2006

Effectiveness of post-fire erosion control techniques in western Montana

Amy Heather Groen

The University of Montana

THE EFFECTIVENESS OF POST-FIRE EROSION CONTROL TECHNIQUES IN WESTERN MONTANA

by

Amy Heather Groen

M.S. Northern Arizona University, 2002

presented in partial fulfillment of the requirements

for the degree of

Master of Science

The University of Montana

May 2006

Approved by:

Committee Chair

Dean, Graduate School

6-1-06

Date

Groen, Amy H. M.S., May 2006 Forestry

The Effectiveness of Post-Fire Erosion Control Techniques in Western Montana

Committee Chair: Scott Woods

Soil erosion rates in undisturbed forested watersheds are typically very low. However, substantial increases in erosion have been observed following forest fires due to the loss of vegetation and duff, and altered soil physical properties. This study used two experiments to evaluate the effectiveness of three commonly used post-fire erosion control treatments: aerial seeding, straw wattles, and straw mulch. The first experiment compared erosion rates from hillslope scale plots treated with straw wattles or straw mulch to untreated control plots in an area burned by the 2001 Moose Fire in western Montana. Silt fences were used to measure the sediment yield from three replicates of each treatment and the untreated control. Total sediment yield nine months following installation ranged from 3.1 kg ha^{-1} to 7.9 kg ha^{-1}, with mulched plots producing the least and straw wattle sites the greatest amount of sediment. Thirteen months later, control, wattle, and mulched sites had produced 46%, 16%, and 19% less sediment per unit of rainfall received compared to previous measurements, indicating a trend toward baseline erosion rates. High yields from the wattle sites were likely due to soil disturbance during installation.

The second experiment used a rainfall simulator to compare erosion and runoff rates from 0.5 m^2 plots in an area burned by the 2002 Fox Creek Fire in western Montana. In the first year after the fire, rainfall was applied to ten replicates each of aerial seeded, mulched and control plots at an intensity of ~80 mm/hr for one hour. Mean values for total runoff from the seeded and mulched plots were 30 and 28 mm, respectively, compared to 44 mm for the controls. Peak runoff rates from the seeded and mulched plots had mean values of 41 mm/hr and 40 mm/hr, respectively, compared to 59 mm/hr for the controls. The mass of sediment lost from the seeded and mulched plots averaged 0.59 kg/m^2 and 0.10 kg/m^2, respectively, compared to 0.79 kg/m^2 for the controls. Limited additional work at the same plots in the following year indicated a decline in runoff and erosion from seeded and control plots but an increase in erosion from mulched plots. The results indicate that while both aerial seeding and straw mulch reduce surface runoff and erosion in the first year after a fire, straw mulch is greater than three times more effective in reducing surface erosion rates. Seeding becomes increasingly effective in the second year, when ground cover exceeds a critical threshold for reducing erosion.

Table of Contents

Abstract ii

List of Figures iv

Acknowledgements vi

Introduction 1

Study Areas 5
Moose Fire 6
Fox Creek Fire 7

Methods 10
Silt fences 10
Rainfall simulations 12
Statistical analysis of rainfall simulator data 17

Results 17
Fox Creek Fire – site variables 17
Rainfall simulations – plot soil characteristics 19
Rainfall simulations – runoff and sediment yield 22
Sediment from silt fences 30

Discussion 34
Hydrologic and geomorphic response to wildfire 34
Effectiveness of erosion control treatments 37

Conclusions and Recommendations 41

APPENDIX A – 2003 and 2004 Fox Creek Fire data table 43

APPENDIX B – Climate station summaries for Babb and Olney, Montana 45

References 46

Table of Figures

Figure 1: Straw wattles installed on a burned hillslope 4

Figure 2: Site map for Moose Fire silt fence locations. 3 fences were located at each of the study sites; Moose-1, Moose-2, and Moose-3 8

Figure 3: Site map for Fox Creek Fire rainfall simulation locations; north (BIAN), central (BIAC), and south (BIAS) 9

Figure 4: Rainfall distribution from hour-long calibration runs 14

Figure 5: Percent sand, silt, and clay in control, seed, and mulch plots at the Fox Creek Fire study area 18

Figure 6: Percent sand, silt, and clay in north, central, and south sites at Fox Creek fire study area 19

Figure 7: Example of soil profile taken after simulated rainfall event 20

Figure 8: Scatter plot depicting the percentage of dry soil blocks observed in post-simulation excavated soil profiles and associated total runoff for all 30 plots 21

Figure 9: Average percent saturated soil after 1-hour simulated rainfall: Fox Creek Fire, 2003 22

Figure 10: Average runoff rate vs. time for control, mulched, and seeded plots during the 2003 Fox Creek Fire rainfall simulations 23

Figure 11: Total runoff by treatment types for 1-hour simulated rainfall events conducted in 2003 24

Figure 12: Peak runoff by treatment types for 1-hour simulated rainfall events conducted in 2003 25

Figure 13: Average sediment yield vs. time for control, mulched, and seeded plots during the 2003 Fox Creek fire rainfall simulations 26

Figure 14: Total sediment by treatment types for 1-hour simulated rainfall events conducted in 2003 27

Figure 15: Total sediment yield per unit of total runoff over time on the Fox Creek Fire, 2003 28

Figure 16: Runoff rate vs. time for the 2004 rainfall simulations on the Fox Creek fire 29

Figure 17: Total mass of sediment eroded per unit of rainfall from the Fox Creek Fire silt fences, 2003 32

Figure 18: Total mass of sediment eroded per unit of rainfall from the Moose fire silt fences in 2003 and 2004 33

Acknowledgements

First and foremost I would like to thank my academic advisor Dr. Scott Woods for his support and commitment to this study. Without his ambition and guidance, I would not have been able to steer myself through all of the various hurdles that were encountered. Thanks also go out to my committee members, Tom DeLuca and Manny Gabet, for the support they provided both in the lab and in dealing with the many complexities inherent in scientific studies. My gratitude also goes out to Skip Rosquist who served as an invaluable mentor in a field he is all too familiar with.

Next, I would like to thank my field assistants for their countless exhausting hours in both the field and lab. Fellow graduate student Anna Birkas was a delight to work with and stuck with me through three field seasons despite knowing what she was getting into. Thanks to Matt Wotherspoon for his drive and to Martin Twer, Mark Flatt, and Robert Funk for providing assistance and optimism, even when the objective seemed unattainable.

This work was funded by The McIntire-Stennis Cooperative Grants Program and Montana Water Center. Backing from the Flathead National Forest and Bureau of Indian Affairs was instrumental in completion of the study and special thanks go out to all of those involved, including Betty Kuropat and Chet Gladstone.

Lastly, I would like to thank all of my friends and family for their love and support. Having my own personal cheering section from my extended family at "Casenor" was an asset I never counted on when I returned to school, and without the inexhaustible encouragement of my immediate family, none of this would have happened.

INTRODUCTION

Wildfires are natural disturbances that play a key role in shaping the forested ecosystems of the western U.S. However, there is considerable debate over the best approach to managing fire in these ecosystems. The Transfer Act of 1905 entrusted immense forest reserves to the U.S.D.A. Forest Service (USFS) for administration purposes (Pyne, 1995). Soon after, the firestorms of 1910 burned over 2 million hectares of national forest lands. The political furor these fires created has led to the development of fire protection systems intended to reduce the risk of future fires and consequent property damage and loss of life (Pyne, 1982). A key component of fire protection was the practice of fire suppression, which involved extinguishing new fires as soon as possible. As a result of continuing concerns over the risk to life and property, fire suppression has remained a cornerstone of USFS fire management policy for almost 100 years.

Due to the long-term effects of fire suppression on forest structure, fuel loads in the northwest have increased over time. This has led to a dramatic shift in the outcome of forest fire events, allowing landscapes that historically endured low and moderate severity fire effects to experience an increasing rate of fuel consumption and higher severity burns (Walstad, Radosevish, and Sandberg, 1990). With higher severity fires comes an increased risk of debris flows and downstream sedimentation, reduced soil productivity, and risks to life and property (Robichaud et al., 2001). The effects can also extend to riparian systems and isolated fish populations (Rieman et al., 2003).

The consumption of soil organic matter after a high-severity wildfire can lead to a reduction in both the aggregate stability and the number of large pore spaces (Benavides-

Solorio and MacDonald, 2001) while increasing soil water repellency (DeBano, 1981; Letey, 2001). When coupled with the loss of vegetation, the result is increased runoff and erosion and elevated peak flows that are capable of transporting increased quantities of bedload and suspended sediment (Robichaud et al., 2000). When burned areas retain less than 10% of their ground cover, erosion rates can increase several orders of magnitude (Robichaud et al., 2000; Benavides-Solorio and MacDonald, 2001) and take years to recover to background levels (Martin and Moody, 2001; Benavides-Solorio and MacDonald, 2001).

In 1974, in an effort to mitigate the risks posed from wildfire, the Forest Service created the Burned Area Emergency Rehabilitation (BAER) authority. Today, BAER team leaders are trained to perform immediate assessments after a wildfire and to recommend treatments aimed at reducing the risk to human life and property and minimizing adverse impacts to water quality and soil productivity. Some of the most commonly used treatments include broadcast seeding, mulching, straw wattles, contour trenching and contour-felled logs (Robichaud et al., 2000).

Broadcast seeding with grasses is one of the most commonly recommended post-burn erosion control treatments (Beyers, 2004; Robichaud et al., 2000). Seed can be distributed over large areas in a short amount of time and at a relatively low cost. Grasses provide protection from soil surface sealing by preventing raindrop splash (Wells et al., 1979) and allow for increased slope stability with their extensive root systems, but the benefits are often not recognized until the second year following a burn (Robichaud et al., 2000; pc Bruce Simms, 2004).

A report on the effectiveness of BAER treatment applications conducted by the USFS found that personnel who used seeding as a treatment were divided over the success of the approach; 52% of respondents reported either "excellent" or "good" results and the remaining 48% reported "fair" or "poor" results. Higher success rates of seeded grass were reported on slopes of less than 40% (Robichaud et al., 2000). Most studies did not include control plot erosion rates for comparison with seeded areas, making it difficult to evaluate the treatment's effectiveness (Wagenbrenner, 2003).

Mulch, although rated "excellent" in effectiveness by 66% of resource specialists, is labor intensive and costly to apply (Robichaud et al., 2000). In the BAER handbook (USFS, 1995), mulch is recognized as an immediate source of ground cover capable of retaining moisture and eliminating extreme soil surface temperatures. It offers protection for seeded and regenerating species necessary for long-term site stability.

Mulch is not often applied to steep slopes or areas where high winds are likely to arise due to the ease with which the material is moved offsite or redistributed into thick mats prone to inhibit seed germination (Robichaud et al., 2000). However, when applied under appropriate conditions mulch can be a highly effective erosion control treatment. Mulch applications on slopes of 19 to 69% reduced sediment loads by 95 and 99%, respectively, in the first and second year after the Colorado fires of 2000 (Wagenbrenner, 2003).

Straw wattles are applied to slopes to reduce effective slope length by providing a barrier to continued flow (Figure 1). Surface runoff is captured by the wattles placed horizontally across the length of the slope, backing up sediment laden flow and, in addition, providing conditions favorable to seed germination. Wattles can be used on slopes of greater than 40%, however, installation is difficult and labor intensive, resulting in high costs to land managers. Their effectiveness has been rated as "fair" to "excellent" depending on the conditions and care with which they were installed (Robichaud et al., 2000).

Figure 1: Straw wattles installed on a burned hillslope.

After the fires of 2000 and 2001, the Forest Service and Department of Interior had collectively allocated $310 million for BAER treatments intended to provide emergency rehabilitation and stabilization. A review by the General Accounting Office (GAO) found that despite monitoring requirements for treatment applications, it was indeterminable whether or not anticipated results were being achieved. A national interagency system was recommended in order to streamline the acquisition of data and consolidate burned area recovery monitoring information (USGAO, 2003).

Recent large wildfires and accompanying hydrologic events have driven researchers and agencies to stress the need for additional quantitative data regarding the effectiveness of post-burn erosion control treatments. Physical characteristics such as geology, vegetation and slope are frequently factors which influence erosion severity and should be considered along with treatment type and application procedures. The ability of a site to respond to various treatment types may be more accurately predicted with an improved quantitative database. The information could then be utilized by land managers faced with the task of post-burn treatment prescription.

The objective of this study was to determine the effectiveness of three post-burn treatment methods: aerial seeding, straw mulch and straw wattles, in reducing runoff and erosion in areas of moderate to high burn severity. Due to the difficulties inherent in relying on natural rainfall events, a rainfall simulator was used in one set of studies to measure runoff and erosion from treatment and control plots. Simulated rainfall events have seldom been utilized to report conditions resulting from high severity fires (Johansen, Hakonson, and Breshears, 2001). Hillslope scale plots exposed to natural rainfall events were used as a baseline with which to compare data from simulated rainfall plots.

STUDY AREAS

Two wildfires in northwestern Montana, the Moose Fire and Fox Creek Fire, were used for this study. The Moose Fire, which burned 28,500 hectares in the summer and fall of 2001, was located in the North Fork Flathead river basin with land ownership divided among Glacier National Park, Flathead National Forest, Coal Creek State Forest and private lands (Figure 2). The Fox Creek Fire burned 2,600 hectares in the summer of 2002 (pc Andrea Gillam, 2004) and was located in the St. Mary river basin east of Glacier National Park on the Blackfoot Indian Reservation, which is under the administration of the Bureau of Indian Affairs (BIA) (Figure 3).

