainfall between 1 May and 31 October was defined as the summer storm season. Discrete storms were defined as being separated by at least 60 minutes with no precipitation. Multiple tips in one second were considered false and were deleted.

The RF program (Petkovsek, 2002) was used to calculate storm depth, storm duration, maximum 30-minute intensity (I_{30}), and storm erosivity. Rainfall erosivity was calculated by multiplying the maximum I_{30} by the total kinetic energy of the storm (Brown and Foster, 1987; Renard et al, 1997). These values were calculated for each storm greater than 5 mm and any other storms that produced sediment as indicated by regular field visits. The value of 5 mm was used because this is typically the minimum amount of precipitation needed to generate sediment from areas recently burned at high severity in the Colorado Front Range (Moody and Martin, 2001; Benavides-Solorio, 2003; Pietraszek, 2006). When there were multiple storms over one day that produced sediment, the total rainfall and erosivity for that day were summed. Long-term (1903 to 2004) precipitation data from Cheesman Reservoir, which is approximately 10 km from the study site, were used to assess the representativeness of the monthly and annual precipitation in 2002, 2003, and 2004.

2.3.5. Sediment Yield Measurements

The sediment fences used to measure sediment yields were placed in small swales rather than planar hillslopes because the contributing area and unit area erosion rates can be more accurately determined. Each fence was constructed from 1.2-m wide geotextile fabric attached to 1.3-cm rebar that has been pounded into the ground (Robichaud and Brown, 2002) (Figure 2.2). Since the geotextile of the original sediment fences burned in the fire, this was replaced in July 2002, just a few weeks after the Hayman Fire. A second sediment fence was added in each swale to increase the storage capacity and catch efficiency.

To the extent possible, the sediment collected in each fence was removed and weighed after each sediment-producing storm. Two samples were collected and placed in airtight plastic bags for transport to a laboratory where samples were weighed, dried for 24 hours at 105°C, and weighed again to determine water content following an equation adapted from Gardner (1986):

$$W_c = [(W_w-\tau)-(W_d-\tau)]/(W_w-\tau) \qquad (1)$$

where W_c is the water content of the collected sample, W_w is the wet weight of the sample, W_d is the weight of the sample after drying, and τ is the tare weight of the container. The water contents were used to convert the field-measured wet weights to a dry mass by:

$$W_d = W_w - (W_c * W_w) \qquad (2)$$

where W_w is the wet weight of the sediment collected from the sediment fence and W_d is the calculated dry weight. Unit area sediment yields were calculated as the dry weight divided by the contributing area. After drying, the samples were sieved to determined the percentages of gravel or coarse material (>2.0 mm) coarse to very coarse sand (0.50 to 2.0 mm), medium sand (0.25 to 0.50 mm), very fine to fine sand (0.063 to 0.25 mm), and clay/silt (<0.053 mm).

2.3.6. Statistical Analyses

Annual sediment yields, cover classes (percent bare soil, percent ground cover, and percent live vegetation), and rill densities were analyzed as dependent variables in a repeated measures mixed effects model (SAS Institute, 2004). Comparisons were made between each treatment group and the corresponding controls. Treatment group and year were considered fixed effects, while treatment condition (control or treated) and pair were treated as random variables. The chronological sampling order (e.g., fall 2003) was used as the period of the repeated measures for percent bare soil, percent ground cover, and percent live vegetation. The year was used for the period of the repeated measures for annual sediment yields (2002, 2003, and 2004) and rill densities (2003 and 2004). Surface cover classes and rill densities also were analyzed as covariates for annual sediment yields since ground cover and rill density can be affected by the treatments.

Annual sediment yields were log-transformed for analysis of significance since a residual plot of the log-transformed data was more normally distributed than the untransformed data (SAS Institute, 2004). Linear regression analysis was used to evaluate the effect of bare soil, rill density, and rainfall erosivity on sediment yields. For graphical purposes, Tukey's HSD (Honestly Significant Differences) test was used to evaluate all pairwise comparisons of annual sediment yields between treatment groups and the pooled control swales.

Soil water repellency was compared between unburned and burned control swales in 2002 using analysis of variance (ANOVA). The was a one-tailed hypothesis in the direction of greater water repellency on the burned swales, with the null hypothesis being lower or equal water repellency on the burned swales. ANOVA also was used to compare soil water repellency for each depth between treated burned plots, untreated burned plots, and unburned plots. The analysis was two-tailed for these comparisons since treatment effect on water repellency was unknown. An alpha of 0.05 was used for all statistical analyses.

2.4. RESULTS

2.4.1. Plot Characteristics

The mean contributing area of the swales was 2,830 m^2 (s.d. = 1,630 m^2) and the range was from 690 to 6,650 m^2. Elevations ranged from 2,200 m to 2,410 m. Of the 28 swales, 13 were northeast facing, and the other 15 ranged from east to southwest (Table 2.1). The side slopes ranged from 11% to 34%, with a mean of 19% and a standard deviation of 6%. Axis slopes were generally steeper as the mean was 24% (s.d. = 4%) and the range was from 18% to 35% (Table 2.1).

There were no significant differences in the mean soil texture between treatment groups, between the treated versus control plots by treatment type, or between the channel, upper, and lower portions of the swales. The average soil texture at the beginning of the study was 50.4% coarse material (s.d.=6.5 %), 39.9% sand (s.d.=5.0%), 9.0% silt (s.d.=2.7%), and 0.6% clay (s.d.=0.2%). The mean organic matter content was 1.9% (s.d.=0.4%).

The mean spacing of the scarification strips was 3.8 m (s.d. = 1.6 m), and the spacing between the scarification strips decreased from 8.3 m to 0.8 m as the local slope increased from 19% to 29%. The mean depth of scarification for the four treated swales was 1.6 cm (s.d. = 0.9 cm).

The mean seed densitiy for the scarification with seeding treatment was 320 seeds m^{-2} (s.d. = 200). The mean seed density for the dry mulch treatment was 300 seeds m^{-2} (s.d. = 240 seeds m^{-2}). These two treatments each had seed densities close to the target density of 280 seeds m^{-2}. Seed densities for both the ground and aerial hydromulch treatments were well below the target density with 54 seeds m^{-2} (s.d. = 75 seeds m^{-2}) and 130 seeds m^{-2} (s.d. = 92 seeds m^{-2}), respectively.

2.4.2. Precipitation

The annual precipitation at Cheesman Reservoir has ranged from 186 mm to 617 mm between 1903 and 2004, with a historic mean annual precipitation of 402 mm (s.d.=83 mm). Both 2002--the year of the Hayman Fire--and 2003 were exceptionally dry with 214 mm of precipitation in 2002 and 304 mm in 2003. These values were respectively 2.3 and 1.2 standard deviations below the historic mean.

The mean precipitation at Cheesman Reservoir between 1 May and 31 October "summer" is 273 mm (s.d.=75 mm). Summer precipitation in 2002 and 2003 at Cheesman Reservoir was 1.3 and 1.8 standard deviations below the historic mean, respectively. In the study area only the USG South gauge was operating for the entire summer of 2002, and this recorded 178 mm or 4% more than the amount recorded at Cheesman Reservoir. In summer 2003 there were three gauges in the study area (Figure

2.1), and precipitation ranged from 142 to 161 mm, or 5-16% more than the corresponding value from Cheesman Reservoir.

The total precipitation at Cheesman Reservoir increased to 468 mm in 2004, or 16% above the historic mean. Summer precipitation was 294 mm or 8% greater than the historic mean. At the three Upper Saloon Gulch gauges summer precipitation ranged from 258 to 350 mm, which was from 12% below to 19% above the corresponding value at Cheesman Reservoir (Figure 2.3). Summer precipitation was spatially variable as indicated by the differences in rainfall between the three gauges in Upper Saloon Gulch.

In the summers of 2002, 2003, and 2004 there were a total of 16 storms that produced sediment, and these all occurred between 10 June and 1 October (Table 2.2). Only the first storm on 21 July 2002 occurred before any of the treatments had been applied. There were four sediment-producing storms that occurred in 2002 after some of the treatments were applied, five in 2003, and six in 2004.

Total summer erosivity could only be calculated for the gauges in the study area that had complete records. Total erosivity in summer 2002 was 203 MJ mm ha^{-1} hr^{-1}, and in summer 2003 this increased by 23-149% to 249-505 MJ mm ha^{-1} hr^{-1} (Table 2.2). In summer 2004 the total summer erosivity ranged from 441-667 MJ mm ha^{-1} hr^{-1}, or a mean of 575 MJ mm ha^{-1} hr^{-1}, which was 53% greater than the mean in 2003 (Table 2.2).

The largest daily rainfall over the study period was 32.8 mm on 30 August 2003, but this total was from three successive storms. The largest single storm rainfall was 23.6 mm on 11 August 2003, and this had a maximum I_{30} of 40.4 mm hr^{-1} and an erosivity of 235 MJ mm ha^{-1} hr^{-1}. The largest single storm erosivity was 252 MJ mm ha^{-1} hr^{-1} on 14 July 2004. This storm also had the highest I_{30} of 42.4 mm hr^{-1} and the second largest storm depth of 23.2 mm. The estimated recurrence interval for the storms on 11 August 2003 and 14 July 2004 is between 2 and 5 years (Hershfield, 1961).

The spatial variability of the precipitation associated with individual storms was higher than the spatial variability of the total summer values, for example, the storm on 14 July 2004 storm had 23.2 mm of rain and an erosivity of 252 MJ mm ha^{-1} hr^{-1} at the north gauge, but only 13.2 mm of rain and 68 MJ mm ha^{-1} hr^{-1} of erosivity at the south gauge, which was less than 2 km away (Table 2.2).

2.4.3. Surface Cover

Pre-fire surface cover for the swales in Upper Saloon Gulch was characterized by Libohova (2004) using the same procedure as this study. Prior to the fire in 2002 the mean percent bare soil for the 23 swales was 11% (Libohova, 2004). Sixty-four percent of the surface was covered with litter, logs, and woody debris, while live vegetation covered 24% of the ground surface (Figure 2.4). At the end of summer 2002, which was three months after the fire, the mean percent bare soil and ash was still 95%, and there was less than 1% live vegetative cover. The lack of an increase in percent live vegetative cover between 18 July 2002 (when the fire was controlled) and late October 2002 is attributed to there being less than 100 mm of precipitation during this period.

Between fall 2002 and fall 2004 the amount of ground cover on the control swales increased almost linearly with time (Figure 2.4). By spring 2003 the mean percent ground cover on the control swales had significantly increased to 19% (p=0.003), with 62% of this cover being due to litterfall. By fall 2003 the amount of ground cover had significantly increased to 32% (p=0.005), and over the 2003 summer season the mean percent live vegetation increased from 2% to 17% ($p<0.0001$). Between fall 2003 and spring 2004 there was no significant change in the amount of ground cover. The largest increase in ground cover occurred during summer 2004, as total ground cover increased from 38% to 58% and the amount of live vegetative cover increased from 18% to 46% ($p<0.0001$) (Figure 2.4). This large increase can be attributed to the above average precipitation in summer 2004.

The changes in ground cover and live vegetation on the swales treated with seeding and scarification were very similar to the control swales (Figure 2.4). The largest difference was in spring 2004, when the mean ground cover was 43% on the treated swales and 32% on the paired controls, but this difference was not significant. The greater ground cover on the treated swales in spring 2004 was mostly due to the higher percentage of litter (19%), relative to the controls (10%). The difference in live vegetative cover was only 2%. At no time was there any significant difference in the amount of live vegetation between the swales treated with scarification and seeding and the paired controls.

The initial ground cover on the swales treated with dry mulch and seeding was 96% immediately after the treatment was applied, and mulch accounted for all but 1% of this cover. Ground cover on the treated swales was significantly higher than the paired controls for all three years. The percent mulch cover decreased to 50% in spring 2003 due to the removal of mulch by wind and overland flow ($p<0.0001$). By fall 2004 mulch cover decreased to 7.1%, but the loss of mulch cover over time was offset by the increase in live vegetative regrowth. After the initial loss of 45% mulch cover between summer 2002 and spring 2003, the ground cover remained stable between 54% and 58% through spring 2004, even though mulch cover decreased from 50% to 23% during this time. The mean percent live vegetative cover increased during this time from 2.7% in spring 2003 to 17% in spring 2004, and then tripled to 53% by fall 2004. The percent live vegetative cover was never significantly higher on the treated swales than the control swales, so the seed added with the dry mulch did not appear to increase the rate of natural vegetative recovery.

The swales treated with the aerial dry mulch averaged 51% ground cover in spring 2004, and this included 26% mulch cover and 17% live vegetation. These values were almost identical to the hand-applied dry mulch treatments, which had 57% ground cover, 23% mulch cover, and 17% live vegetation. The similarity in these values indicates that the aerial dry mulch application was comparable to the hand application. However, in fall 2004 the aerial dry mulch treatment still had 23% mulch cover as compared to only 7% mulch cover in the swales treated by hand, and this difference was significant at $p=0.008$. At the time of these measurements the swales treated with the aerial dry mulch still had some piles of mulch that were up to 55 cm thick, and this is due to the incomplete dispersion of the large mulch bales dropped from helicopters. The thicker accumulations of mulch are less likely to be transported by wind and surface runoff, and this largely explains the observed differences in the amount of mulch cover in fall 2004.

By fall 2004 the swales with the hand-applied dry mulch had 72% ground cover versus 57% ground cover on the swales treated with the aerial dry mulch treatment ($p=0.003$). This difference was due mostly to significantly more live vegetation on the swales treated by hand (53%) versus the aerially-treated swales (29%). These results suggest that the aerial dry mulch treatment either hindered vegetative regrowth relative to the hand-applied mulch treatment, or that the seeding in the hand-applied treatment helped facilitate vegetative regrowth relative to the mulch treatment without seeding.

The aerial hydromulch treatment had a greater initial and a longer-term effect on ground cover than the ground hydromulch. In fall 2002 there was 92% ground cover on the swales treated with aerial hydromulch, and only 2% of this was due to other types of cover besides mulch. The ground cover on the swales treated with aerial hydromulch declined to 72% by spring 2003, and by fall 2003 the mean ground cover was 56% (Figure 2.4). During summer 2004 the amount of ground cover slightly increased to 60%, and this was primarily due to an increase in the amount of live vegetative cover from 27% to 48% (Figure 2.4). The ground cover on the treated swales was significantly higher than the controls through spring 2004, but by fall 2004 the swales treated with aerial hydromulch did not have significantly more ground cover than the controls. The significant differences in ground cover through spring 2004 were primarily due to the hydromulch cover because the amount of live vegetative cover was never significantly different between the swales treated with the aerial hydromulch and the control swales.

Three of the four swales treated with ground hydromulch had at least 90% cover in fall 2002. The fourth treated swale had only 60% ground cover due to poor coverage on the upper portion of the swale. On average, the swales treated with ground hydromulch had significantly higher ground cover than the paired controls in fall 2002 ($p<0.0001$). The percent cover dropped to 78% in spring 2003, but this reduction was not significant and the ground hydromulch treatment still maintained significantly higher ground cover than the paired controls in spring 2003 ($p<0.0001$). Over the summer of

2003 the ground cover on the swales treated with the ground hydromulch significantly declined to 54% ($p=0.03$), whereas the ground cover on the paired controls increased from 23% in spring 2003 to 37% in fall 2003. From fall 2003 to fall 2004, there was no significant difference in the amount of ground cover on the swales treated with the ground hydromulch versus the paired control swales.

2.4.4. Rill Density

The mean rill density on the control swales in fall 2003 was 0.22 rills m^{-2} (s.d. = 0.08 rills m^{-2}) (Figure 2.5). The mean rill density on the dry mulch treatment (0.12 rills m^{-2}) was 46% lower than the paired controls, but this difference was not quite significant ($p=0.06$) due to the high variability between swales. The mean rill density on the aerial hydromulch treatment also was 43% lower than the controls, but again this difference was not significant. The mean rill densities on the swales treated with scarification with seeding and ground hydromulch were almost identical to the paired controls (Figure 2.5).

Rill densities in 2004 were statistically comparable to 2003. The mean rill density in the control swales was 0.15 rills m^{-2} (s.d. = 0.07 rills m^{-2}). None of the treatments had significantly lower rill densities relative to the controls, although the mean rill density on the swales treated with dry mulch was 0.09 rills m^{-2}, or 36% less than the controls, and rill density on the swales treated with aerial hydromulch was 28% lower than the controls. The swales treated with scarification with seeding had an average rill density of 0.17 rills m^{-2}, which was 29% higher than the paired controls, but this difference was not significant ($p=0.63$) (Figure 2.5).

2.4.5. Soil Water Repellency

Critical surface tension on the unburned swales in Trumbull ranged from 55 dynes cm^{-1} at the soil surface to 69 dynes cm^{-1} at 9 cm below the surface (Figure 2.6) (Libohova, 2004). The 0 cm and 3 cm depths were not significantly different from each other, but they both had significantly stronger soil water repellency (lower CST) than the 6 cm and 9 cm depths ($p \leq 0.0001$). The higher water repellency at the 0 cm and 3 cm depths was consistent with the greater amounts of organic matter observed at these depths and the greater potential for the accumulation of aliphatic compounds.

Soil water repellency on the burned control swales was strongest in the first summer after burning and generally decreased over time and with increasing depth (Figure 2.6). In summer 2002, the mean CST on the burned control swales was 40 dynes cm^{-1} at the surface and this increased to 69 dynes cm^{-1} at a depth of 12 cm. The burned swales had significantly stronger water repellency at 0, 3, 6, and 9 cm than the unburned controls. The mean CST at 12 cm in the burned control swales was not significantly different from the CST at 9 cm in the unburned swales ($p=0.42$).

In summer 2003 the mean soil water repellency in the burned swales was significantly weaker at 0, 3, 6, and 9 cm than in summer 2002 (Figure 2.6). The greatest reduction was at the soil surface, where the mean CST increased from 40 dynes cm^{-1} to 61 dynes cm^{-1} ($p<0.0001$). This caused the soil water repellency at the surface of the burned controls to be significantly weaker (11% greater CST) than in the unburned swales ($p=0.03$). Conversely, the soil water repellency was still significantly stronger at 6 cm in the burned swales than the control swales ($p=0.005$). There was no significant difference in soil water repellency between the burned and unburned swales at either the 3 cm or 9 cm depths.

In 2003 soil water repellency was measured for each treatment, and none of the treatments had any significant effect on soil water repellency relative to their respective controls (Figure 2.7a-d). However, both the burned controls and each of the treatment groups had significantly weaker soil water repellency at the soil surface and significantly stronger soil water repellency at 6 cm than the unburned swales (Figure 2.7a-d). There was no significant difference between the burned and unburned swales at the 3, 9, and 12 cm depths.

By summer 2004 the only significant difference in soil water repellency between the burned and unburned swales was the weaker soil water repellency at the surface of the burned swales ($p<0.0001$). As in 2003, none of the treatments had significantly different levels of water repellency than their respective controls (Figure 2.7a-d).

2.4.6. Sediment Yields from the Control Swales

The 16 sediment-producing storms were predominantly due to high-intensity summer convective storms (Table 2.2). No sediment was produced by snowmelt during the winters of 2002-03 and 2003-04. The sediment-producing storm on 21 July 2002 occurred before any treatments were applied. This storm only generated 11 mm of rainfall at the USG South rain gauge and ranked 11th highest in terms of I_{30} and erosivity, but the mean sediment yield was 6.2 Mg ha^{-1}, which makes it the third largest storm in terms of sediment production (Table 2.2). The four subsequent sediment-producing storms in 2002 had lower intensities and much lower erosivities, and they generated only another 0.8 Mg ha^{-1} or 11% of the annual sediment yield from the control swales (Table 2.3; Figure 2.8). In summer 2002 the smallest storms that still produced sediment had 4.8 mm of rainfall, an I_{30} of 3.6 mm hr^{-1}, and and erosivity of 2.6 MJ mm ha^{-1} hr^{-1} (Table 2.2).

In 2003 there were five sediment-producing storms and the mean sediment yield on the control swales was 11 Mg ha^{-1} (Table 2.3). The most intense storm occurred on 11 August 2003 at the USG North 2 gauge, and for the nearest control swales this storm generated over 70% of the measured sediment yield for 2003 (Table 2.2). The second highest erosivity measured at any gauge in 2003 was from this same storm at the USG North gauge. Here the erosivity was 32% less and this storm generated 59% of the annual sediment yield from the corresponding control swales. The third most intense storm was on 30 August 2003 and this produced 27% of the mean annual sediment yield for the corresponding control swales. The smallest storms that produced sediment had 3.2 mm of rainfall, an I^{30} of 4.4 mm hr^{-1}, and an erosivity of 1.8 MJ mm ha^{-1} hr^{-1}. These values are slightly smaller than the sediment-producing thresholds observed in summer 2002.

In 2004 there were six sediment-producing storms, even though the total precipitation and erosivity were almost twice the values measured in 2003. The mean sediment yield on the control swales was 8.9 Mg ha^{-1} (Table 2.2). The largest storm on 14 July 2004 was nearly identical to the largest storm in 2003, but the mean sediment yield from the nearest control swales was only 2.3 Mg ha^{-1}, or 25% of the sediment yield from the comparable storm in 2003 (Table 2.2). These data indicate that the post-fire recovery in runoff and erosion rates was already underway in 2004, even though the total sediment yields were only 20% less than in 2003. The smallest storms that produced sediment in 2004 had 7.9 mm of rainfall, an I_{30} of 9.7 mm hr^{-1}, and an erosivity of 18 MJ mm ha^{-1} hr^{-1}, which were ten times the values from 2003.

The data indicate that the rainfall threshold for sediment-producing storms was higher in 2004 than in 2003. In 2004 there were 15 storms that did not generate sediment but still had an erosivity that was larger than the smallest sediment-producing storm in 2003. Regression analysis showed that the relationship between storm erosivity and sediment yields was statistically comparable between 2002 and 2003 ($p=0.46$), but statistically different between 2003 and 2004 ($p<0.0001$). Storm erosivity explained 84% of the variability in sediment yields in 2002 ($p<0.0001$), and 75% in 2003 ($p<0.0001$), but this decreased to 44% in 2004 ($p<0.0001$) (Figure 2.9).

2.4.7. Sediment Yields from the Treated Swales

The comparisons between the treated and control swales are based on one to three storms in 2002 depending on the timing of each treatment, five storms in 2003, and five storms in 2004. The scarification with seeding treatment did not significantly reduce sediment yields relative to the paired controls in 2002, 2003, or 2004 (Table 2.3). In 2002, the mean sediment yield from the treated swales was 0.29 Mg ha^{-1} or 45% more than the controls, and each of the four treated swales produced more sediment than the corresponding controls. The higher sediment yields from the treated swales was not significant due to the variability in sediment yields within the treated and control groups. In 2003 the treated swales produced 8.86 Mg ha^{-1}, or 8.9% less than the controls, and in

2004 the mean sediment yield from the treated swales was 17% less than the paired controls. Neither of these differences were significant (Table 2.3).

In 2002 the dry mulch treatment reduced annual sediment yields relative to the corresponding controls by 99%, but the low sediment yields after treatment and the high variability meant that this reduction was not significant (Table 2.3). In 2003 the mean sediment yield from the swales treated with dry mulch was only 0.74 Mg ha^{-1}, and this was a 94% reduction relative to the paired controls ($p<0.0001$). In summer 2004 the mean sediment yield on the swales treated with dry mulch was 2.49 Mg ha^{-1}, or more than three times higher than in summer 2003. Nevertheless, the dry mulch treatment reduced sediment yields in summer 2004 by 77% relative to the controls ($p=0.002$) (Table 2.3).

The aerial hydromulch treatment had a similar effect on sediment yields as the dry mulch (Table 2.3; Figure 2.8). In 2002, the swales treated with aerial hydromulch produced an average of 0.00 Mg ha^{-1} compared to 0.51 Mg ha^{-1} for the control group, but this difference was not significant due to the variability in the controls (s.d. = 0.71 Mg ha^{-1}). In 2003, the mean sediment yield for the aerially hydromulched swales was 0.39 Mg ha^{-1}, and this was only 5% of the mean sediment yield from the controls ($p=0.001$). In 2004 the mean sediment yield from the four treated swales increased to 2.3 Mg ha^{-1}, and the 49% reduction in sediment yields relative to the controls was significant at $p=0.04$. In all three years the absolute sediment yields from the swales treated with the aerially hydromulch were similar to, but slightly less than, the mean sediment yields from the swales treated with dry mulch and seeding (Table 3; Figure 2.8).

Unlike the dry mulch and aerial hydromulch treatments, the ground hydromulch treatment did not significantly reduce sediment yields relative to the paired controls (Table 2.3; Figure 2.8). In 2002 there was only one small sediment-producing storm after the application of the ground hydromulch on 1 October 2002. The treated swales didn't produce any sediment while the control swales had a mean sediment yield of 0.02 Mg ha^{-1} (s.d.=0.03 Mg ha^{-1}), but this difference was not significant due to the low values and high variability. In 2003 the first sediment-producing storm generated 0.06 Mg ha^{-1} on the treated swales, which was 93% lower than the mean value of 0.86 Mg ha^{-1} from the paired controls, but this difference also was not significant due to the high variability for both the treated and control groups (coefficient of variation>150%). By the second storm in 2003, the ground hydromulch treatment no longer reduced sediment yields relative to the controls, and in summer 2003 the mean sediment yield from the swales treated with ground hydromulch was only 17% less than the controls. In 2004, the mean sediment yield from the treated swales was 19% less than the controls, but neither of these differences was significant. These results did not change, even when the data from the fourth pair, where the treated swale was only partially hydromulched, were excluded.

The relationship between storm-specific sediment yields and storm erosivity varied among treatment groups and time since burning. In 2002, erosivity was a significant control on sediment yields for the control and scarification with seeding groups ($p \leq 0.05$), explaining 84% and 31% of the variability in sediment yields, respectively. The dry mulch and two hydromulch treatments produced almost no sediment in 2002, so there was no relationship between storm erosivity and sediment yields for these three treatment groups. There were no significant differences in regression slopes between 2002 and 2003 for any of the treatment groups, but in 2003 erosivity became a significant control on sediment yields for all of the treatment groups ($p<0.03$). In 2003 storm erosivity explained between 22% and 88% of the variability in sediment yields with the lowest R^2 for the dry mulch treatment and the highest for the controls. The regression slopes significantly decreased between 2003 and 2004 for the control, scarification and seeding, and ground hydromulch treatment groups suggesting that the influence of storm erosivity on sediment yields weakened in 2004. The regression slope was not statistically different between 2003 and 2004 for the dry mulch and aerial hydromulch treatment groups ($p=0.75$ and $p=0.38$, respectively).

Over the three years combined, erosivity explained between 18-73% of the variability in sediment yields ($p<0.003$) (Figure 2.10). The control group had the steepest regression slope ($y=0.03x$), and this was 10 times higher than the slopes for the dry mulch and aerial hydromulch treatment groups ($y=0.003x$).

Mean annual sediment yields for each treatment group in 2003 and 2004 also were related to the mean percent bare soil (2.11) and the mean rill density for each treatment group (Figure 2.12). Percent bare soil explained 28% of the variability in annual sediment yields, while rill density explained 20% of the variability. Rill density was significantly related to percent bare soil ($R^2=0.39$; $p<0.0001$). When both percent bare soil and rill density were analyzed as covariates, however, rill density was not a significant covariate. These results indicate that storm erosivity and percent bare soil were the dominant factors controlling sediment yields.

2.5. DISCUSSION

2.5.1. Effectiveness of Scarification with Seeding

The scarification with seeding treatment was not effective in reducing post-fire sediment yields for any of the three years. The scarification may have initially increased sediment yields, as the mean sediment yield from the treated swales was 45% higher than the controls in 2002 as compared to 9% less in 2003 and 16% less in 2004 (Table 2.3). Other researchers have suggested that mechanical disturbance can increase erosion and decrease vegetation biomass (Kattelmann, 1996; Sexton, 1998; McIver and Starr, 2001; Beshchta et al., 2004; Karr et al., 2004).

Post-fire scarification or mechanical disturbance has been suggested as a means to break up the water repellent layer, and thereby increase infiltration and decrease overland flow (McIver and Starr 2001). In 2002 soil water repellency in the control swales decreased with depth, but was significantly stronger than in the unburned swales to a depth of 9 cm. The average depth of scarification was 1.6 cm, and the maximum possible depth of scarification was 9 cm, which is the length of the teeth on the McLeod. Hence scarification was not sufficient to break through the fire-induced water repellent layer, and it is unlikely that the use of hand rakes can break up the water repellent layer. The ineffectiveness of the raking is also indicated by the lack of any significant difference in soil water repellency in both 2003 and 2004 between the swales treated by scarification and seeding and the paired controls. The most likely effect of the scarification would have been at the soil surfaces, but the rapid decay of the surface water repellency in the control swales precluded the detection of any treatment effect.

The scarification and seeding treatment in this study did not significantly increase the amount of ground cover or the percent of live vegetative cover in 2002, 2003, or 2004. The percent of live vegetation was nearly identical to the controls throughout the study period (Figure 2.4). A different study evaluated seed germination for two years after the Hayman Fire in the areas treated with scarification and seeding, and this found no barley germination and less than 1% triticale cover on both the treated and control plots (Fornwalt and Kaufmann, 2006).

The lack of treatment effect on vegetative cover can be partially explained by the climate, soils, and topography. Some researchers have found that seeding increases the amount of vegetative cover after a fire (Gautier, 1983; Taskey et al., 1989; Robichaud et al., 2000), but most studies have found that seeding has no effect on vegetative regrowth (e.g. Beyers et al., 1998; Robichaud et al., 2000; Wagenbrenner et al., 2006). Gentle, consistent rain storms, loamy soils, and flat or gentle slopes are ideal for germination and subsequent growth. The Hayman Fire occurred in an area where summer potential evapotranspiration greatly exceeds the mean rainfall, slopes are steep, and the soils are rocky, shallow, and have little organic matter. Surface runoff and erosion is more likely to occur on these coarse, steep hillslopes, and field observations indicated that the seeds from the scarified strips were transported downslope by Horton overland flow (HOF) rather than being retained in the scarification furrows. The below normal rainfall in 2002 and 2003 also may have contributed to the ineffectiveness of the seeding in increasing cover and reducing sediment yields.

The lack of effectiveness of seeding in reducing post-fire erosion is consistent with other studies (Taskey et al., 1989; Wohlgemuth et al., 1998; Robichaud et al., 2006;

Wagenbrenner et al., 2006). Robichaud et al. (2000) reviewed seeding studies in chapparal and conifer vegetation types that used paired designs and measured erosion from seeded and unseeded groups for two years after burning. In only one of eight studies did seeding reduce erosion in the first year after burning. In the second year after burning two of nine studies showed that seeding reduced erosion. Four of these studies evaluated seeding in coniferous forests, which is more representative of the ponderosa pine vegetation type in this study. One study was in the first year after burning and three were in the second year. Of these four studies seeding did not significantly reduce erosion in the first year after the burning, and only one of three studies found seeding to be effective in reducing erosion in the second year after burning (Robichaud et al., 2000).

2.5.2. Effectiveness of Dry Mulch with Seeding

Overall, the dry mulch with seeding reduced sediment yields by 77% to 99% for the three years monitored. These results are consistent with other studies showing that mulching can significantly reduce post-fire erosion. In Spain post-fire soil loss was 7.2 times higher on control plots than plots treated with straw mulch (Bautista et al. 1996). In northern Colorado mulch reduced sediment yields in severely-burned areas by over 95% for three years after burning (Wagenbrenner et al., 2006). Plots burned at moderate-severity in Spain that were treated with mulch and seeding produced 2.7 to 3.3 times less sediment than control plots (Badía and Martí, 2000). Studies on other disturbed sites such as construction areas, have shown that mulch reduces sediment yields by up to 10 times relative to controls (Meyer et al., 1970; Golman et al., 1986; Benik et al., 2003). Preliminary results from a watershed-scale study on the Hayman Fire showed that the aerial application of straw mulch reduced sediment yields over a period of 15 months by 69% relative to the three untreated controls (Robichaud and Wagenbrenner, 2004).

The initial ground cover on the swales treated with dry mulch and seeding was 96% immediately after the treatment was applied, and mulch accounted for all but 1% of this cover. Ground cover on the treated swales was significantly higher than the paired controls for all three years. The dry mulch treatment also retained more mulch cover than the two hydromulch treatments from fall 2003 to fall 2004. By fall 2004 mulch cover decreased to 7.1%, but the loss of mulch cover over time was offset by the increase in live vegetative cover which increased to 53% by fall 2004. The seed added with the dry mulch did not increase the vegetative cover, but the mulch treatment still reduced sediment yields in all three years. This suggests that the mulch treatment provided enough ground cover to reduce erosion for the first three summers when most of the post-fire erosion occurs, until natural vegetative recovery could effectively replace the cover provided by mulch. The increase in ground cover from 57% in spring 2004 to 72% in fall 2004 suggests that the mulch treatment was no longer needed by fall 2004.

The swales treated with dry mulch also had 46% lower rill densities relative to the paired controls in 2003, although this reduction was only marginally significant at p=0.06 (Figure 2.5). Cross-sectional incision in the central rills in the swales treated with dry mulch was 80% lower than the incision in the untreated swales (Pietraszek, 2006). Hence, mulching appears to reduce rill incision as well as rill densities (Morin et al., 1989). The lower rill density may be due to the redistribution of the dry mulch into surface depressions such as small rills, which can increase surface roughness and decrease concentrated flow velocities. The mulch also may help maintain higher infiltration rates by reducing surface sealing, and this would decrease the amount of overland flow to the extent of rilling.

The hand application of dry mulch had the highest initial percent mulch cover, but also had the most rapid removal of all the mulch treatments due to wind and water transport. Comparable rates of mulch removal were observed after the 2000 Bobcat Fire where swales treated with dry mulch had 0% mulch cover after three years (Wagenbrenner et al., 2006). The aerial dry mulch treatment still had 23% mulch cover in the third summer after burning. The resistance of the aerially-applied dry mulch to wind and water transport may be attributed to the incomplete dispersion of the hay bales upon impact, and greater depth of mulch in some areas. Since the scale of hand application is limited by access and the availablity of hand crews, the aerial application of straw bales may be the most effective alternative for large scale treatments.

2.5.3. Effectiveness of Aerially-Applied Hydromulch

The aerially-applied hydromulch treatment was nearly as effective in reducing erosion as the hand-applied dry mulch, and again this was attributed to the significantly higher percent ground cover provided by the mulch for all three years. The reduction in sediment yields relative to the controls dropped from 95% in 2003 to 49% in 2004, and this suggests that either this treatment was progressively less effective in reducing sediment yields as the mulch cover decomposed or was redistributed, or natural vegetative recovery on the control swales reduced the relative difference in sediment yields between the treated and control swales.

The aerial hydromulch lost over half of its mulch cover during summer 2003, but this was offset by a corresponding increase in percent live vegetative cover that was twice that of the dry mulch, even though the mean seed density in the areas treated with dry mulch was 2.3 times higher than the seed density in the areas treated with the aerial hydromulch. The aerial hydromulch slurry formed a relatively cohesive cover on the soil surface, and so the hydromulch may have been more effective in retaining and germinating seeds than the dry mulch. Field observations support this view, as there were numerous seeds in depositional areas below the dry mulch treatment, but not downslope of the aerially hydromulched areas. The initial effectiveness of the aerial hydromulch was attributed to the high percent ground cover provided by the treatment. In the second and third years, the rapid removal of hydromulch was offset by the relatively higher increase in vegetative regrowth, which may have resulted from the seed retention and increased soil moisture provided by the cohesive carpet. The combination of initial mulch cover and higher seed germination explain why the aerial hydromulch treatment significantly reduced sediment yields in summer 2003 and 2004.

2.5.4. Effectiveness of Ground Hydromulch

The ground hydromulch treatment was applied more than a month after the other treatments, so in 2002 there was only one small sediment-producing storm after this treatment was applied. The treated swales did not produce any sediment from this storm while the paired controls produced 0.02 Mg ha^{-1}, but this difference was not significant. The lack of large storms may explain why the ground hydromulch treatment retained a higher proportion of mulch cover between summer 2002 and spring 2003 than the dry mulch and aerial hydromulch treatments (Appendix 2).

In 2003 the first sediment-producing storm generated 0.06 Mg ha^{-1} from the treated swales, and this was only 7% of the mean sediment yield from the control swales. However, this difference was not significant due to the variability in sediment yields among the control swales. By the second storm in 2003, the ground hydromulch treatment no longer reduced sediment yields relative to the controls, as the treated swales produced 0.15 Mg ha^{-1} or about 67% more than the control swales (0.09 Mg ha^{-1}).

During summer 2003 the swales treated with ground hydromulch lost 39% of the mulch cover. By fall 2003 the ground hydromulch treatment had comparable amounts of ground and mulch cover as the other two mulch treatments, indicating a more rapid loss of mulch cover since this treatment was applied later and was subjected to fewer storms than the other two mulch treatments. From spring 2003 to fall 2004 there was no significant difference in the percent ground cover on the treated swales versus the control swales.

The differences in the formulation of the hydromulch may explain why the aerial hydromulch was very effective in reducing post-fire erosion and the ground hydromulch was not. First the ground hydromulch mixture did not contain the 11 kg ha^{-1} of the PAM binding agent that was in the aerial hydromulch. PAM mixed with mulch makes the mulch more cohesive and thereby more resistant to removal by wind and water (Bjorneberg et al., 2000). Second, the mean seed density in the swales treated with ground hydromulch was less than half that of the mean value in the areas treated with aerial hydromulch, and there were virtually no seeds present on three of the four treated swales in summer 2002. The relative variability of the seed density (s.d./mean seed density) for the ground hydromulch treatment was 149% versus 70% for the aerial hydromulch, indicating poor distribution. Third, the ground hydromulch slurry had 9,000 L ha^{-1} more water than the aerial hydromulch slurry. The additional water may have improved dispersion of the hydromulch at the cost of a thinner and less cohesive cover, as was observed in the field. These differences between the two hydromulch treatments help explain why the ground hydromulch treatment did not reduce sediment yields relative to the controls.

2.5.5. Dominant Controls on Sediment Yields

The dominant control on sediment yields appeared to be ground cover. This is consistent with other studies on burned areas in the Colorado Front Range where cover, or percent bare soil, explained 64% to 84% of the variability in sediment yields (Benavides-Solorio and MacDonald, 2001; Johansen et al., 2001; Pietraszek, 2006). Plots with greater than 64% cover produced little to no sediment (Pietraszek, 2006). The ground cover immediately provided by the dry mulch and hydromulch can reduce sediment yields by: 1) protecting the newly exposed and erodible soil particles from raindrop impact, aggregate dispersion, and soil sealing; 2) reducing evaporation and increasing soil moisture retention, which can improve seed germination and decrease soil water repellency; and 3) increasing surface roughness and decreasing overland flow velocities. The retention of small amounts of sediment by mulch mimicks natural surface barriers such as litter dams, root mats, and ants' nests, which have been shown to trap and accumulate sediment (Shakesby et al., 2007).

Precipitation also was an important control on sediment yields. Storm erosivity explained between 18 and 84% of the variability in storm-based sediment yields, depending on the treatment group and time since burning (Figures 2.9 and 2.10). Mean percent bare soil explained 28% of the variation in annual sediment yields (Figure 2.11). Other studies in the Colorado Front Range have shown that storm erosivity can explain over 50% of the variability in storm-based sediment yields, while annual erosivity combined with percent bare soil can explain over 60% of the variability in annual sediment yields (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006). While the largest sediment yields were typically associated with the larger and more intense storms, storm precipitation and storm erosivity became progressively less important over time. In 2004 the total precipitation and total erosivity were approximately twice the values in 2003, but the annual sediment yields from the control swales were 11-30% lower in 2004 than in 2003. Further evidence for the changing role of storm erosivity is provided by comparing the nearly identical large storms on 11 August 2003 at the North 2 gauge and 14 July 2004 at the North gauge. For the 2004 storm the sediment yields from the control swales were 70% lower than from the 2003 storm (Table 2.2). Given the similarity in precipitation, the large difference in sediment yields has to be attributed to the increase in percent cover on the control swales from 32% in fall 2003 to 58% in fall 2004. This indicates a decreasing importance of storm size and storm intensity with increasing percent cover (or time since burning) as shown in figures 2.9, 2.10, and 2.11.

Water repellency did not explain differences in sediment yields between years, swales, or treatment groups. The degree of water repellency decreased from 2002 when soil water repellency was stronger at the surface of the burned swales than the unburned swales, to 2004 when the fire-induced soil water repellency was no longer detectable down to 12 cm. The loss of water repellency over time was attributed to a number of factors including increased soil moisture due to the reduction in interception and evapotranspiration, increased exposure of the water repellent compounds to solar radiation, and increased rainsplash and erosion of the finer water repellent soil particles leaving behind an armoring of coarse soil particles that were too large to be consistently water repellent (DeBano, 1981; Doerr et al., 2000; Doerr and Thomas, 2000; Huffman et al., 2001; MacDonald and Huffman, 2004). The strength of soil water repellency significantly declined each year but the annual sediment yields did not significantly decline between consecutive years, indicating a lack of relationship between soil water repellency and sediment yields. The naturally high variability in soil water repellency may also have contributed to the lack of any significant differences between treatments and their controls.

The specific values from this study are directly applicable only to those climates and soils that are similar to the Colorado Front Range, but the processes that control the effectiveness of the different erosion control treatments are more universal. Differences in soils, vegetation, and precipitation should not alter the relative effectiveness of the treatments that immediately provide ground cover, because these treatments will reduce rainsplash, soil sealing, and surface runoff. On very steep slopes it may be harder to keep the mulch in place, in which case well-formulated hydromulch treatments may be more effective than dry mulch treatments in binding the mulch to the soil particles. The success of treatments such as scarification and seeding depend much more on the local soils, geography, and climate for successful seed germination and reducing post-fire erosion. Understanding the controlling factors for treatment effectiveness is crucial to knowing which treatments have the most potential to be effective for a given area. Efforts to extrapolate the results from this study must consider these treatment-specific factors in order to make good decisions regarding post-fire rehabilitation treatments.

2.5.6. Future Investigations

This and other studies have shown that mulching is an effective means for reducing post-fire erosion, but there are ecological issues with respect to the potential introduction of weeds and chemical residues (Robichaud et al., 2000; Foltz and Dooley, 2003). An alternative to straw mulch would be to use the mulch from small diameter trees being cleared in nearby National Fire Plan thinning projects, or to mulch the burned trees. These treatments could reduce transport costs and use local source material. The exact type of mulch may not matter as 70% cover of wood chips caused a 98% reduction in plot-scale erosion from a gravelly sandy soil on 30% slopes (Foltz and Dooley, 2003). Previous studies have shown that treatments that provide 60% cover are effective erosion control treatments (Robichaud et al., 2000). Alternative materials that immediately provide ground cover but don't have the negative effects associated with straw mulch should be evaluated as potential post-fire erosion control treatments.

Hydromulch treatments should be evaluated using varying formulations of PAM or other binding agents, wood fiber, and seeds to more accurately determine the relative importance of these different components. Both ground and aerial applications should be applied to directly compare application methods using the same hydromulch mixture.

The different mixtures of hydromulch used in this study made it difficult to directly compare the relative effectiveness of aerial and ground-based application methods.

The scarification with seeding treatment was not effective given the high-intensity storms, dry climate, and steep, coarse-textured hillslopes in the Colorado Front Range. The effectiveness of seeding in increasing cover and reducing post-fire erosion should be tested in wetter environments with more low-intensity storms, gentle hillslopes, and finer-textured soils. Seeding with and without scarification should be compared to determine whether the scarification improves germination or increases erosion due to the disturbance of the soil surface.

2.6. CONCLUSIONS

Four treatments (scarification with seeding, ground hydromulch, aerial hydromulch, and dry mulch) were evaluated for their effectiveness in reducing post-fire erosion in a ponderosa pine forest that burned at high severity in June 2002. Each of the four treatments was applied to four randomly selected swales, and 12 swales were left as untreated controls. Sediment yields, surface cover, and precipitation were measured from summer 2002 through fall 2004. Site variables such as soil texture, hillslope morphology, soil water repellency, and rill density were also measured to help explain differences in sediment yields between swales and treatment groups over time.

The scarification with seeding treatment was not effective in reducing erosion because it never increased the percent live vegetation or percent ground cover relative to the paired controls. The lack of effectiveness may have been partially due to the relatively dry conditions during the growing season, the steep slopes, coarse-textured soils, and preponderance of high-intensity convective storms. The scarification was not effective in breaking up the soil water repellency because the soils were water repellent down to 9 cm. In the first year after the fire sediment yields were 45% higher on the scarified and seeded swales than the control swales, and this suggests that the scarification may have increased the soil erodibility.

The dry mulch and aerial hydromulch treatments were highly effective in reducing post-fire erosion, although the aerial hydromulch treatment was not as effective in reducing sediment yields in the third year after burning as the dry mulch treatment. The mulch treatments were successful because they provided an immediate carpet of cover that reduces rainsplash erosion and soil sealing, decreases evaporation from the soil surface, and provides surface roughness to impede surface runoff and trap sediment. Both the dry mulch and aerial hydromulch treatments had significantly more ground cover than their respective controls from summer 2002 to spring 2004.

The ground hydromulch appeared to reduce sediment yields for one small storm in 2002 and the first storm in 2003, but not from the second storm in 2003 through fall 2004. The swales treated with ground hydromulch had significantly more ground cover than the controls in fall 2002 and spring 2003 due to the later application date, but by fall 2003 this difference had been eliminated because the hydromulch layer had broken down into a non-cohesive thin coating of residual wood fiber. The lack of a persistent treatment effect from the ground hydromulch is attributed to the absence of a binding agent, low seed density, and high water content in the slurry formulation.

Post-fire sediment yields depend primarily on storm erosivity and ground cover (or time since burning). The effect of storm erosivity was greatest in the first two years after burning when ground cover was at a minimum. Percent bare soil and rill density were found to be collinearly related, with bare soil being a primary control on both sediment yields and rill density. These relationships help explain why the mulch treatments were highly effective, while the treatments that do not immediately increase ground cover, such as scarification with seeding, were not effective.

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Table 2.1. Plot characteristics for treatment groups and their corresponding controls. Values represent means and standard deviations.

Treatment group	**Treatment**	**Aspects**	**Mean axis slope (%)**	**Mean side slope (%)**	**Contributing area (m^2)**
Scarification with seeding	Control	NE, E	27 ± 5	16 ± 4	2930 ± 2473
	Treated	NE, E	24 ± 4	16 ± 5	2668 ± 2703
Ground hydromulch	Control	NE, E, S	23 ± 3	19 ± 5	2478 ± 460
	Treated	NE, SE, S	24 ± 1	18 ± 4	2898 ± 945
Aerial hydromulch	Control	NE	24 ± 4	15 ± 3	3418 ± 2145
	Treated	SE, S, SW	24 ± 7	22 ± 5	2393 ± 1458
Dry mulch with seeding	Control	NE, E, SE, S	21 ± 3	22 ± 6	3278 ± 1484
	Treated	NE, E, S	22 ± 5	22 ± 10	3163 ± 2058

Table 2.2. Rainfall depth, maximum 30-minute intensity (I_{30}), erosivity, and mean sediment yields from the control swales for the sediment-producing storms from July 2002 to October 2004. Values in parentheses are standard deviations, and shaded values represent annual maximums. In 2002 the north rain gauge was not installed until 5 August. na=not applicable.

Year	Storm date	Rain gauge	Rainfall (mm)	I_{30} (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})	Sediment produced by controls (Mg ha^{-1})
2002	21 Jul	South	11.2	22	62	6.94
	28 Aug	South	4.8	8.1	6.1	0.07
		North	5.0	10.0	10	0.29
	12 Sep	South	5.1	10.0	10	0.51
	18 Sep	North	6.4	3.6	2.6	0.10
	1 Oct	South	16	5.6	11	0.01
		North	13.6	5.6	9.2	0.02
	Totals	**South**	**177.8**	na	**203**	**3.62 (3.44)**
		North	**na**	na	**na**	**5.66 (3.88)**
2003	10 Jun	South	6.9	13.7	21	0.05
		North	7.6	13.2	19	1.42
		North 2	8.2	15.2	27	1.14
	19 Jun	South	8.1	13.2	20	1.17
		North	3.2	4.4	1.8	0.0016
		North 2	3.6	4.8	2.3	0.00
	19 Jul	South	8.6	11.2	17	0.13
		North	10.0	16.0	31	0.57
		North 2	10.0	17.6	35	0.45
	11 Aug	South	12.7	18.8	47	1.54
		North	20.2	33.6	160	7.53
		North 2	23.6	40.4	235	9.07
	30 Aug	South	32.8	37.6	90	2.96
		North	31.8	23.6	98	3.26
		North 2	**	**	**	2.08
	Totals	**South**	**155.4**	na	**249**	**5.8 (4.7)**
		North	**160.8**	na	**376**	**12.8 (3.6)**
		North 2	**141.8***	na	**505***	**12.7 (7.6)**
2004	16 Jun	South	12.2	22.9	65	2.76
		North	10.6	18.8	44	4.59
		North 2	9.2	16.0	32	2.84
	25 Jun	South	7.9	14.2	21	0.68
	27 Jun	North	16.4	32.8	141	2.45
		North 2	15.0	20.4	59	2.10
	14 Jul	South	13.2	23.4	68	0.40
		North	23.2	42.4	252	2.73
		North 2	19.6	36.4	179	2.31
	23 Jul	South	12.4	9.7	18	0.00
		North	11.6	12.4	24	0.26
		North 2	10.4	12.4	22	0.82
	21 Aug	South	12.7	24.9	76	1.38
		North	10.0	18.0	39	0.69
		North 2	9.6	17.2	36	0.82
	Totals	**South**	**349.5**	na	**616**	**5.2 (1.9)**
		North	**301.8**	na	**667**	**10.7 (5.3)**
		North 2	**258.0**	na	**441**	**8.9 (10.3)**

*Due to rain gauge malfunction, data from USG North gauge was used for storms between 17 August and 31 October 2003.

Table 2.3. Mean annual sediment yields, percent reduction due to treatment, and significance of differences by treatment group and year. The numbers in parentheses are the sediment yields in 2002 after the fire but prior to the installation of the treatments. ± values are standard deviations.

Treatment group	Year	Mean annual sediment yield: Control plots ($Mg\ ha^{-1}$)	Mean annual sediment yield: Treated plots ($Mg\ ha^{-1}$)	Reduction in sediment yields (%)	p-value
Scarification with seeding	2002	(5.98) 0.20 ± 0.12	(6.54) 0.29 ± 0.16	-45	0.84
Dry mulch with seeding		(7.77) 0.65 ± 0.31	(9.14) 0.0087 ± 0.00	99	0.21
Aerial hydromulch		(NA) 0.51 ± 0.35	(NA) 0.00 ± 0.00	100	0.40
Ground hydromulch		(5.05) 0.02 ± 0.01	(6.87) 0.00 ± 0.00	100	0.96
Scarification with seeding	2003	9.72 ± 2.06	8.86 ± 1.53	9	0.89
Dry mulch with seeding		13.19 ± 2.22	0.74 ± 0.40	94	<0.0001
Aerial hydromulch		7.19 ± 2.34	0.39 ± 0.14	95	0.001
Ground hydromulch		10.20 ± 4.01	8.47 ± 2.12	17	0.94
Scarification with seeding	2004	7.09 ± 2.48	5.96 ± 1.95	16	0.72
Dry mulch with seeding		11.04 ± 2.93	2.49 ± 1.26	77	0.002
Aerial hydromulch		4.54 ± 1.04	2.30 ± 1.85	49	0.04
Ground hydromulch		8.52 ± 4.22	6.87 ± 1.54	19	0.81

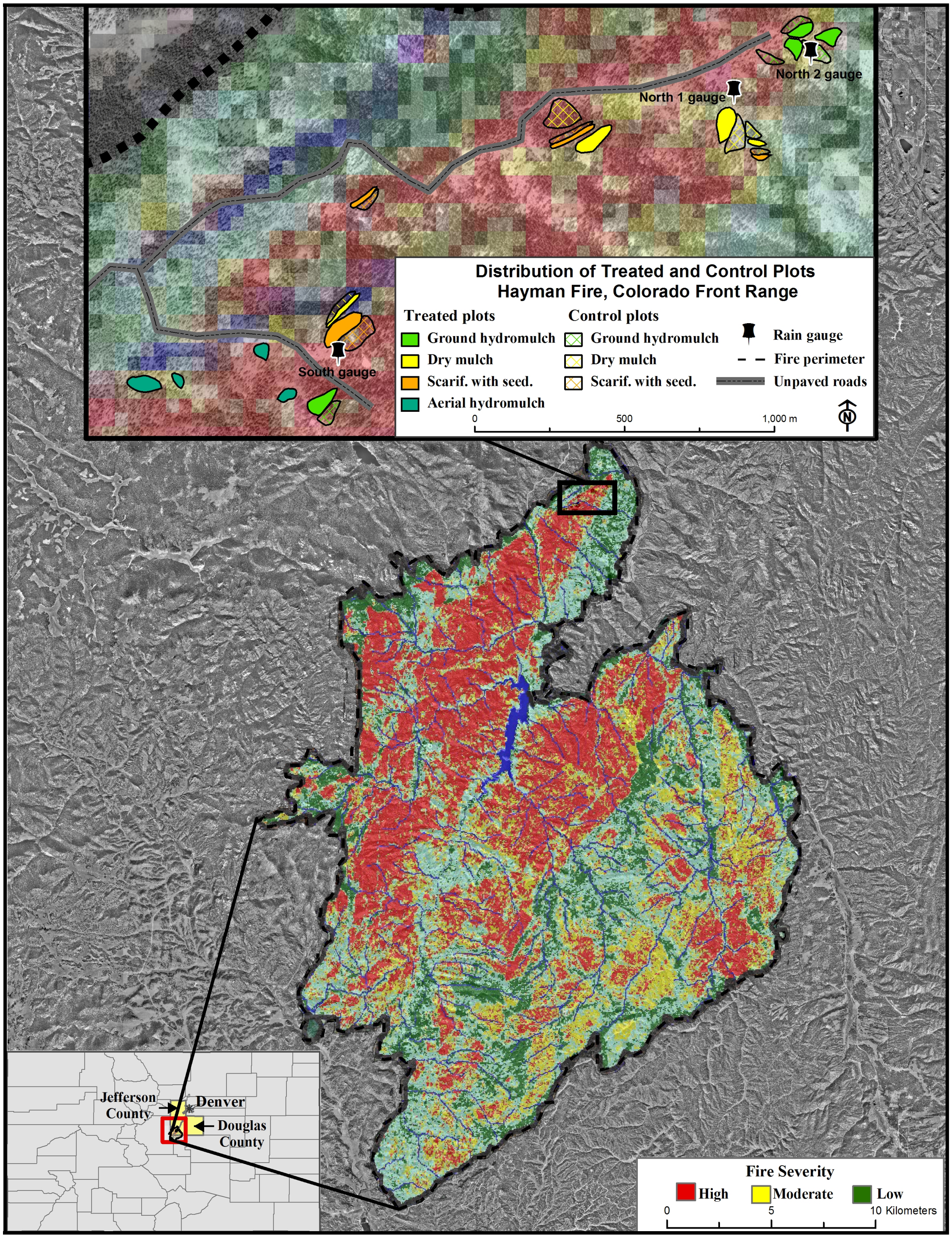

Figure 2.1. Map of the Hayman Fire and the study sites. The fire severity legend applies to both maps.

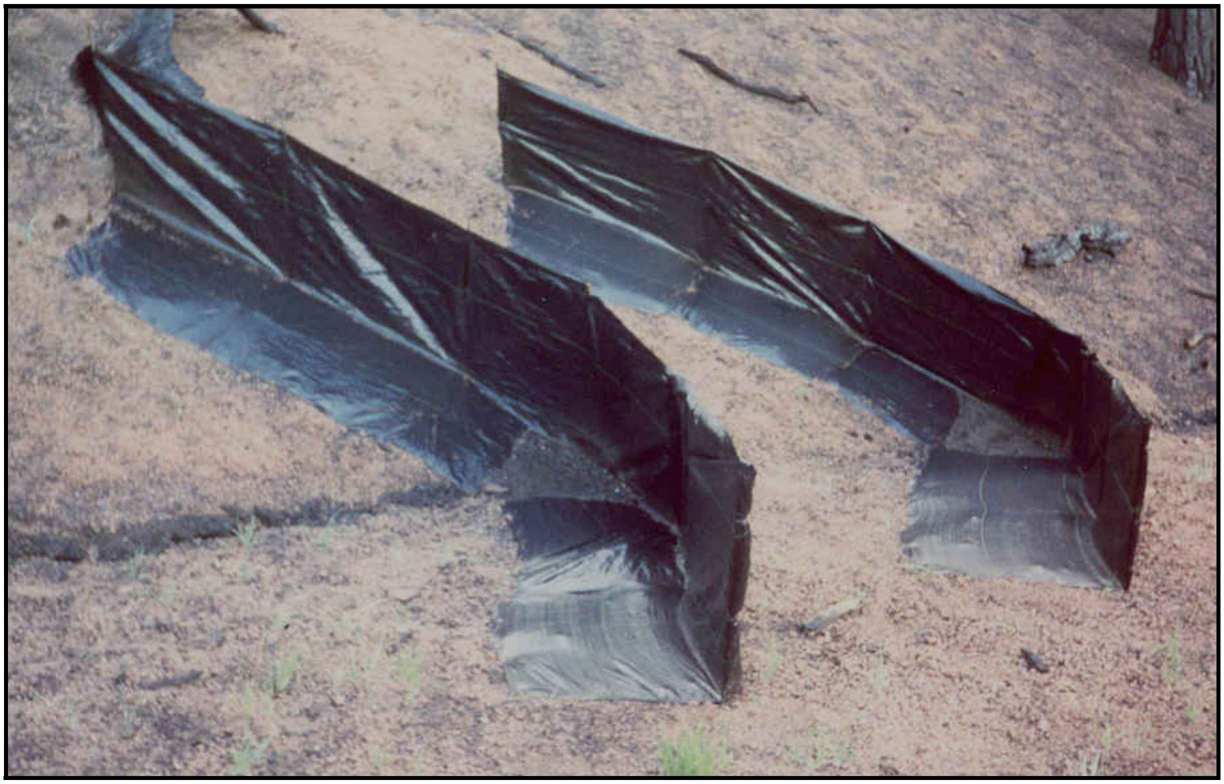

Figure 2.2. Typical double sediment fence in a swale that burned at high severity. Photo was taken two months after the Hayman Fire.

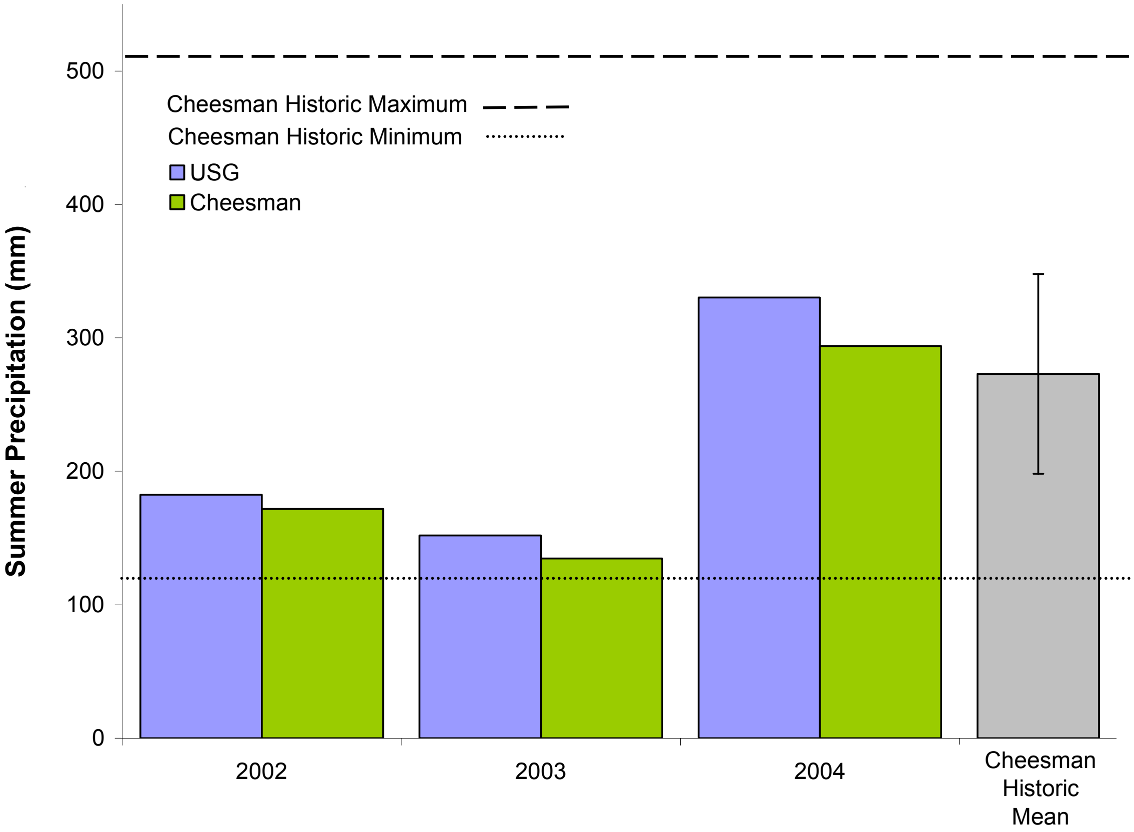

Figure 2.3. Summer precipitation for 1 May-31 October for 2002, 2003, and 2004 at Upper Saloon Gulch (USG) and Cheesman Reservoir relative to the historic mean, maximum, and minimum at Cheesman Reservoir.

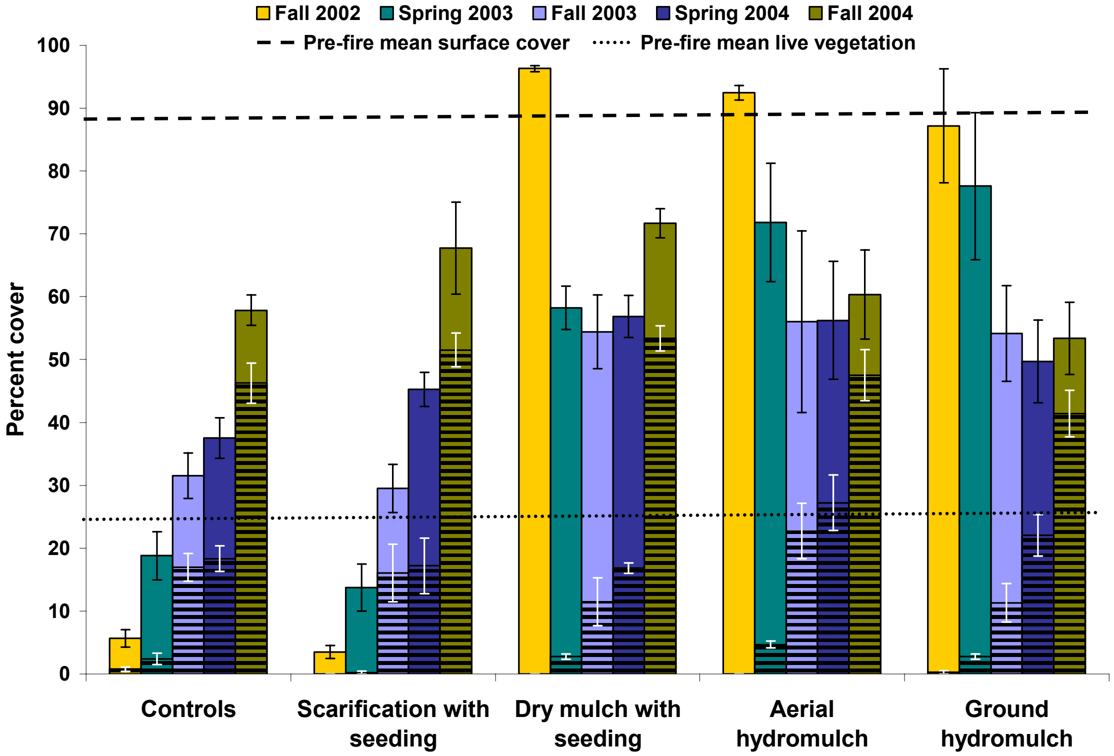

Figure 2.4. Percent ground cover (solid bars) and live vegetation (striped bars) by treatment and growing season from immediately after the fire until fall 2004. Bars indicate one standard error. The horizontal lines show the mean percent of ground cover and live vegetation, respectively, in the summer prior to the 2002 Hayman Fire.