Moose Fire

The Moose Fire was started by lightning and burned in a mosaic pattern across the landscape. The areas utilized for the study were primarily ponderosa pine (*Pinus ponderosa* var. *scopulorum*) and Rocky Mountain Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) overstory and had an average elevation of 1,500 meters. The mean slope was 47% with a range of 40 to 60%. Soils in the study area are well-drained glacial tills with a high percentage of angular rock (USDA, 1999). Fires within the immediate study area were classified by the Flathead National Forest as high severity, resulting in complete consumption of overstory and understory vegetation and protective duff layers. Ground cover was not assessed, but natural re-growth was evident during treatment application 1 year postfire and at the time of silt fence collections, 2 and 3 years postfire.

The research plots for the Moose Fire were located above and below Forest Road 1693 within the Deadhorse Creek drainage, immediately south of the boundary between the Flathead National Forest and the Coal Creek State Forest (Figure 2). The first study area, Moose-1, was located above the road while the second and third study areas, Moose-2 and Moose-3 were both located below. No hillslope treatments were recommended for these areas under the initial BAER team report. Precipitation data for the Moose Fire study sites was obtained from the Olney, Montana climate station, 24 kilometers southwest of the research site (Appendix B). Mean annual precipitation at Olney is 57 cm, and mean monthly temperatures range from -6°C in January to 17°C in July.

Fox Creek Fire

The Fox Creek Fire, also ignited by lightning, started near St. Mary's Lake and burned up to the crest of St. Mary's ridge at an elevation of 1800 meters. Rocky Mountain Douglas-fir is the dominant tree species in this area and soils are predominantly clayey-skeletal, mixed Typic Cryoboralfs of the Oberg Series (USDA, 1980). They were formed from glacial till and contain 30 to 60% rock fragments. The area was subject to moderate and high burn severities that resulted in complete removal of the overstory canopy and nearly complete duff consumption.

Research sites on the Fox Creek Fire were located in three areas where fire severity and access with a vehicle provided favorable conditions for rainfall simulations (Figure 3). The sites were located immediately below the crest of St.Mary's ridge on 21 to 29% slopes with a west-facing aspect. Precipitation data for the Fox Creek site was obtained from the Babb, Montana climate station, 12 kilometers to the northwest (Appendix B). Mean annual precipitation at Babb is 46 cm, and mean monthly temperatures range from -14.2 °C in January to 24.4 °C in August.

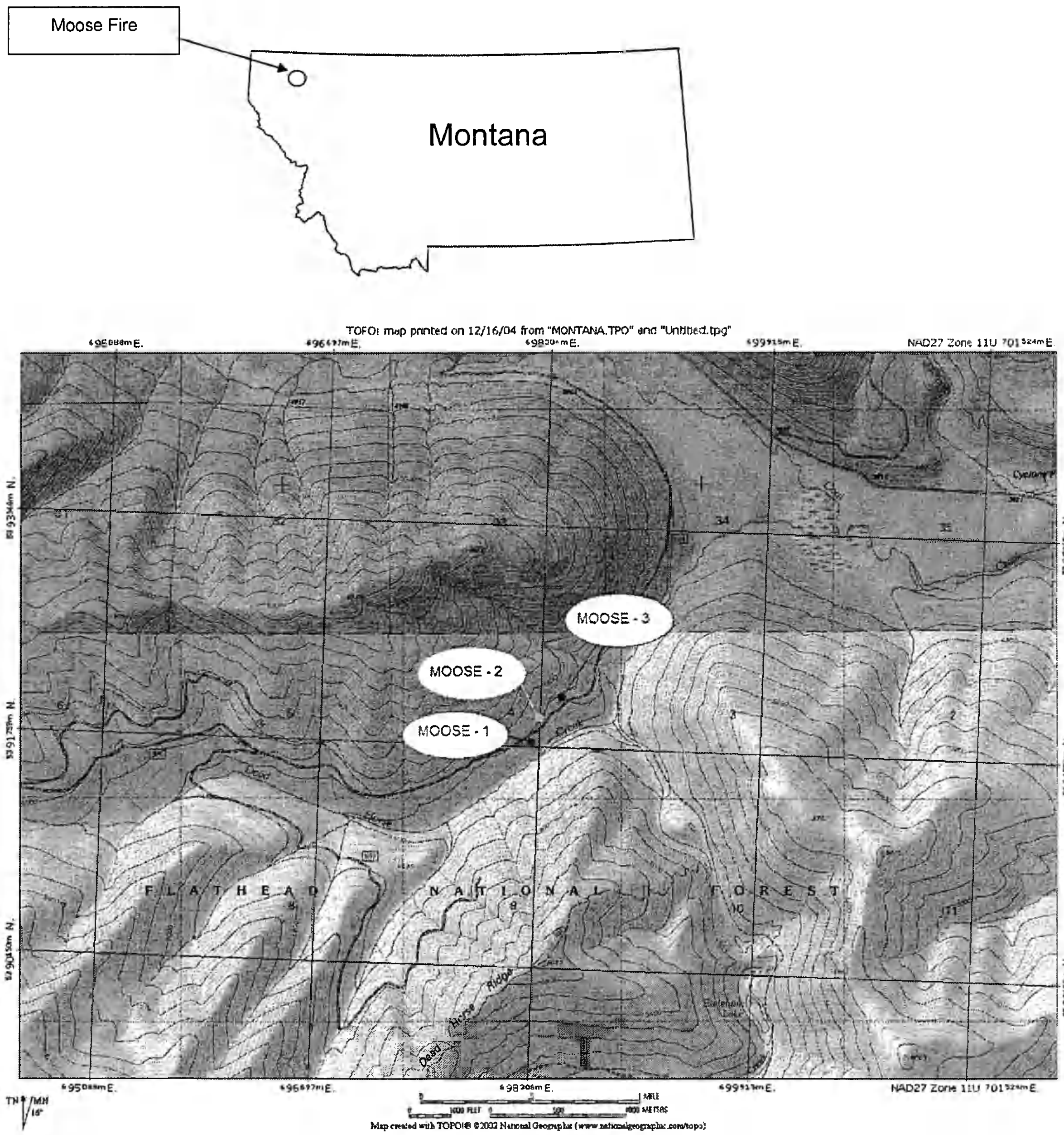

Figure 2: Site map for Moose Fire silt fence locations. 3 fences were located at each of the study sites; Moose-1, Moose-2 and Moose-3.

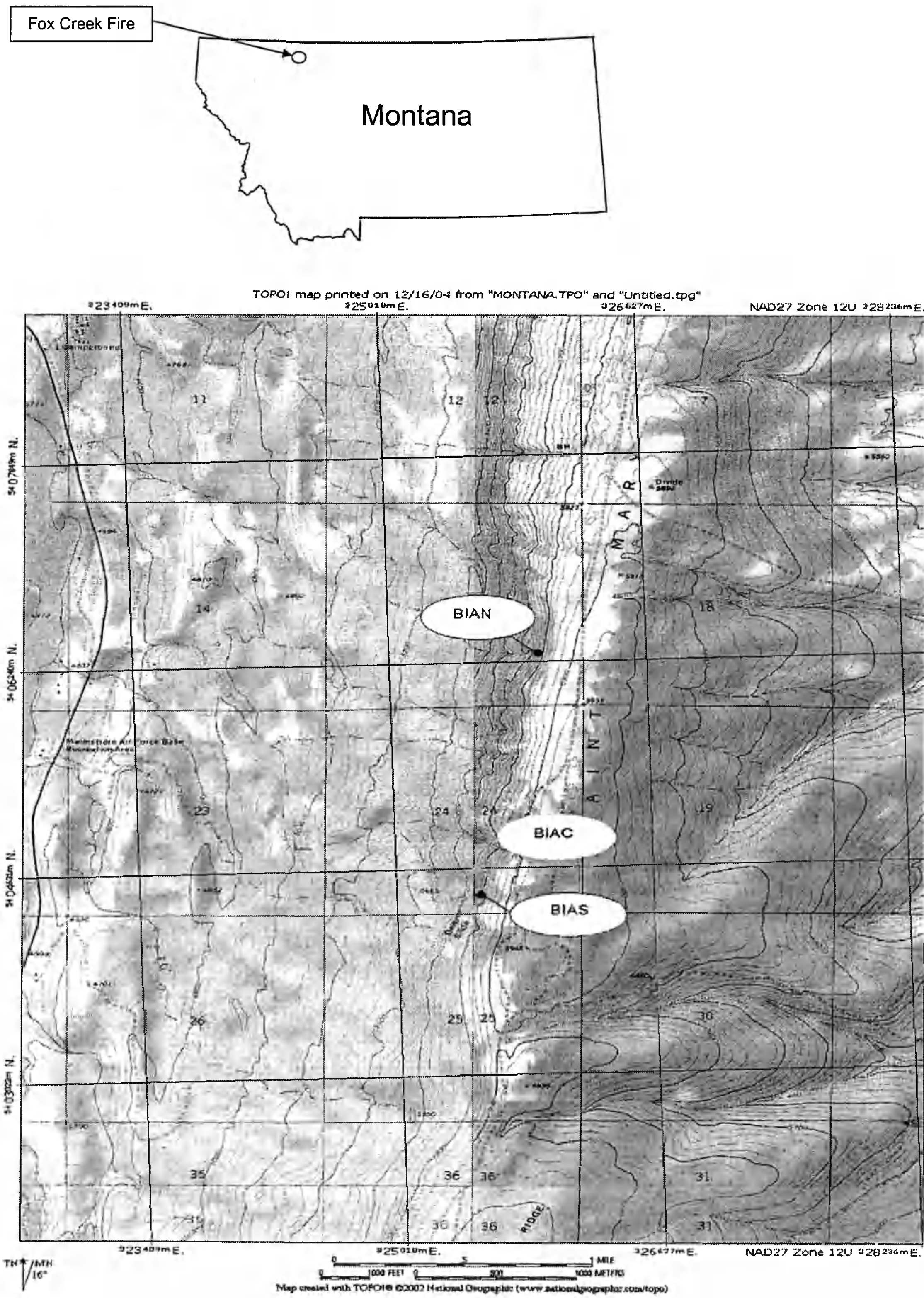

Figure 3: Site map for Fox Creek Fire rainfall simulation locations; BIA north site (BIAN), BIA central site (BIAC) and BIA south site (BIAS)

METHODS

The effectiveness of grass seeding, straw mulch and straw wattles for reducing post fire erosion was assessed by measuring runoff and erosion from 0.5 m^2 treated and control plots during rainfall simulation experiments at the Fox Creek Fire site. In addition, silt fences were used to measure the erosion rates from treated and untreated hillslope plots at the Moose and Fox Creek fire sites.

Silt Fences

Thirteen silt fences measuring approximately 9 m in width were installed on the Moose and Fox Creek Fires to measure hillslope erosion under natural rainfall conditions. The fences were installed according to methods outlined by Robichaud and Brown (2002). Four fences were placed on the Fox Creek Fire in early September, 2002; 1 each at the central and south sites and 2 at the north site. These fences were in place immediately after the fire was fully contained, prior to the aerial seeding operation in late May of 2003, and measured the erosion rate in areas treated with aerial seeding. Due to the size of the area treated with grass seed, no suitable control sites for silt fence measurements could be identified for comparison.

Nine silt fences were placed on the Moose Fire in late August, 2002, 1 year after the fire. The fences were installed at 3 locations with one control, straw mulch, and straw wattle treatment plot at each location. Both of the erosion control treatments were installed in accordance with BAER recommendations (USFS, 1995). No BAER treatments were prescribed for this area, and due to the age of the fire at the time of silt fence installation, natural regeneration of the sites had already begun. Contributing area to the fences was defined by slope breaks, such as a ridge line or road bed, and the flow lines perpendicular to the slope breaks.

The first samples from the Fox Creek Fire silt fences were collected on May 29, 2003 and returned to the lab for processing. They were weighed on a scale and split with a sample splitter at the Lolo National Forest soils lab. Sub-samples were then re-weighed and baked at 440°C for a period of 4 hours to remove moisture and organic material. The remaining sediment was weighed on a scale and a ratio of dry weight to wet weight was applied to the entire sample in order to obtain total sediment collection weights. These totals were then correlated to precipitation recorded at the Babb climate station.

The second collection of samples from the Fox Creek Fire was conducted on July 7, 2003. These samples were weighed in the field with a 5-gallon bucket and hand-held scale with sub-samples returned to the lab for moisture content analysis and removal of organic material. The ratios of dry weight to wet weight were applied to the silt fence data obtained in the field to determine the total amount of sediment delivered to the fences. These amounts were also correlated to rainfall at Babb, MT.

Moose Fire silt fence collections were made on May 20, 2003 and June 24, 2004 and the samples were small enough that subsampling for moisture content analysis was unnecessary. Due to the nature of the parent material, samples were divided into 2 fractions; $\geq$ 2mm and $<$ 2mm, once they were removed from the oven. Sediment collected from these locations was correlated to rainfall rates at Olney, MT. No particle size analysis was performed on these samples due to the limited amount of material collected from the fences. After the data were normalized for precipitation, there was no significant difference in sediment collected between treatment types ($P > 0.05$).