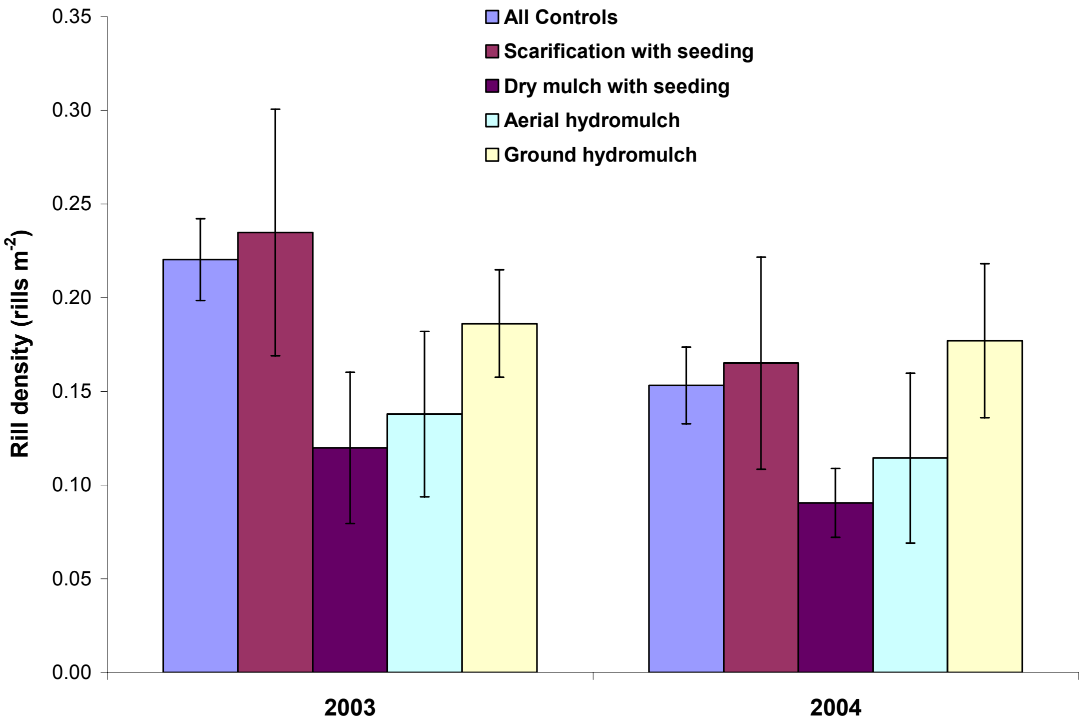

Figure 2.5. Rill density by treatment group in fall 2003 and fall 2004. Bars represent one standard error. There were no significant differences between treatments and between years.

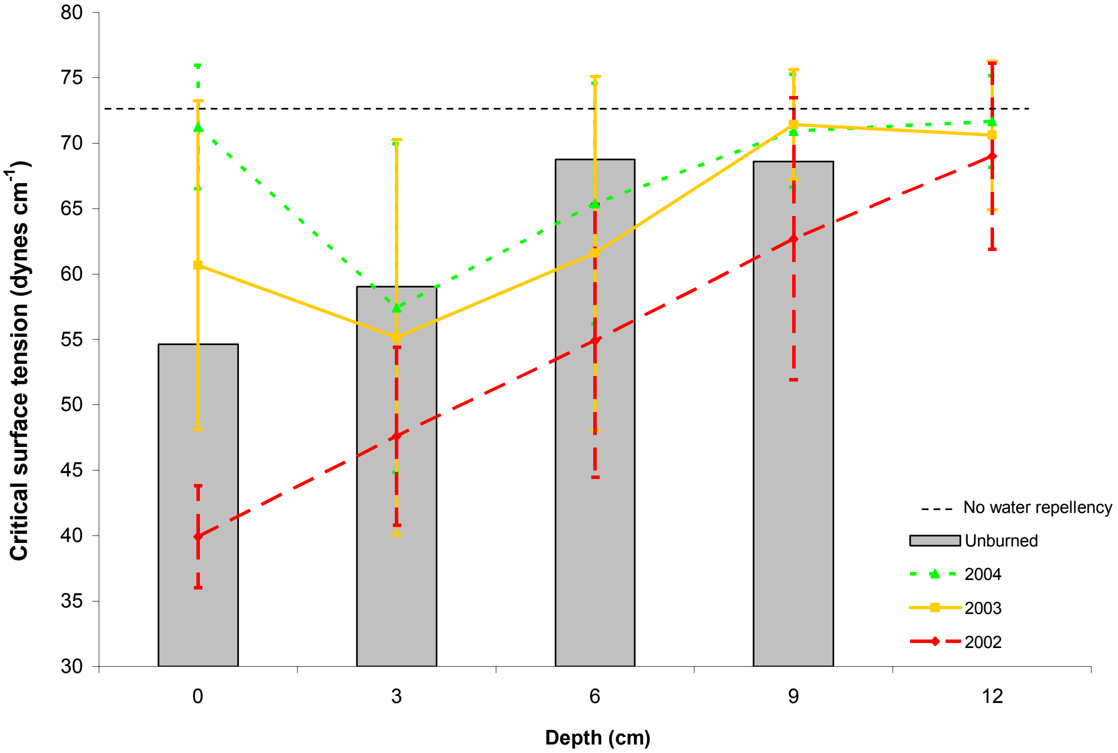

Figure 2.6. Mean critical surface tension by depth for the unburned swales and the burned but untreated swales for 2002-2004. Error bars represent one standard deviation.

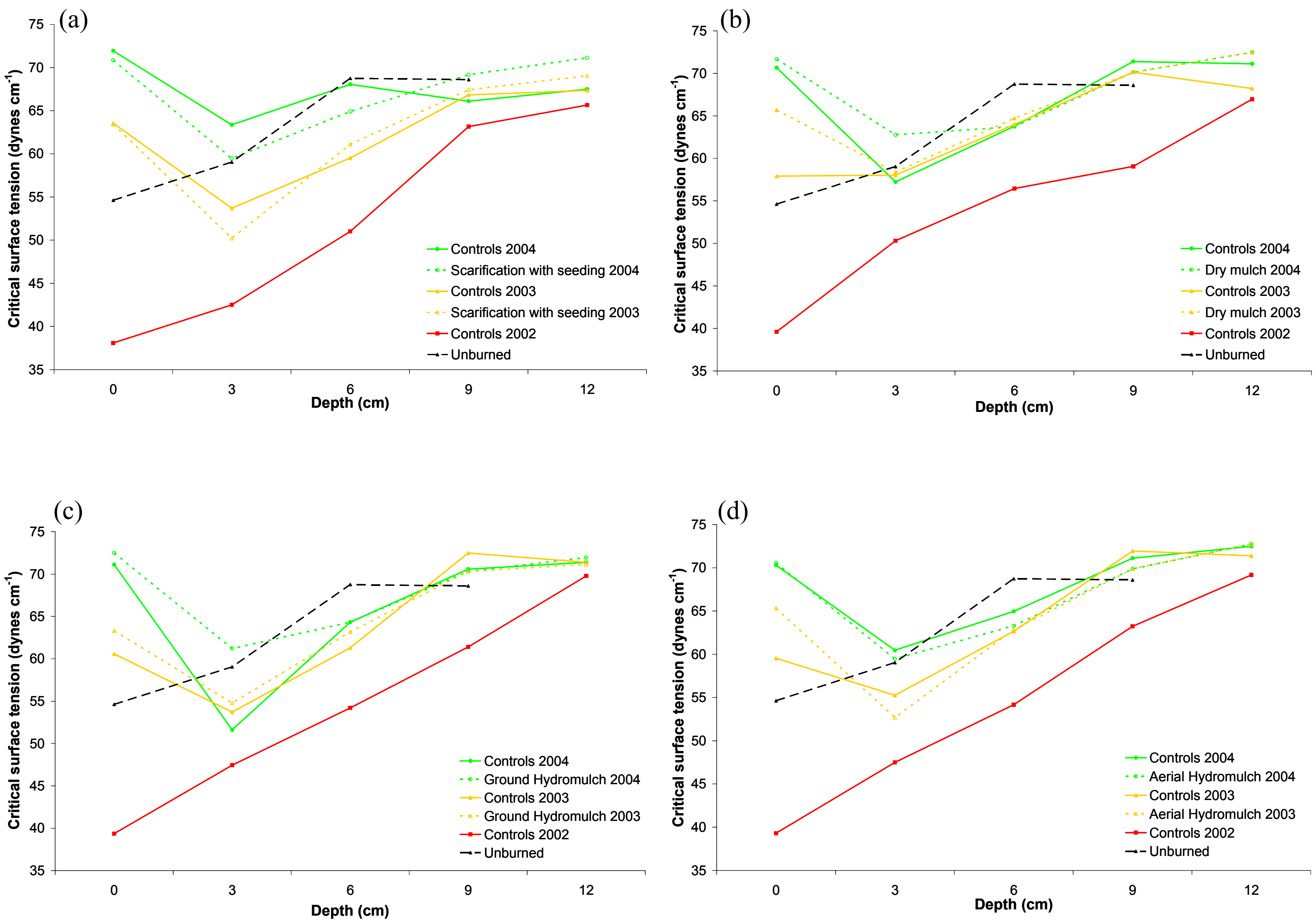

Figure 2.7. Mean critical surface tension for the untreated controls and treated swales by depth and year for: (a) scarification with seeding, (b) dry mulch, (c) ground hydromulch, and (d) aerial hydromulch.

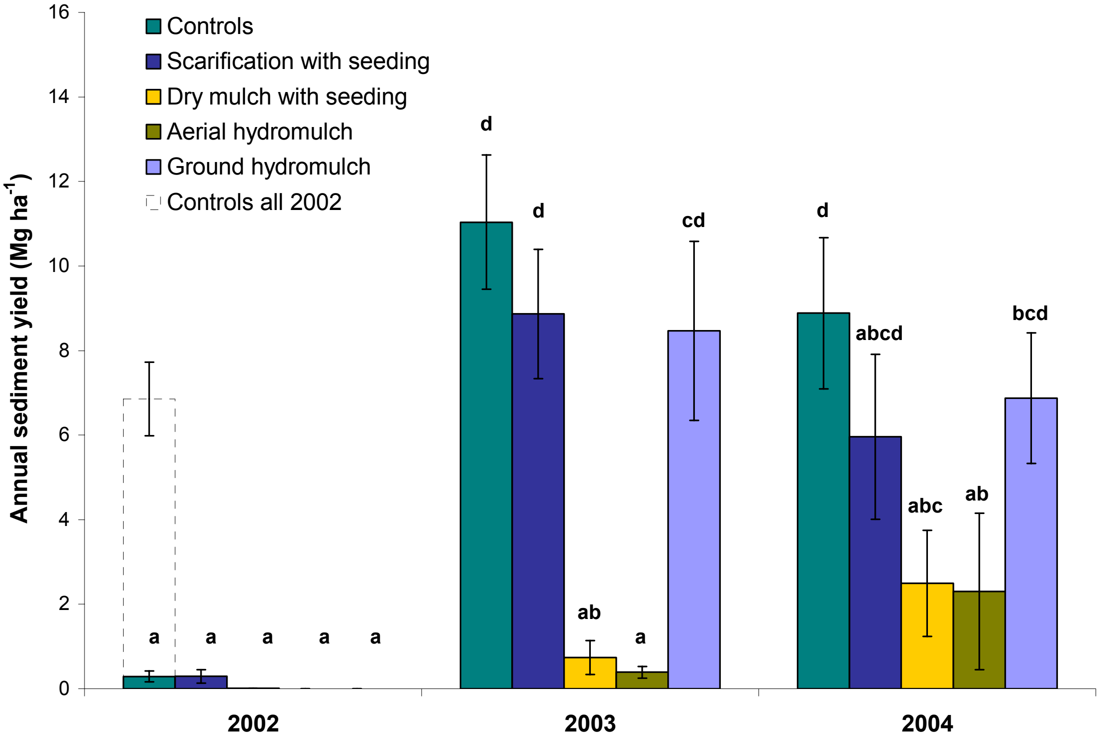

Figure 2.8. Mean annual sediment yields by treatment and year. The “controls” represents the mean of all 12 control swales. The dashed column in 2002 is the mean pre-treatment sediment yield for the pooled control swales. Bars represent one standard error. Different letters indicate significant differences between the treatments and the pooled control swales.

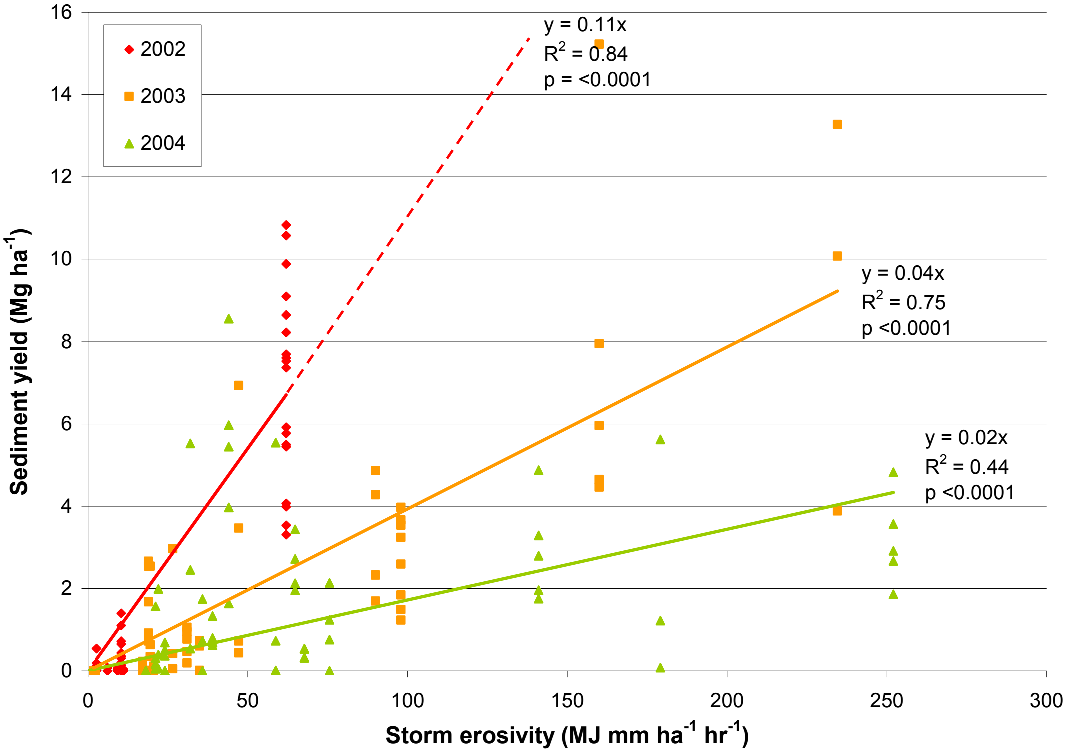

Figure 2.9. Storm-specific sediment yields for the individual control swales versus storm erosivities for 2002, 2003, and 2004. The 2002 data also include pre-treatment sediment yields.

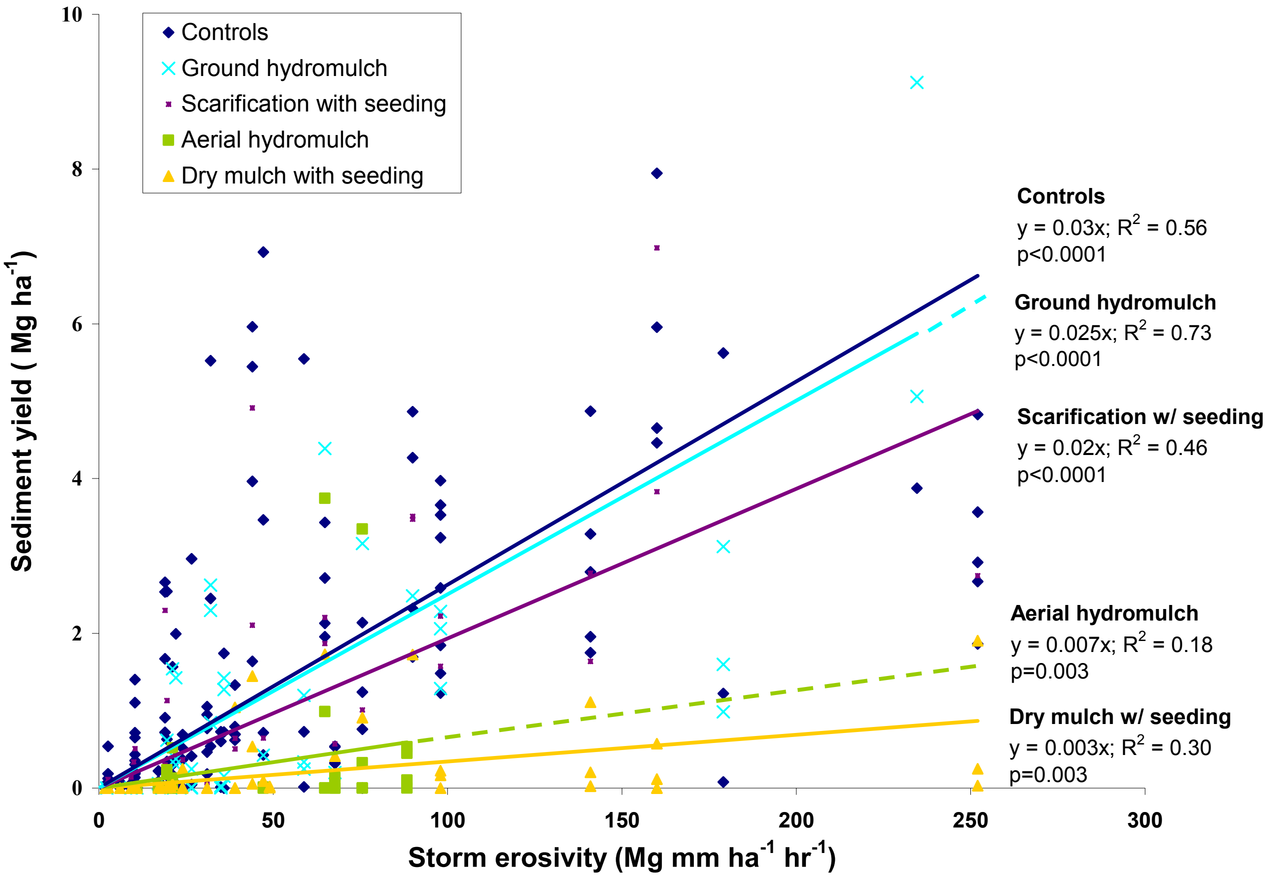

Figure 2.10. Storm-specific sediment yields by treatment group versus storm erosivities in 2002, 2003, and 2004.

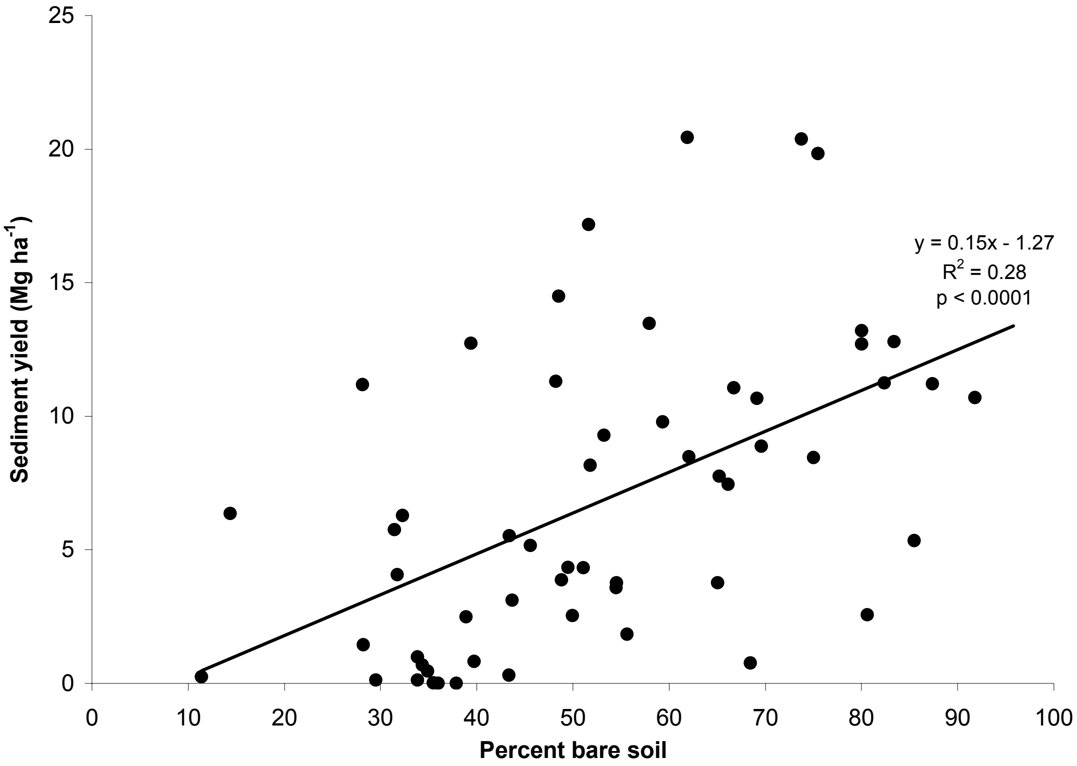

Figure 2.11. Annual sediment yields for all swales versus mean percent bare soil in 2003 and 2004.

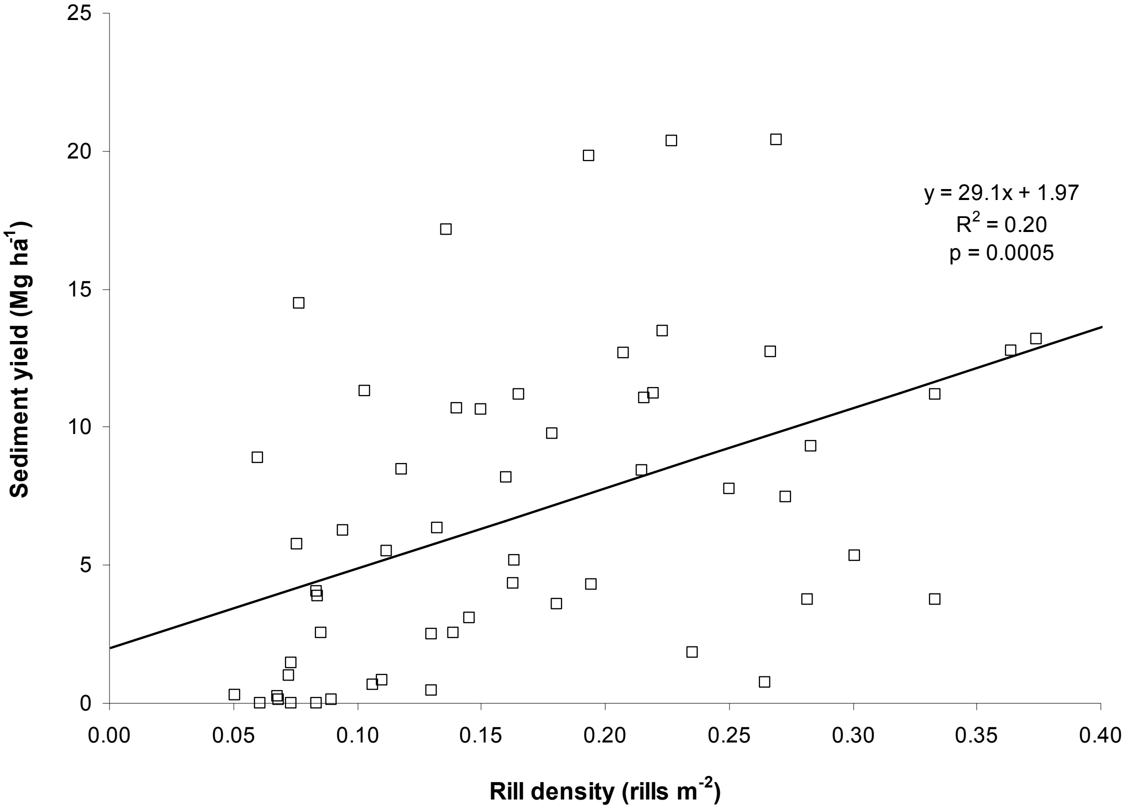

Figure 2.12. Annual sediment yields for all swales versus rill density in 2003 to 2004.

3. EFFECTIVENESS OF PAM IN REDUCING POST-FIRE EROSION, COLORADO FRONT RANGE

3.1. ABSTRACT

Increases in runoff and erosion following high severity wildfires pose ecological threats to fish and wildlife habitat as well as economic impacts on human resources such as reservoirs, roads, and structures. Burned area emergency rehabilitation (BAER) treatments are often implemented to reduce the risk of these losses, and the use of polyacrylamide (PAM) has been proposed as post-fire rehabilitation treatment because it has been highly successful in reducing agricultural erosion.

In May 2002 the Schoonover Fire burned 1,600 ha approximately two kilometers southeast of Deckers, Colorado. PAM treatments were evaluated on six pairs of swales that were burned at high severity in the Schoonover Fire. One swale from each of three paired swales was treated with wet PAM in ammonium sulfate (AMS) solution at a rate of 11.2 kg ha^{-1}, and one swale from each of three other paired swales was treated with dry micronized PAM at a rate of 5.6 kg ha^{-1}. Sediment yields from the swales treated with wet PAM were 85% lower than the paired controls for two small storms in 2002 ($p=0.004$). The wet PAM treatment did not significantly reduce sediment yields in either 2003 or 2004.

The dry micronized PAM had no effect on sediment yields, so the same wet PAM treatment was applied to these swales in 2003 and in 2004 to test whether repeated applications of wet PAM were effective in reducing post-fire erosion. Neither of these wet PAM applications significantly reduced sediment yields.

A laboratory experiment showed that PAM preferentially binds to ash versus mineral soil. The combined field and lab results suggest that when the ash cover was greater than 60%, the interception of PAM by ash may have reduced the ability of PAM to bind with and aggregate underlying soil particles. On the other hand, the lack of treatment effect by the new wet PAM treatments in the second and third years may be due to the erosion of ash in the first year and the resulting loss of soluble cation binding agents.

The use of PAM on burned areas will require further studies to assess the role of both soluble cation availability and ash interception before PAM can be recommended as a potential BAER treatment.

3.2. INTRODUCTION

High-severity wildfires in the Colorado Front Range can increase runoff and erosion rates by two or more orders of magnitude relative to unburned conditions (Morris and Moses, 1987; Moody and Martin, 2001). These increases in runoff and erosion are typically attributed to the development of a fire-induced water repellent layer at or near the soil surface and the loss of ground cover (DeBano, 1981, 2000; Shakesby et al., 2000). The water repellent layer impedes infiltration and causes a shift in runoff processes from subsurface stormflow to Horton overland flow (Scott and Van Wyk, 1990; Shakesby and

Doerr, 2006). In areas burned at high severity the exposure of the bare mineral soil to high-intensity rains can reduce infiltration rates by rainsplash and soil sealing (Shainberg et al., 1990a; DeBano, 2000). The shift to surface runoff and lack of a protective litter layer can result in very high rates of sheetwash and rill erosion (Campbell et al., 1977; DeBano et al., 1998). Increases in runoff and erosion rates after wildfires are generally highest during the first and second storm seasons after burning, and the magnitude of these increases varies with fire severity, rainfall depth and intensity, topography, soils, percent ground cover, and soil water repellency (DeBano et al., 1996, 1998; Robichaud and Brown, 1999; Benavides-Solorio and MacDonald, 2001; Benavides-Solorio and MacDonald, 2005).

After high-severity wildfires, land managers commonly apply burned area emergency rehabilitation (BAER) treatments to reduce the magnitude and impact of the post-fire increases in runoff and erosion (Robichaud et al., 2000). Typical BAER treatments include the application of grass seed with or without ground scarification, felling burned trees across the slope to act as dams for water and sediment (contour log erosion barriers), and the application of mulch. While the use of these treatments is widespread, there have been few rigorous studies on the effectiveness of these techniques (Robichaud et al., 2000).

In the case of the Bobcat Fire west of Fort Collins, CO, over $600,000 was spent on post-fire rehabilitation treatments. The effectiveness of these treatments was monitored for four years and the results showed that: (1) over 90% of the annual erosion occurred as a result of convective storms between early June and late September, and (2) mulching and contour felling were the only treatments that resulted in statistically significant reductions in hillslope-scale sediment yields (Wagenbrenner et al. 2006). The effectiveness of mulching is consistent with studies in other disturbed areas, such as construction sites and reclaimed mined lands (Meyer et al., 1970; Goldman et al., 1986; Benik et al., 2003). However, the disadvantages of mulching after forest fires include the logistics of applying mulch in unroaded areas, keeping the mulch in place on steeper slopes, limited availability after large fires, and the potential introduction of non-native species and noxious weeds (Weeks and Colter, 1952; Kruse et al., 2004). Mulching also can be ineffective once runoff and rilling occurs beneath the mulch layer (Kramer and Meyer, 1969; Foster et al., 1982).

An alternative to these traditional BAER treatments is the application of polymers, particularly anionic polyacrylamides. These polymer soil amendments function by flocculating fine soil particles together to form aggregates. The heavier aggregates are less erodible, and the larger pore spaces allow for increased infiltration (Laird, 1997). A variety of polymers have been used for different soil amendment purposes since the 1940s (Seybold, 1994; Sojka et al., 2000). The initial use of polymers was to stabilize dirt roads and runways constructed during World War II, but in the 1950s researchers began to study the use of natural and synthetic polymers on agricultural fields. The application of these polymers can improve soil structure by aggregating soil particles, reduce wind and water erosion, and increase plant growth (Weeks and Colter, 1952; Seybold, 1994). However, the high costs and difficulty of applying polymers has hindered their use in agricultural applications (Wallace and Wallace, 1990; Seybold, 1994). Recent advances in the chemical formulation of synthetic polymers have increased their cost-effectiveness and manageability for large-scale applications (Wallace and Wallace, 1990; Seybold, 1994; Sojka et al., 2000).

Hundreds of formulations of polyacrylamides (PAM) exist. PAM is a generic term referring to polymers that are made up of copolymerized polyacrylamide homopolymers (Seybold, 1994). PAM formulations are distinguished by variations in chain lengths, functional group substitutions, and water solubility. PAMs can be cationic, anionic, or nonionic, depending on the charge of the functional groups. The charge densities are a function of the level of hydrolysis or quantity of bound functional groups (Barvenik, 1994; Seybold, 1994; Sojka et al., 2000). The most commonly used and effective PAM for erosion control is an anionic, high molecular weight (12-15 Mg mole^{-1}), low to moderate charge density (2-20% hydrolysis), water-soluble, linear chain formulation (Barvenik, 1994; Seybold, 1994; Sojka et al., 2000). This anionic PAM can be broken down by physical factors such as sunlight and radiant heat. The duration of treatment efficacy depends on various factors, including slope, climate, and the amount and method of application, which varies with the formulation (Seybold, 1994).

A key concern is the environmental toxicity of PAM, and this varies with the ionic formulation. Anionic PAM is not harmful to animals, humans, fish, and plants as long as the acrylamide monomer (AMD), a known neurotoxin, is kept at a concentration below 0.05% (Asada et al., 1985; Biesinger and Stokes, 1986; Krautter et al., 1986; Shanker and Seth, 1986; Petersen et al., 1987; King and Noses, 1989; Sojka et al., 2000). In contrast, cationic PAM can be very toxic to aquatic organisms at low concentrations, as the positive charge on the cationic PAM is attracted to the negative charge of fish gills, resulting in asphyxiation. For this reason, cationic PAM is not used for erosion control near streams or other aquatic resources (Biesinger and Stokes, 1986; Goodrich et al., 1991).

Agricultural studies have shown that PAM can reduce furrow and sprinkler erosion by more than 90% (e.g., Sojka and Lentz, 1997; Sojka et al., 2000). Other uses for PAM include flocculating suspended particles for water treatment, reducing hillslope erosion from fallow crops (Santos et al., 2001), enhancing infiltration, and increasing crop growth and yields (Wallace and Wallace, 1986b; Seybold, 1994). The effectiveness of PAM in reducing erosion in agricultural settings has led land managers to ask whether PAM also could be used to reduce post-fire erosion.

Three preliminary studies have yielded varying results on whether PAM reduces runoff and surface erosion after wildfires (Benavides-Solorio and MacDonald, 2000; Gaines and Bauder, 2002; Woghlgemuth, 2003). In the first study, rainfall simulations were used to determine whether PAM can reduce post-fire erosion from a 1 m^2 plot that burned at high severity in the Bobcat Fire near Drake, Colorado (Benavides-Solorio and MacDonald, 2000). Approximately 87 mm of rain was applied over 60 minutes, and the plot treated with PAM averaged 13% less runoff and 80% less sediment yield than the comparable untreated plots. The PAM was most effective in the first 30 minutes, when the mean sediment concentration from the treated plot was 8 g L^{-1}. During the second 30-minute period the sediment yields slowly increased from 8.5 to 15 g L^{-1}, while the average sediment yield from the untreated plots was 23.5 g L^{-1}. The PAM did not seem to decrease the soil water repellency, as approximately 95% of the area underneath the litter and ash was still dry at the end of the simulation (Benavides-Solorio and MacDonald, 2000).

The second study evaluated whether different concentrations of anionic PAM could increase the flocculation and settling rates for 20 g of both burned and unburned soils from the Hayman Fire mixed with PAM-treated water (Gaines and Bauder, 2002). Neither the degree of soil water repellency nor the PAM concentrations significantly affected flocculation and settling rates. The high variability of particle sizes in the coarse sand fraction had more effect on the flocculation rate than the PAM treatment, so the PAM treatment had no significant effect. The key limitations of this study were the small mass of soil (20 g) and the relatively large influence of the coarse sand fraction. Removing the coarse sand fraction would help detect differences between treatments, but this would make the experiment less representative of natural conditions, because coarse sand is often an important component of forest soils in the Colorado Front Range (Moore, 1992). The application of these results is difficult because the mixtures of soils and water are more relevant to agricultural practices, such as furrow irrigation, than surface runoff and erosion on burned hillslopes from natural rainstorms.

The third study evaluated the effectiveness of PAM in reducing sediment yields on a treated watershed relative to an untreated watershed in the San Dimas Experimental Forest in Southern California (Wohlgemuth, 2003). The study measured the sediment accumulated behind earth-filled dams at the base of each catchment using repeated surveys at permanent cross sections. In the first year after burning the treated watershed produced 32% more sediment per unit area than the control watershed (Wohlgemuth, 2003). The interpretation of the results is hindered by possible differences between the two watersheds, the lack of replication and the lack of information on the amount and type of PAM that was applied.

There are still many uncertainties as to how the chemical and physical properties of burned soils may influence the binding potential of PAM and the treatment longevity. The binding efficiency of PAM can be reduced by low amounts of clay in the soil (Barvenik, 1994; Seybold, 1994; Sojka et al., 2000). Spikes in soluble cations such as K, Ca, and Mg are commonly associated with the burned organic material or ash at the soil surface following fires (Christensen, 1976; Raison, 1979; DeBano, 1977). The cationic ash can readily bind with the negatively charged OH^- functional groups on PAM, resulting in interception and adsorption during treatment application (Wallace, 1986a; Peterson et al., 2002). Steep slopes may cause unacceptably high losses of PAM-treated soil. Low clay concentrations, soil chemistry, and steep slopes are all important considerations in the lower montane forests in the Colorado Front Range. These areas typically have coarse-textured soils, high rainfall intensities from summer convective storms, and a strong water repellent layer at or near the soil surface after burning at moderate or high severity (Huffman et al., 2001).

A final concern is the effect of anionic PAM on the viscosity of water and infiltration rates. Column infiltration rates for a sandy loam soil were reduced by 35-72% when two types of anionic PAM were added to the infiltrating water at concentrations of 5-20 mg L^{-1} (Ajwa and Trout, 2006). The decline in infiltration was attributed to the blockage of soil pores due to the increase in viscosity with increasing PAM concentrations. The potential blockage of soil pores would be a major drawback for the use of PAM in burned areas.

These issues indicate a need to further test the use of anionic PAM for reducing post-fire erosion using replicated, larger-scale field experiments. Hence the first and primary objective of this study was to test whether the application of PAM could reduce erosion from severely-burned hillslopes. Single and repeated PAM treatments were tested to evaluate the ability of PAM to reduce post-fire erosion for up to three years after burning. A second objective was to evaluate the relative effect of contributing area, aspect, soil type, percent ground cover, percent ash cover, slope steepness, rill density, and precipitation on sediment yields. The inconsistency in the results of the field studies and the potential effects of ash on PAM effectiveness led to the addition of a third objective. This objective was to conduct a controlled experiment on the preferential binding of PAM with ash relative to mineral soil from the study area. The combined results should provide a more detailed understanding of the potential use of PAM for reducing post-fire erosion.

3.3. SITE DESCRIPTION AND METHODS

3.3.1. Site Description

The field study was conducted on the Schoonover Fire, which burned nearly 1,600 ha approximately two km southeast of Deckers, Colorado in May 2002 (Figure 3.1). Over 60% of the area burned at high severity as defined by the U.S.D.A. Forest Service (USFS, 1995). Elevations at the site range from 2,200 to 2,300 m. Prior to the fire the area was dominated by ponderosa pine (*Pinus ponderosa*). The soil is a gravelly coarse sandy loam in the Kassler series with moderate to rapid permeability (5-15 cm hr^{-1}), and this was formed from the Pikes Peak granite (Moore, 1992; U.S.D.A. NRCS, 2005). Infiltration-excess overland flow is rare and annual erosion rates are typically around 0.0 to 0.28 Mg ha^{-1} (Moody and Martin, 2001; Libohova, 2004).

3.3.2. Study Design and Treatment Applications

Sediment yields were measured from six paired zero-order basins (swales) that burned at high severity in the Schoonover Fire in May 2002. For the purpose of this study, a swale is defined as a topographic hollow or convergent area without a defined channel prior to burning. The swales within each pair were selected to have similar slopes, aspects, and contributing areas (Figure 3.1). One swale from each pair was randomly selected and treated with PAM, and the other swale was left as a control. The six pairs of swales were divided into two treatment groups: (1) a single PAM treatment; and (2) repeated PAM treatments (Table 3.1). Both of the PAM treatments were applied on 8 August 2002. The single treatment group was treated with a wet PAM slurry consisting of 11 kg ha^{-1} of PAM, 280 L ha^{-1} of water, and 120 kg ha^{-1} of ammonium sulfate (AMS). The ammonium sulfate was added to reduce the viscosity of the slurry. The repeated treatment group was initially treated with a dry application of PAM at a rate of 5.6 kg ha^{-1}. These swales were re-treated with the same wet PAM slurry on 6 June 2003 and again on 10 June 2004 (Table 3.1). All treatments were applied using a 12-L motorized seed spreader. The PAM used was Floerger^{TM} AN 900 series micronized anionic formulation (30-150 microns) with a high molecular weight and a linear water-soluble structure.

3.3.3. Plot Characterization

A series of independent variables were measured to ensure comparability between sites and to better understand the potential causes of any differences or trends in sediment yields. These variables included the contributing area, slope, aspect, soil texture, surface cover (ground cover and bare soil), and rill density.

The contributing area of each swale was measured in July 2002 using a Trimble GeoExplorer III GPS with a resolution of 3-7 m. Axis and side slopes were measured with a clinometer. Aspect was measured with a compass adjusted for declination.

Surface cover was measured at 100 to 150 points on each swale using a systematic point count on evenly spaced horizontal transects with random starting points (Parker, 1951). Each point was classified as ash, bare soil, live vegetation, trees, litter or duff, woody debris (>1 cm and <10 cm diameter), logs (>10 cm diameter), or rocks (>5 cm secondary axis). The first cover count was conducted in July 2002, and these were repeated in spring and fall of 2003 and 2004. In fall 2003 and fall 2004 rill densities were measured by counting the number of rills along five to ten 1-m wide horizontal transects that were systematically spaced from a random origin. Rills were defined as distinct channels caused by surface runoff that were small enough (less than 10 cm deep) to be smoothed out by normal tillage. Aside from the primary axis for each swale, there were no channels deeper than 10 cm in any of the swales used in this study.

Soil samples were collected prior to the initial treatment from a depth of 0-5 cm from the top, bottom, and primary channel of each swale. Each of the three soil samples per swale weighed approximately 1 kg and represented a composite of ten randomly selected locations within the specified area. Samples were homogenized and sieved to determine percentages of gravel or coarse material (> 2mm), coarse to very coarse sand (0.50 to 2 mm), medium sand (0.25 to 0.50 mm), very fine to fine sand (0.0625 to 0.25 mm), and clay plus silt (<0.053 mm). Percent organic matter was determined by incinerating the samples for 6 hours at 400°C and determining the difference in weight pre- and post- incineration (Cambardella et al., 2001).

3.3.4. Precipitation

Precipitation was measured with a recording tipping-bucket rain gauge with a resolution of 0.25 mm. Storms were defined by periods of at least one hour with no rainfall. The depth, duration, maximum 30-minute intensity (I_{30}), and rainfall erosivity were calculated using the RF program (Petkovsek, 2002) for each sediment-producing storm and storms with at least 5 mm of rainfall. The value of 5 mm was used because this amount of precipitation can generate sediment from areas burned at high severity in the Colorado Front Range (Moody and Martin, 2001; Benavides-Solorio, 2003). Erosivity was calculated following Brown and Foster (1987).

In the Colorado Front Range at least 90-95% of post-fire sediment production occurs during the summer thunderstorm season between 1 May and 31 October (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006). This period was defined as the storm season and it included all potential sediment-producing storms observed during the study.

Long-term (1903-2004) precipitation data from Cheesman Reservoir, which is approximately 8 km to the southwest of the study area, were used to assess the representativeness of the precipitation measured in 2002, 2003, and 2004. Since the rain gauge in Schoonover was not set up until 22 July 2002, precipitation data between 1 May and 22 July 2002 were obtained from a recording rain gauge located 1.5 km to the northwest (Libohova, 2004).

3.3.5. Sediment Yields

Sediment fences were built in late July 2002 at the bottom of each swale to capture the eroded sediment (Robichaud and Brown, 2002). The placement of the sediment fences in small swales rather than on planar hillslopes allows a more accurate determination of the contributing areas, and thus the calculation of unit area erosion rates. A second sediment fence was added in each swale to ensure that the two fences could easily hold the sediment eroded during the larger storms. The sediment fences consisted of 1.2-m wide geotextile fabric attached to 1.3-cm rebar that had been pounded into the ground (Figure 3.2).

To the extent possible, the sediment collected in each fence was removed and weighed after each sediment-producing storm. Two samples were collected and placed in airtight plastic bags for transport to a laboratory where samples were weighed and dried for 24 hours at 105°C, and weighed again to determine water content following an equation adapted from Gardner (1986):

$$W_c = [(W_w-\tau)-(W_d-\tau)]/(W_w-\tau) \tag{1}$$

where W_c is the water content of the collected sample, W_w is the wet weight of the sample, W_d is the weight of the sample after drying, and τ is the tare weight of the container. The water contents were used to convert the field-measured wet weights to a dry mass by:

$$W_d = W_w - (W_c * W_w) \tag{2}$$

where W_w is the wet weight of the sediment collected from the sediment fence and W_d is the calculated dry weight. Unit area sediment yields were calculated as the dry weight divided by the contributing area. After drying the samples were sieved to determined the percentages of coarse material, coarse to very coarse sand, medium sand, very fine to fine sand, and clay plus silt, as defined previously.

3.3.6. Interaction of PAM with Ash and Mineral Soil

The laboratory experiment was designed to compare the chemical affinity of PAM to ash versus the mineral soil found in the study area. Three different mixtures of dry ash and mineral soil were added to a solution of PAM, and these were 100% ash, 100% mineral soil, and a 50:50 mix by weight of ash and mineral soil. The mineral soil was collected from 0-5 cm on the six control swales and the ash was collected from nearby depositional areas in summer 2003. The soil and ash samples were homogenized and sieved to remove particles >1 mm in diameter. The blanks and base solution for each treatment was the same 43% aqueous ammonium sulfate (AMS) solution that was used in the field application of the wet PAM treatment. Three replicates of 1.5 g of each of the ash and/or soil mixtures were added to 30 mL of 20 ppm PAM in solution (Lu et al., 2003). Samples were shaken for 36 hours and centrifuged for 10 min at a force of 3,000 x g. The PAM concentration in each of the 13 supernatent samples was analyzed by size exclusion chromatography in Dr. Lu's laboratory at the University of California at Riverside.

3.3.7. Statistical Analyses

The annual sediment yields, three surface cover classes (percent bare soil, percent ash, and percent live vegetation), and the rill density data were analyzed as dependent variables using both repeated measures and discrete year mixed effects models. Surface cover and rill density also were analyzed as covariates to sediment yields. Treatment group (single or repeated) was considered a fixed effect, and treatment condition (control or treated) was treated as a random variable (SAS Institute 9.1, 2004). Tukey's HSD test was used to compare the swale slopes, aspects, and soil textures between treatment and control groups. Linear regression was used to evaluate the effect of bare soil on storm sediment yields within years, and the effect of rainfall erosivity on storm sediment yields between years. PAM adsorption in the laboratory experiment was evaluated for all pairwise comparisons with Tukey's HSD test. All data analyses were run with SAS 9.1 (2004) and a significance level of 0.05.

3.4. RESULTS

3.4.1. Plot Characteristics

The physical characteristics and treatments for each swale are listed in Table 3.1. The mean contributing areas was 1,880 m^2 and the range was from 940 m^2 to 3,020 m^2. The greatest difference in contributing area within a pair was 550 m^2 or 29% (Table 3.1). The side slopes of the swales ranged from 11% to 33% and the axis slopes ranged from 30% to 43%. The swales were on west- to north-facing slopes except for one pair that was south-facing.

The mean soil texture was 60.3% coarse material (s.d.=7.4%), 20.3% coarse sand (s.d.=3.9%), 18.0% fine to medium sand (s.d.=4.0%), and 1.4% silt and clay (s.d.=0.8%). The mean organic matter content was 1.7% (s.d.=0.8%). There were no significant differences in the mean soil texture between treatment groups or the treated and control swales. However, the mean percent of coarse material was 12% higher in the channels than on the hillslopes (p=0.005). The channels also had 21% less medium to fine sand than the hillslopes (p=0.002). This suggests that some of the finer particles had been eroded from the channel after the fire but prior to the application of the treatments on 8 August 2002. The two storms that occurred during this period were 9.1 mm on 6 July and 5.1 mm on 21 July, but no sediment data were collected since the fences had not yet been installed.

3.4.2. Precipitation

The annual precipitation at Cheesman Reservoir has ranged from 186 mm to 617 mm between 1903 and 2004, with a historic mean annual precipitation of 402 mm (s.d.=83 mm). Both 2002--the year of the Schoonover Fire--and 2003 were exceptionally dry with 214 mm of precipitation in 2002 and 304 mm of precipitation in 2003. These values were 2.3 and 1.2 standard deviations below the historic mean, respectively.

The mean “summer” precipitation at Cheesman Reservoir between 1 May and 31 October is 273 mm (s.d.=75 mm). Summer precipitation in 2002 and 2003 at Cheesman Reservoir was 1.3 and 1.8 standard deviations below the historic mean, respectively. Summer precipitation at Schoonover was consistently less than at Cheesman Reservoir (Figure 3.3). Total precipitation at the Schoonover site was only 120 mm in 2002 and 122 mm in 2003.

The total precipitation at Cheesman Reservoir increased to 468 mm in 2004, or 16% above the historic mean. Summer precipitation was 294 mm or 8% greater than the historic mean. Summer precipitation at Schoonover was 245 mm in 2004, or about twice as much as in summer 2002 and summer 2003.

Table 3.2 lists the storm rainfall, maximum I_{30}, and erosivity for all storms that produced sediment and all storms greater than 5 mm. In 2002 there were seven storms with at least 5 mm of precipitation, but these generally were small (mean=6.9 mm) and the total erosivity was only 88 MJ mm ha^{-1} hr^{-1}. Two of these storms occurred in July before the sediment fences were installed, and one occured in early August before the treatments were applied but this storm did not produce any sediment. After the treatments were applied there were four storms, but only two produced sediment. The biggest storm on 21 August had only 8.4 mm of precipitation, but it had the fourth highest maximum I_{30} at 16.3 mm hr^{-1} and the fifth highest storm erosivity (Table 3.2).

In 2003 there were eleven storms, and six of these storms had 30-minute rainfall intensities greater than 10 mm hr^{-1}. The total erosivity was 170 MJ mm ha $^{-1}$ hr $^{-1}$, or more than twice the total from 2002. Four storms and one combined storm generated substantial amounts of sediment, but the largest storm only had 10.2 mm of rain.

In 2004 there were 14 storms and the total erosivity of 352 MJ mm ha $^{-1}$ hr $^{-1}$ was over twice the value from 2003. The largest storm over the study period was 17.8 mm in 48 minutes on 25 June 2004, and this had an erosivity of 145 MJ mm ha $^{-1}$ hr $^{-1}$ or 24% of the total erosivity from 2002 to 2004. The estimated recurrence interval for a 48-minute storm with an I_{30} of 33 mm hr^{-1} is about 2 years (Hershfield, 1961). Three other storms had more than 11 mm of rainfall, but the I_{30} was 16.8 mm and the maximum erosivity was 37.6 MJ mm ha^{-1} hr^{-1} (Table 3.2).

3.4.3. Surface Cover

Surface cover was first measured in July 2002, which was two months after burning and two weeks prior to the treatments. The surface cover was 91-97% bare soil and ash (Figure 3.4). Only 4-9% of the ground surface was covered by live vegetation, trees, logs, rocks, woody debris, or litter and duff, and these are grouped as "other" in Figure 3.4. Less than 2% of the ground cover in fall 2002 was live vegetation.
On average there was slightly more ash (mean = 50%) than bare soil (mean = 44%) on the surface.

There was virtually no change in the amount of ground cover between fall 2002 and spring 2003. There also were no significant differences in the amounts of ground cover between the treatment groups and their corresponding control swales or between treatment groups in either fall 2002 or spring 2003 (Figure 3.5). Between spring 3003 and fall 2003 the mean amount of ground cover doubled to 13% (p = 0.001), and this was due to an increase in the amount of live vegetative cover (mean=6%) and litter and duff, mostly from needlefall (mean=4%). Again there were no significant differences in ground cover between the treatment groups and their controls.

Overall, the mean percent ground cover for each treatment group ranged from 18-20% in spring 2004, and from 27-39% in fall 2004 (Figure 3.5). These increases over time were highly significant for each treatment group (p<0.0001). In fall 2004 the swales treated with the single wet PAM treatment had the highest mean percent ground cover (mean=39%). This was signficantly higher than the mean value of 27% in the untreated controls (Figure 3.5; p=0.02). This difference was predominantly due to the treated swales having 31% live vegetative cover versus 23% live vegetative cover on the paired controls. This difference in the amount of live vegetative cover in fall 2004 was the only significant difference in surface cover between either of the PAM treatments and their respective controls. Figure 3.6 also shows that the mean percent of ash cover for all treatment groups dropped from 44-59% in fall 2002 to 16-28% in spring 2003, and to only 5-11% in fall 2003. The overall trends in ground cover were a slow increase in litter and live vegetative cover, and a rapid loss of ash cover.

3.4.4. Rill Density

In 2003 the average rill density was 0.31 rills m^{-1}. The rill density was 0.21 rills m^{-2} in 2004, but this difference over time was not signficant (p=0.08). Neither of the PAM treatments significantly reduced rill densities relative to their paired controls in either 2003 or 2004. In 2003 the mean rill density for the single PAM treatment of 0.21 rills m^{-2} was only half of the mean value from the paired controls, but this difference was not significant (p=0.19) due to the high variability between swales. The swales subjected to the repeated PAM treatment had 25% lower rill densities than the paired controls, but again this was not significant (p=0.56). In 2004 the results were similar except that the mean rill density for the repeated PAM treatment group was 21% higher than the control group; again this difference was not significant. Rill density was inversely related to percent live vegetation (Figure 3.7; R^2=0.26; p=0.01).

3.4.5. Sediment Yields

All of the sediment generated during the study period resulted from the convective storms that are the dominant source of precipitation between 1 May and 31 October. No sediment was generated from either snowmelt or frontal rain storms between 1 November and 30 April even though one-third of the annual precipitation typically falls during these months.

Over the entire study period there were 12 sediment-producing storms, and 11 of these occurred between 1 June and 31 August. The total mean sediment yield from the control swales was 32 Mg ha^{-1}, with 10% of the total being produced in 2002, 56% in 2003, and 34% in 2004 (Figure 3.8).

In 2002 there were only two sediment-producing storms after the PAM treatments were applied on 10 August. The first of these storms occurred on 21 August, and for 2002 this 8.4 mm storm generated over 95% of the post-treatment sediment yields in 2002 for both the control swales the treated swales (Figure 3.8). The mean sediment yield from the dry PAM treatment was 2.3 Mg ha^{-1} in 2002, or 82% of the mean value from the three paired control swales. The difference in mean sediment yields between these two groups was not significant because of the high variability between pairs (p=0.53).

The mean sediment yield for the wet PAM treatment was 0.55 Mg ha^{-1}, or just 15% of the mean value of 3.6 Mg ha^{-1} from the corresponding control swales (Figure 3.8), and this difference was significant at p=0.004. Two of the three swales treated with wet PAM generated no sediment in the first and largest storm in 2002, while the sediment yield in the third treated swale was 60% less than its corresponding control. Since the first two pairs had 33-41% ash cover while the third pair had 62-63% ash cover (Figure

3.9), the lower treatment effectiveness for the third pair might be due to greater adsorption of PAM to ash and resulting decrease in the ability of PAM to bind with the underlying mineral particles.

In 2003 the mean annual sediment yield from the three swales with the single wet PAM treatment was 10.2 Mg ha^{-1}, and this was 39% less than the mean value from the controls (Figure 3.8). In contrast to 2002, this difference was not significant (p=0.10) due to the high variability among the treated swales (coefficient of variation=72%).

Since the dry PAM treatment had no apparent effect on sediment yields, a new wet PAM treatment was applied to these swales on 6 June 2003. This treatment did not significantly reduce sediment yields relative to the controls in summer 2003 (p=0.85), as the mean sediment yield from the treated swales was only 6% lower than the untreated swales (Figure 3.8). For the first large storm in 2003 the mean sediment yield from the newly-treated swales was 2.7 Mg ha^{-1}, and this was 38% higher than the mean value from the three control swales (p=0.44). The ineffectiveness of the new wet PAM treatment is in marked contrast to the results from the wet PAM treatment in 2002. Since there were nearly two weeks between the treatment application and the first major sediment-producing storm in both 2002 and 2003, the timing of the treatment cannot explain the observed difference in treatment effect.

In 2004 the swales treated with the single wet PAM treatment produced 5.8 Mg ha^{-1} or 57% less than the controls (Figure 3.8), but again this difference was not significant due to the high variability within treatment groups. The mean sediment yield from the swales subjected to the repeated wet PAM treatment was 8.1 Mg ha^{-1}, and almost exactly the same amount of sediment was produced from the paired controls (Figure 3.8).

Storm erosivity explained 58% of the variability in sediment yields ($p<0.0001$) (Figure 3.10). In 2002 the lowest intensity storm that produced sediment had an erosivity of 7.1 MJ mm ha^{-1} hr^{-1} and 13 mm of rainfall. The threshold for sediment production did not seem to increase in 2003, as the smallest storm that generated sediment was a combination storm with a total erosivity of 3.4 MJ mm ha^{-1} hr^{-1} and a combined rainfall of 8.2 mm.

In 2004 the total erosivity was nearly twice the value from 2003, but the mean sediment yield from the controls was only 66% of the value from 2003. In 2004 the threshold for generating sediment seemed to increase, as the smallest storm that produced sediment had 11.9 mm of rainfall and an erosivity of 31 MJ mm ha^{-1} hr^{-1}. Altogether there were 14 storms in 2004 with over 5 mm of rainfall, but only 3 of these produced sediment. In contrast 9 of the 11 storms in 2003 with at least 5 mm of rainfall produced sediment. The decrease in sediment yields over time also is illustrated by the 18 mm storm on 25 June 2004, as this had more than twice the erosivity of any other storm during the study period with 145 MJ mm ha^{-1} hr^{-1} (Figure 3.10). The mean sediment yield for this storm from the control swales was 9.4 Mg ha^{-1}, which is the highest sediment yield measured during the study period. However, a storm on 21 August 2003 had a much lower erosivity of 23.3 MJ mm ha $^{-1}$ hr $^{-1}$ but almost the same sediment yield (8.9 Mg ha^{-1}). The other two sediment-generating storms in 2004 produced a mean sediment yield from the control swales of only 1.5 Mg ha^{-1}, even though the total amount of rainfall after the 25 June 2004 storm was similar to total rainfall in summer 2003 when the control swales produced 18.0 Mg ha^{-1}.

Percent live vegetative cover was not a signficant control on sediment yields for any treatment group, so there is no evidence to suggest that any reduction in sediment yields is due to a treatment-enhanced vegetative recovery. However, the swales treated with the single wet PAM treatment had signficantly higher percent vegetative cover than the paired controls in fall 2004, and this corresponded with reduction in sediment yields of 57% relative to the controls, although this difference was not significant. This reduction in sediment yields was higher than the previous year when the mean sediment yield generated by the treated swales was 39% less than the corresponding controls.

Rill density explained 46% of the variability in sediment yields ($p = 0.0003$) (Figure 3.11). Rill density was significantly related to sediment yields for all treatment groups. Vegetation and rill density were inversely related ($R^2=0.26$; $p=0.01$) (Figure 3.7), suggesting that higher percent live vegetation may reduce rill formation. The increase in percent vegetative cover over time (or the decrease in bare soil) can help to explain the observed in sediment yields over time.

3.4.6. Interaction of PAM with Ash and Mineral Soil

The laboratory experiment showed that the ash mixture and the 50:50 mixture of ash and mineral soil both adsorbed over half of the PAM in solution (Figure 3.12). The mineral soil removed 33% of the PAM, and the difference in PAM removal between the mineral soil mixture and the two mixtures with ash were each significant at $p<0.0001$. Each of the mixtures also had a significantly lower concentration of PAM in solution relative to the blanks ($p<0.0001$). These results show that the anionic PAM used in this study preferentially binds to ash relative to mineral soil.

3.5. DISCUSSION

3.5.1. Controlling Variables on Sediment Yields

Storm erosivity explained over half of the variability in sediment yields, but was less important in 2004 when the threshold for sediment production increased an order of magnitude relative to 2003. Other studies in the Colorado Front Range have shown that storm erosivity can explain over 50% of the variability in storm-based sediment yields, while annual erosivity combined with percent bare soil can explain over 60% of the variability in annual sediment yields (Benavides-Solorio and MacDonald, 2005; Pietraszek, 2006).

Storm erosivity was not a significant control on sediment yields for the wet PAM treatment applied in 2002 because the increased aggregation of particles from the PAM treatment makes them heavier and less erodible during large storms (Barvenik, 1994; Seybold, 1994; Sojka et al., 2000). While this treatment appeared to reduce sediment yields by 39-85% for all three years, this difference was only significant in the first year. This lack of treatment effect in the second and third years may be a result of Type II error, due to the small sample size ($n=3$), but further research with higher sample numbers would be necessary to determine whether this is true.

Live vegetative cover was not a significant control on sediment yields for any of the three years. Mean percent live vegetation didn’t exceed 10% until the third year after burning, and no treatment increased vegetative cover until fall 2004 when the swales treated with the single PAM treatment had significantly higher percent vegetative cover than the controls. This higher vegetative cover corresponded with a greater reduction in sediment yields relative to the previous year. While the primary treatment goal for PAM is to reduce the erodibility of soil particles, PAM also can increase vegetative regrowth by increasing infiltration and reducing surface sealing for more effective seed germination (Sojka et al., 2000). Because the reduction in sediment yields was not significant in 2004, however, it cannot be said whether the relative increase in vegetative cover and decrease in sediment yields relative to the controls are truly related.

Rill density also appeared to be an important control on sediment yields, explaining about 50% of the variability in annual sediment yields. PAM can potentially decrease rill formation by reducing the erodibility of fine particles that are normally detached in the initial stages of rill formation. The swales treated with the single wet PAM treatment had 38-51% lower rill densities in 2003 and 2004, which may have been an effect of the PAM treatment. The swales treated with the repeated PAM treatments did not reduce sediment yields and had 22% higher rill densities than the controls in 2004. Studies in the Colorado Front Range have found that rill density and channel incision generate 60-80% of the sediment production from burned hillslopes (Moody and Martin, 2001; Pietraskek, 2006). These results suggest that the single PAM treatment may have reduced rill formation as a result of soil particle aggregation and reduced surface runoff, which helps to explain the lower sediment yields.

3.5.2. Treatment Type and Application Method

PAM in both dry and wet formulations has been very successful in agricultural applications where the slopes are low and the PAM settles in furrows until it is dispersed with irrigation (Sojka et al., 2000). The results from this study were different as the dry PAM treatment did not reduce sediment yields relative to the controls. The micronized formulation of the dry PAM was a very fine powder with a diameter of 30-150 μm. As the dry PAM was being applied, a light breeze was sufficient to redistribute some of the PAM. These losses or redistribution effectively reduced the application rate and this may have contributed to the lack of any effect on surface cover, rill density, or soil erosion. Other studies have also found that dry applications of PAM were not as effective as liquid applications for reducing runoff and erosion (Cook and Nelson, 1986, Peterson et al., 2002). For a loamy soil in Utah a wet PAM treatment maintained aggregate stability, reduced penetrometer resistance, and improved seedling emergence, while a dry granular PAM applied at the same concentration had no significant effect on the same characteristics (Cook and Nelson, 1986).

The higher effectiveness of the wet PAM formulation is primarily due to the immediate binding and aggregation of PAM and soil particles. The dry PAM requires precipitation or irrigation before soil binding can occur, which increases the potential for redistribution offsite by wind and surface runoff, and/or chemical breakdown at the soil surface.

The higher application rate of the wet PAM may have also explained the difference in effectiveness between the wet and dry treatments. The application rate varies with precipitation rainfall and intensity, slope, soil texture, and other factors (Sojka et al., 2000; Flanagan et al., 2002). As little as 2 kg ha^{-1} PAM reduced soil loss by 12% from a rainfall simulation (Abu-Zreig, 2006), but other studies have found that application rates must be to 20 kg ha^{-1} to signficantly reduce erosion (Wallace & Wallace, 1986b; Sojka et al., 1998; Bjorneberg and Aase, 2000; Flanagan et al., 2002; Peterson et al., 2002).