Rainfall Simulations

Rainfall simulations were conducted in three areas burned in the Fox Creek Fire that had burned at moderate to high severity, that were accessible by road, and which lay within the area where grass seeding was conducted following the fire. The three areas were not chosen for any assumed degree of hydrophobicity. In May of 2003, approximately 1670 kilograms of grass seed was dropped by helicopter over 190 hectares of the steepest slopes within the burned area, beginning at the north end of the fire and working south until the seed was gone. The mix consisted of 25% Rough Fescue (*Festuca campestris*), 20% Slender Wheatgrass (*Agropyron trachycaulum*), 15% Green Needlegrass (*Stipa viridula*), and 10% of the remaining species: Idaho Fescue (*Festuca idahoensis*), Bluebunch Wheatgrass (*Agropyron spicatum*), Western Wheatgrass (*Agropyron smithii*), and Needle and Thread (*Stipa comata*). To measure the density of seeds at each site, pans lined with Tanglefoot and mounted on wooden stakes were erected; however, ungulates rendered these ineffective after damaging the posts.

In order to provide control sites and areas where the effect of straw mulch could be evaluated, 3 m x 3 m tarpaulin sheets were placed in several areas prior to the seeding operation. These areas were selected for their proximity to the road. An object tossed blindly into the air determined the exact location of the tarps. Due to the delay in seeding operations, these tarps remained on the ground until after the snow had melted. Multiple areas contained under the tarps provided an excellent environment for seed germination and several were utilized for seeded plots.

Thirty 0.5m^2 plot frames were installed within the 3 study areas to a depth of approximately 6 centimeters in late June and early July of 2003. Seeded plots were installed either where grass seed had been applied but tarps were not present or where seed had washed under the tarps and germination had begun. Straw mulch and control plots were located in areas that had been covered by the tarpaulins. Straw mulch was applied to 10 plots and was secured from high winds and foraging animals with garden netting and staples. Following simulations in 2003, the netting was again secured over the plots in order to retain the treatment for simulations in 2004. Both seeding and mulch treatments were conducted in accordance with BAER recommendations (USFS, 1995). The plots were left in place for a month or more before rainfall simulations began to allow for settling of the disturbed sediment.

Due to the location of the Fox Creek Fire study sites, consideration of wind effect was necessary for both treatment applications and silt fence data. Frequent high winds required mulch be secured to the ground and affected the outcome of least 1 silt fence collection. Windy conditions attributed to the topography of the area may have been considered when treatment recommendations were being proposed and was likely a reason that mulch wasn't considered a viable alternative in the BAER assessment.

An oscillating head Norton-type rainfall simulator was utilized in this study in order to control for raindrop size and rainfall intensity. Initial calibration of the simulator was conducted before field work was started on the Fox Creek Fire. A 1 m^2 board was situated directly below the simulator with soil cans placed in 10x10 rows for collection. The goal was to determine the rainfall intensity settings required for field application, and the maximum plot size over which rainfall intensity would be reasonably uniform. The average rate of rainfall application during these sample runs was 36 mm h^{-1} and ranged from 33 to 38 mm h^{-1}. The distribution of rainfall during the four simulated events was plotted in Mathematica in order to visually assess the distribution of rainfall application (Figure 4) and was deemed acceptable for the intended purposes.

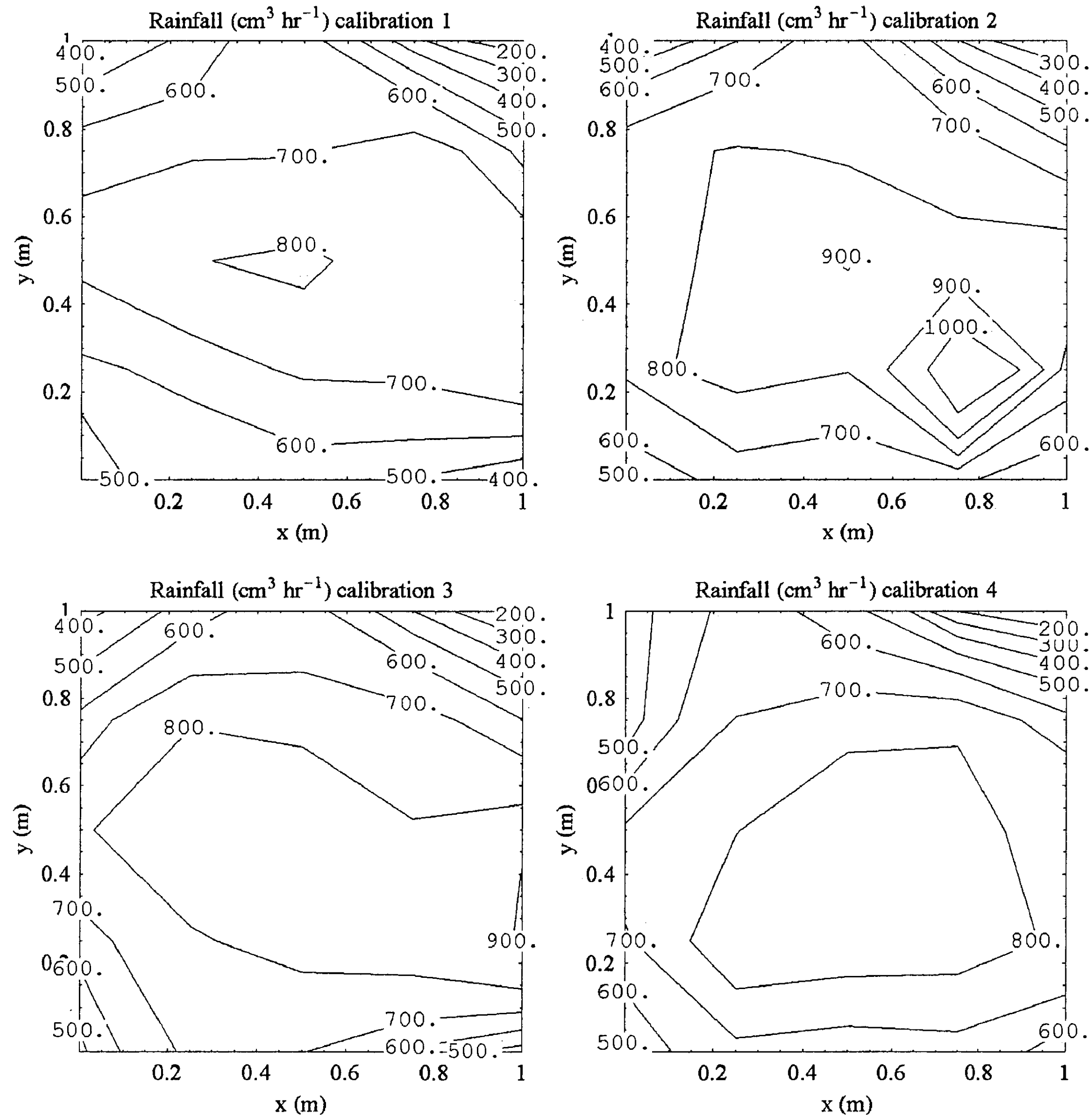

Figure 4: Rainfall distribution from hour-long calibration runs.

Rainfall simulations were run on each of the 30 plots from July 30 to August 27, 2003 and were repeated on 4 controls, 3 mulched, and 2 seeded plots from July 16 to July 27, 2004. Prior to each rainfall simulation, a 5 minute calibration was conducted to determine the rainfall rate. A calibration pan was fitted directly over the plot to capture the rainfall which was then collected and measured using a graduated cylinder. If any adjustments were made to the simulator, the calibration was run again prior to the simulation experiment.

Each simulation was 60 minutes in length. All of the runoff and sediment from the plot were collected every minute for the first 10 minutes and every 2 minutes for the remainder of the hour. Tarps were placed around the simulator to ensure that wind and/or light rains did not affect the rainfall intensity. Runoff rates occasionally exceeded the capacity of the 1 liter container during a 2-minute measurement period. If this happened, the runoff during the second minute of the period was collected, and the calculated runoff rate was assumed to represent the mean runoff rate for the 2-minute period. At the end of each simulation, any sediment remaining in the headwall (a device attached to the plot perimeter pans to collect runoff and sediment) was collected and analyzed with the other samples to provide the total sediment yield for each plot.

Water used for the simulations was obtained from Lower St. Mary's lake using a hand pump and drawing from a depth of approximately 0.5 meters and was not filtered. The tank was refilled each day and any leftover water at the end of each day was pumped out, allowing any debris that had settled to be removed. A small amount of bleach was occasionally added to maintain the purity of water being fed through the simulator by discouraging growth of organic material in the holding tank.

Soil samples were collected adjacent to each of the plots and returned to the laboratory for textural analysis (Gee and Bauder, 1986). Soil moisture contents were taken at three points within the plot before and immediately after the simulation using a Hydrosense soil moisture probe (Campbell Scientific Inc., Logan, Utah). The probes were placed in the upper left and right-hand corners as well as the lower right-hand corner. Visual assessments of the plots were recorded on the data sheets and included any disturbances, natural or otherwise. Vegetation was determined using a 100-point vegetation grid placed over each plot perimeter pan. Soil profiles were taken immediately adjacent to the pan once the simulation was complete. Areas of wet, moist, and dry soil, as well as large root structures and rocks, were recorded on a grid sheet to assist in determining whether soil hydrophobicity affected the runoff rate (Figure 8). Percent of dry soil was compared between treatment types and by site to give a general indication of the degree to which hydrophobic layers may have modified runoff. These profiles, 50 cm long and 20 cm deep, were thought to be sufficiently large enough to capture general trends in hydrophobic layer development.

Runoff and sediment samples collected during each simulation were taken back to the lab for analysis. The volumetric yield for each collection interval was measured using a graduated cylinder. These data were used to determine the total runoff (mm), peak runoff rate (mm/hr), and runoff rate over time (mm/hr). The samples were then filtered through a pre-weighed 8µm filter paper, and the sediment and paper were then oven dried at 105°C for 24 hours. The dry weight of sediment from each sample was recorded and total sediment yield for each plot was calculated. Soil samples were collected from each plot as the soil profiles were excavated and a particle size analysis was done on each sample using the hydrometer method (Gee and Bauder, 1986).

Statistical Analysis of Rainfall Simulator Data

A one-way analysis of variance (ANOVA) was used to determine whether there were significant differences in total runoff, peak runoff rates and total mass of sediment eroded between treatment types. If there was a significant difference ($p \leq 0.05$), multiple comparisons (Bonferroni) were used to verify which treatment types were significantly different. Boxplots were used as a visual tool to compare total runoff, peak runoff rates and total sediment eroded. Statistical analyses were completed using SPSS (SPSS Version 11.0, 1999).

RESULTS

Fox Creek Fire - Site Variables

Soils at the Fox Creek Fire site are predominantly sandy loam. When grouped by treatment type, average sand-silt-clay percentages for control plots were 66%-24%-9%, aerial seeded plots were 68%-23%-8%, and mulched plots were 66%-26%-8% (Figure 5). There was no significant difference ($p > 0.05$) in soil texture between treatment types. When plots were grouped by location, the sand-silt-clay average was 60%-28%-12% for the north site (BIAN), 69%-23%-8% for the central site (BIAC), and 72%-22%-6% for the south site (BIAS) (Figure 6). Sand, silt, and clay percentages as measured at the north site were significantly different than the south and central sites ($P < 0.05$), but all sites have soils that are classified as sandy loam, with similar erodibility factors. Percentages obtained from the south site were not significantly different than the north or central sites ($p > 0.05$).

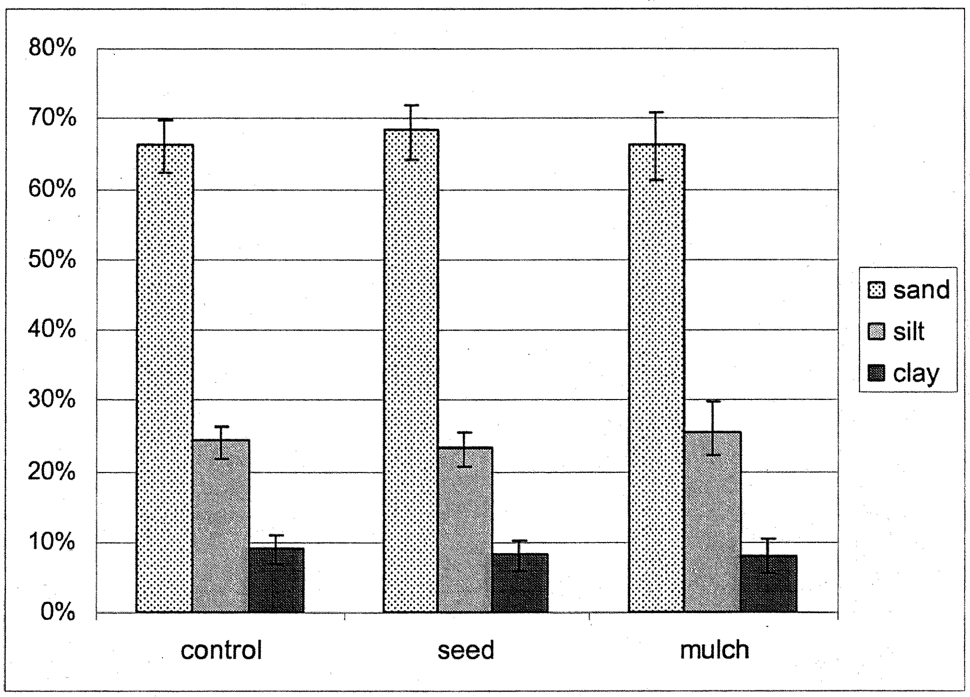

Figure 5: Percent sand, silt and clay in control, seed and mulch plots at the Fox Creek fire study area. Percentages for each treatment are the mean of 10 samples. Error bars represent 1 standard error.