Steep slopes can increase the potential for surface runoff and erosion in infiltration limited areas such as disturbed soils that are prone to surface sealing or burned areas that have a fire-induced water repellent layer (Flanagan et al., 2002; Shakesby and Doerr, 2006). Higher runoff velocities increase the potential for particle detatchment and erosion of larger soil particles. Therefore on steeper, disturbed slopes such as burned areas PAM may need to be applied at a higher rate in order to form larger more resistant soil aggregates. The application of PAM at 80 kg ha^{-1} reduced erosion by over 50% on steep hillslopes ranging from 34-37% (Chaudhari and Flanagan, 1998). In another study in Canada, PAM was applied at 10 and 20 kg ha^{-1}, and this did not reduce erosion on plots with 30% slopes (Partington and Mehuys, 2005). These studies would suggest that on steep slopes an application rate between 20 and 80 kg ha^{-1} may be needed to reduce erosion rates.

Soil texture also changes the application rate. Anionic PAM works by binding to negatively charged clay particles through cation bridging. The presence of these divalent cations is imperitive for anionic PAM to work properly (Shainberg, 1990a; Laird, 1997). Coarser soils with a low clay content and low ionic strength may need higher application rates in order to form continuous bridges between the large particles. PAM applied at 11 kg ha^{-1} was effective in reducing erosion off plots with a slope of 25% on clay loam soil, but application rates of 11 kg ha^{-1} and 20 kg ha^{-1} did not reduce erosion on comparable plots with a sandy soil (McLaughlin, 2002).

Other fire-induced changes such as water repellency, ash cover, and loss of organic matter may also change the necessary application rate, but no studies have evaluated these factors specifically with respect to PAM use for post-fire erosion control. The effectiveness of the wet PAM in the first year suggests that PAM has potential for post-fire applications. The paucity of PAM studies on steep sandy slopes, however, makes it difficult to determine what the ideal application rate would be for the gravelly steep hillslopes in the Colorado Front Range.

3.5.3. Interactions between Ash, Soluble Cations, and PAM

The observed differences in effectiveness between the different PAM treatments in this study raise a series of issues that may merit further research. The first is whether high amounts of ash reduce the effectiveness of PAM by intercepting the PAM before it has a chance to bind with the soil particles. Since anionic PAM is negatively charged, the positive charge of the carbon in ash can be highly adsorbant of PAM on contact. The laboratory experiment in this study indicated that ash is capable of intercepting and preferentially binding to PAM during treatment application. In a study where coal fly ash and PAM were applied to a calcareous clay soil to enhance wheat yields, the PAM tended to bind directly to the fly ash (Wallace, 1986a). Ash is very light and likely to erode during even small storms, so any PAM that is bound to ash will also be removed during the first few small storms and is not likely to provide much treatment benefit.

A related issue is whether the ineffectiveness of the repeated wet PAM treatments was due to the lack of soluble cations in 2003 and 2004. Soluble cations such as Ca and Mg are associated with ash in elevated concentrations immediately after fires. These cations have the divalent properties necessary for PAM binding to occur, but they are also removed during the first few storms due to erosion of ash, leaching, and dilution from runoff (DeBano et al., 1977; Kutiel and Naveh, 1987; DeBano and Conrad, 1978; Stark, 1979; Wells, 1979; Christensen, 1979; Raison, 1979; Kutiel and Naveh, 1987). In 2002, ash and organic material accounted for 29% by weight of the eroded sediment and by spring 2004 ash cover on the newly treated swales had decreased to 3% (Figure 3.6). If the majority of soluble cations were removed with the ash, the PAM would not have been able to bind with the negatively charged soil particles in the second and third years, thus explaining the lack of treatment effectiveness for the repeated treatments.

So in summary, PAM appeared to work well when ash cover could provide the needed cation bridging agents, but not so well when too much ash may have intercepted a majority of the PAM. This would seem to require a complicated understanding of the cation balance of the individual hillslope to be treated. While there isn't much to be done about percent ash cover on burned areas, one possible solution to the issue of too few available cations would be to amend the soil with a calcareous electrolyte such as gypsum. Gypsum is relatively inexpensive and numerous studies have found the combination of gypsum and PAM to be effective in reducing erosion relative to controls (Zhang, 1998; Peterson et al., 2002; Yu et al., 2003; Ajwa and Trout, 2006). Mixtures of PAM (40 kg ha^{-1}) with either gypsum (5,000 kg ha^{-1}) or Nutra-Ash (8,042 kg ha^{-1}) reduced erosion relative to controls by 74% and 77%, respectively (Peterson et al., 2002).

In soils with sufficient soluble cations, however, gypsum can slightly decrease the ability of PAM to reduce erosion due to greater coiling of the PAM and clay particles. The anionic PAM alone is a linear chain which can can link to form continuous chains of up to 0.1 to 0.2 mm long between soil particles when divalent cations are in short supply. These longer chains can potentially block soil pores and reduce infiltration, but they also provide greater cohesion of soil particles and create larger aggregates that are more resistant to erosion (Yu et al., 2003). The combination of PAM and gypsum results in a greater density of aggregate formation due to increased coiling of the negatively charged functional groups, so the resulting the aggregates are smaller than they are with PAM alone. This was illustrated in a study where PAM without gypsum reduced erosion by up to 85% relative to the control, but a PAM and gypsum mixture only reduced erosion by up to 55% (Yu et al., 2003). When the soluble cations have been eroded, leached, or diluted, however, gypsum (or a similar compound) may be the best option.

3.6. CONCLUSIONS

A dry micronized PAM treatment and a wet PAM treatment were evaluated for their effectiveness in reducing post-fire erosion in a ponderosa pine forest that burned at high severity in May 2002. Each of two treatments was applied to three swales, and each treated swale had a corresponding untreated control. Precipitation, surface cover, and post-fire erosion were measured for three consecutive years. Site variables such as hillslope morphology, rill density, and soil texture also were measured.

The dry PAM treatment was applied at a rate of 5.6 kg ha^{-1} in summer 2002, and this did not significantly reduce sediment yields relative to the paired controls. This lack of effectiveness may be due to the low application rate and possible loss of the PAM by wind before the first rain could provided the needed water for soil binding.

The mean sediment yield from the swales treated with 11.2 kg ha^{-1} of wet PAM in aqueous solution was 85% lower than the mean value from the control swales for two sediment producing storms in 2002 ($p = 0.004$). The two swales with 33-35% ash cover produced 99% less sediment than the swale with 63% surface ash cover in 2002. This difference was attributed to the greater interception of PAM by ash cover and resultingly lower soil aggregation. The preferential interception of PAM by ash was supported by a laboratory experiment that showed that ash removed almost twice as much PAM from solution as mineral soil. Sediment yields from the treated swales were 39% lower than the controls in 2003 and 57% in 2004, but these reductions were not significant.

Subsequent wet PAM treatments in June 2003 and June 2004 did not reduce sediment yields relative to the controls. Over half of the surface ash had eroded by spring 2003, and by spring 2004 only 3% ash cover remained at the soil surface. Erosion of surface ash may have removed the soluble cations that are typically associated with burned organic material immediately after a fire. These divalent cations are critical for PAM binding and aggregation with soil particles, which may explain the lack of treatment effect in the second and third years. In general, the PAM treatments did not significantly increase vegetative regrowth or decreased rill density relative to the paired controls.

The results suggest that polyacrylamide could be an effective post-fire rehabilitation treatment, but further research is needed to determine the best application methods and rates for different climates, slopes, ash cover, and soil types. Additional research is needed on the use of PAM in burned areas with finer-textured soils types with their ionic binding capacities, and on newly burned-hillslopes with high concentrations of soluble cations. The addition of gypsum or other electrolyte-rich amendments should be evaluated to see if this improves the binding efficiency of PAM in burned areas. Rainfall simulations are needed to isolate the influence of factors such as soil textures, percent ash cover, higher application rates, and the addition of soil additives to determine their relative importance to the use of PAM as a post-fire erosion control treatment.

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Table 3.1. Swale characteristics and treatments by year for the two treatment groups (S=single wet treatment; M=multiple treatments). The initial dry treatment on the multiple treatment group was 5.6 kg ha^{-1} micronized PAM. The wet treatment was 11 kg ha^{-1} micronized PAM in ammonium sulfate solution.

Pair ID	Contributing Area (m^2)	Axis slope (%)	Side slope (%)	Aspect	Treatment Class	2002 Treatment	2003 Treatment	2004 Treatment
S1	2470	38	17	NW	Control	Control	None	None
	1920	43	25	NW	Treated	Wet	None	None
S2	2830	30	15	S	Control	Control	None	None
	3020	36	25	S	Treated	Wet	None	None
S3	1280	35	28	W	Control	Control	None	None
	1410	37	33	W	Treated	Wet	None	None
M1	1190	37	17	NW	Control	Control	None	None
	940	35	11	NW	Treated	Dry	Wet	Wet
M2	2370	40	18	W	Control	Control	None	None
	1970	35	28	W	Treated	Dry	Wet	Wet
M3	1470	37	31	W	Control	Control	None	None
	1650	35	31	W	Treated	Dry	Wet	Wet

Table 3.2. Rainfall depth, maximum 30-minute intensity (I_{30}), storm erosivity and sediment yields from the control swales from 1 May - 31 October in 2002, 2003, and 2004. The storms listed generated sediment or had at least 5.0 mm of rainfall. na=not applicable.

	Date	**Storm depth (mm)**	**I_{30} (mm hr^{-1})**	**Erosivity (MJ mm ha $^{-1}$ hr $^{-1}$)**	**Mean sediment yield from controls (Mg ha^{-1})**
2002 (n=7)	06 July	9.1	11.2	15.7	NA
	21 July	5.1	9.7	9.1	NA
	03 August	5.1	5.1	3.4	0
	21 August	8.4	16.3	28.7	3.1
	18 September	5.6	3.0	1.9	0
	01 October	13.0	4.6	7.1	0.1
	26 October	5.1	5.1	3.1	0
	Totals	**120.1**	**na**	**88.1**	**3.2**
2003 (n=11)	05 June	5.8	2.5	1.6	0
	06 June	3.6	3.0	1.5	0.01
	06 June	4.6	3.6	1.9	
	19 June	9.9	18.3	40.1	2.8
	19 July	7.4	11.2	13.5	0
	01 August	6.9	13.7	23.3	8.9
	03 August	4.3	7.6	6.3	0.2
	11 August	6.4	11.7	16.2	2.2
	18 August	5.1	9.1	10.0	1.8
	30 August	10.2	10.7	16.0	2.2
	30 August	9.7	13.2	22.9	
	Totals	**122.2**	**na**	**170.2**	**18.0**
2004 (n=14)	12 May	8.6	6.6	7.4	0
	16 June	6.9	8.6	10.4	0
	21 June	8.1	11.7	17.0	0
	21 June	8.6	6.1	6.8	0
	25 June	17.8	33.0	144.6	9.4
	27 June	7.4	8.1	8.2	0
	16 July	7.6	5.1	4.5	0
	23 July	11.9	14.2	31.0	1.0
	05 August	11.7	16.8	37.6	0.5
	19 August	5.1	2.0	1.2	0
	27 August	5.3	6.6	5.0	0
	27 September	14.2	7.6	15.0	0
	13 October	6.4	4.1	3.0	0
	13 October	7.9	10.2	12.7	0
	Totals	**245.4**	**na**	**351.9**	**10.9**

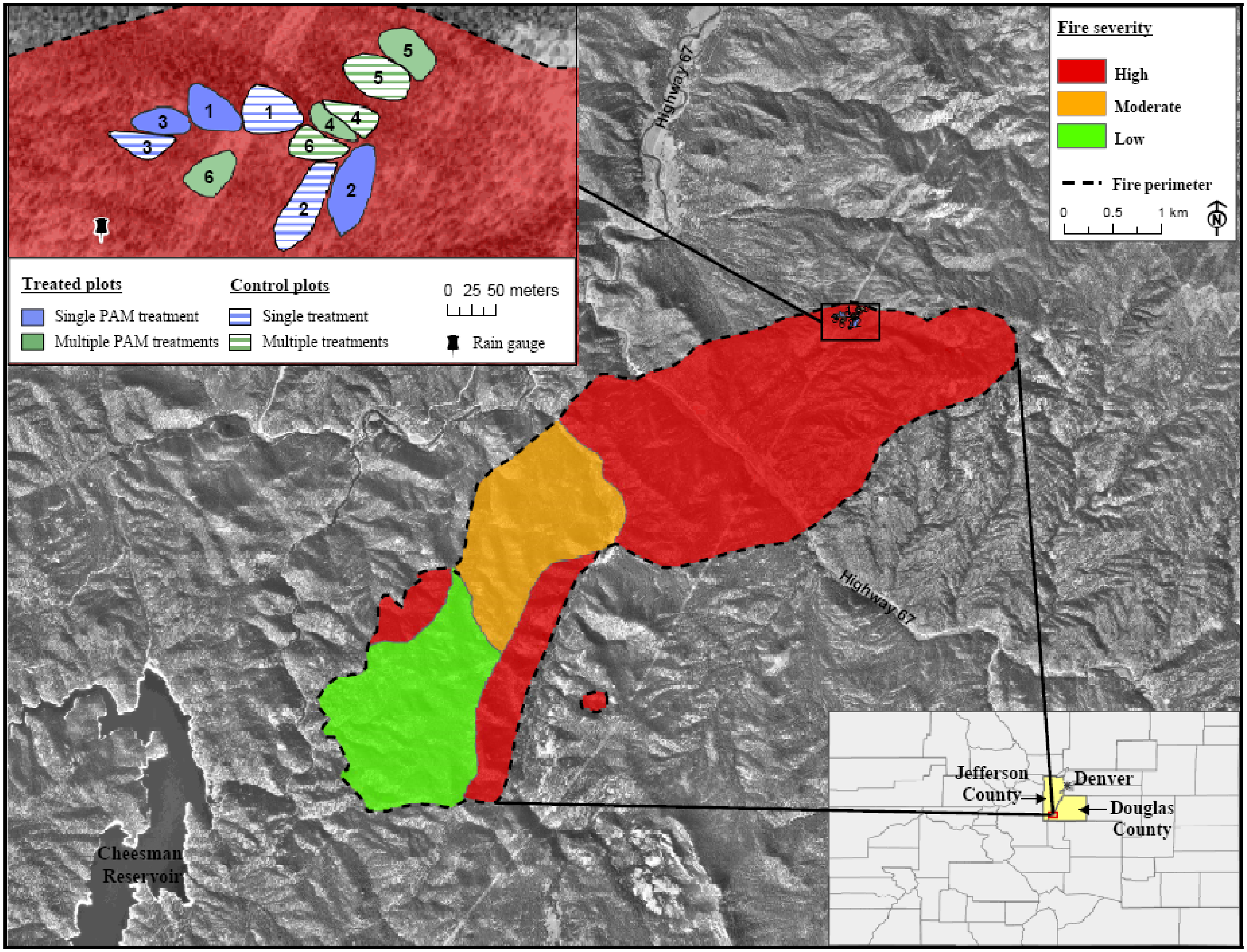

Figure 3.1. Location of the Schoonover Fire and the six pairs of study swales.

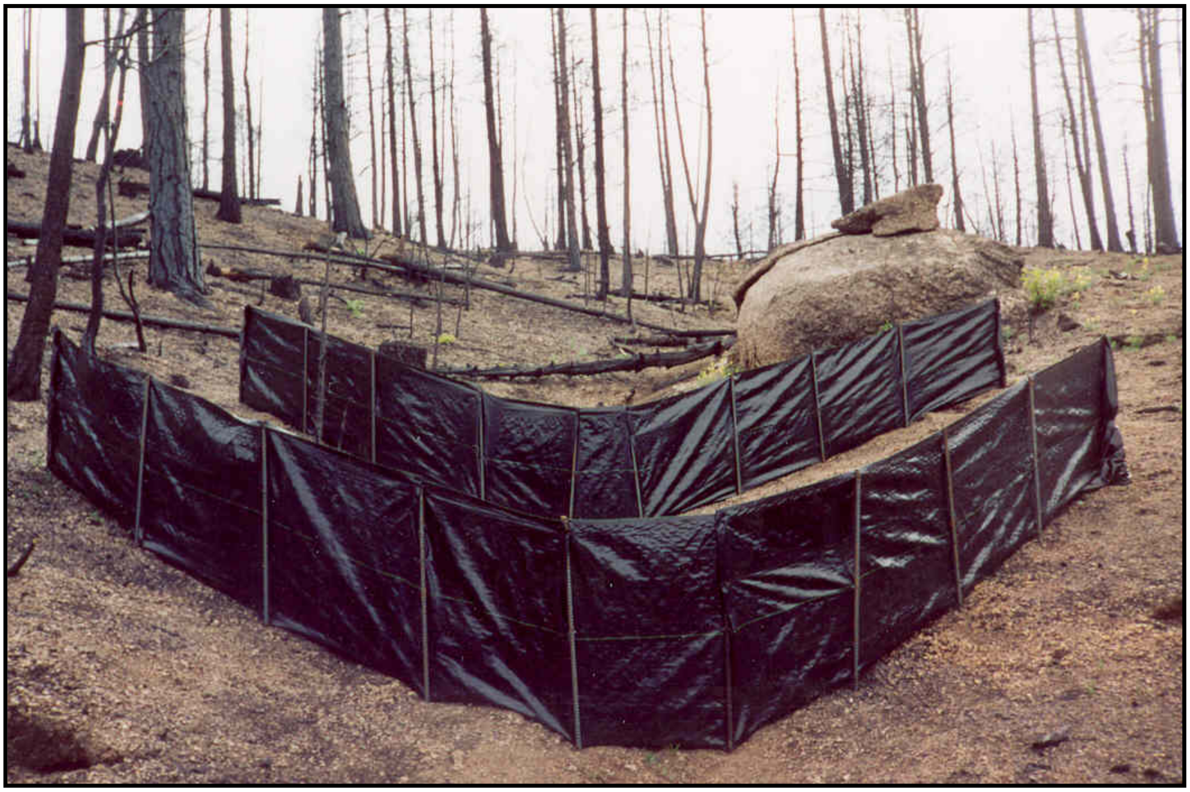

Figure 3.2. Typical sediment fences used to measure sediment yields.

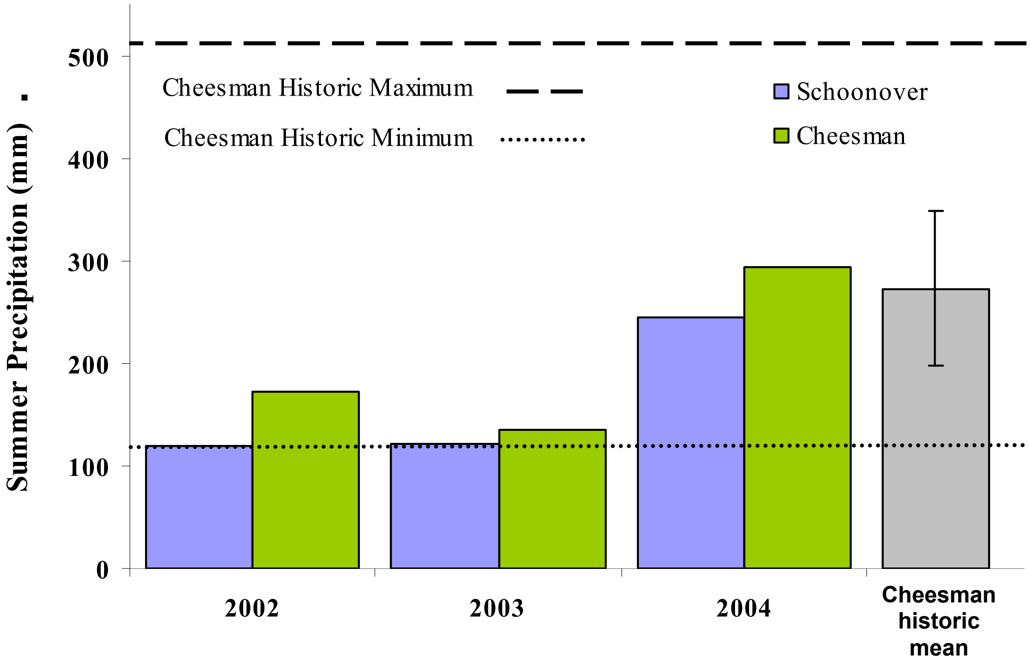

Figure 3.3. Summer precipitation for 1 May-31 October for 2002, 2003, and 2004 at Schoonover and Cheesman Reservoir relative to the historic mean, maximum, and minimum at Cheesman Reservoir.

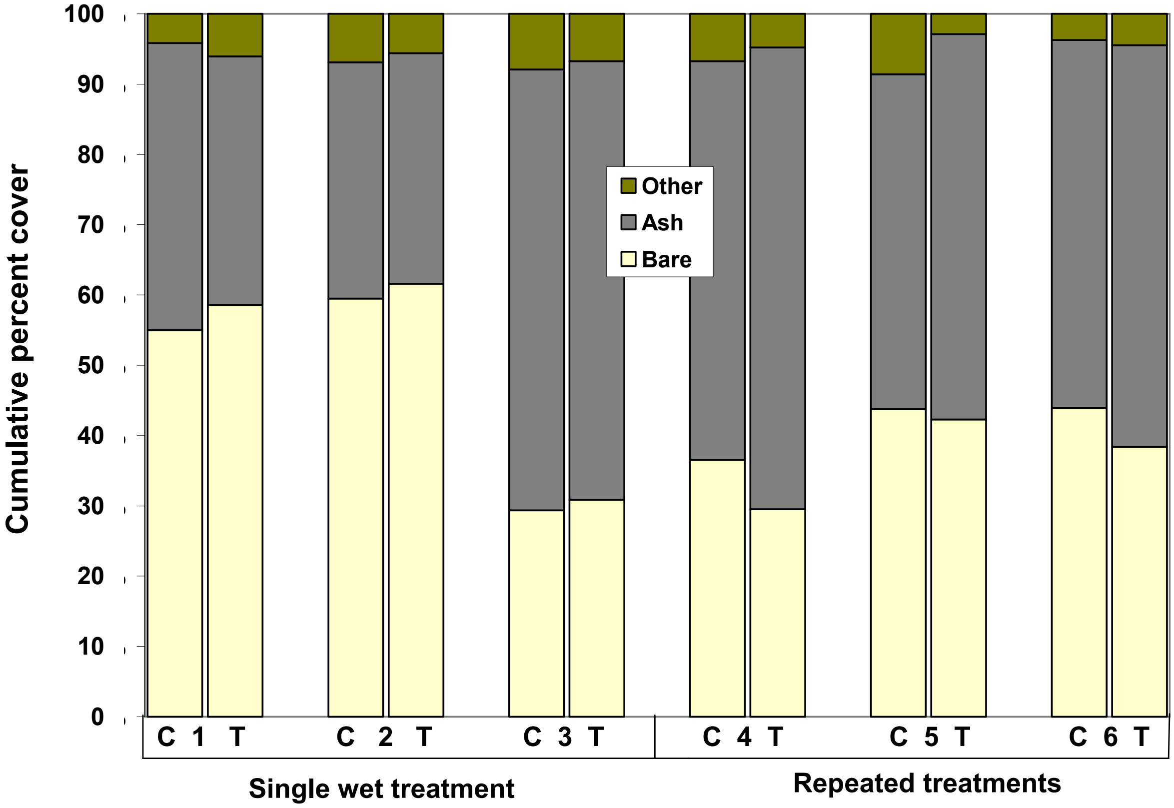

Figure 3.4. Surface cover for each pair of swales by treatments in July 2002. C and T indicate control and treated swales, respectively.

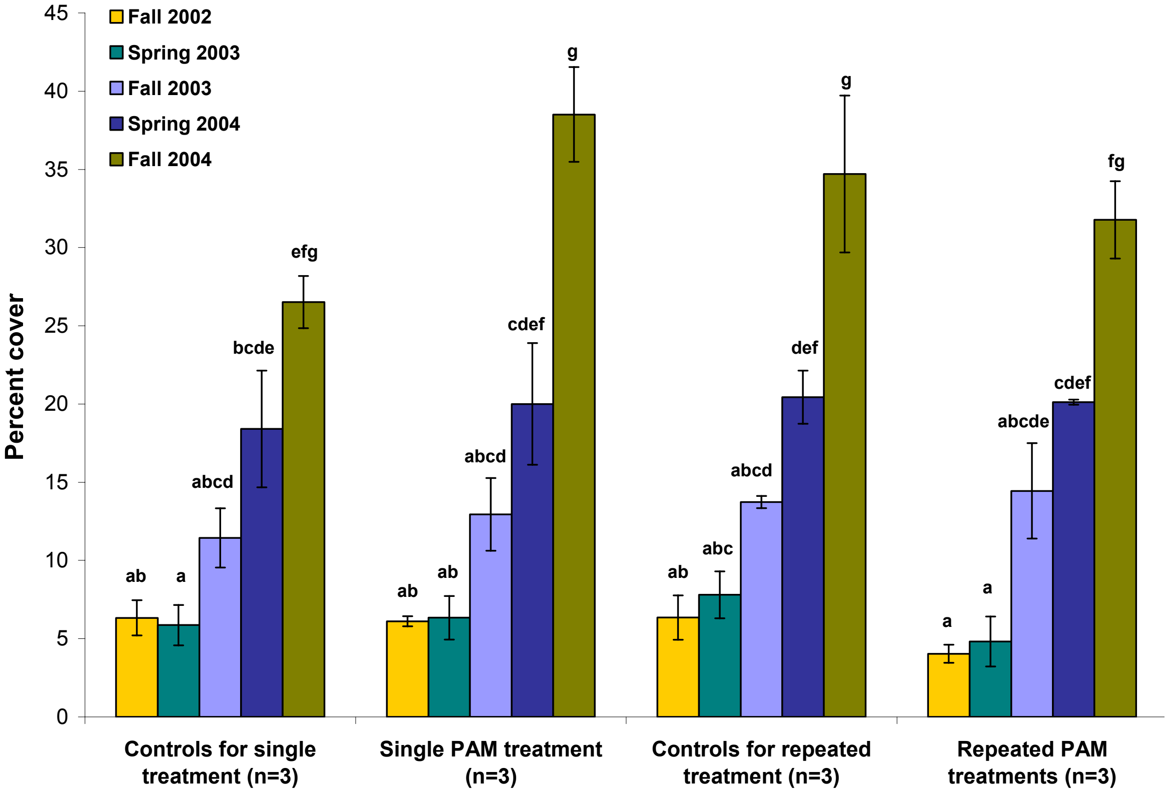

Figure 3.5. Mean percent ground cover by treatment over time. Error bars represent one standard error. Letters indicate significant differences between groups over time.

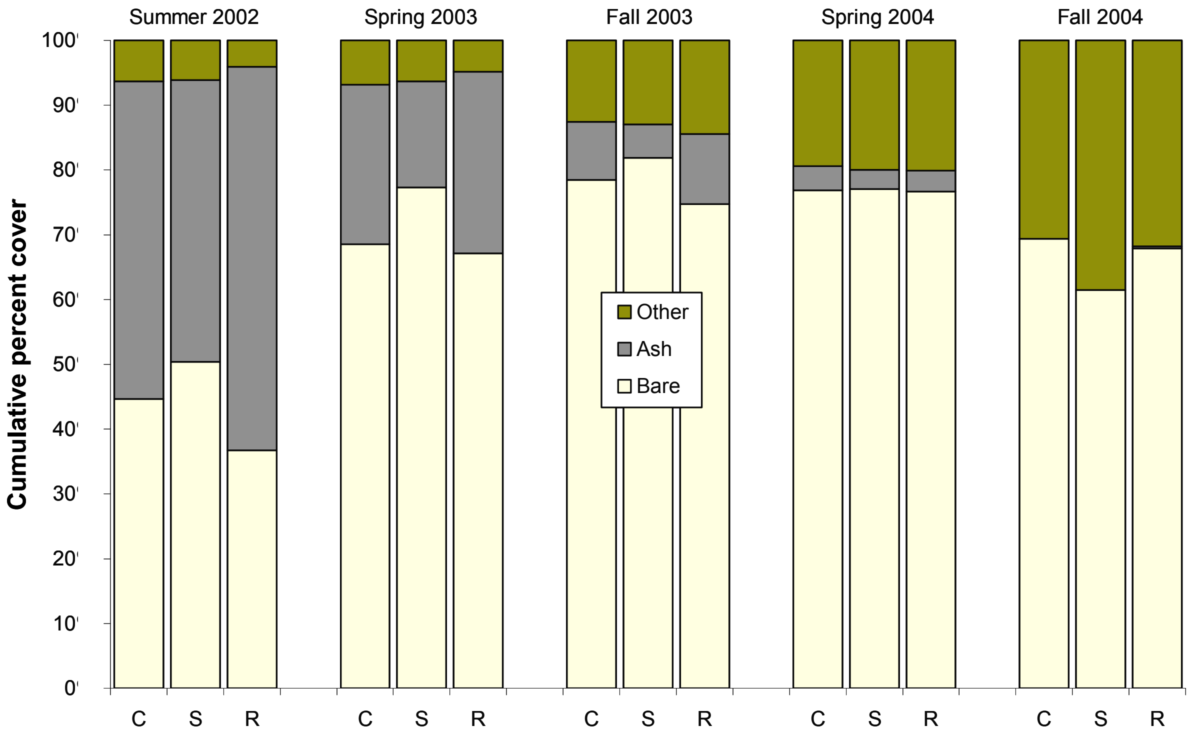

Figure 3.6. Mean surface cover for each treatment group from summer 2002 through spring 2004. C represents the controls, S is the single treatment group, and R is the repeated treatment group.

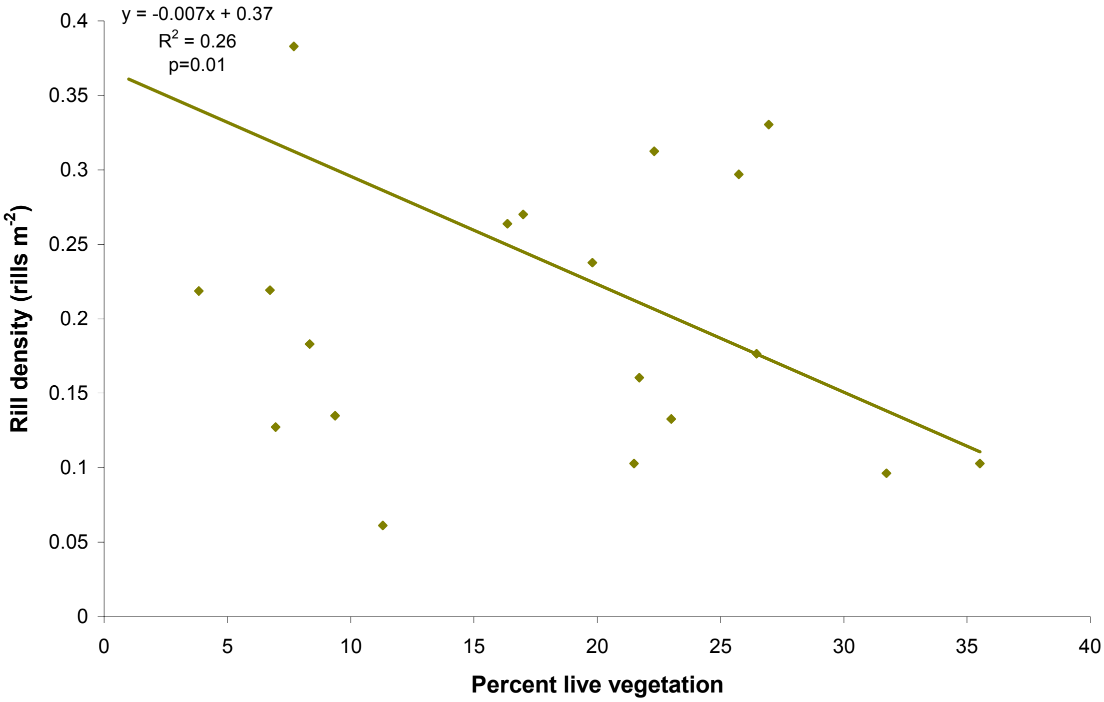

Figure 3.7. Scatter plot showing the inverse relationship between percent vegetative cover and bare soil versus rill density for fall 2003 and fall 2004.

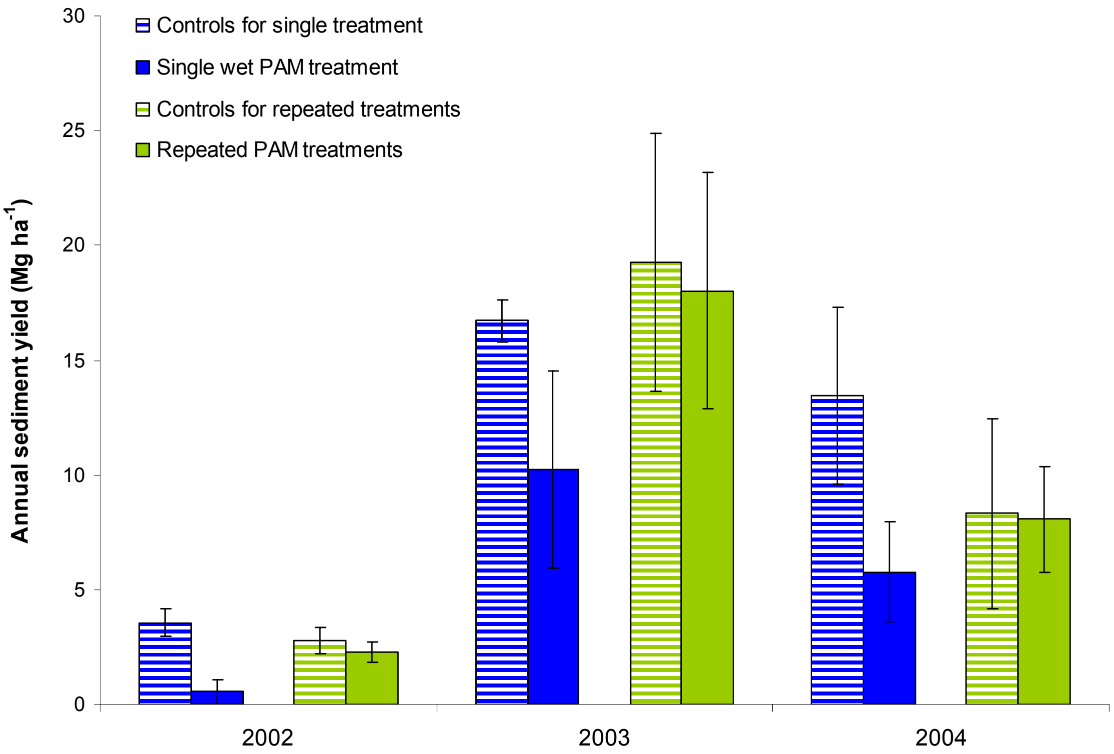

Figure 3.8. Mean annual sediment yields for the single treatment group, repeated treatment group, and their corresponding controls for 2002-2004. Bars indicate one standard error.

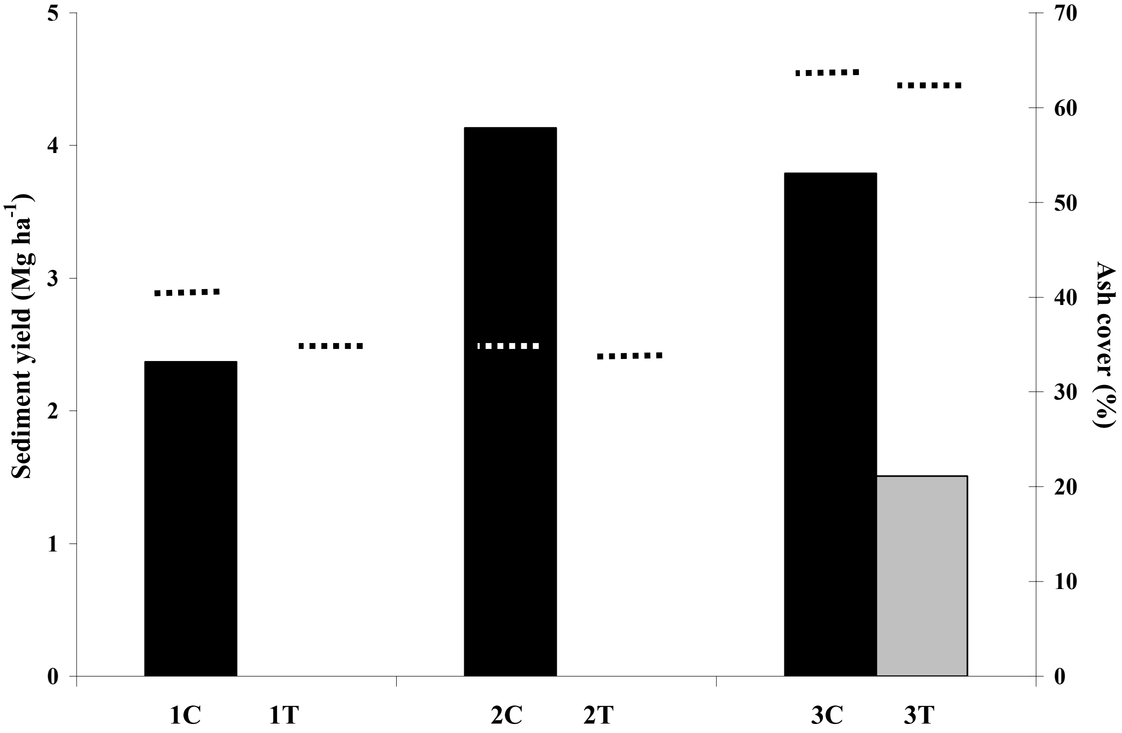

Figure 3.9. Sediment yields from the 21 August 2002 storm for the control swales (C) and the swales treated with wet PAM (T). The bars indicate the sediment yield for each swale and the horizontal dotted lines indicate the percent ash cover for each swale prior to this storm.

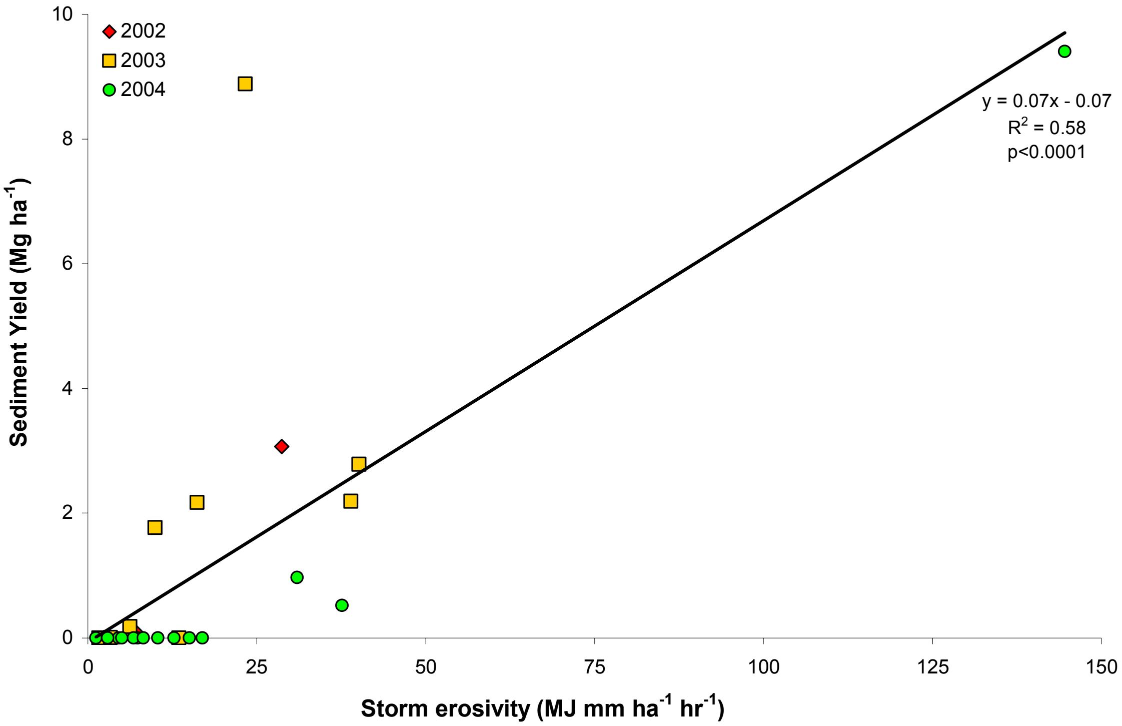

Figure 3.10. Storm erosivity versus the corresponding mean sediment yields from the control swales for storms with at least 5 mm of rainfall and all sediment producing storms, regardless of total rainfall.

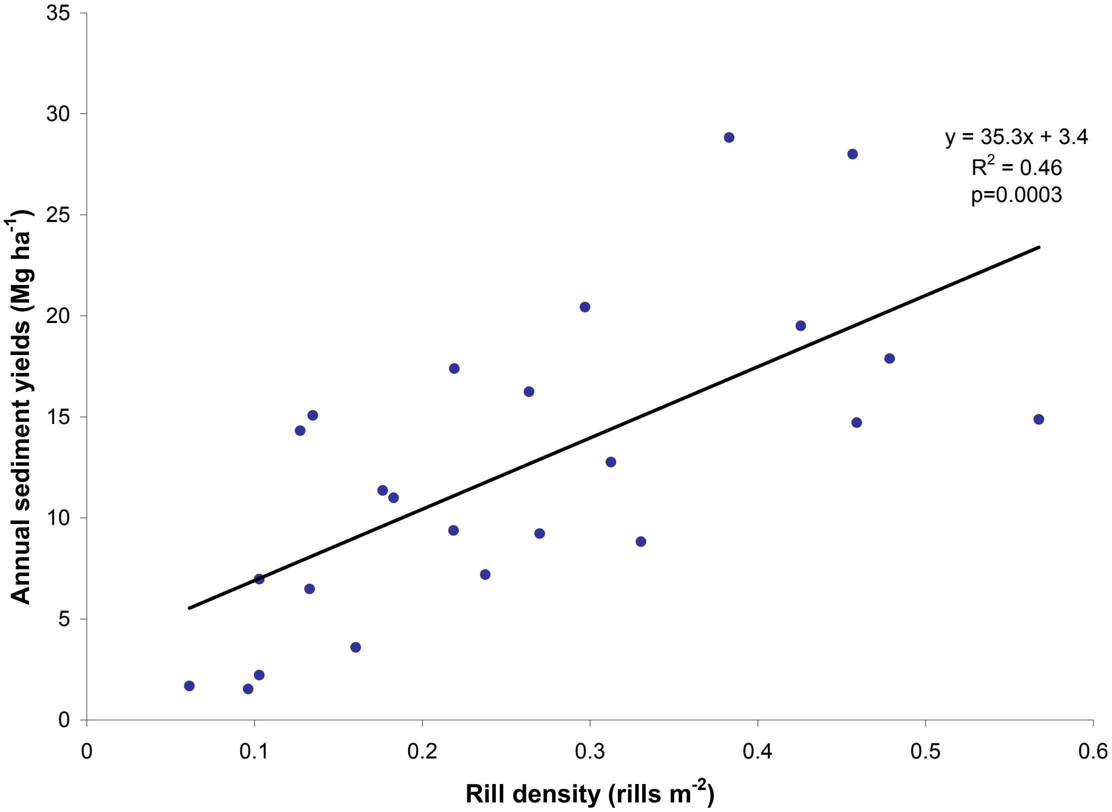

Figure 3.11. Rill density in fall 2003 and fall 2004 versus annual sediment yields.

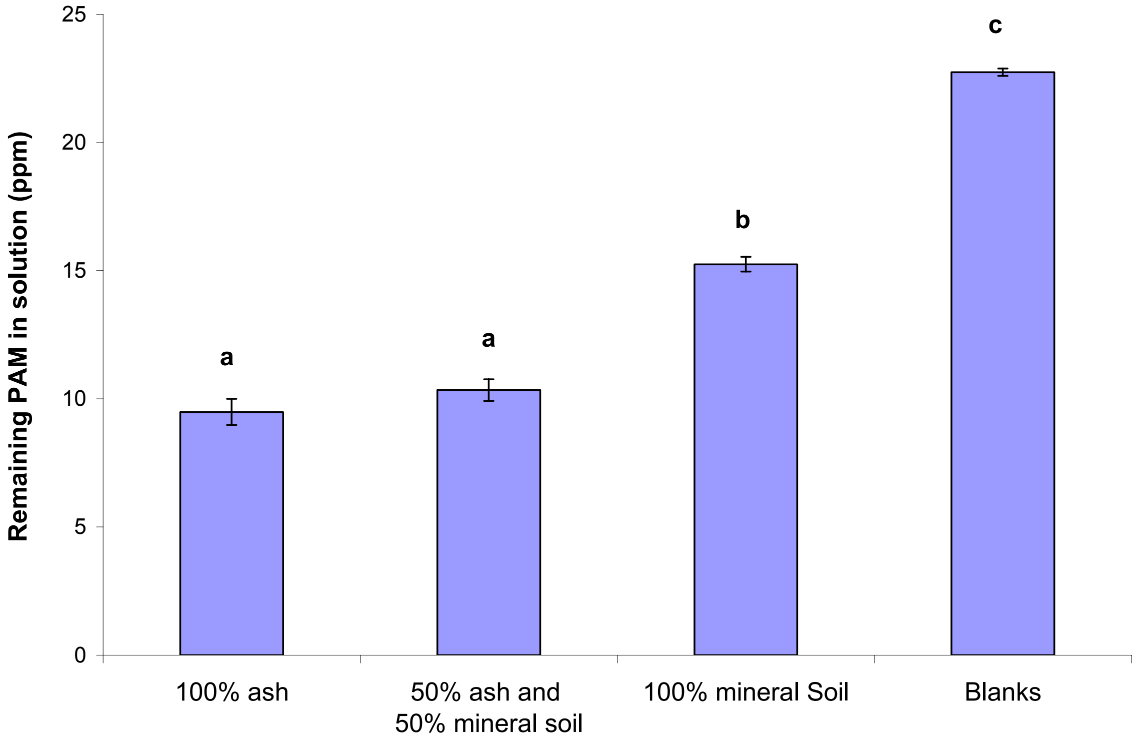

Figure 3.12. Amount of PAM remaining in solution for different mixtures of ash and mineral soil in water. Letters indicate significant differences between means. Bars indicate one standard deviation.

4. CONCLUSIONS

The primary objective of this research was to evaluate the effectiveness of four common treatments (Chapter 2) and one alternative treatment (Chapter 3) for reducing post-fire erosion at the hillslope-scale in the Colorado Front Range. The data collected in this study also helped evaluate the influence of physical characteristics, such as hillslope morphology, soil texture, surface cover, and precipitation, on treatment effectiveness.

The ability of different rehabilitation treatments to reduce post-fire erosion has been rigorously evaluated in only a few studies (Miles et al., 1989; Bautista et al., 1996; Robichaud et al., 2000; Wagenbrenner et al., 2006). Many studies intended to evaluate post-fire rehabilitation treatments have lacked replicated treatments, replicated controls, and longer-term measurements to assess changes in effectiveness over time. The present study was facilitated by the presence of proximate and topographically comparable swales, which minimized the physical and climatic variability between the the treated and control sites, and allowed at least three replicates per treatment. Longer-term funding allowed the sites to be monitored for three years following their application. Since the post-fire erosion rates are highest in the first two years after burning (Robichaud and Brown, 1999; Benavides-Solorio and MacDonald, 2005; Wagenbrenner et al., 2006), this study covers the most critical period for evaluating the effectiveness of post-fire erosion control treatments.

The results from Chapter 2 confirm that straw mulch is a highly effective erosion control treatment (Kay, 1983; Miles et al., 1989; Sidle et al., 1993; Lichter and Lindsey, 1994; Megahan et al., 2001; Wagenbrenner, 2006). The swales treated with dry mulch had 77-99% lower sediment yields than the controls in all three years of monitoring While some treatments are limited by soil texture, soil chemistry, climate, or slope, mulching is effective in a wide variety of conditions because it intercepts rainfall before rainsplash and soil sealing can occur, increases surface roughness, dissipates runoff energy, serves as miniature sediment control dams, and reduces evaporation from the soil surface.

The aerial hydromulch treatment caused a similar reduction in sediment yields as the dry mulch treatment. The effectiveness of the dry mulch and aerial hydromulch treatments is attributed to the immediate "carpet" they provide, as each treatment had significantly more ground cover from summer 2002 through summer 2004 than the corresponding controls. The mulch treatments did not enhance vegetative regrowth, as the treated swales did not have significantly higher live vegetative cover than the corresponding controls in any of the three years monitored.

The ground hydromulch was applied in late August, and in the first year after burning there was only one small sediment-producing storm. The treatment was highly effective for this storm, but it did not significantly reduce sediment yields in the subsequent two years of monitoring. One possible reason for the lack of effectiveness was the lower concentration of wood fiber mulch and seeds in the slurry and the lack of a polyacrylamide (PAM) soil binding agent relative to the aerial hydromulch. PAM probably helped to bind the aerial hydromulch to itself and the underlying soil particles whereas the fine wood fiber mulch in the ground hydromulch had no cohesive agent to bind it to the soil surface, and was much less cohesive one it was applied.

The treatment objectives for the scarification and seeding treatment were to break up the water repellent layer, increase infiltration, provide surface roughness to help retain seeds, and facilitate germination, and ultimately to reduce post-fire erosion. Field observations indicated that surface runoff removed the seeds during large storms and deposited them in channels and toe slopes. The depth of scarification was less than 2 cm, even though the potential depth of scarification was the length of the McLeod tines (9 cm). Since the fire-induced water repellency extended to 9 cm in places, the scarification was not able to break up the water repellent layer. The larger-scale scarification treatments dragged a harrow behind an all terrain vehicle (ATV), but this also was probably too shallow to break up the water repellent layer. The ground disturbance associated with the scarification treatment may increase erosion rates, as the sediment yields in the first year after the hand scarification treatment were 45% higher on the treated swales than the corresponding controls. In summary, the scarification and seeding treatment did not achieve the objectives because there were never any significant differences in soil water repellency, percent live vegetation, or sediment yields between the treated sites and the controls.

Chapter 3 evaluated the use of a anionic polyacrylamide (PAM) to reduce post-fire erosion. The dry PAM treatment did not significantly reduce sediment yields relative to the paired controls. This was most likely due to too low an application rate, and/or wind removal of PAM before a rain event provided the necessary water for soil binding. The dry PAM is more effective in furrow irrigation applications where water is immediately available to dissolve and infiltrate the PAM, and furrow depressions can reduce the amount of wind dispersal. The swales treated with the single wet PAM in 2002 had significantly lower sediment yields for the two small storms in the first summer after burning. The treated swales also had lower sediment yields in the second and third years, athough these reductions were not significant. The swales treated with wet PAM in the second and third years after burning did not signficantly reduce sediment yields in either year.

The observed differences in effectiveness between the different PAM treatments in this study raised a series of issues that need further study. A key issue related to percent ash cover and whether the interception of PAM by ash reduces soil aggregation. The erosion and cover data suggest that an ash cover of around 35% was low enough to allow PAM to penetrate to the soil particles, but high enough to provide sufficient cations for the PAM to bind with the mineral particles. An ash cover of 62% may have intercepted a majority of the PAM treatment, which would reduce the aggregation of the underlying mineral soil and explain the observed variations in effectiveness. Soil chemistry data were not collected prior and during the study period so a rigorous connection could not be made between the availablity of cation electrolytes and treatment effectiveness. The rapid loss of the cation-rich ash may help explain why the repeated wet PAM treatments in years two and three were not effective, even though these were identical to the first year's treatment.

The basic processes that control the effectiveness of post-fire erosion control treatments are universal, but the relative importance of each varies with treatment and location. Some physical factors--such as soil type, slope, and precipitation--may not be as important for treatments that provide immediate ground cover, as these will consistently reduce rainsplash and soil sealing, and thereby immediately reduce surface runoff and erosion. The ability of other treatments to reduce post-fire runoff and erosion--such as scarification, seeding, and PAM--may vary more with local physical factors such as soil type, geography, and climate. Other treatments, such as contour felling and check dams, are designed to capture runoff and erosion after they have occurred, but these types of treatments are often only effective for a few storms before their sediment holding capacity is exceeded (Wagenbrenner et al., 2006).

Land managers need to consider the treatment goals (short or long term, hillslope or watershed scale), resources of concern, and the available funds in order to determine the most appropriate treatment after high-severity fires. This study clearly shows that the dry mulch and aerial hydromulch applied after the Hayman Fire were highly effective erosion control treatments. The results for other treatments in this study were highly variable and appeared to be more dependent on environmental factors such as precipitation, ground cover, soil properties, and slope. The extensive data set from this study can help land managers make better decisions regarding post-fire erosion control treatments, as well as guide further research into why different treatments will vary in this effectiveness.

4.1. FUTURE RESEARCH

The results from this and other studies confirm that mulch is a highly effective method for erosion control. One possible disadvantage is that mulch can potentially introduce weeds and chemical residues. Future research should investigate other treatments that could immediately provide cover without introducing weeds and chemical residues (Robichaud et al., 2000; Foltz and Dooley, 2003). One possibility is to mulch the partially burned trees after wildfires. Hydro-axing is a common and inexpensive technique for mulching trees, and this could reduce transportation costs by using on-site source materials. The dominant considerations in the use of this alternative treatment would be the amount of source material that would be available and the magnitude of the potential increase in percent ground cover. Plot-scale studies have shown that a 70% cover of wood chips can reduce sediment yields by over 98% on a gravelly sandy soil on 30% slopes (Foltz and Dooley, 2003).

The results from this and other studies do not support further research into seeding and scarification treatments on steep, coarse-textured hillslopes where moisture limits plant germination and growth. Future research should evaluate the effectiveness of scarification with seeding in low slope environments with more mesic conditions where seeds are more likely to germinate. Additional studies are needed to determine whether scarification can benefit seed germination or increase infiltration without increasing sediment yields.

The use of PAM as a post-fire rehabilitation treatment needs a great deal of further research to determine whether PAM can be applied in a way that makes it an effective and dependable method of erosion control. In burned areas with a high percent of ash cover, future studies should investigate whether adding environmentally-safe surfactants or increasing the water content in the PAM slurry improves surface penetration. Improved penetration would allow the PAM to bind with both the electrolytes from the ash and the underlying mineral soil. Another concern is whether there are sufficient cations to aggregate the anionic polymers and soil particles in coarse-textured soils when there is little or no ash on the soil surface. Future studies should first quantify the relationship between ash cover and cation availability in different burned soils, and then evaluate what concentrations of soluble cations are necessary for PAM to have adequate binding agents. In cation-deficient soils, PAM should be evaluated with and without additives (e.g., gypsum) in order to evaluate whether additives can increase the aggregation of PAM and soil particles. Rainfall simulation experiments may be the best way to determine whether PAM can be effective under varying conditions and with different formulations. Specific experiments should be conducted to evaluate the ability of PAM to reduce post-fire erosion on different soil textures, as the availability of soluble cations change, at different application rates (e.g., 80 kg ha^{-1}), and with different soil additives, particularly in the second and third years after burning.

The low sample number in this study (four for the treatments in Chapter 2; three for the PAM treatments in Chapter 3) resulted in a high probabability of Type II error (β), which is the failure to detect a difference even when there is a difference. Future studies can use the present results to conduct an a-priori power analysis to estimate the desired number of replicates for each treatment. This will help ensure that significant differences in percent live vegetation, sediment yields, and rill densities can be detected when they actually exist.

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Appendix I. Sediment yields by storm and treatment for each swale in Upper Saloon Gulch in the Hayman Fire and the Schoonover Fire, 2002-2004.

Upper Saloon Gulch 2002 sediment yields. Highlighted cells are pre-treatment sediment yields; na indicates not available.

Treatment	Treatment type	Swale	Storm Date				Total sediment yield (Mg ha^{-1})	
			7/21	8/28	9/12 & 9/18	10/1	Pre treatment	Post treatment
Scarification with seeding	control	4E	na	0.00	0.02	0.00	na	0.02
Scarification with seeding	control	24	8.65	0.19	0.08	0.00	8.65	0.26
Scarification with seeding	control	26	3.31	0.08	0.43	0.01	3.31	0.52
Scarification with seeding	control	33	na	0.00	0.01	0.00	na	0.01
Scarification with seeding	treated	4W	na	0.00	0.03	0.00	na	0.03
Scarification with seeding	treated	25	9.09	0.34	0.11	0.14	9.09	0.59
Scarification with seeding	treated	27	3.99	0.02	0.51	0.00	3.99	0.54
Scarification with seeding	treated	32	na	0.00	0.01	0.00	na	0.01
Dry mulch	control	18	10.58	0.00	0.54	0.05	10.58	0.59
Dry mulch	control	21	7.69	0.30	0.18	0.01	7.69	0.50
Dry mulch	control	22	7.37	0.00	0.01	0.01	7.37	0.02
Dry mulch	control	29	5.44	0.07	1.40	0.04	5.44	1.51
Dry mulch	treated	19	10.83	0.00	0.01	0.00	10.83	0.01
Dry mulch	treated	20	7.60	0.00	0.01	0.00	7.60	0.01
Dry mulch	treated	23	9.89	0.00	0.01	0.00	9.89	0.01
Dry mulch	treated	28	8.23	0.00	0.01	0.00	8.23	0.01
Ground hydromulch	control	12	4.06	0.72	0.04	0.02	4.82	0.02
Ground hydromulch	control	15	3.53	0.02	0.06	0.00	3.61	0.00
Ground hydromulch	control	17	5.50	1.11	0.12	0.06	6.72	0.06
Ground hydromulch	control	30	na	na	0.07	0.00	0.07	0.00
Ground hydromulch	treated	13	5.91	0.36	0.03	0.00	6.30	0.00
Ground hydromulch	treated	14	7.52	0.65	0.07	0.00	8.25	0.00
Ground hydromulch	treated	16	5.77	0.20	0.07	0.00	6.05	0.00
Ground hydromulch	treated	31	na	na	0.14	0.00	0.14	0.00
Aerial hydromulch	control	4E	na	na	0.02	0.00	na	0.02
Aerial hydromulch	control	26	3.31	0.08	0.43	0.01	3.39	0.44
Aerial hydromulch	control	29	5.44	0.07	1.40	0.04	5.51	1.44
Aerial hydromulch	control	30	na	na	0.07	0.00	na	0.07
Aerial hydromulch	treated	34	na	na	0.00	0.00	na	0.00
Aerial hydromulch	treated	35	na	na	0.00	0.00	na	0.00
Aerial hydromulch	treated	36	na	na	0.00	0.00	na	0.00
Aerial hydromulch	treated	37	na	na	0.00	0.00	na	0.00

Upper Saloon Gulch 2003 sediment yields.

Treatment	Treatment type	Swale	Storm date					Total sediment yield (Mg ha^{-1})
			6/10	6/19	7/19	8/11	8/30	
Scarification with seeding	control	4E	0.03	0.01	0.01	6.93	4.27	11.24
Scarification with seeding	control	24	2.54	0.00	1.05	5.96	3.66	13.20
Scarification with seeding	control	26	0.02	0.63	0.07	0.72	2.32	3.76
Scarification with seeding	control	33	0.72	0.00	0.18	7.95	1.84	10.69
Scarification with seeding	treated	4W	0.03	0.03	0.04	9.18	3.51	12.79
Scarification with seeding	treated	25	2.30	0.00	0.09	3.83	2.22	8.44
Scarification with seeding	treated	27	0.01	1.13	0.08	0.65	3.48	5.34
Scarification with seeding	treated	32	0.30	0.00	0.02	6.98	1.58	8.88
Dry mulch	control	18	2.66	0.00	0.95	4.46	2.59	10.66
Dry mulch	control	21	1.67	0.00	0.77	4.65	3.97	11.07
Dry mulch	control	22	0.91	0.00	0.46	15.22	3.24	19.83
Dry mulch	control	29	0.11	2.54	0.22	3.47	4.86	11.20
Dry mulch	treated	19	0.02	0.00	0.00	0.11	0.16	0.30
Dry mulch	treated	20	0.01	0.00	0.00	0.00	0.00	0.01
Dry mulch	treated	23	0.02	0.00	0.00	0.57	0.22	0.82
Dry mulch	treated	28	0.01	0.00	0.00	0.09	1.73	1.83
Ground hydromulch	control	12	0.41	0.00	0.73	10.07	1.48	12.69
Ground hydromulch	control	15	0.05	0.00	0.01	3.88	1.23	5.17
Ground hydromulch	control	17	2.96	0.00	0.60	13.27	3.53	20.37
Ground hydromulch	control	30	0.01	0.34	0.09	0.43	1.69	2.56
Ground hydromulch	treated	13	0.01	0.00	0.00	5.06	1.29	6.36
Ground hydromulch	treated	14	0.00	0.00	0.01	9.12	2.06	11.19
Ground hydromulch	treated	16	0.25	0.00	0.03	10.18	2.28	12.74
Ground hydromulch	treated	31	0.00	0.62	0.06	0.42	2.48	3.59
Aerial hydromulch	control	4E	0.03	0.01	0.01	6.93	4.27	11.24
Aerial hydromulch	control	26	0.02	0.63	0.07	0.72	2.32	3.76
Aerial hydromulch	control	29	0.11	2.54	0.22	3.47	4.86	11.20
Aerial hydromulch	control	30	0.01	0.34	0.09	0.43	1.69	2.56
Aerial hydromulch	treated	34	0.00	0.00	0.00	0.00	0.45	0.45
Aerial hydromulch	treated	35	0.00	0.24	0.00	0.00	0.00	0.24
Aerial hydromulch	treated	36	0.00	0.02	0.00	0.00	0.10	0.12
Aerial hydromulch	treated	37	0.00	0.19	0.01	0.01	0.53	0.76

Upper Saloon Gulch 2004 sediment yields.