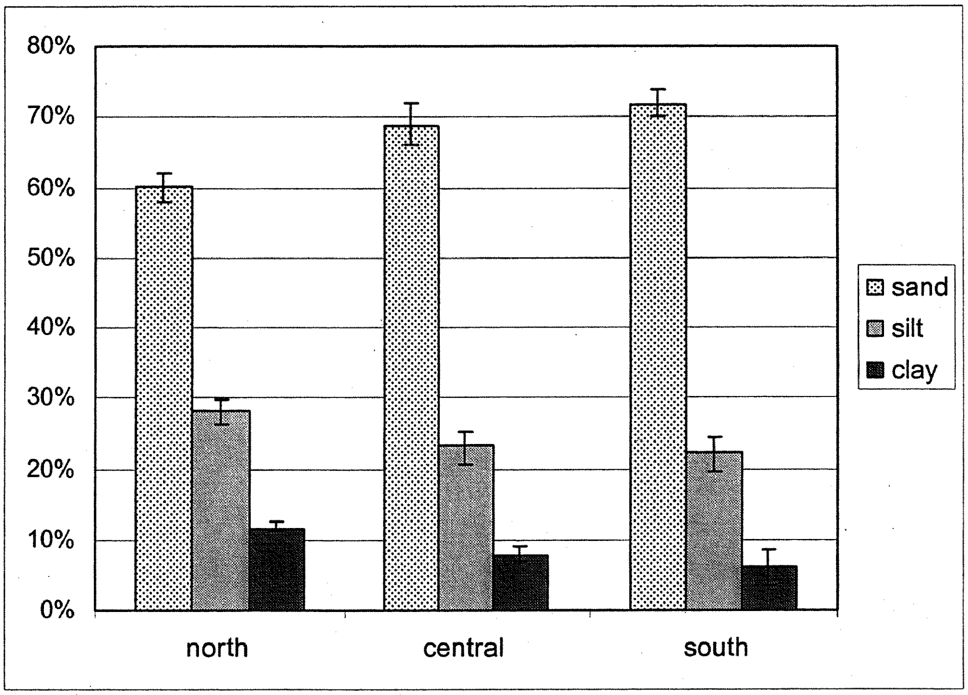

Figure 6: Percent sand, silt and clay in north, central and south sites at Fox Creek fire study area. Percentages for each site are the mean of 10 samples. Error bars represent 1 standard error.

Mean slope for the 3 study sites at the Fox Creek fire was 24.7%, with a range of 21% to 29%. Pan slope varied from 9% to 20% with an average of 15% and was not significantly different ($P = 0.636$) between treatment types. Ground cover within the plots, excluding mulch, varied from 0% to 12% with an average of 7% during the 2003 field season. In the 6 plots where ground cover measurements were taken in 2004, the mean coverage was 39%, with a range of 29% to 51%, indicating a significant increase since 2003 ($P < 0.05$) (Appendix A).

Rainfall simulation – plot soil characteristics

Soil profiles excavated adjacent to each of the plots directly after each simulation helped to determine patterns of infiltration and the presence or absence of hydrophobic layers (Figure 7). The average percent of dry soil was highest on the central site (10.1%)

and fairly similar between the north (7.0%) and south (6.9%) sites. All 3 sites displayed comparable ranges in the percentage of soil saturation observed, with a minimum of 0.0% on all sites to a maximum of 28.0% on the central and south sites and 27.4% on the central site.

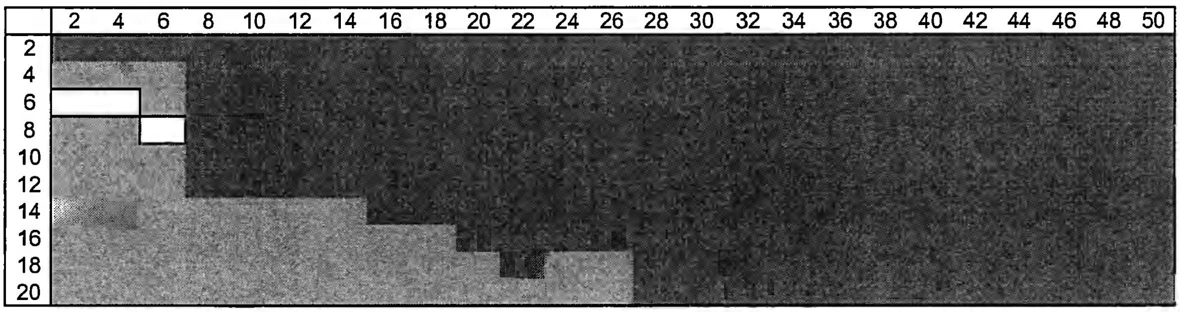

Figure 7: Example of soil profile taken after simulated rainfall event. White boxes indicate dry soil, dark gray indicate soil saturated from the rainfall simulation and light gray indicate soil not likely affected by the rainfall simulation.

When averaging the percentage of dry soil by treatment type, control plots had the highest percentage of dry soil (9.8%). Aerial seeded and mulched plots were similar with 7.6% and 7.2% dry soil, respectively. The range of dry soil percentages for all 3 sites was 0.0% to 28% with no significant differences between them ($p = 0.786$). There was no correlation between the percentage of dry soil measured at each plot and the percentage of total runoff measured during rainfall simulations, suggesting that differences in hydrophobicity had little or no effect on the measured runoff and erosion rates (Figure 8).

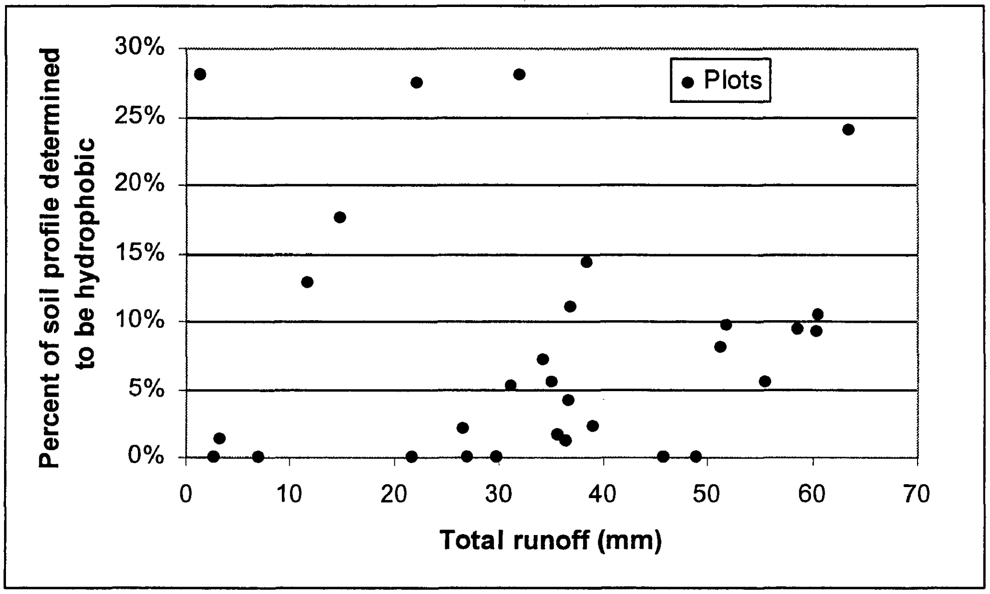

Figure 8: Scatter plot of the percentage of dry soil blocks observed in post-simulation excavated soil profiles versus total runoff from the 30 plots (10 controls, 10 mulched, and 10 aerially seeded).

Both control and mulched plots displayed similar patterns of soil saturation, experiencing a lower percentage of saturated soil at depths up to 6 cm and then leveling out. Aerial seeding tended to have a higher percentage of saturated soil in the first 6 cm to 7 cm of soil profile and a lower percentage after 8 cm of depth (Figure 9). There was no statistically significant difference in soil saturation across treatment types ($P > 0.05$).

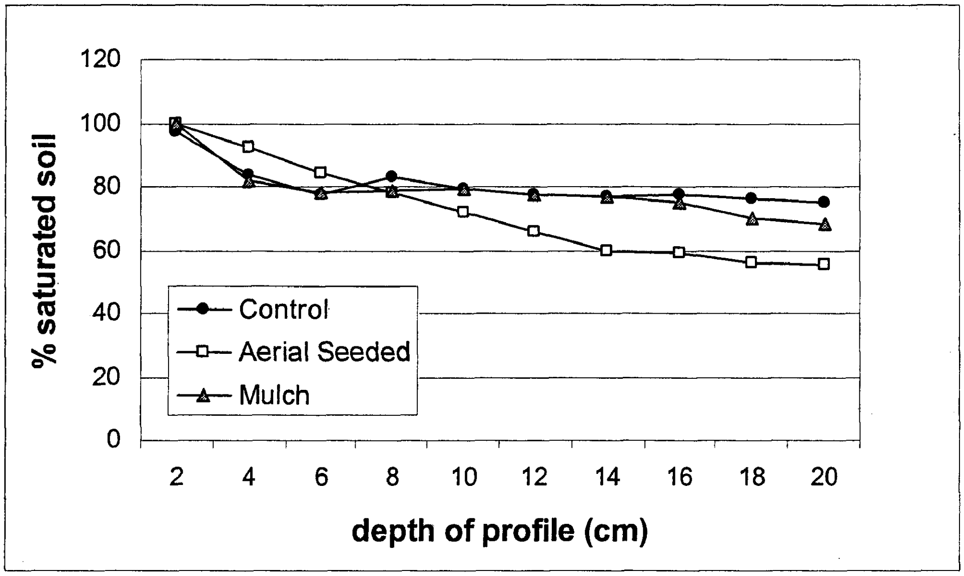

Figure 9: Average percent saturated soil after 1-hour simulated rainfall: Fox Creek Fire, 2003. Data is based on 10 plots for each treatment type.

Volumetric water content was measured pre- and post-simulation for each plot. The average water content pre-simulation was 6.6% with a low of 5.0% and a high of 10.0%. Post-simulation water content measurements averaged 34.6% with a low of 21.0% and a high of 48.0% (Appendix A). Neither pre- nor post-simulation water contents were significantly different across treatment types ($p > 0.05$). Pan slope was also not significantly different across treatment types ($p = 0.636$).

Rainfall simulations – runoff and sediment yield

In 2003, rainfall intensities measured prior to each simulation ranged from 69 mm hr^{-1} to 94 mm hr^{-1} with a mean of 83mm hr^{-1}. Mean rainfall intensities in the aerial seeded, straw mulch and control plots were 82, 84 and 83 mm hr^{-1}, respectively, and were not significantly different ($p = 0.720$).

In all 30 plots on which rainfall simulations were performed, runoff began between 1 and 4 minutes after the start of rainfall. Runoff rates then increased to a peak and then leveled off, indicating that steady state infiltration was occurring (Figure 10). Higher runoff rates throughout the simulations in the control plots may be due to soil surface sealing due to raindrop impacts. Time to peak runoff varied between treatment types, but was not statistically significantly different ($P > 0.05$). Control and seeded plots averaged approximately 21 and 23 minutes to peak runoff, respectively, and mulched plots averaged approximately 30 minutes. Gradual declines in the runoff rates following the peak indicate a break down of hydrophobic layers within the plots due to wetting of the soil (Figure 10).

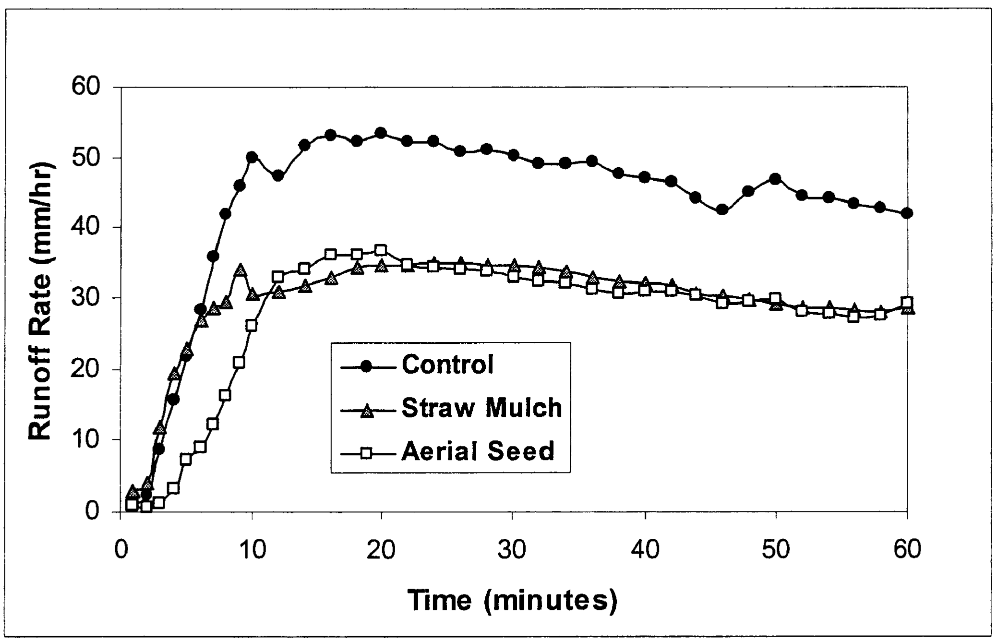

Figure 10: Average runoff rate vs. time for control, mulched, and seeded plots during the 2003 Fox Creek fire rainfall simulations. Seeded grass had not germinated on many of the plots at the time the simulations were conducted.