Treatment	Treatment type	Swale	Storm date					
			6/16	6/25 & 6/27	7/14	7/23	8/21	Total sediment yield (Mg ha^{-1})
Scarification with seeding	control	4E	1.96	0.05	0.53	0.00	0.00	2.54
Scarification with seeding	control	24	5.96	3.29	2.92	0.52	0.79	13.47
Scarification with seeding	control	26	2.13	0.17	0.33	0.00	1.24	3.87
Scarification with seeding	control	33	3.96	1.96	1.86	0.00	0.69	8.48
Scarification with seeding	treated	4W	1.87	0.06	0.57	0.00	0.00	2.50
Scarification with seeding	treated	25	4.91	2.78	2.74	0.37	0.51	11.31
Scarification with seeding	treated	27	2.21	0.15	0.39	0.00	1.01	3.76
Scarification with seeding	treated	32	2.11	1.64	1.89	0.00	0.64	6.27
Dry mulch	control	18	5.45	4.87	4.83	0.69	1.33	17.17
Dry mulch	control	21	1.64	2.79	2.67	0.37	0.70	8.16
Dry mulch	control	22	8.55	1.75	3.57	0.00	0.62	14.49
Dry mulch	control	29	2.71	0.30	0.54	0.00	0.76	4.32
Dry mulch	treated	19	1.45	1.11	1.91	0.25	1.04	5.76
Dry mulch	treated	20	0.05	0.03	0.03	0.01	0.00	0.12
Dry mulch	treated	23	0.54	0.20	0.25	0.00	0.00	0.99
Dry mulch	treated	28	1.73	0.05	0.41	0.00	0.91	3.10
Ground hydromulch	control	12	2.45	0.73	1.22	0.40	0.73	5.52
Ground hydromulch	control	15	0.54	0.01	0.08	0.06	0.00	0.69
Ground hydromulch	control	17	5.52	5.55	5.62	1.99	1.74	20.43
Ground hydromulch	control	30	3.43	1.57	0.32	0.00	2.14	7.45
Ground hydromulch	treated	13	2.30	0.34	0.98	0.30	0.15	4.07
Ground hydromulch	treated	14	0.85	0.24	1.60	0.38	1.28	4.34
Ground hydromulch	treated	16	2.62	1.20	3.12	1.42	1.42	9.79
Ground hydromulch	treated	31	4.39	1.54	0.20	0.00	3.16	9.29
Aerial hydromulch	control	4E	1.96	0.05	0.53	0.00	0.00	2.54
Aerial hydromulch	control	26	2.13	0.17	0.33	0.00	1.24	3.87
Aerial hydromulch	control	29	2.71	0.30	0.54	0.00	0.76	4.32
Aerial hydromulch	control	30	3.43	1.57	0.32	0.00	2.14	7.45
Aerial hydromulch	treated	34	0.99	0.13	0.00	0.00	0.33	1.45
Aerial hydromulch	treated	35	0.00	0.00	0.00	0.00	0.00	0.00
Aerial hydromulch	treated	36	0.00	0.01	0.00	0.00	0.00	0.01
Aerial hydromulch	treated	37	3.75	0.52	0.14	0.00	3.35	7.75

Schoonover 2002 sediment yields.

Treatment	Treatment type	Swale	Storm date		Total sediment yield (Mg ha^{-1})
			8/21	10/2	
Single	control	1b	2.37	0.02	2.39
Single	control	4b	4.13	0.32	4.45
Single	control	6a	3.79	0.07	3.86
Single	treated	1a	0.00	0.00	0.00
Single	treated	4a	0.00	0.02	0.02
Single	treated	6b	1.51	0.10	1.61
Repeated	control	2b	2.88	0.08	2.97
Repeated	control	3a	1.68	0.03	1.71
Repeated	control	5a	3.56	0.10	3.66
Repeated	treated	2a	2.38	0.05	2.43
Repeated	treated	3b	1.41	0.06	1.47
Repeated	treated	5b	2.81	0.11	2.92

Schoonover 2003 sediment yields.

Treatment	Treatment type	Swale	Storm date							Total sediment yield (Mg ha^{-1})
			6/5 & 6/6	6/24	8/1	8/3	8/11	8/18	8/30	
Single	control	1b	0.00	3.71	4.07	0.10	1.35	3.20	2.44	14.88
Single	control	4b	0.00	2.74	8.66	0.22	2.99	0.18	2.61	17.39
Single	control	6a	0.01	4.28	7.24	0.09	0.51	2.73	3.03	17.89
Single	treated	1a	0.00	0.00	0.57	0.00	0.27	0.10	0.74	1.68
Single	treated	4a	0.00	1.26	7.18	0.15	3.74	0.67	1.31	14.31
Single	treated	6b	0.01	1.79	7.60	0.14	0.19	2.75	2.23	14.71
Repeated	control	2b	0.01	2.84	17.27	0.31	3.96	2.31	2.12	28.83
Repeated	control	3a	0.00	1.08	5.61	0.05	1.36	0.54	0.73	9.38
Repeated	control	5a	0.01	2.03	10.46	0.33	2.83	1.64	2.21	19.51
Repeated	treated	2a	0.01	4.03	12.96	0.31	4.25	3.73	2.72	28.01
Repeated	treated	3b	0.01	1.58	4.68	0.16	6.15	1.20	1.30	15.08
Repeated	treated	5b	0.00	2.61	4.95	0.16	0.36	0.24	2.67	10.99

Schoonover 2004 sediment yields.

Treatment	Treatment type	Swale	Storm date		Total sediment yield (Mg ha^{-1})
			8/21	10/2	
Single	control	1b	2.37	0.02	2.39
Single	control	4b	4.13	0.32	4.45
Single	control	6a	3.79	0.07	3.86
Single	treated	1a	0.00	0.00	0.00
Single	treated	4a	0.00	0.02	0.02
Single	treated	6b	1.51	0.10	1.61
Repeated	control	2b	2.88	0.08	2.97
Repeated	control	3a	1.68	0.03	1.71
Repeated	control	5a	3.56	0.10	3.66
Repeated	treated	2a	2.38	0.05	2.43
Repeated	treated	3b	1.41	0.06	1.47
Repeated	treated	5b	2.81	0.11	2.92

Appendix II. Percent cover by treatment, summer 2002 to fall 2004.

Upper Saloon Gulch surface cover, summer 2002, na is not applicable.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter, logs, and rocks	% Mulch (post-trt)
Scarification with seeding	control	4E	26	72	0	2	na
Scarification with seeding	control	24	50	50	0	0	na
Scarification with seeding	control	26	42	50	1	7	na
Scarification with seeding	control	33	32	67	0	1	na
Scarification with seeding	treated	4W	29	70	0	1	na
Scarification with seeding	treated	25	35	62	0	3	na
Scarification with seeding	treated	27	41	55	0	4	na
Scarification with seeding	treated	32	29	65	0	6	na
Dry mulch	control	18	50	42	0	8	na
Dry mulch	control	21	55	30	2	13	na
Dry mulch	control	22	44	53	0	3	na
Dry mulch	control	29	40	59	0	1	na
Dry mulch	treated	19	46	48	0	6	95
Dry mulch	treated	20	53	36	0	11	95
Dry mulch	treated	23	37	58	0	5	95
Dry mulch	treated	28	43	55	0	2	96
Ground hydromulch	control	12	54	40	2	4	na
Ground hydromulch	control	15	51	37	4	8	na
Ground hydromulch	control	17	51	40	0	9	na
Ground hydromulch	control	30	43	54	0	3	na
Ground hydromulch	treated	13	51	41	1	7	95
Ground hydromulch	treated	14	56	37	0	7	95
Ground hydromulch	treated	16	69	25	0	6	95
Ground hydromulch	treated	31	41	56	0	3	60
Aerial hydromulch	control	4E	na	na	na	na	na
Aerial hydromulch	control	26	na	na	na	na	na
Aerial hydromulch	control	29	na	na	na	na	na
Aerial hydromulch	control	30	na	na	na	na	na
Aerial hydromulch	treated	34	na	na	na	na	90
Aerial hydromulch	treated	35	na	na	na	na	92
Aerial hydromulch	treated	36	na	na	na	na	90
Aerial hydromulch	treated	37	na	na	na	na	91

Upper Saloon Gulch surface cover, spring 2003.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees	% Mulch
Scarification with seeding	control	4E	41	51	1	6	1	0	0	0
Scarification with seeding	control	24	71	19	1	9	0	0	0	0
Scarification with seeding	control	26	29	46	0	13	3	9	0	0
Scarification with seeding	control	33	48	44	0	5	2	1	0	0
Scarification with seeding	treated	4W	36	55	1	5	3	0	0	0
Scarification with seeding	treated	25	56	25	0	19	0	0	0	0
Scarification with seeding	treated	27	34	60	0	3	2	2	0	0
Scarification with seeding	treated	32	45	34	0	20	1	0	0	0
Dry mulch	control	18	50	20	0	28	2	0	0	0
Dry mulch	control	21	68	5	4	20	1	1	1	0
Dry mulch	control	22	40	35	4	19	1	1	0	0
Dry mulch	control	29	45	53	0	0	0	2	0	0
Dry mulch	treated	19	35	5	3	7	1	0	0	49
Dry mulch	treated	20	38	3	2	1	0	4	0	52
Dry mulch	treated	23	17	18	3	1	3	0	1	56
Dry mulch	treated	28	22	29	2	0	3	1	1	42
Ground hydromulch	control	12	45	42	1	11	0	0	1	0
Ground hydromulch	control	15	42	9	9	38	1	1	0	0
Ground hydromulch	control	17	51	26	8	13	2	1	0	0
Ground hydromulch	control	30	41	51	1	0	3	4	0	0
Ground hydromulch	treated	13	4	1	2	6	0	1	0	87
Ground hydromulch	treated	14	2	7	4	15	1	0	0	71
Ground hydromulch	treated	16	16	4	2	4	1	2	0	70
Ground hydromulch	treated	31	18	38	3	1	0	2	0	39
Aerial hydromulch	control	4E	41	51	1	6	1	0	0	0
Aerial hydromulch	control	26	29	46	0	13	3	9	0	0
Aerial hydromulch	control	29	45	53	0	0	0	2	0	0
Aerial hydromulch	control	30	41	51	1	0	3	4	0	0
Aerial hydromulch	treated	34	20	7	5	5	1	0	0	62
Aerial hydromulch	treated	35	8	1	4	19	1	0	0	67
Aerial hydromulch	treated	36	23	1	6	4	2	0	0	65
Aerial hydromulch	treated	37	45	8	4	2	3	0	0	38

Upper Saloon Gulch surface cover, fall 2003.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees	% Mulch
Scarification with seeding	control	4E	67	5	20	4	2	0	2	0
Scarification with seeding	control	24	69	1	23	6	1	0	0	0
Scarification with seeding	control	26	55	0	9	22	1	13	1	0
Scarification with seeding	control	33	83	8	4	4	0	0	1	0
Scarification with seeding	treated	4W	70	5	23	1	0	1	0	0
Scarification with seeding	treated	25	69	0	5	25	0	0	1	0
Scarification with seeding	treated	27	70	7	12	8	2	0	1	0
Scarification with seeding	treated	32	56	4	24	12	2	0	2	0
Dry mulch	control	18	67	1	13	18	0	0	2	0
Dry mulch	control	21	60	0	19	20	0	0	0	0
Dry mulch	control	22	69	7	13	10	1	0	1	0
Dry mulch	control	29	70	7	10	8	0	3	2	1
Dry mulch	treated	19	47	0	17	8	0	0	0	28
Dry mulch	treated	20	31	0	19	17	0	1	1	31
Dry mulch	treated	23	43	2	5	8	3	0	1	39
Dry mulch	treated	28	56	4	5	4	1	4	1	25
Ground hydromulch	control	12	73	0	25	1	0	0	1	0
Ground hydromulch	control	15	39	1	30	29	0	0	1	0
Ground hydromulch	control	17	71	0	16	8	3	3	0	0
Ground hydromulch	control	30	66	3	22	3	1	5	1	0
Ground hydromulch	treated	13	24	0	20	9	1	0	0	46
Ground hydromulch	treated	14	48	0	11	23	1	3	1	14
Ground hydromulch	treated	16	57	2	8	3	0	10	0	20
Ground hydromulch	treated	31	44	9	6	5	3	1	1	32
Aerial hydromulch	control	4E	67	5	20	4	2	0	2	0
Aerial hydromulch	control	26	55	0	9	22	1	13	1	0
Aerial hydromulch	control	29	70	7	10	8	0	3	2	1
Aerial hydromulch	control	30	66	3	22	3	1	5	1	0
Aerial hydromulch	treated	34	43	0	24	11	1	0	0	21
Aerial hydromulch	treated	35	13	1	29	21	1	0	0	34
Aerial hydromulch	treated	36	35	0	27	7	2	0	0	29
Aerial hydromulch	treated	37	83	0	10	1	1	0	1	5

Upper Saloon Gulch surface cover, spring 2004.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees	% Mulch
Scarification with seeding	control	4E	58	2	19	20	1	0	1	0
Scarification with seeding	control	24	73	2	19	7	0	0	0	0
Scarification with seeding	control	26	63	2	14	11	0	9	1	0
Scarification with seeding	control	33	68	4	11	13	3	0	1	0
Scarification with seeding	treated	4W	48	3	30	17	1	0	1	1
Scarification with seeding	treated	25	54	2	10	32	2	0	0	0
Scarification with seeding	treated	27	70	2	16	9	1	1	2	0
Scarification with seeding	treated	32	47	3	16	32	1	1	0	0
Dry mulch	control	18	56	0	17	26	1	0	0	0
Dry mulch	control	21	65	0	14	20	0	0	0	0
Dry mulch	control	22	46	6	18	28	1	0	0	0
Dry mulch	control	29	64	3	21	9	3	0	0	0
Dry mulch	treated	19	38	0	18	25	1	3	0	15
Dry mulch	treated	20	43	0	17	13	0	1	0	25
Dry mulch	treated	23	36	3	18	13	3	0	0	28
Dry mulch	treated	28	51	2	14	4	2	2	0	25
Ground hydromulch	control	12	48	1	37	13	1	0	0	0
Ground hydromulch	control	15	40	0	25	34	1	0	1	0
Ground hydromulch	control	17	73	0	13	9	2	2	1	0
Ground hydromulch	control	30	75	0	12	10	1	1	1	0
Ground hydromulch	treated	13	31	2	22	9	0	1	1	35
Ground hydromulch	treated	14	54	0	31	10	0	0	1	4
Ground hydromulch	treated	16	64	0	21	4	1	2	1	8
Ground hydromulch	treated	31	47	4	15	7	1	0	1	25
Aerial hydromulch	control	4E	58	2	19	20	1	0	1	0
Aerial hydromulch	control	26	63	2	14	11	0	9	1	0
Aerial hydromulch	control	29	64	3	21	9	3	0	0	0
Aerial hydromulch	control	30	75	0	12	10	1	1	1	0
Aerial hydromulch	treated	34	32	0	29	17	2	0	0	21
Aerial hydromulch	treated	35	38	0	24	18	3	0	1	16
Aerial hydromulch	treated	36	34	0	39	12	1	0	1	14
Aerial hydromulch	treated	37	72	0	18	2	1	2	1	5
Aerial dry mulch	treated	1	47	2	18	8	0	6	0	20
Aerial dry mulch	treated	2	35	0	19	4	0	1	1	40
Aerial dry mulch	treated	3	58	1	19	4	0	0	0	18
Aerial dry mulch	treated	4	54	1	14	5	0	0	1	26

Upper Saloon Gulch surface cover, fall 2004.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees	% Mulch
Scarification with seeding	control	4E	40	0	54	3	3	0	0	0
Scarification with seeding	control	24	42	0	54	2	0	0	2	0
Scarification with seeding	control	26	33	0	26	11	1	28	1	0
Scarification with seeding	control	33	51	0	37	7	2	0	3	0
Scarification with seeding	treated	4W	27	0	59	10	3	0	0	0
Scarification with seeding	treated	25	40	0	49	11	0	0	0	0
Scarification with seeding	treated	27	47	0	48	4	0	1	0	0
Scarification with seeding	treated	32	14	0	50	34	2	0	0	0
Dry mulch	control	18	47	0	35	17	1	0	0	0
Dry mulch	control	21	38	0	45	15	1	0	1	0
Dry mulch	control	22	44	0	52	3	0	0	1	0
Dry mulch	control	29	35	0	63	1	0	1	0	0
Dry mulch	treated	19	25	0	53	11	1	0	0	10
Dry mulch	treated	20	25	0	50	11	2	1	1	11
Dry mulch	treated	23	29	0	52	13	2	0	0	5
Dry mulch	treated	28	35	0	59	2	0	1	1	3
Ground hydromulch	control	12	38	0	59	3	0	0	0	0
Ground hydromulch	control	15	29	0	51	20	0	0	1	0
Ground hydromulch	control	17	51	0	40	3	5	1	0	0
Ground hydromulch	control	30	57	0	38	2	1	1	1	0
Ground hydromulch	treated	13	31	0	52	8	0	2	1	7
Ground hydromulch	treated	14	45	0	42	7	1	2	2	1
Ground hydromulch	treated	16	55	0	38	4	1	3	0	0
Ground hydromulch	treated	31	55	1	35	2	0	0	0	8
Aerial hydromulch	control	4E	40	0	54	3	3	0	0	0
Aerial hydromulch	control	26	33	0	26	11	1	28	1	0
Aerial hydromulch	control	29	35	0	63	1	0	1	0	0
Aerial hydromulch	control	30	57	0	38	2	1	1	1	0
Aerial hydromulch	treated	34	23	2	58	10	0	0	1	6
Aerial hydromulch	treated	35	38	0	44	15	1	0	0	3
Aerial hydromulch	treated	36	37	0	50	10	1	0	0	2
Aerial hydromulch	treated	37	59	0	39	1	1	1	0	0
Aerial dry mulch	treated	1	36	1	28	3	0	0	0	31
Aerial dry mulch	treated	2	43	1	34	4	0	0	1	17
Aerial dry mulch	treated	3	46	0	22	7	0	0	0	25
Aerial dry mulch	treated	4	44	1	32	4	1	0	1	17

Schoonover surface cover, summer 2002.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees
Single	control	1b	55	41	0	1	2	0	2
Single	control	4b	59	34	2	2	2	2	0
Single	control	6a	29	63	0	3	2	2	2
Single	treated	1a	59	35	1	1	2	1	2
Single	treated	4a	62	33	1	1	1	2	2
Single	treated	6b	31	62	1	3	1	1	1
Repeated	control	2b	37	57	1	0	2	2	2
Repeated	control	3a	44	48	1	2	2	2	2
Repeated	control	5a	44	52	1	1	1	1	0
Repeated	treated	2a	30	66	0	3	1	0	1
Repeated	treated	3b	42	55	0	1	0	1	1
Repeated	treated	5b	38	57	0	2	2	1	0

Schoonover surface cover, spring 2003.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees
Single	control	1b	58	37	0	3	2	0	1
Single	control	4b	87	9	1	2	0	1	0
Single	control	6a	73	18	2	1	3	1	3
Single	treated	1a	68	23	0	1	4	0	4
Single	treated	4a	84	12	3	0	1	0	0
Single	treated	6b	80	14	0	3	3	0	1
Repeated	control	2b	57	38	1	0	1	1	2
Repeated	control	3a	66	24	2	2	2	3	2
Repeated	control	5a	70	21	1	6	1	0	2
Repeated	treated	2a	58	39	0	2	2	0	0
Repeated	treated	3b	73	24	0	1	0	0	1
Repeated	treated	5b	71	21	1	5	1	1	1

Schoonover surface cover, fall 2003.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees
Single	control	1b	83	7	5	3	2	0	1
Single	control	4b	80	5	7	7	2	0	0
Single	control	6a	79	12	3	2	3	0	1
Single	treated	1a	78	4	11	4	0	0	2
Single	treated	4a	84	6	7	2	1	0	0
Single	treated	6b	83	5	7	2	0	0	3
Repeated	control	2b	76	11	8	0	2	0	4
Repeated	control	3a	79	7	4	8	0	2	1
Repeated	control	5a	74	13	6	8	0	0	0
Repeated	treated	2a	79	12	1	5	0	0	3
Repeated	treated	3b	70	10	9	8	2	0	0
Repeated	treated	5b	75	10	8	6	0	0	1

Schoonover surface cover, spring 2004.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees
Single	control	1b	78	4	7	6	2	0	2
Single	control	4b	75	0	17	6	2	1	0
Single	control	6a	83	5	8	2	1	0	2
Single	treated	1a	67	6	23	2	2	0	1
Single	treated	4a	82	0	13	2	2	1	0
Single	treated	6b	83	3	8	4	2	0	1
Repeated	control	2b	76	6	14	2	2	0	0
Repeated	control	3a	76	5	15	4	1	0	0
Repeated	control	5a	74	3	8	12	4	0	0
Repeated	treated	2a	75	5	6	10	1	0	3
Repeated	treated	3b	76	4	10	6	2	0	2
Repeated	treated	5b	79	1	8	9	1	2	0

Schoonover surface cover, fall 2004.

Treatment	Treatment type	Swale	% Bare	% Ash	% Live vegetation	% Litter	% Logs	% Rocks	% Trees
Single	control	1b	74	0	20	1	3	1	1
Single	control	4b	70	0	26	1	3	0	0
Single	control	6a	76	0	22	0	0	0	2
Single	treated	1a	56	0	32	7	5	0	1
Single	treated	4a	63	0	36	0	2	0	0
Single	treated	6b	66	0	27	3	1	1	2
Repeated	control	2b	74	0	23	0	1	0	2
Repeated	control	3a	57	0	21	16	5	0	1
Repeated	control	5a	65	0	16	15	3	0	1
Repeated	treated	2a	73	0	17	6	4	0	0
Repeated	treated	3b	67	0	22	8	1	0	2
Repeated	treated	5b	64	1	26	4	3	1	1

Appendix III. Storm depth, maximum 30-minute intensity, and erosivity for each storm from 1 May to 31 October by rain gauge and year.

USG South 2002: RF output for all storms between 1 May and 31 October 2002.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
12-May	11:35	5.08	8.13	6.01
16-May	13:55	1.52	2.54	0.43
16-May	16:50	2.03	3.05	0.72
20-May	12:45	1.02	2.03	0.25
23-May	19:30	2.03	2.54	0.64
23-May	22:15	2.03	1.02	0.23
24-May	09:05	3.56	2.54	1.03
24-May	12:00	9.91	8.64	12.73
04-Jun	00:30	2.29	2.54	0.64
04-Jun	08:15	2.03	2.54	0.66
19-Jun	22:55	1.52	2.54	0.43
20-Jun	16:35	4.32	6.10	4.38
20-Jun	20:00	3.30	4.06	1.68
21-Jun	17:40	2.79	4.57	1.70
21-Jun	21:00	1.78	2.54	0.50
05-Jul	22:35	3.30	3.56	1.67
06-Jul	05:55	16.26	17.27	49.09
21-Jul	08:20	11.18	21.84	61.97
22-Jul	02:55	1.52	3.05	0.59
03-Aug	10:05	4.06	3.56	1.69
04-Aug	12:20	1.02	1.52	0.17
05-Aug	02:05	3.81	7.62	5.03
05-Aug	07:20	1.27	2.03	0.31
06-Aug	04:40	1.27	2.03	0.31
07-Aug	04:50	1.27	2.54	0.39
21-Aug	04:20	3.81	7.11	4.79
27-Aug	08:25	2.79	5.08	2.16
28-Aug	04:10	4.83	8.13	6.09
08-Sep	11:45	2.03	4.06	1.11
09-Sep	09:05	5.84	5.08	3.61
10-Sep	04:10	5.08	1.52	0.86
10-Sep	12:25	3.05	5.08	2.03
12-Sep	16:35	5.08	10.16	10.38
13-Sep	12:10	1.02	2.03	0.25
18-Sep	14:05	1.52	2.03	0.34
18-Sep	18:55	4.83	3.05	1.63
26-Sep	04:10	1.52	2.54	0.43
26-Sep	10:40	2.54	4.06	1.30
01-Oct	20:50	16.00	5.59	10.91
26-Oct	20:50	2.54	2.03	0.57
27-Oct	10:15	3.56	4.06	1.76
30-Oct	09:55	1.02	2.03	0.23
31-Oct	11:05	2.03	4.06	1.02

USG South 2003: RF output for all storms between 1 May and 31 October 2003.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
20-May	07:40	2.29	4.57	1.54
31-May	11:50	1.78	2.03	0.47
31-May	16:45	5.33	6.60	5.47
04-Jun	21:05	5.59	7.62	5.93
05-Jun	06:40	8.38	2.54	2.36
06-Jun	21:35	5.84	4.06	2.84
07-Jun	01:40	2.54	2.54	0.71
10-Jun	17:00	6.86	13.72	20.68
12-Jun	14:55	1.78	3.05	0.71
18-Jun	19:40	1.02	1.52	0.17
19-Jun	13:55	8.13	13.21	19.55
25-Jun	20:35	1.78	3.56	0.87
25-Jun	23:55	4.32	5.08	2.81
18-Jul	22:20	2.29	4.06	1.23
19-Jul	18:40	8.64	11.18	17.09
01-Aug	17:25	2.03	4.06	1.33
02-Aug	20:30	1.02	2.03	0.25
03-Aug	17:10	4.83	8.64	8.05
06-Aug	12:20	1.02	2.03	0.30
11-Aug	18:15	12.70	18.80	47.20
18-Aug	17:55	1.52	2.54	0.52
22-Aug	17:05	7.62	12.19	17.66
30-Aug	00:40	16.00	10.16	23.38
30-Aug	16:10	2.79	5.08	2.16
30-Aug	20:45	13.97	22.35	64.96
07-Sep	10:20	1.02	2.03	0.30
07-Sep	14:00	1.52	1.52	0.26

USG South 2004: RF output for all storms between 1 May and 31 October 2004.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
01-May	09:45	2.79	3.56	1.15
12-May	13:00	4.32	4.57	2.48
12-May	17:15	2.79	3.05	1.05
13-May	17:45	6.60	3.05	2.27
14-May	11:25	8.64	6.10	6.52
25-May	15:10	1.02	1.02	0.13
03-Jun	16:20	1.27	2.54	0.36
14-Jun	19:20	1.78	3.56	0.83
14-Jun	20:30	1.78	3.56	0.98
16-Jun	18:15	12.19	22.86	64.82
17-Jun	01:40	1.78	2.54	0.59
18-Jun	03:35	1.52	1.02	0.20
18-Jun	12:30	6.35	12.70	19.07
19-Jun	14:40	2.79	4.57	1.80
19-Jun	20:05	1.78	3.56	1.07
21-Jun	04:50	1.78	3.56	0.98
21-Jun	10:15	7.37	13.21	19.24
21-Jun	12:25	8.89	5.08	5.91
24-Jun	22:10	2.29	4.57	1.44
25-Jun	16:20	7.87	14.22	21.14
25-Jun	21:55	1.52	2.03	0.34
26-Jun	13:30	2.29	4.06	1.13
26-Jun	19:25	3.30	3.56	1.47
27-Jun	16:40	1.27	2.54	0.39
27-Jun	19:00	6.60	6.60	5.64
28-Jun	17:25	5.33	3.56	2.24
29-Jun	16:35	1.27	2.54	0.45
30-Jun	14:25	3.30	2.03	0.77
09-Jul	20:05	5.08	10.16	12.35
09-Jul	22:30	1.52	1.52	0.26
10-Jul	18:30	3.30	6.60	3.14
14-Jul	17:45	13.21	23.37	67.73
15-Jul	15:55	1.02	1.52	0.19
16-Jul	12:40	1.27	1.52	0.21
16-Jul	16:25	9.65	5.08	5.76
16-Jul	21:15	1.52	2.54	0.46
19-Jul	19:00	5.08	4.06	2.50
20-Jul	19:20	1.52	3.05	0.63
22-Jul	18:10	1.02	2.03	0.25
22-Jul	22:40	2.79	5.08	2.04

USG South 2004: RF output for all storms between 1 May and 31 October 2004. (continued)

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
23-Jul	13:10	2.29	4.57	1.69
23-Jul	15:50	12.45	9.65	18.09
24-Jul	18:10	1.02	1.52	0.21
05-Aug	02:40	3.05	3.56	1.29
05-Aug	17:00	3.05	3.05	1.22
17-Aug	17:10	1.02	1.52	0.17
19-Aug	02:30	8.64	4.57	4.61
19-Aug	15:20	1.52	2.54	0.43
20-Aug	17:40	1.27	2.54	0.36
21-Aug	14:00	12.70	24.89	75.59
27-Aug	13:45	5.84	11.68	13.13
31-Aug	20:00	3.30	6.60	3.63
04-Sep	14:35	3.05	6.10	3.38
09-Sep	01:00	12.70	25.40	89.86
21-Sep	08:10	4.06	2.03	0.91
21-Sep	17:25	1.52	1.52	0.26
22-Sep	09:25	2.79	3.56	1.19
25-Sep	19:00	6.86	11.68	13.56
27-Sep	21:45	21.59	15.75	54.37
28-Sep	15:20	1.02	1.52	0.17
30-Sep	12:50	2.03	4.06	1.11
01-Oct	06:05	3.56	2.03	0.80
04-Oct	15:20	3.05	6.10	2.98
04-Oct	17:05	5.33	9.14	7.90
06-Oct	11:15	4.57	2.54	1.29
06-Oct	16:10	4.57	4.06	2.63
10-Oct	11:25	1.27	2.54	0.62
13-Oct	00:05	5.33	3.56	2.19
13-Oct	11:55	8.13	8.13	9.57
24-Oct	06:55	9.14	18.29	42.33
24-Oct	17:40	1.02	2.03	0.36
26-Oct	13:05	1.02	2.03	0.36

USG North 2002: RF output for all storms between 1 August and 31 October 2002.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
05-Aug	08:10	1.20	2.40	0.42
06-Aug	05:15	1.20	2.00	0.27
07-Aug	04:50	1.00	2.00	0.23
07-Aug	07:10	1.00	2.00	0.23
21-Aug	04:15	2.20	4.40	1.45
27-Aug	08:25	4.20	7.60	5.82
28-Aug	04:10	5.00	10.00	10.28
08-Sep	11:45	1.60	3.20	0.67
09-Sep	09:00	3.80	4.40	2.00
09-Sep	11:45	1.80	2.40	0.45
10-Sep	03:45	1.80	1.20	0.23
10-Sep	06:25	1.60	1.20	0.20
10-Sep	12:10	2.20	3.20	0.82
12-Sep	16:40	3.60	6.80	3.95
13-Sep	12:50	1.00	1.20	0.14
18-Sep	14:15	1.40	2.00	0.29
18-Sep	18:45	6.40	3.60	2.60
26-Sep	04:10	1.00	2.00	0.21
26-Sep	10:40	2.60	4.80	1.68
01-Oct	20:50	13.60	5.60	9.19
26-Oct	21:50	4.00	3.20	1.42
26-Oct	23:05	1.20	0.40	0.05
27-Oct	07:05	1.20	0.80	0.10
30-Oct	09:35	3.00	1.60	0.50
31-Oct	09:35	2.00	1.20	0.25

USG North 2003: RF output for all storms between 1 May and 31 October 2003.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
20-May	06:25	1.80	1.20	0.23
31-May	12:35	1.00	0.80	0.08
31-May	16:50	3.80	4.00	1.91
04-Jun	21:10	4.40	6.40	3.70
05-Jun	04:15	2.60	1.60	0.44
05-Jun	06:45	4.60	2.40	1.18
05-Jun	14:25	1.20	2.40	0.38
06-Jun	21:35	8.00	4.40	3.98
10-Jun	17:10	7.60	13.20	18.87
12-Jun	14:30	2.60	3.20	1.04
18-Jun	18:50	1.40	0.80	0.12
19-Jun	14:00	3.20	4.40	1.76
25-Jun	20:25	1.40	2.80	0.50
25-Jun	23:45	2.60	2.80	0.83
18-Jul	22:15	2.80	4.40	1.56
19-Jul	18:40	10.00	16.40	31.46
01-Aug	17:30	3.80	7.20	4.48
03-Aug	17:10	3.80	7.20	4.44
11-Aug	18:05	20.20	33.60	159.81
17-Aug	13:40	1.60	2.80	0.56
18-Aug	18:00	2.20	4.00	1.30
22-Aug	14:30	2.00	2.80	0.70
22-Aug	17:05	9.40	16.40	32.66
30-Aug	00:55	14.80	10.80	22.82
30-Aug	16:15	2.40	4.80	1.58
30-Aug	20:45	14.60	23.60	73.24
02-Sep	20:25	4.20	8.40	6.22

USG North 2004: RF output for all storms between 1 May and 31 October 2004.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
01-May	08:55	1.20	1.20	0.15
12-May	12:55	4.60	4.40	2.42
12-May	17:50	6.20	4.00	2.83
13-May	10:45	2.00	1.20	0.25
13-May	14:45	5.00	2.40	1.35
14-Jun	19:05	1.20	1.60	0.21
14-Jun	20:30	1.20	2.40	0.38
16-Jun	18:10	10.60	18.80	44.28
17-Jun	01:40	1.40	2.00	0.38
18-Jun	05:25	1.20	0.80	0.10
18-Jun	12:35	4.40	8.80	7.90
18-Jun	15:30	1.60	2.40	0.53
19-Jun	14:35	2.80	3.60	1.40
19-Jun	20:20	2.00	3.60	1.04
21-Jun	04:45	1.60	3.20	0.79
21-Jun	10:15	3.40	6.00	3.21
21-Jun	12:20	7.20	5.20	4.85
24-Jun	22:15	1.40	2.80	0.43
25-Jun	16:05	3.60	5.60	3.25
26-Jun	13:35	1.60	3.20	0.64
26-Jun	19:35	3.20	3.60	1.49
27-Jun	16:30	16.40	32.80	141.42
27-Jun	19:10	5.60	4.80	3.09
28-Jun	17:20	5.60	4.40	3.21
30-Jun	14:25	3.80	2.00	0.80
09-Jul	20:10	3.40	6.80	5.08
09-Jul	23:00	1.00	1.20	0.13
10-Jul	18:20	2.60	4.40	1.44
14-Jul	17:35	23.20	42.40	252.15
15-Jul	15:10	10.20	18.80	43.40
16-Jul	12:45	1.40	1.60	0.23
16-Jul	16:40	11.20	4.80	6.41
19-Jul	19:05	3.60	3.20	1.26
20-Jul	19:20	1.40	2.40	0.35
22-Jul	18:05	1.20	2.00	0.27
22-Jul	22:40	2.20	4.00	1.06
23-Jul	16:20	11.60	12.40	24.10
24-Jul	18:00	1.20	1.20	0.15
02-Aug	16:00	1.60	3.20	0.79
05-Aug	02:35	2.20	2.40	0.59
05-Aug	17:00	2.80	4.80	1.82

USG North 2004: RF output for all storms between 1 May and 31 October 2004. (continued)

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
17-Aug	17:15	1.20	1.60	0.20
19-Aug	02:25	6.20	3.20	2.16
19-Aug	15:20	1.20	2.40	0.34
20-Aug	17:35	1.40	2.40	0.37
21-Aug	13:55	10.00	18.00	39.15
27-Aug	13:40	3.40	6.40	3.19
31-Aug	19:50	4.80	9.60	9.91
04-Sep	14:35	2.40	4.00	1.17
21-Sep	08:10	2.40	1.60	0.40
21-Sep	17:35	1.60	1.20	0.20
25-Sep	18:55	2.20	4.40	1.43
27-Sep	21:55	16.60	13.60	33.70
04-Oct	15:20	1.20	2.40	0.36
04-Oct	17:00	2.60	5.20	1.99
06-Oct	11:15	1.60	1.20	0.20
06-Oct	16:15	4.40	4.00	2.38
12-Oct	23:50	5.00	3.60	1.98
13-Oct	10:35	4.80	4.00	2.21

USG North 2 2003: RF output for all storms between 1 May and 31 October 2003.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
10-Jun	17:05	8.20	15.20	26.58
12-Jun	14:25	3.40	4.80	2.30
18-Jun	19:20	2.00	1.60	0.35
19-Jun	14:00	3.60	4.80	2.27
25-Jun	20:25	1.40	2.80	0.50
25-Jun	23:50	2.80	2.80	0.87
18-Jul	22:15	2.60	4.80	1.62
19-Jul	18:40	10.00	17.60	34.97
01-Aug	17:30	2.80	5.60	2.50
02-Aug	20:20	1.00	1.60	0.18
03-Aug	17:15	3.60	6.40	3.37
11-Aug	18:05	23.60	40.40	234.57
13-Aug	07:05	11.00	22.00	56.24
17-Aug	13:40	1.60	2.80	0.56
18-Aug	18:00	2.20	4.00	1.30
22-Aug	14:30	2.00	2.80	0.70
22-Aug	17:05	9.40	16.40	32.66
30-Aug	00:55	14.80	10.80	22.82
30-Aug	16:15	2.40	4.80	1.58
30-Aug	20:45	14.60	23.60	73.24
02-Sep	20:25	4.20	8.40	6.22

USG North 2 2004: RF output for all storms between 1 May and 31 October 2004.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
01-May	09:35	2.00	2.00	0.42
12-May	12:55	4.40	4.00	2.05
12-May	17:50	5.60	3.20	2.04
13-May	11:10	2.40	1.60	0.40
13-May	14:40	5.60	2.40	1.43
08-Jun	18:45	1.20	2.40	0.36
14-Jun	19:20	1.20	2.00	0.27
14-Jun	20:30	1.40	2.80	0.52
16-Jun	18:10	9.20	16.00	32.02
17-Jun	01:40	1.40	2.00	0.38
18-Jun	12:35	4.20	8.40	7.07
18-Jun	15:30	1.20	1.60	0.24
19-Jun	14:40	2.40	3.20	1.01
19-Jun	20:10	1.60	2.80	0.62
21-Jun	04:45	1.20	2.40	0.47
21-Jun	10:10	9.00	5.60	6.81
24-Jun	22:15	1.20	2.40	0.32
25-Jun	16:15	3.00	4.40	2.04
26-Jun	13:35	1.40	2.80	0.48
26-Jun	19:35	2.60	3.60	1.37
27-Jun	16:30	15.00	20.40	58.79
28-Jun	17:25	4.60	4.00	2.31
30-Jun	14:20	3.20	1.60	0.54
09-Jul	20:10	2.60	5.20	2.61
09-Jul	23:05	1.00	1.60	0.17
10-Jul	18:25	2.00	3.20	0.77
14-Jul	17:35	19.60	36.40	179.10
15-Jul	15:10	8.60	15.60	30.05
16-Jul	16:35	6.00	3.60	2.38
16-Jul	20:25	2.40	2.40	0.66
19-Jul	19:10	3.80	2.80	1.16
20-Jul	19:20	1.20	2.00	0.27
22-Jul	22:40	1.80	3.20	0.68
23-Jul	16:20	10.40	12.40	22.05
02-Aug	16:00	1.80	3.60	1.02

USG North 2 2004: RF output for all storms between 1 May and 31 October 2004. (continued)

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
05-Aug	02:40	2.00	2.80	0.61
05-Aug	17:00	3.80	6.80	4.03
19-Aug	02:25	4.80	2.40	1.21
21-Aug	14:00	9.60	17.20	35.85
27-Aug	13:40	3.60	6.80	3.73
31-Aug	19:50	4.00	8.00	6.59
04-Sep	14:35	2.20	3.60	0.98
21-Sep	08:10	1.40	1.20	0.20
21-Sep	17:30	1.40	1.20	0.18
25-Sep	18:55	1.80	3.60	0.93
27-Sep	21:55	13.20	10.00	18.17
04-Oct	17:00	1.60	3.20	0.76
06-Oct	11:55	1.60	1.20	0.20
06-Oct	16:05	3.40	4.80	2.28
12-Oct	23:50	4.20	2.80	1.30
13-Oct	10:40	3.20	2.80	0.96

Schoonover 2002: RF output for all storms between 1 May and 31 October 2002.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
12-May	01:25	1.27	1.02	0.14
12-May	09:20	1.52	1.52	0.26
16-May	13:50	1.02	2.03	0.25
16-May	17:00	3.05	5.08	2.24
23-May	19:40	3.30	3.05	1.11
24-May	00:20	1.02	1.02	0.11
24-May	06:30	1.52	3.05	0.55
24-May	10:40	3.81	3.56	1.64
03-Jun	23:50	1.27	1.02	0.14
20-Jun	16:40	3.05	6.10	3.58
20-Jun	20:05	1.78	2.03	0.43
06-Jul	05:45	9.14	11.18	15.65
21-Jul	19:55	5.08	9.65	9.11
29-Jul	06:55	1.02	2.03	0.25
03-Aug	07:30	5.08	5.08	3.39
06-Aug	05:00	2.29	3.56	1.14
21-Aug	04:20	8.38	16.26	28.68
27-Aug	08:35	1.78	2.54	0.59
09-Sep	06:50	1.27	2.03	0.29
09-Sep	08:45	2.54	2.54	0.71
09-Sep	11:45	2.03	3.05	0.72
10-Sep	02:25	2.79	1.02	0.31
10-Sep	06:40	2.54	1.52	0.43
10-Sep	12:20	1.52	2.03	0.34
12-Sep	04:10	2.54	4.06	1.34
18-Sep	07:30	5.59	3.05	1.93
26-Sep	04:20	1.27	2.03	0.29
26-Sep	10:50	1.27	2.03	0.31
01-Oct	19:55	12.95	4.57	7.09
24-Oct	10:45	3.56	3.56	1.54
26-Oct	21:35	5.08	5.08	3.12
27-Oct	02:20	2.03	1.02	0.23
27-Oct	08:10	1.27	1.02	0.14

Schoonover 2003: RF output for all storms between 1 May and 31 October 2003.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
19-May	22:00	1.02	1.02	0.11
29-May	19:00	2.03	4.06	1.16
31-May	16:55	4.57	4.06	2.68
01-Jun	10:20	1.02	1.52	0.19
04-Jun	21:10	3.05	4.06	1.48
05-Jun	09:10	5.84	2.54	1.64
06-Jun	21:40	3.56	3.05	1.48
06-Jun	23:55	4.57	3.56	1.89
09-Jun	14:15	1.02	2.03	0.36
09-Jun	17:45	1.78	3.56	0.98
10-Jun	17:25	2.03	4.06	1.07
19-Jun	13:35	9.91	18.29	40.14
20-Jun	15:05	1.02	2.03	0.30
26-Jun	00:35	2.29	1.52	0.39
30-Jun	10:05	1.02	2.03	0.30
19-Jul	06:55	7.37	11.18	13.48
23-Jul	03:55	2.79	5.59	2.15
29-Jul	04:25	1.02	1.52	0.17
01-Aug	17:40	6.86	13.72	23.33
03-Aug	17:05	4.32	7.62	6.26
07-Aug	14:10	2.29	3.56	0.99
11-Aug	17:55	6.35	11.68	16.16
18-Aug	13:05	5.08	9.14	9.97
18-Aug	17:55	1.02	1.52	0.17
29-Aug	17:35	3.05	5.59	2.67
30-Aug	01:35	10.16	10.67	15.99
30-Aug	16:10	1.78	3.56	1.07
30-Aug	20:50	9.65	13.21	22.92
02-Sep	19:40	1.02	2.03	0.25
07-Sep	13:25	1.78	1.52	0.30
25-Oct	10:30	1.02	1.52	0.17

Schoonover 2004: RF output for all storms between 1 May and 31 October 2004.

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
01-May	09:55	2.03	4.06	1.07
12-May	12:55	3.81	3.56	1.59
12-May	18:05	8.64	6.60	7.35
13-May	10:40	2.03	3.56	0.89
13-May	14:35	3.05	6.10	3.40
13-May	17:00	1.27	1.52	0.21
14-May	10:45	1.02	2.03	0.36
04-Jun	13:40	1.02	2.03	0.25
08-Jun	18:35	2.03	3.56	1.08
16-Jun	18:15	6.86	8.64	10.38
18-Jun	12:50	2.79	5.59	2.58
18-Jun	14:20	2.29	4.57	1.88
19-Jun	14:35	3.05	4.06	1.79
19-Jun	20:45	2.03	4.06	1.33
21-Jun	10:35	8.13	11.68	16.97
21-Jun	13:20	8.64	6.10	6.80
24-Jun	21:50	1.52	1.52	0.26
25-Jun	16:30	17.78	33.02	144.60
25-Jun	22:15	2.03	3.56	0.89
26-Jun	19:50	1.78	2.54	0.59
27-Jun	19:00	7.37	8.13	8.21
28-Jun	18:30	2.54	3.05	0.86
30-Jun	14:45	3.81	1.52	0.64
09-Jul	22:55	2.79	5.08	1.98
14-Jul	17:55	2.29	3.56	1.07
16-Jul	16:15	7.62	5.08	4.55
16-Jul	21:15	2.54	3.56	1.05
19-Jul	12:55	1.27	2.54	0.39
19-Jul	19:05	3.05	4.06	1.48
20-Jul	19:45	1.78	3.05	0.64
21-Jul	18:50	2.54	5.08	2.02
22-Jul	18:20	1.27	2.54	0.39
22-Jul	22:40	3.05	6.10	2.70
23-Jul	16:05	11.94	14.22	30.95
24-Jul	18:10	1.02	1.02	0.11
02-Aug	15:55	1.02	2.03	0.28
05-Aug	16:40	11.68	16.76	37.64
18-Aug	21:15	1.27	2.03	0.29
19-Aug	02:20	5.08	2.03	1.17

Schoonover 2004: RF output for all storms between 1 May and 31 October 2004. (continued)

Date	Time	Storm depth (mm)	Maximum 30-min intensity (mm hr^{-1})	Erosivity (MJ mm ha^{-1} hr^{-1})
19-Aug	07:50	1.02	1.52	0.17
19-Aug	15:30	1.02	2.03	0.23
21-Aug	12:45	3.05	6.10	2.95
21-Aug	14:50	3.81	7.11	4.27
27-Aug	13:55	5.33	6.60	5.04
27-Aug	22:05	1.27	2.03	0.29
30-Aug	16:15	3.81	7.11	4.08
04-Sep	14:20	1.27	2.54	0.45
21-Sep	08:15	3.05	1.52	0.53
21-Sep	17:45	1.78	1.52	0.30
21-Sep	21:55	1.27	1.02	0.14
27-Sep	23:25	14.22	7.62	15.01
28-Sep	15:55	1.27	1.52	0.23
01-Oct	06:30	2.54	2.03	0.57
01-Oct	10:15	1.27	1.02	0.14
06-Oct	07:55	1.02	1.02	0.11
06-Oct	12:10	1.52	2.03	0.37
06-Oct	16:35	1.52	3.05	0.55
13-Oct	00:35	6.35	4.06	2.96
13-Oct	11:20	7.87	10.16	12.75

Appendix IV. Rill density data by swale and year.

Upper Saloon Gulch rill density measurements for 2003 and 2004.

Treatment	Treatment type	Swale	2003 Rill density (rills m^{-2})	2004 Rill density (rills m^{-2})
Scarification with seeding	control	4E	0.22	0.09
Scarification with seeding	control	24	0.37	0.22
Scarification with seeding	control	26	0.28	0.08
Scarification with seeding	control	33	0.14	0.12
Scarification with seeding	treated	4W	0.36	0.13
Scarification with seeding	treated	25	0.21	0.10
Scarification with seeding	treated	27	0.30	0.33
Scarification with seeding	treated	32	0.06	0.09
Dry mulch	control	18	0.15	0.14
Dry mulch	control	21	0.22	0.16
Dry mulch	control	22	0.19	0.08
Dry mulch	control	29	0.33	0.19
Dry mulch	treated	19	0.05	0.08
Dry mulch	treated	20	0.08	0.07
Dry mulch	treated	23	0.11	0.07
Dry mulch	treated	28	0.24	0.15
Ground hydromulch	control	12	0.21	0.11
Ground hydromulch	control	15	0.16	0.11
Ground hydromulch	control	17	0.23	0.27
Ground hydromulch	control	30	0.14	0.27
Ground hydromulch	treated	13	0.13	0.08
Ground hydromulch	treated	14	0.17	0.16
Ground hydromulch	treated	16	0.27	0.18
Ground hydromulch	treated	31	0.18	0.28
Aerial hydromulch	control	4E	0.22	0.09
Aerial hydromulch	control	26	0.28	0.08
Aerial hydromulch	control	29	0.33	0.19
Aerial hydromulch	control	30	0.14	0.27
Aerial hydromulch	treated	34	0.13	0.07
Aerial hydromulch	treated	35	0.07	0.07
Aerial hydromulch	treated	36	0.09	0.06
Aerial hydromulch	treated	37	0.26	0.25

Schoonover rill density measurements for 2003 and 2004.

Treatment	Treatment type	Swale	2003 Rill density (rills m^{-2})	2004 Rill density (rills m^{-2})
Single	control	1b	0.57	0.24
Single	control	4b	0.22	0.30
Single	control	6a	0.48	0.31
Single	treated	1a	0.06	0.10
Single	treated	4a	0.13	0.10
Single	treated	6b	0.46	0.33
Repeated	control	2b	0.38	0.13
Repeated	control	3a	0.22	0.10
Repeated	control	5a	0.43	0.26
Repeated	treated	2a	0.46	0.27
Repeated	treated	3b	0.13	0.16
Repeated	treated	5b	0.18	0.18

Appendix V. Mean critical surface tension by swale location, swale, depth, and year.

Upper Saloon Gulch critical surface tension data for 2002.

	Swale	Treatment type	Location	0 cm	3 cm	6 cm	9 cm	12 cm
Scarification with seeding	4	Control	upper	36.95	36.95	36.95	63.01	72.75
		Control	middle	36.95	36.95	46.06	69.5	72.75
		Control	lower	36.95	51.03	56.37	72.75	72.75
	24	Control	upper	41.5	51.03	63.01	72.75	72.75
		Control	middle	46.06	51.03	69.5	72.75	72.75
		Control	upper	41.5	41.5	51.03	63.01	72.75
	26	Control	upper	36.95	41.5	51.03	63.01	72.75
		Control	middle	41.5	46.06	63.01	72.75	72.75
		Control	lower	41.5	41.5	41.5	46.06	46.06
	33	Control	upper	51.03	51.03	63.01	72.75	72.75
		Control	middle	41.5	46.06	56.37	69.5	72.75
		Control	lower	36.95	46.06	51.03	72.75	69.5
	4	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	25	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	upper	NA	NA	NA	NA	NA
	27	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	32	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
Dry mulch	18	Control	upper	36.95	36.95	41.5	63.01	72.75
		Control	middle	36.95	41.5	46.06	46.06	51.03
		Control	lower	36.95	46.06	46.06	51.03	72.75
	21	Control	upper	36.95	51.03	69.5	72.75	72.75
		Control	middle	41.5	51.03	63.01	69.5	72.75
		Control	lower	46.06	56.37	51.03	56.37	69.5
	22	Control	upper	36.95	41.5	46.06	51.03	51.03
		Control	middle	41.5	56.37	69.5	72.75	72.75
		Control	lower	36.95	46.06	46.06	46.06	56.37
	29	Control	upper	41.5	51.03	56.37	51.03	69.5
		Control	middle	41.5	69.5	72.75	72.75	72.75
		Control	lower	41.5	56.37	69.5	56.37	69.5
	19	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	20	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	23	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	28	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA

Upper Saloon Gulch critical surface tension data for 2002 (continued).

	Swale	Treatment type	Location	0 cm	3 cm	6 cm	9 cm	12 cm
Ground hydromulch	12	Control	upper	36.95	46.06	46.06	46.06	69.5
		Control	middle	41.5	46.06	69.5	72.75	72.75
		Control	lower	33.24	41.5	46.06	46.06	63.01
	15	Control	upper	41.5	51.03	56.37	69.5	72.75
		Control	middle	36.95	46.06	41.5	46.06	72.75
		Control	lower	41.5	56.37	69.5	56.37	69.5
	17	Control	upper	46.06	51.03	63.01	72.75	72.75
		Control	middle	36.95	46.06	51.03	63.01	72.75
		Control	lower	41.5	46.06	51.03	72.75	63.01
	30	Control	upper	33.24	36.95	36.95	46.06	63.01
		Control	middle	36.95	51.03	63.01	72.75	72.75
		Control	upper	46.06	51.03	56.37	72.75	72.75
	13	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	14	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	16	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	31	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	upper	NA	NA	NA	NA	NA
Aerial hydromulch	4	Control	upper	36.95	36.95	36.95	63.01	72.75
		Control	middle	36.95	36.95	46.06	69.5	72.75
		Control	lower	36.95	51.03	56.37	72.75	72.75
	26	Control	upper	36.95	41.5	51.03	63.01	72.75
		Control	middle	41.5	46.06	63.01	72.75	72.75
		Control	lower	41.5	41.5	41.5	46.06	46.06
	29	Control	upper	41.5	51.03	56.37	51.03	69.5
		Control	middle	41.5	69.5	72.75	72.75	72.75
		Control	lower	41.5	56.37	69.5	56.37	69.5
	30	Control	upper	33.24	36.95	36.95	46.06	63.01
		Control	middle	36.95	51.03	63.01	72.75	72.75
		Control	upper	46.06	51.03	56.37	72.75	72.75
	34	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	35	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	36	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA
	37	treated	upper	NA	NA	NA	NA	NA
		treated	middle	NA	NA	NA	NA	NA
		treated	lower	NA	NA	NA	NA	NA

Upper Saloon Gulch critical surface tension data for 2003.

	Swale	Treatment type	Location	0 cm	3 cm	6 cm	9 cm	12 cm
Scarification with seeding	4	Control	upper	72.75	56.37	72.75	72.75	72.75
		Control	middle	63.01	56.37	63.01	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	24	Control	upper	41.5	41.5	51.03	72.75	72.75
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	upper	51.03	36.95	56.37	72.75	69.5
	26	Control	upper	56.37	41.5	46.06	72.75	72.75
		Control	middle	72.75	46.06	46.06	63.01	72.75
		Control	lower	51.03	72.75	72.75	72.75	72.75
	33	Control	upper	63.01	41.5	51.03	72.75	72.75
		Control	middle	72.75	33.24	36.95	69.5	69.5
		Control	lower	72.75	72.75	72.75	72.75	72.75
	4	treated	upper	72.75	36.95	41.5	56.37	63.01
		treated	middle	56.37	51.03	63.01	72.75	72.75
		treated	lower	72.75	72.75	72.75	72.75	72.75
	25	treated	upper	51.03	36.95	72.75	72.75	72.75
		treated	middle	72.75	51.03	51.03	56.37	63.01
		treated	upper	72.75	69.5	72.75	72.75	72.75
	27	treated	upper	36.95	63.01	69.5	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	72.75	33.24	72.75	72.75	72.75
	32	treated	upper	51.03	36.95	56.37	41.5	51.03
		treated	middle	72.75	36.95	51.03	72.75	72.75
		treated	lower	56.37	41.5	36.95	72.75	69.5
Dry mulch	18	Control	upper	56.37	63.01	72.75	72.75	72.75
		Control	middle	72.75	46.06	36.95	51.03	51.03
		Control	lower	51.03	72.75	72.75	72.75	72.75
	21	Control	upper	69.5	72.75	72.75	72.75	72.75
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	22	Control	upper	46.06	36.95	56.37	72.75	72.75
		Control	middle	36.95	56.37	72.75	63.01	56.37
		Control	lower	41.5	46.06	51.03	72.75	72.75
	29	Control	upper	46.06	33.24	41.5	72.75	56.37
		Control	middle	56.37	72.75	72.75	72.75	72.75
		Control	lower	72.75	51.03	72.75	72.75	72.75
	19	treated	upper	72.75	72.75	46.06	63.01	72.75
		treated	middle	51.03	46.06	72.75	72.75	72.75
		treated	lower	69.5	63.01	72.75	72.75	72.75
	20	treated	upper	51.03	46.06	51.03	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	72.75	51.03	69.5	51.03	69.5
	23	treated	upper	51.03	41.5	56.37	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	72.75	41.5	51.03	72.75	72.75
	28	treated	upper	72.75	72.75	69.5	72.75	72.75
		treated	middle	56.37	51.03	72.75	72.75	72.75
		treated	lower	72.75	69.5	69.5	72.75	72.75

Upper Saloon Gulch critical surface tension data for 2003 (continued).

	Swale	Treatment type	Location	0 cm	3 cm	6 cm	9 cm	12 cm
Ground hydromulch	12	Control	upper	51.03	63.01	72.75	72.75	72.75
		Control	middle	72.75	41.5	46.06	72.75	72.75
		Control	lower	46.06	41.5	72.75	72.75	72.75
	15	Control	upper	72.75	36.95	41.5	69.5	56.37
		Control	middle	69.5	46.06	51.03	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	17	Control	upper	46.06	72.75	72.75	72.75	72.75
		Control	middle	72.75	36.95	41.5	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	30	Control	upper	63.01	46.06	72.75	72.75	72.75
		Control	middle	41.5	72.75	72.75	72.75	72.75
		Control	upper	46.06	41.5	46.06	72.75	72.75
	13	treated	upper	56.37	46.06	36.95	56.37	63.01
		treated	middle	72.75	51.03	56.37	69.5	72.75
		treated	lower	72.75	41.5	72.75	72.75	72.75
	14	treated	upper	72.75	46.06	51.03	72.75	63.01
		treated	middle	36.95	36.95	72.75	63.01	72.75
		treated	lower	72.75	63.01	72.75	72.75	72.75
	16	treated	upper	72.75	63.01	63.01	72.75	72.75
		treated	middle	72.75	69.5	72.75	72.75	72.75
		treated	lower	72.75	63.01	72.75	72.75	72.75
	31	treated	upper	41.5	41.5	41.5	72.75	72.75
		treated	middle	46.06	72.75	72.75	72.75	72.75
		treated	upper	69.5	63.01	72.75	72.75	72.75
Aerial hydromulch	4	Control	upper	72.75	56.37	72.75	72.75	72.75
		Control	middle	63.01	56.37	63.01	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	26	Control	upper	56.37	41.5	46.06	72.75	72.75
		Control	middle	72.75	46.06	46.06	63.01	72.75
		Control	lower	51.03	72.75	72.75	72.75	72.75
	29	Control	upper	46.06	33.24	41.5	72.75	56.37
		Control	middle	56.37	72.75	72.75	72.75	72.75
		Control	lower	72.75	51.03	72.75	72.75	72.75
	30	Control	upper	63.01	46.06	72.75	72.75	72.75
		Control	middle	41.5	72.75	72.75	72.75	72.75
		Control	upper	46.06	41.5	46.06	72.75	72.75
	34	treated	upper	72.75	56.37	72.75	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	63.01	51.03	72.75	72.75	72.75
	35	treated	upper	56.37	56.37	69.5	72.75	72.75
		treated	middle	72.75	46.06	51.03	72.75	72.75
		treated	lower	63.01	63.01	72.75	72.75	72.75
	36	treated	upper	72.75	41.5	36.95	41.5	72.75
		treated	middle	46.06	36.95	72.75	72.75	72.75
		treated	lower	72.75	51.03	63.01	72.75	72.75
	37	treated	upper	72.75	46.06	51.03	72.75	72.75
		treated	middle	72.75	69.5	72.75	72.75	72.75
		treated	lower	46.06	41.5	46.06	69.5	72.75

Upper Saloon Gulch critical surface tension data for 2004.

	Swale	Treatment type	Location	0 cm	3 cm	6 cm	9 cm	12 cm
Scarification with seeding	4	Control	upper	72.75	56.37	51.03	56.37	69.5
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	24	Control	upper	72.75	51.03	72.75	72.75	72.75
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	upper	72.75	46.06	63.01	69.5	72.75
	26	Control	upper	72.75	63.01	69.5	69.5	72.75
		Control	middle	63.01	56.37	72.75	72.75	72.75
		Control	lower	72.75	51.03	51.03	72.75	72.75
	33	Control	upper	72.75	72.75	72.75	72.75	72.75
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	4	treated	upper	72.75	72.75	46.06	56.37	63.01
		treated	middle	72.75	72.75	63.01	72.75	72.75
		treated	lower	72.75	56.37	72.75	72.75	72.75
	25	treated	upper	69.5	46.06	72.75	72.75	72.75
		treated	middle	72.75	51.03	51.03	72.75	72.75
		treated	upper	72.75	69.5	72.75	72.75	72.75
	27	treated	upper	72.75	63.01	69.5	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	72.75	51.03	72.75	72.75	72.75
	32	treated	upper	72.75	51.03	56.37	46.06	63.01
		treated	middle	56.37	56.37	72.75	72.75	72.75
		treated	lower	69.5	51.03	56.37	72.75	72.75
Dry mulch	18	Control	upper	72.75	72.75	56.37	63.01	63.01
		Control	middle	51.03	46.06	51.03	72.75	72.75
		Control	lower	69.5	36.95	72.75	72.75	72.75
	21	Control	upper	72.75	41.5	63.01	72.75	72.75
		Control	middle	72.75	46.06	51.03	72.75	72.75
		Control	lower	72.75	63.01	72.75	72.75	72.75
	22	Control	upper	72.75	72.75	72.75	72.75	72.75
		Control	middle	72.75	63.01	69.5	69.5	72.75
		Control	lower	72.75	56.37	63.01	69.5	63.01
	29	Control	upper	72.75	46.06	51.03	72.75	72.75
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	lower	72.75	69.5	69.5	72.75	72.75
	19	treated	upper	72.75	72.75	46.06	63.01	72.75
		treated	middle	72.75	56.37	63.01	72.75	72.75
		treated	lower	69.5	72.75	72.75	72.75	72.75
	20	treated	upper	72.75	72.75	51.03	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	63.01	46.06	51.03	51.03	69.5
	23	treated	upper	72.75	69.5	72.75	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	72.75	51.03	72.75	72.75	72.75
	28	treated	upper	72.75	51.03	69.5	72.75	72.75
		treated	middle	72.75	46.06	51.03	72.75	72.75
		treated	lower	72.75	69.5	69.5	72.75	72.75

Upper Saloon Gulch critical surface tension data for 2004 (continued).

	Swale	Treatment type	Location	0 cm	3 cm	6 cm	9 cm	12 cm
Ground hydromulch	12	Control	upper	72.75	51.03	56.37	72.75	72.75
		Control	middle	72.75	46.06	51.03	72.75	72.75
		Control	lower	72.75	36.95	56.37	63.01	56.37
	15	Control	upper	72.75	41.5	72.75	72.75	72.75
		Control	middle	72.75	63.01	72.75	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	17	Control	upper	72.75	46.06	72.75	72.75	72.75
		Control	middle	72.75	46.06	51.03	56.37	72.75
		Control	lower	72.75	51.03	69.5	72.75	72.75
	30	Control	upper	72.75	46.06	51.03	72.75	72.75
		Control	middle	56.37	72.75	72.75	72.75	72.75
		Control	upper	69.5	46.06	72.75	72.75	72.75
	13	treated	upper	72.75	63.01	46.06	56.37	72.75
		treated	middle	72.75	46.06	56.37	69.5	72.75
		treated	lower	72.75	72.75	72.75	72.75	72.75
	14	treated	upper	72.75	56.37	51.03	72.75	63.01
		treated	middle	72.75	51.03	72.75	63.01	72.75
		treated	lower	72.75	63.01	72.75	72.75	72.75
	16	treated	upper	72.75	63.01	63.01	72.75	72.75
		treated	middle	72.75	69.5	72.75	72.75	72.75
		treated	lower	72.75	63.01	72.75	72.75	72.75
	31	treated	upper	72.75	51.03	46.06	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	upper	69.5	63.01	72.75	72.75	72.75
Aerial hydromulch	4	Control	upper	72.75	56.37	51.03	56.37	69.5
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	lower	72.75	72.75	72.75	72.75	72.75
	26	Control	upper	72.75	63.01	69.5	69.5	72.75
		Control	middle	63.01	56.37	72.75	72.75	72.75
		Control	lower	72.75	51.03	51.03	72.75	72.75
	29	Control	upper	72.75	46.06	51.03	72.75	72.75
		Control	middle	72.75	72.75	72.75	72.75	72.75
		Control	lower	72.75	69.5	69.5	72.75	72.75
	30	Control	upper	72.75	46.06	51.03	72.75	72.75
		Control	middle	56.37	72.75	72.75	72.75	72.75
		Control	upper	69.5	46.06	72.75	72.75	72.75
	34	treated	upper	72.75	56.37	72.75	72.75	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	72.75	51.03	72.75	72.75	72.75
	35	treated	upper	56.37	56.37	69.5	72.75	72.75
		treated	middle	72.75	46.06	51.03	72.75	72.75
		treated	lower	63.01	63.01	72.75	72.75	72.75
	36	treated	upper	72.75	51.03	36.95	41.5	72.75
		treated	middle	72.75	72.75	72.75	72.75	72.75
		treated	lower	72.75	51.03	63.01	72.75	72.75
	37	treated	upper	72.75	72.75	56.37	72.75	72.75
		treated	middle	72.75	69.5	72.75	72.75	72.75
		treated	lower	72.75	51.03	46.06	69.5	72.75