Total runoff from the 30 plots on which rainfall simulations were conducted in 2003 ranged from 1.4 mm to 63.5 mm with a mean of 34.1 mm. The control plots had the highest total runoff with a mean of 44.1 mm and a range of 11.7 mm to 63.5mm (Figure 11). The mean total runoff was lower for both the mulched (28.0 mm) and the seeded (30.1 mm) plots. The range of values was wider and the minimum total runoff was lower on the mulched plots than on the seeded plots. The mean runoff-to-rainfall ratio for the control, mulched and seeded plots was 0.53, 0.36 and 0.37, respectively. Total runoff was not statistically significant between any of the 3 treatments ($p = 0.090$).

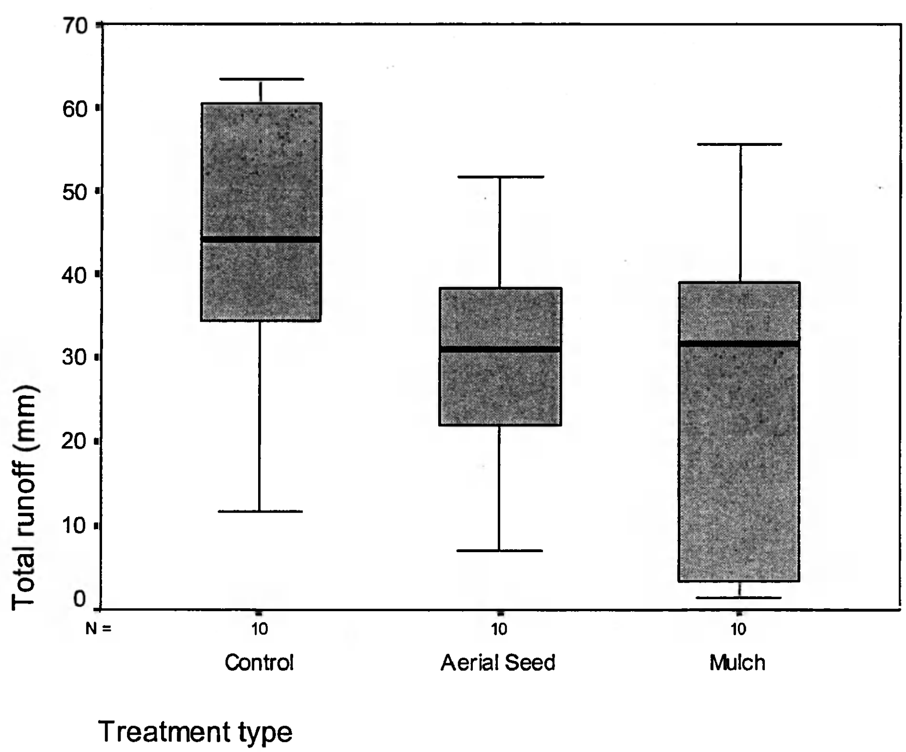

Figure 11: Total runoff by treatment types for 1-hour simulated rainfall events conducted in 2003. The box corresponds to the middle 50% of values and whiskers represent the highest and lowest values not including outliers. Median values are represented by a bar within the box.

Control plots had the highest peak runoff rates with a mean of 59 mm h^{-1} and a range of 18 mm h^{-1} to 79 mm h^{-1} (Figure 13). The mean peak runoff rates for mulched (40 mm h^{-1}) and seeded (41 mm h^{-1}) plots were similar to each other, although peak runoff rates from the mulched plots were more variable, ranging from 4 mm h^{-1} to 75 mm h^{-1}. Peak runoff rates between the two treatment types and controls were not significantly different in 2003 ($p = 0.093$). The average time to peak runoff for control, seeded and mulched plots was 21, 23 and 30 minutes, respectively, making the time to peak runoff for mulched plots 43% longer than control plots (Figure 12).

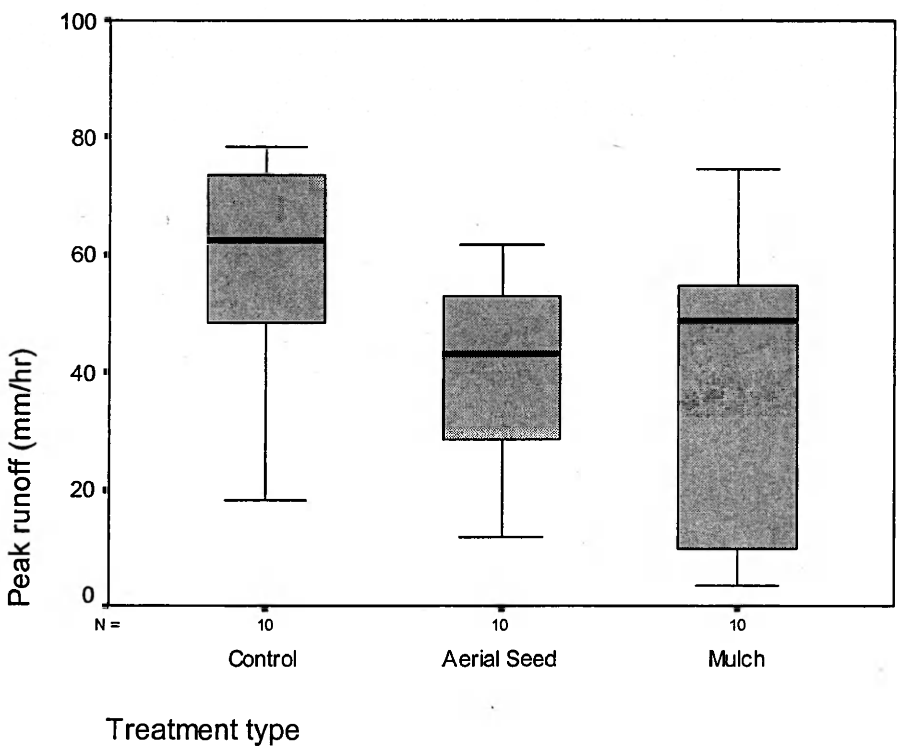

Figure 12: Peak runoff by treatment types for 1-hour simulated rainfall events conducted in 2003. The box corresponds to the middle 50% of values and whiskers represent the highest and lowest values not including outliers. Median values are represented by a bar within the box.

Control plots had a large spike in sediment production within the first 15 minutes (Figure 13), corresponding to the rise in runoff during that same time (Figure 10). A nearly continuous decline in sediment followed for the remainder of the simulation. Seeded plots saw a steady rise in erosion rates in the first 20 minutes followed by comparatively constant erosion rate during the remainder of the simulation. Mulched plots saw an increase in sediment for approximately 12 minutes, after which erosion rates steadily declined.

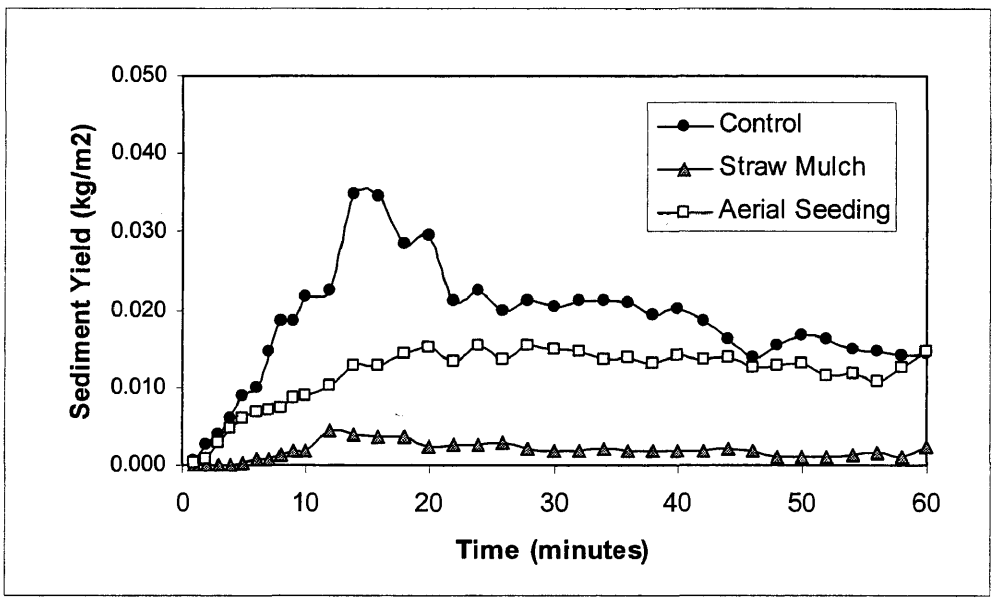

Figure 13: Average sediment yield vs. time for control, mulched, and seeded plots during the 2003 Fox Creek fire rainfall simulations.

Total sediment yield from the 30 plots ranged from 0.01 kg m^{-2} to 1.75 kg m^{-2} in 2003. With the exception of the extreme value obtained from a seeded plot (1.75 kg m^{2}), the highest values were from control plots, where total sediment yield ranged from 0.04 kg m^{-2} to 1.22 kg m^{-2} with a mean of 0.79 kg m^{-2} (Figure 14). Mulched plots had the lowest average sediment yield (0.01 kg m^{-2}), two orders of magnitude less than from the control plots. Sediment yields from the mulched plots were significantly less than from both the control plots ($p = 0.001$) and the seeded plots ($p = 0.021$). Sediment yields from the seeded plots ranged from 0.01 to 1.75 kg m^2, with a mean of 0.59 kg m^2, which is 0.19 kg m^2 less than from the control plots but considerably higher than from the mulched plots. The difference between the amount of sediment obtained from control and seeded plots was not significant ($p = 0.804$) (Figure 14).

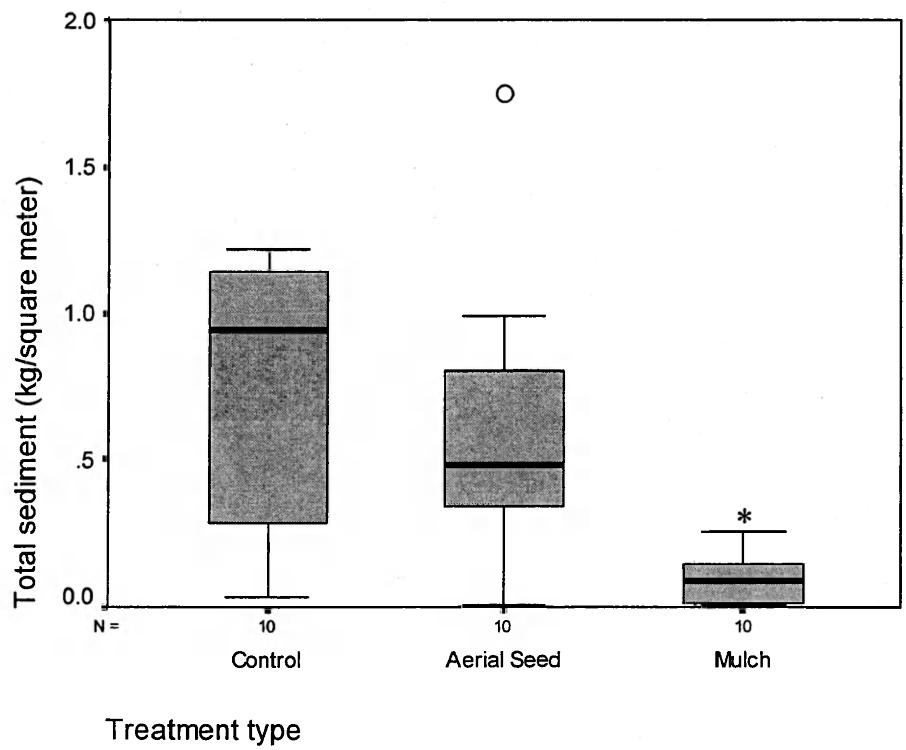

Figure 14: Total sediment by treatment types for 1-hour simulated rainfall events conducted in 2003. The box corresponds to the middle 50% of values and whiskers represent the highest and lowest values. Median values are represented by a bar within the box. The open circle indicates an outlier. The asterisk indicates that the sediment yield in the mulch plots was significantly lower than in the control and seeded plots.

When normalized by runoff rate, the sediment yield (kg/m^2) for each of the treatment types varied greatly. Aerial seeded plots generally experienced the highest rates of sediment per unit of runoff for the first 9 minutes (Figure 15). At its peak, aerial seeding produced more than twice the rate of sediment per unit of runoff than that observed on control plots. Both control and seeded plots spiked within the first 5 minutes of the simulated rainfall events while mulched plots reached their highest peak at 12 minutes. This high point for mulched plots was considerably less than the lowest points observed for the other treatment types and sediment per unit of runoff for mulched plots was consistently lower throughout the 1-hour simulation.

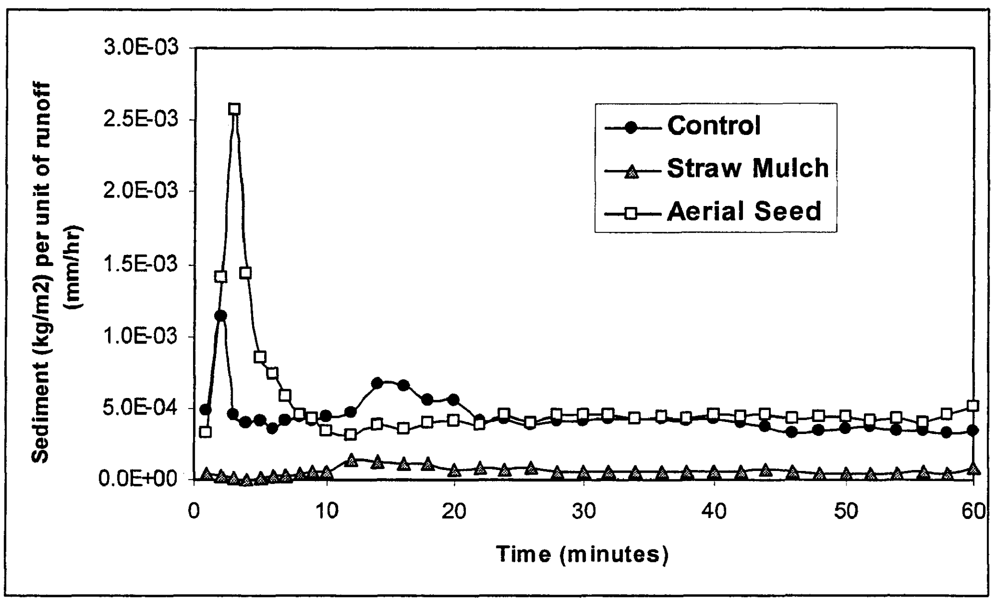

Figure 15: Total sediment yield per unit of total runoff over time on the Fox Creek Fire, 2003. Data are an average of the treatment types; 10 control, 10 straw mulch, and 10 aerial seeded plots.

In 2004, rainfall simulations were conducted on 2 seeded, 3 mulched, and 4 control plots. Simulations could not be conducted on all of the plots because of an equipment failure that could not be resolved before winter snowfall made the site inaccessible. Plot perimeter pans utilized for the simulations in 2003 were reused in 2004, subjecting the plots to a second round of rainfall. Mean rainfall intensities for the simulations in 2003 were approximately 15% lower than in 2003, averaging 66, 68 and 69 mm h^{-1}, for the control, seeded, and mulched plots respectively. Rainfall rates were not significantly different (p=0.836) across treatment types. Runoff on all plots began within the first 2 minutes (Figure 16). Aerial seeded plots maintained a higher level of runoff than mulched or control plots until approximately 45 minutes into the simulations. Runoff was generally lower across all of the treatment types than in 2003. Infiltration capacity was generally reached within the first 10 minutes of the simulation. As in 2003, declining runoff rates after the peak indicate that soil hydrophobicity was still present, but dissipated as the soil wetted up during the simulation.

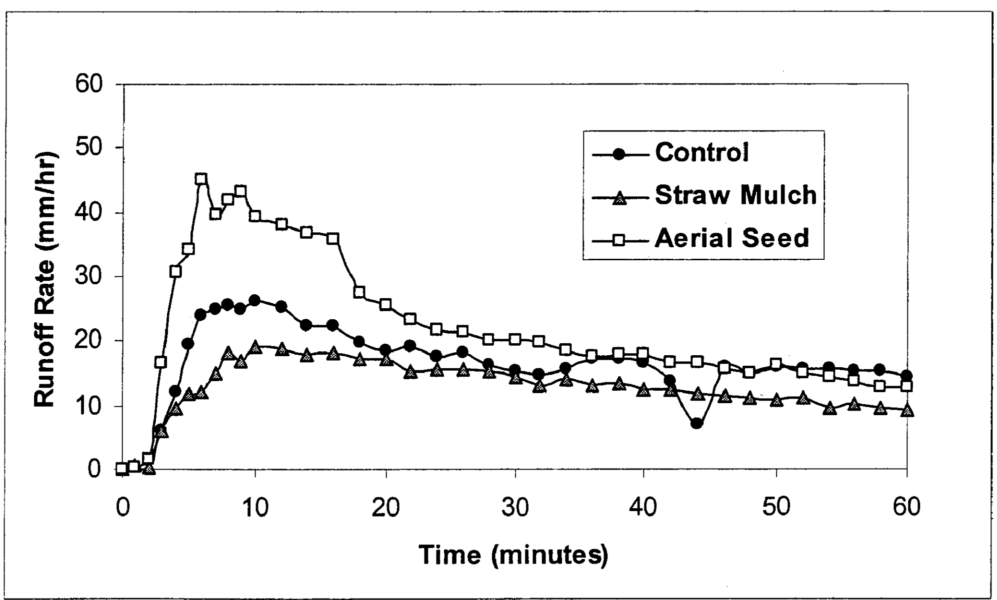

Figure 16: Runoff rate vs. time for the 2004 rainfall simulations on the Fox Creek fire. Graph is based on replicates of 4 controls, 3 mulched, and 2 seeded plots.

Control plots displayed the widest range of variability in total runoff with a range of 0.3 mm to 40.2 mm and a mean of 16.8 mm in 2004. Mean total runoff was lowest on the mulched plots (13.1 mm) and highest on the seeded plots (20.9 mm). Runoff to rainfall ratios were 0.25, 0.19 and 0.31 for the control, mulched and seeded plots respectively, indicating a ~50% reduction in runoff from the control and mulch plots and a 15% reduction in runoff from the seeded plots relative to 2003.

In addition to having the lowest total runoff, mulched plots also had the lowest mean peak runoff rate (20.2 mm h^{-1}), which is approximately half that observed in 2003. The peak runoff rate from the control plots also declined by approximately 50% relative to 2003, with a mean of 28.9 mm h^{-1}. The peak runoff rate from the seeded plots was only slightly lower than in 2003, averaging 39.5 mm h^{-1} compared to 41.3 mm h^{-1} in 2003.

Mean sediment yields from the treatment and control plots were less variable in 2004 than in 2003, and the treatment effects were not as distinct (Appendix A). In the control plots, the mean sediment yield of 0.21 kg m^{-2} indicates a more than 70% decrease in erosion from the previous year. Sediment yield from the seeded plots had a mean of 0.18 kg m^{-2}, indicating a 50% decline in erosion relative to the previous year. The sediment yield from the mulched plots increased relative to 2003, to a mean of 0.11 kg m^{-2}, but was still more than 50% lower than in the control plots.

Sediment from silt fences

The first collection of sediment from the four silt fences installed on the Fox Creek fire occurred approximately 9 months after the fire, on May 29, 2003. The northeastern (BIAN-E), northwestern (BIAN-W), central (BIAC) and south (BIAS) fences yielded 145, 183, 339 and 287 kg ha^{-1}, respectively. Precipitation at the Babb climate station was 81% of average in the period between fence installation and the first sediment collection. Sediment per unit of rainfall yielded 0.91, 1.14, 2.12, and 1.85 kg ha mm^{-1} for the BIAC-E, BIAC-W, BIAC, and BIAS sites, respectively (Figure 18).

The second silt fence sediment collection took place on July 7, 2003, less than 2 months after the first collection. The sediment yields from the 4 fences, BIAN-E, BIAN-W, BIAC, and BIAS, were 8, 205, 317 and 508 kg ha^{-1} respectively. Even when normalized for the difference in total precipitation, this means that the erosion rate (kg ha^{-1} yr^{-1}) in June and July 2003 in 3 of the 4 plots was 5 to 8 times higher than the erosion rate over the 9 month period prior to the first sampling event (Figure 17). This is likely because precipitation in the period prior to the first sampling event occurred mostly as snowfall, while precipitation in June and July typically occurs as high intensity thunderstorms that have much higher erosivity. The low sediment yield from BIAN-E may be due to the fact that the plot was highly exposed to wind, so that most of the accumulating sediment was blown from behind the fence before it could be collected. Sediment per unit of rainfall for the BIAC-E, BIAC-W, BIAC, and BIAS sites was 0.16, 3.80, 5.87, and 9.41 kg ha^{-1} mm^{-2}, respectively (Figure 18). Total sediment yield from the fences in the 11 months postfire period ranged from 8 to 5.1×10^2 kg ha^{-1}. During a third visit to the site in late July, further accumulation of sediment behind the fences was observed. However, the sediment was not collected because the silt fences had deteriorated significantly due to the high winds at the study site.

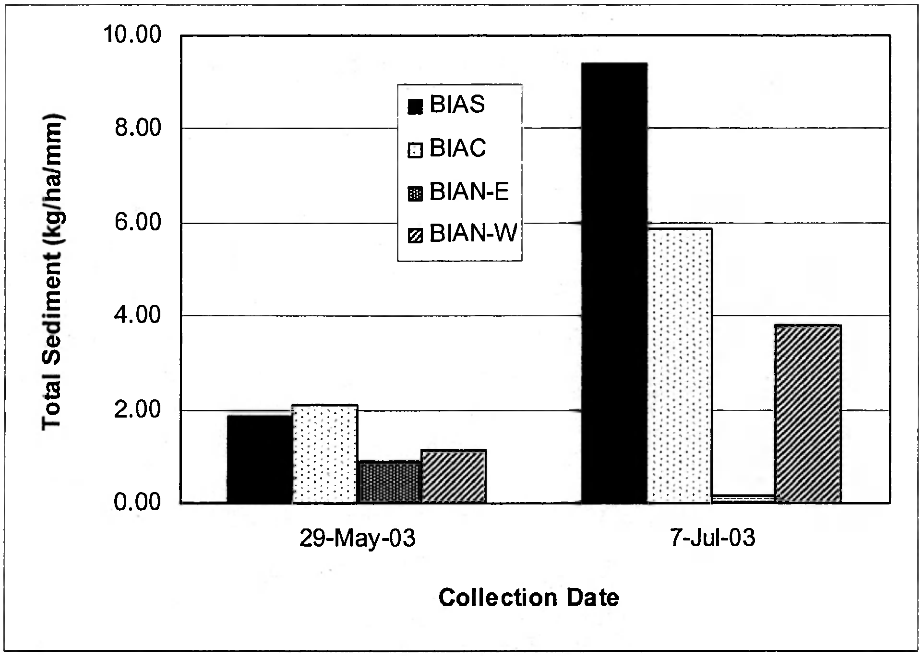

Figure 17: Total mass of sediment eroded per unit of rainfall from the Fox Creek Fire silt fences, 2003. Collections were taken prior to seed germination and do not reflect any treatment effects.

The Moose Fire study plots yielded considerably less sediment than the Fox Creek Fire. In the first collection, on May 20, 2003 approximately 9 months after the fences were installed the fences produced a combined total of 4.8 kg ha^{-1} of sediment from the 3 control plots. Particles ≤ 2mm in diameter made up 77% of this total. Sites treated with straw wattles produced the most sediment, 7.9 kg ha^{-1} with 53% ≤ 2mm in diameter. The sediment yield from the straw wattle sites was 61% higher than for the control plots. Mulched sites produced the least amount of sediment, totaling 3.1 kg ha^{-1} with 34% ≤ 2mm in diameter. Precipitation at Olney MT was 270 mm (62% of average) in the period between fence installation and the first sediment collection. Sediment yield per unit of rainfall amounted to 0.017, 0.028, and 0.011 kg ha^{-1} mm^{-1} for the control, wattle, and mulched sites, respectively (Figure 18).

The second Moose Fire silt fence collections, on June 24, 2004, also produced relatively little sediment. Control plots totaled 5.1 kg ha^{-1} with 43% ≤ 2mm in diameter. As in the previous year, the straw wattle sites produced the greatest amount of sediment at 13.0 kg ha^{-1} with 26% ≤ 2mm in diameter. Mulched plots produced the least amount of sediment, totaling 4.9 kg ha^{-1}, with only 11% ≤ 2mm in diameter. The Olney, MT climate station recorded 530 mm of precipitation (80% of average) for this time period, almost twice the amount recorded prior to the first collection. Sediment yield per unit of rainfall for the control, wattle, and mulched sites was 0.010, 0.025, and 0.009 kg ha^{-1} mm^{-1}, respectively. This amounts to reductions in sediment yield of 46%, 16% and 19% for the control sites, straw wattle sites, and mulch sites, respectively (Figure 18). The total amount of sediment collected was not significantly different across years (P = 0.547).

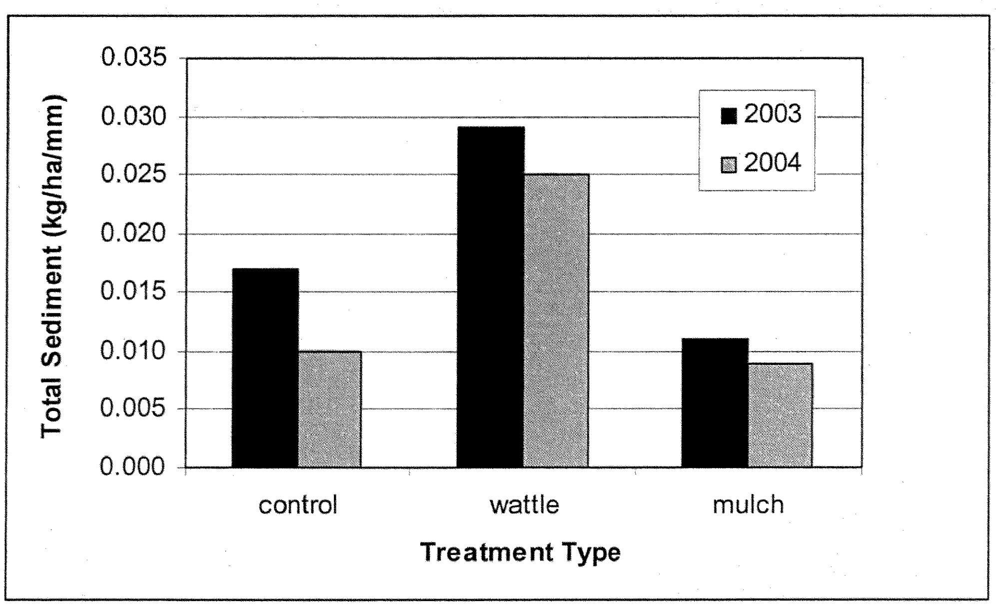

Figure 18: Total mass of sediment eroded per unit of rainfall from the Moose fire silt fences in 2003 and 2004. Total sediment collected was not statistically significant across years (P = 0.547).

DISCUSSION

Hydrologic and geomorphic response to wildfire

Considerable increases in surface erosion and runoff have been observed after wildfires (Robichaud et al., 2001; Moody and Martin, 2001). The magnitude of the increase varies considerably depending on the severity of the fire, the soil characteristics, and the magnitude of precipitation events, particularly in the first year after the fire when ground cover is minimal (Bisson et. al., 2003). In our study, sediment yields from the seeded hillslope plots at the Fox Creek fire site averaged 5×10^{2} kg ha^{-1} in the first 11 months following the fire. Ground cover in the small plots averaged just 1.7% in the first year, suggesting that similar erosion rates would have occurred on untreated slopes. The first year erosion rates from the Fox Creek hillslope plots are much lower than those recorded in many other burned areas. For example, on the Wallowa-Whitman National Forest in eastern Oregon, erosion rates from burned hillslopes with 20%, 30%, and 60% slope were 2.1×10^{4}, 4.4×10^{4}, and 4.9×10^{4} kg ha^{-1}, respectively (Robichaud and Brown, 1999).

Even when corrected for differences in total precipitation, the erosion rate (kg ha^{-1} yr^{-1}) on 3 of the 4 hillslope plots at the Fox Creek fire in June and July 2003 was 5 to 8 times higher than the erosion rate over the first 9 months after the fire. This is likely because much of the precipitation in the first 9 months, which included the winter period, occurred as snowfall. In contrast, precipitation in June and July typically occurs as high intensity thunderstorms that have much higher erosivity. The implication is that burned sites in the Rocky Mountain region are most vulnerable to erosion in the first 2 or 3 large storms in the spring and early summer of the following year. The low sediment yield from the fourth site (BIAN-E) may be due to the fact that the plot was highly exposed to wind, so that most of the accumulating sediment was blown from behind the fence before it could be collected.

Comparisons between erosion rates from the small plots used for rainfall simulations at the Fox Creek and larger hillslope scale plots are inappropriate because small plots do not account for hillslope water storage and because rainfall simulations typically use rainfall rates that are much higher than what would occur during natural rainfall events. However, comparisons can be made with other studies that used small plots and rainfall simulators to assess erosion rates after fire. One such study was conducted following the 2000 Cerro Grande Fire in New Mexico. For 2 burned sites in ponderosa pine forest supporting 31% and 20% ground cover, the average sediment yield was 76 kg ha^{-1} mm^{-1} (Johansen, Hakonson, and Breshears, 2001). This is more than 2 orders of magnitude greater than the erosion rate from the control plots at the Fox Creek Fire when normalized by rainfall amount. Taken in combination, the data from the seeded hillslope plots and the untreated rainfall simulation plots at the Fox Creek fire indicate a much lower erosion rate than has been measured after fires in other environments. The low erosion rates on the Fox Creek plots occurred despite the fact that ground cover was very low, suggesting that soils in the area have an inherently low erodibility.

Sediment yields from the control plots at the Moose Fire site were 1 to 2 orders of magnitude less than those recorded at the Fox Creek site. This is likely due to the fact that the data were collected 2 and 3 years after the Moose Fire, whereas the Fox Creek fire site data were collected in the first year after the fire. Surface erosion rates from burned areas are typically at their highest in the first year after the fire, when ground cover is at a minimum and soil water repellency, if present, is strongest. Surface erosion rates typically decline rapidly in subsequent years as new vegetation covers the ground surface and hydrophobicity breaks down (Benavidos-Solorio and MacDonald, 2001). Ground cover of more than 30% typically halves the surface erosion rate relative to a site with zero cover and greater than 60% ground cover reduces the erosion rate to near-background levels (Robichaud et al., 2000). However, in areas where mass movements are an important soil erosion mechanism, the post-fire erosion response can be entirely different. Large scale tree mortality after higher severity fire can lead to the decay of roots that provide soil cohesion and increase the risk of mass failure 5 to 10 years after the fire (Wondzell and King, 2003) and require alternate methods of remediation.

Increases in overland flow and soil erosion from burned areas are often attributed to the presence of water repellent (hydrophobic) soils. Although water repellency is often found in unburned soils, fire increases its effect on infiltration by concentrating the hydrophobic compounds in a discrete layer at or near the soil surface (Brady, Robichaud, and Pierson, 2001). The strength of the hydrophobicity depends on factors such as soil moisture content at the time of the burn, particle size, vegetation type and fire severity (DeBano, 1981). In our study, the percentage and pattern of dry soil observed after rainfall simulations conducted on the Fox Creek Fire in 2003 suggest that hydrophobic layers were present, although water resistant layers that may have been present prior to fire were not recorded. Most of the 2003 runoff hydrographs exhibited a declining runoff rate after the initial peak, indicating gradual wetting of a hydrophobic soil layer and a resultant increase in the infiltration rate. This increase in infiltration with time is the opposite of what is typically observed in unsaturated hydrophytic soils (Dingman, 2002), but it is consistent with the hydrologic response from hydrophobic soils observed in other areas (e.g. Robichaud, 2000; Benavides-Solorio and Mac Donald, 2001). The 2004 runoff rates were substantially lower than those observed in 2003, indicating that the hydrophobic layer was at least partially broken down. In most cases, hydrophobic soils tend to disappear within 1 to 2 years after a fire, although the rate of breakdown varies with the initial fire intensity and the amount of precipitation.

Effectiveness of Erosion Control Treatments

This study considered the effectiveness of 3 of the most commonly used post fire erosion control treatments: straw mulch, grass seeding and straw wattles. Straw mulching was highly effective in reducing erosion at both of the study sites, and was considerably more effective than grass seeding in reducing erosion rates in the first year after the Fox Creek fire. Erosion rates from the mulched plots in the Fox Creek fire site were reduced by 88% and 51% relative to the control in the first and second years post-fire, respectively. Similarly, at the Moose Fire site, erosion rates from mulched hillslope plots were 35% and 10% lower than the control in the second and third years after the fire. These results are consistent with the limited number of similar studies that included an untreated control. For example, in a semiarid ecosystem on the southeastern coast of Spain, soil loss from mulched plots was 2 to 16 times less than from untreated plots (Bautista et al., 1996). Wheat straw mulch applied to fill slopes adjacent to perennial streams, firelines and areas of high erosion hazard reduced erosion rates by 11 to 19 m^3 ac^{-1} compared to untreated sites (Miles et al., 1989). Edwards et al., (1995) noted significant reductions in soil loss on sites where mulch was applied at rates of 2 and 4 Mg ha^{-1} on slopes ranging from 5 to 9 percent.

The effectiveness of the mulching treatment can be attributed primarily to the immediate increase in ground cover that it provides, and the consequent decrease in rainsplash erosion as observed in the low sediment per unit of runoff ratios. However, the mulch treatment also reduced the total runoff and the peak runoff from the plots at the Fox Creek site, indicating that mulching may also have reduced the rate of overland flow. Presumably the mulch layer acts much like the duff layer in an undisturbed forest soil profile, providing a temporary storage reservoir for rainfall which then infiltrates the ground over a longer time period.

Although the erosion rate from the mulched plots at the Fox Creek fire was lower than in the control in both years, sediment yield from the mulched plots increased in the second year by almost 200%. This was largely due to a decrease in ground cover as straw mulch was either blown off the sites, decomposed, or was eaten by ungulates. Many areas that were mulched in late May 2003 were completely bare by early August of the same year. In a comprehensive study of treatment effectiveness in burned areas in Colorado, Wagenbrenner (2003) also found a decrease in the effectiveness of straw mulch in the second year after fire due to a loss of ground cover. In that study, sites that were retreated with mulch in the second year produced only 4% of the sediment produced by mulch sites that were not retreated.

Loss of the mulch due to wind may be less of a problem where a larger area is treated because mulch may simply be redistributed rather than being blown out of the area completely. However, periodic maintenance is needed to ensure that the mulch remains effective during the first summer after a fire, when vegetation cover is at a minimum. Soil loss rates from the mulched plots were reduced by spreading nylon netting across the plots, and a similar approach could be employed in areas treated on a larger scale. An additional concern related to the use of mulch is the potential for introducing weeds into treated areas. Burned areas are already vulnerable to weed invasion due to the large scale disturbance of the soil and loss of the existing vegetation cover. Use of weed-free straw is essential in treated areas if weed problems are to be minimized.

Erosion rates from grass seeded rainfall simulation plots at the Fox Creek fire site were lower than from the control plots, but the treatment was not nearly as effective as mulching in reducing post-fire erosion. The effectiveness of aerial seeding in reducing erosion is largely dependent on the amount of additional ground cover that the treatment produces. At the Fox Creek fire site, the mean vegetation cover in the seeded plots was not significantly greater than in the control plots at the time of the 2003 simulations, and this is largely why the seeding treatment had such a limited effect in reducing erosion. The limited ground cover was largely due to the fact that seeding was not conducted until nearly 9 months after the fire because of logistical and climatic limitations, so that there was only a 3 month period between the application of the grass seed and the rainfall simulations. In addition, due to the timing of application in the late spring months, much of the seed may have been lost to snowmelt creep and early spring storm events, or washed off the plots during simulated rainfall events. Application of the seeding treatment prior to snowfall in the same year as the fire may have increased its effectiveness in reducing erosion the following year. The limited additional ground cover created by the aerial grass seeding in 2003 may also have been partly due to the exceptionally dry conditions; total precipitation at Babb, Montana for 1 June – 31 July 2003 was just 42% of average. Greater success might be expected in a wetter year, although the effect of increased ground cover might be offset by the increased rainfall erosivity.

The results of the present study are generally consistent with other studies that have examined the effectiveness of grass seeding. In order to determine the effectiveness of seeding following a high severity fire that burned through a clearcut and adjoining forested areas in the Siskiyou Mountains of southwestern Oregon, 27 kg ha^{-1} of Italian rye grass (*Lolium multiflorum*) and 260 kg ha^{-1} of ammonium phosphate fertilizer were applied. Mineral soil was exposed on 85% to 95% of the study site immediately after the fire. Despite the fact that seeding reduced the amount of bare soil by 42% within 8 months, the treatment was ineffective at reducing surface erosion because most of the erosion occurred in the first 3 months, when the seeding had produced very little ground cover (Amaranthus, 1989). The limited ground cover produced by seeding in the first few months represents a serious limitation in its effectiveness for reducing post fire erosion. Grass seeding may not be an appropriate treatment in many burned areas.

Erosion rates from the plots treated with straw wattles at the Moose Fire site were actually greater than the control plots, suggesting that ground disturbance associated with wattle installation increased the amount of available sediment. Straw wattle sites accounted for 50% of all sediment produced from the Moose Fire plots in 2003, and 57% in 2004. Since the wattles were not installed until almost a year after the fire, erosion rates had likely declined substantially relative to the period immediately following the fire. Straw wattles may have had a positive effect in reducing erosion immediately after the fire, when the wattles would have been able to trap considerably more sediment than was created by their installation. Straw wattles have been found to be effective in reducing erosion in other areas, although the amount of sediment storage is often not sufficient for them to be effective during very large rainfall events.

CONCLUSIONS AND RECOMMENDATIONS

This study used simulated rainfall events on small plots and silt fences below larger hillslope plots to assess the effectiveness of 3 commonly prescribed post-burn erosion controls: mulching, grass seeding and straw wattles. Significant reductions in total sediment yield were observed in mulched plots relative to control plots, while grass seeding was relatively ineffective and straw wattles actually increased the erosion rate.

Taken in combination, the results of this study indicate that mulching is an excellent post-burn treatment because of its effectiveness at providing immediate ground cover when percentage of bare mineral soil and accompanying threat of sedimentation is highest (Robichaud et al., 2000; Faust, 1998). Mulching shields the soil from rain splash erosion and by reducing surface sealing it also limits overland flow and rill erosion. However, due to the high costs and intensive labor required to apply this treatment, mulching is often not the favored approach when considering treatment options, despite the fact that it has proven effective at reducing total sediment in this and several other studies (e.g. Wagenbrenner, 2003; Robichaud et al., 2000; Bautista et al., 1996).

Grass seeding is commonly used as a post fire erosion control treatment because of the ease of application and relatively low cost. However, consistent with other studies, post burn seeding had very little effect in reducing erosion rates in areas included in the present study. The benefits of seeding are likely limited to the growth which occurs prior to the return of native vegetation, which will vary depending on the amount of seed applied and the climatic conditions (Beyers, 2004; Robichaud et al., 2000). Seeding may be helpful in situations where natural revegetation is slow and grass cover can be quickly established. Under these circumstances, Simms (2004) suggests that land managers may gain a year of slope stability with the application of grass seed.

The greatest benefit of seed and mulch applications occurs primarily in areas that are exposed to overland flow (MacDonald, 1989). By allowing for a reduction in flow velocity through the use of soil surface protection, the likelihood of rill and gully erosion is decreased and opportunities for revegetation are improved. In order to effectively mitigate for potential impacts arising from post-burn environments, BAER treatment recommendations should focus on sites with characteristics that make them more susceptible to erosion. Treatments should be prescribed with a complete understanding of both positive and potential negative effects that may ensue. Given the likelihood of large fires in the future, there is a continued need to develop new post-fire erosion control treatments and to refine existing treatments.

APPENDIX A: Rainfall simulation data for Fox Creek Fire rainfall simulations, 2003 and 2004

2003 Fox Creek Fire Rainfall Simulation Data											
Plot #	Treatment	Date of Simulation	Total Runoff (mm)	Total Sediment (kg/m2)	Peak runoff (mm/hr)	Ground Cover (%) *	Average Soil Moisture (%) pre-simulation	Average Soil Moisture (%) post-simulation	Pan Slope (%)	Measured mm/hr from calibration	Measured ml for calibration run
1	control	9-Aug-03	36.74	0.974	48.36	1%	7.3%	33.0%	15.0%	86.9	3620
2	seed	9-Aug-03	27.02	0.475	39.36	8%	5.3%	33.0%	17.0%	85.9	3580
3	seed	10-Aug-03	38.37	0.800	45.18	10%	9.0%	36.7%	12.5%	83.0	3460
4	seed	10-Aug-03	22.32	0.340	61.56	3%	8.0%	38.3%	16.0%	82.0	3415
5	mulch	10-Aug-03	31.26	0.198	53.64	0%	7.0%	38.3%	16.5%	79.2	3300
6	control	11-Aug-03	26.80	0.287	46.40	0%	10.0%	37.3%	16.0%	89.0	3710
7	control	11-Aug-03	51.30	0.820	68.80	0%	8.7%	31.7%	13.5%	84.7	3530
8	mulch	11-Aug-03	3.40	0.014	5.80	0%	9.0%	46.3%	11.5%	93.6	3900
9	mulch	11-Aug-03	2.80	0.016	9.80	0%	7.0%	45.0%	12.0%	–	–
10	control	30-Jul-03	11.70	0.037	18.00	0%	8.3%	48.0%	15.0%	68.6	2860
11	seed	30-Jul-03	14.90	0.196	24.80	12%	5.0%	37.0%	16.0%	74.4	3100
12	mulch	31-Jul-03	35.60	0.023	54.60	2%	–	35.7%	–	85.2	3550
13	control	1-Aug-03	63.50	1.219	78.50	0%	5.0%	25.7%	20.0%	75.6	3150
14	seed	1-Aug-03	35.10	0.375	41.60	2%	5.7%	34.7%	15.0%	78.0	3250
15	mulch	1-Aug-03	29.90	0.082	37.90	0%	5.3%	35.3%	17.0%	84.7	3530
16	control	2-Aug-03	34.30	1.141	51.10	0%	8.0%	33.3%	18.0%	85.2	3550
17	mulch	2-Aug-03	1.40	0.009	3.60	0%	6.0%	34.7%	17.0%	89.8	3740
18	seed	3-Aug-03	51.80	0.990	61.80	1%	–	24.3%	17.0%	86.2	3590
19	control	3-Aug-03	36.80	0.264	55.90	0%	6.7%	38.3%	12.5%	90.2	3760
20	seed	24-Aug-03	36.40	0.529	45.10	2%	5.0%	41.7%	15.0%	83.6	3485
21	mulch	24-Aug-03	39.00	0.097	46.70	0%	5.0%	29.3%	12.5%	80.3	3345
22	control	25-Aug-03	60.40	1.143	77.00	0%	6.7%	21.0%	14.0%	82.0	3415
23	mulch	25-Aug-03	48.90	0.120	63.40	0%	6.3%	26.0%	16.0%	78.8	3283
24	seed	24-Aug-03	7.10	0.006	11.90	4%	6.3%	40.3%	13.0%	81.2	3385
25	seed	26-Aug-03	45.80	1.752	53.10	6%	6.3%	34.7%	11.0%	83.0	3460
26	control	26-Aug-03	58.60	1.076	68.60	0%	6.0%	22.3%	14.0%	81.4	3393
27	mulch	26-Aug-03	32.00	0.255	51.10	0%	5.3%	34.3%	16.0%	82.8	3451
28	control	26-Aug-03	60.70	0.908	73.60	0%	6.7%	30.3%	14.0%	88.6	3693
29	mulch	27-Aug-03	55.60	0.148	74.60	0%	6.7%	32.3%	9.0%	84.2	3510
30	seed	27-Aug-03	21.90	0.481	28.70	0%	6.3%	38.0%	11.5%	85.8	3575

2004 Fox Creek Fire Rainfall Simulation Data											
Plot #	Treatment	Date of Simulation	Total Runoff (mm)	Total Sediment (kg/m2)	Peak runoff (mm/hr)	Ground Cover (%) *	Average Soil Moisture (%) pre-simulation	Average Soil Moisture (%) post-simulation	Pan Slope (%)	Measured mm/hr from calibration	Measured ml for calibration run
1	control	17-Jul-04	40.25	0.522	63.60	_	8.0%	32.3%	15.0%	74.9	3120
2	seed	17-Jul-04	11.78	0.289	34.80	_	6.7%	33.0%	17.0%	69.0	2875
6	control	16-Jul-04	0.26	0.001	0.66	_	10.0%	37.3%	16.0%	60.0	2500
7	control	16-Jul-04	6.87	0.189	21.00	_	8.3%	38.3%	13.5%	68.3	2845
8	mulch	16-Jul-04	1.61	0.000	3.27	_	9.0%	42.7%	11.5%	75.7	3155
9	mulch	17-Jul-04	5.02	0.025	15.36	_	9.7%	39.7%	12.0%	66.5	2770
28	control	27-Jul-04	19.59	0.129	30.30	_	10.7%	34.7%	14.0%	60.8	2535
29	mulch	27-Jul-04	32.79	0.298	41.94	_	6.7%	29.3%	9.0%	63.7	2655
30	seed	27-Jul-04	29.93	0.072	44.16	_	8.3%	32.3%	11.5%	67.6	2815

* all vegetation readings taken on 08-24-03; plots 1-19 had undergone simulations at this point

APPENDIX B: Climate station data for Babb and Olney, Montana

	Climate Summary: Babb, MT												
	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Average Max Temp (°C)	-0.2	2.4	5.5	10.5	15.9	20.6	24.3	24.3	18.8	13.4	4.8	0.2	11.8
Average Min Temp (°C)	-13.5	-10.9	-7.3	-2.8	1.5	5.0	6.7	6.2	2.2	-1.2	-7.3	-12.4	-11.1
Average Precipitation (mm)	19.1	18.0	22.4	33.8	65.8	76.5	44.7	48.8	48.3	22.9	19.1	19.3	438.9
2002 Precipitation (mm)	18.8	33.0	32.8	34.3	116.1	144.0	22.9	55.4	57.4	16.5	0.0	17.5	548.6
2003 Precipitation (mm)	7.6	16.8	45.5	27.4	44.2	54.1	2.5	0.0	33.8	17.8	31.2	6.6	270.8

	Climate Summary: Olney, MT												
	Jan	Feb	Mar	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
Average Max Temp (°C)	1.6	2.4	7.4	13.4	18.7	22.7	26.7	26.8	20.7	12.4	2.2	-2.3	12.6
Average Min Temp (°C)	10.9	9.4	5.9	2.7	1.4	4.8	6.3	5.5	1.2	-2.8	-6.4	-10.2	-2.4
Average Precipitation (mm)	62.0	51.3	37.3	36.1	58.9	68.8	50.3	37.1	31.8	39.9	59.9	58.9	592.1
2002 Precipitation (mm)	64.3	45.7	47.8	25.4	54.9	54.9	12.4	10.7	22.1	3.8	39.9	32.8	414.5
2003 Precipitation (mm)	27.7	19.3	70.9	24.1	30.2	54.1	1.3	17.3	51.3	47.8	67.6	40.1	451.6
2004 Precipitation (mm)	78.5	3.8	25.7	50.0	52.3	37.1	61.5	83.1	56.1	38.6	40.9	39.4	566.9

LITERATURE CITED

Amaranthus, M.P., 1989. Effect of grass seeding and fertilizing on surface erosion in two intensely burned sites in southwest Oregon. *Proceedings of the Symposium on Fire and Watershed Management*, USDA Forest Service General Technical Report PSW-GTR-109. Berkeley, CA, pp. 148-150.

Bautista, S., J. Bellot, and V.R. Vellejo, 1996. Mulching treatment for postfire soil conservation in a semiarid ecosystem. *Arid Soil Research and Rehabilitation*, 10: 235-242.

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

Beyers, J.L., 2004. Postfire seeding for erosion control: effectiveness and impacts on native plant communities. *Conservation Biology*, 18, no 4: 947-956.

Bisson, P.A., B.E. Rieman, C. Luce, P.F. Hessburg, D.C. Lee, J.L. Kershner, G.H. Reeves, and R.E. Gresswell, 2003. Fire and aquatic ecosystems of the western USA: current knowledge and key questions. *Forest Ecology and Management*, 178: 213-229.

Brady, J.A., P.R. Robichaud, and F.B. Pierson, Jr., 2001. Infiltration Rates After Wildfire in the Bitterroot Valley. Written for presentation at the 2001 ASAE Annual Meeting, held July 30-August 1, 2001, in Sacramento, California.

DeBano, L.F., 1981. Water repellent soils: a state of the art. USDA Forest Service General Technical Report PSW-GTR-46. Berkeley, CA, 21 pp.

Dingman, S.E., 2002. *Physical Hydrology*. Prentice Hall. Upper Saddle River, NJ, 646 pp.

Edwards, L., J. Burney, and R. DeHaan, 1995. Researching the effects of mulching on cool period soil erosion in Prince Edward Island, Canada. Journal of Soil and Water Conservation, 50: 184-187.

Faust, R., 1998. Lesson Plan: Fork Fire soil loss validation monitoring. Unit VIII, Long-term Recovery and Monitoring. In: Burned Area Emergency Rehabilitation (BAER) Techniques, 1998. San Francisco: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region (course notebook).

Gee, G.W., and J.W. Bauder, 1986. Particle-size analysis. In: Klute, A. (ed.) *Methods of Soils Analysis Part I.* American Society of Agronomy. Madison, WI, pp. 383-411.

Gillam, Andrea, 2004, Personal communication regarding total acreage burned on the Fox Creek fire in 2003.

Heiri, O., A.F. Lotter, and G. Lemcke, 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25: 101-110.

Johansen, M.P., T.E. Hakonson, and D.D. Breshears, 2001. Post-fire runoff and erosion from rainfall simulation: contrasting forests with shrublands and grasslands. *Hydrological Processes*, 15: 2953-2965.

Letey, J., 2001. Causes and consequences of fire-induced soil water repellency. *Hydrologic Processes*, 15: 2867-2875.

MacDonald, L.H., 1989. Rehabilitation and recovery following wildfires: a synthesis. *Proceedings of the Symposium on Fire and Watershed Management*, USDA Forest Service General Technical Report PSW-GTR-109. Berkeley, CA, pp.141-144.

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

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

Miles, S.R., D.M. Haskins, and W. Darrel, 1989. Emergency Rehabilitation: cost, risk and effectiveness. In: Berg N. (tech. coord.) Proceedings of the symposium on fire and watershed management. October 26-28, 1988. Sacramento, California. General Technical Report PSW-109. USDA Forest Service Pacific Southwest Forest and Range Experiment Station.

Pyne, S.J., 1982. *Fire in America: A Cultural History of Wildland and Rural Fire.* Princeton University Press. Princeton, NJ, 654 pp.

Pyne, S.J., 1995. *World fire: the culture of fire on earth.* Henry Holt and Company. New York, NY, 379 pp.

Rieman, B., D. Lee, D. Burns, R. Gresswell, M. Young, R. Stowell, J. Rinne, and P. Howell, 2003. Status of Native Fishes in the Western United States and Issues for Fire and Fuels Management. *Forest Ecology and Management*, 178: 197-211.

Robichaud, P.R., 2000. Fire effects on infiltration rates after prescribed fire in Northern Rocky Mountain forests, USA. *Journal of Hydrology*, 220-229, 231-232.

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

Robichaud, P.R., J.L. Beyers, and D.G. Neary, 2001. After the fire, before the storm: post-erosion control efforts explored. CE News, pp. 54-62.

Robichaud, P.R., and R.E. Brown, 1999. What happened after the smoke cleared: onsite erosion rates after a wildfire in eastern Oregon. *Wildland Hydrology*: proceedings, specialty conference, June 30-July 2, 1999, Bozeman, Montana. Technical publication series (American Water Resources Association); TPS-99-9: 419-426.

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

Simms, Bruce, 2004, Personal communication related to effectiveness of seeding as a post-burn erosion control technique.

SPSS Inc. (1999). *SPSS Base 11.0 for Windows User's Guide.* SPSS Inc., Chicago IL.

USDA, 1980. Soil Survey of Glacier County and Park of Pondera County, Montana. United States Department of Agriculture, Natural Resource Conservation Service.

USDA, 1999. Soil Survey of Flathead National Forest Area, Montana. United States Department of Agriculture, Natural Resource Conservation Service in Cooperation with the Montana Agricultural Experimental Station.

USFS, 1995. Burned area emergency rehabilitation handbook. Forest Service Handbook No. 2509.13. Washington, D.C., 91 pp.

USGAO, 2003. Wildland Fires: Better information needed on effectiveness of emergency stabilization and rehabilitation treatments. Report to Congressional Requesters. GAO-03-430. Washington, D.C., 63 pp.

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

Walstad, J.D., S.R. Radosevich, and D.V. Sandberg, 1990. Natural and prescribed fire in the pacific northwest forests. Oregon State University Press. Corvallis, OR, 332 pp.

Wells, C.G., R.E. Campbell, L.F. DeBano, C.E. Lewis, R.L. Lewis, E.C. Fredrickson, R.C. Franklin, R.C. Froelich, and P.H. Dunn, 1979. Effects of Fir on Soil: A

State-of-Knowledge Review. USDA Forest Service General Technical Report WO-7. Washington D.C., 34 pp.

Wondzell, S.M., and J.G. King, 2003. Postfire erosional processes in the Pacific Northwest and Rocky Mountain Regions. *Forest Ecology and Management*, 178: 75-87.