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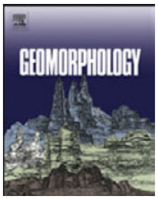

Evaluating the effectiveness of wood shred and agricultural straw mulches as a treatment to reduce post-wildfire hillslope erosion in southern British Columbia, Canada

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ABSTRACT

After the 2009 Terrace Mountain fire near Kelowna, BC, Canada, wood shred and agricultural straw mulch effects on post-fire runoff and sediment yields were compared using three experimental techniques: rainfall simulations on 1-m^2 plots, concentrated flow (rill) simulations on 9-m long plots, and sediment yields from natural rainfall on 30-m^2 plots. All experimental plots were located on and along a planar hillslope burned at high severity. Experiments were conducted once a year for three consecutive years beginning in Sep 2009, except for the rainfall simulations which only were conducted the first two years. Although results varied by experiment and time since fire, both agricultural straw and wood shred mulch treatments performed similarly for reducing runoff and sediment; thus were combined into a single "treated" class for analyses. The mulch treatments were effective in reducing sediment yields as compared to the controls in all three experiments in 2009. In the rill simulation experiment, the mulch treatments significantly reduced overland flow velocity and increased the proportion of overland flow that infiltrated the soil before reaching the plot outlet. The elapsed time since the fire, which was strongly related to the increase in vegetative ground cover, was a significant factor for predicting sediment yields in the statistical models. Favorable spring rainfall in 2010 and 2011 supported rapid regrowth of vegetation, which recovered similarly on all plots regardless of treatment. The runoff and sediment yields on the treated plots were similar to those measured on the control plots a year later; we concluded that the mulch was, in effect, a surrogate for a year of recovery. Given that agricultural straw mulch is an established and effective post-fire hillslope treatment, it was important to find that wood shred mulch was similarly effective in reducing post-fire runoff and sediment yields. Thus, the choice of agricultural straw or wood shreds for a post-fire mulch treatment may be based on the performance characteristics (longevity, potential to carry invasive species seeds, cost, etc.) that best fit the needs of the site.

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1. Introduction

Forested slopes that have been burned at high severity can experience significant increases in post-fire runoff, flooding, and erosion that may put human life and safety, infrastructure, buildings, drinking water quality, aquatic habitat, and valued natural and cultural resources at risk for damage or loss (Kunze and Stednick, 2006; Lane et al., 2006; Shakesby and Doerr, 2006; Moody et al., 2008; Moody and Martin, 2009; Silins et al., 2009). Although wildfires are fairly common in the inland forests of south-central British Columbia (BC), Canada, no large post-fire responses had been documented prior to the severe wildfire season of 2003 when debris flows and other erosion events caused significant damage to highways, houses, and aquatic habitat (Jordan and Covert, 2009). Given the warmer temperatures, earlier spring snow melt, the large and expanding area of beetle-killed trees, and other effects of climate change, the number and severity of wildfires in the southern interior of BC is likely to continue to increase (Haughian et al., 2012). In addition, the number of people living in and around forested areas continues to increase (Peter et al., 2006). Land managers in BC, like their counterparts in other fire prone areas around the world, are expanding and systematizing post-fire assessment and use of treatments to reduce runoff, flooding, and erosion from burned areas (Jordan, 2011).

Studies conducted over the past decade have identified key factors that influence the magnitude of the potential post-fire hydrologic response: 1) the amount of ground cover or, conversely, the amount of bare soil exposed (Benavides-Solorio and MacDonald, 2005); 2) the rainfall intensity (Benavides-Solorio and MacDonald, 2005; Moody and Martin, 2009); 3) the amount and degree of soil water repellency (DeBano, 2000; Shakesby and Doerr, 2006; Doerr et al., 2009); and 4) the time since the fire (Gimeno-García et al., 2007). Many of these factors have been incorporated into the soil burn severity classification system—a designation of soil disturbance based on residual ground cover, ash color and depth, effects on soil structure and fine roots, and changes in soil water repellency

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(Neary et al., 2005; Parsons et al., 2010). Several studies have correlated the degree of soil burn severity with the magnitude of the post-fire response (e.g., Doerr et al., 2006; Moody et al., 2008).

The relative effect of individual factors on post-fire hydrologic response is not well understood and may vary between regions, sites, vegetation, and soil types. Yet, understanding these relative effects is needed to predict where post-fire erosion will likely occur and design effective hillslope treatments to mitigate the post-fire responses. Despite the interrelationships among the factors related to post-fire responses, the importance of ground cover seems the least ambiguous in its effect in reducing post-fire hillslope erosion rates. Areas burned at low and moderate burn severity have greater residual cover and lower post-fire erosion rates than areas burned at high severity. Given that mulches (agricultural straw, wood products, hydromulch, etc.) can provide immediate ground cover for exposed soil, they are increasingly being applied as post-fire hillslope treatments to reduce rain drop impact, runoff, and erosion (Wagenbrenner et al., 2006; Bautista et al., 2009; Robichaud et al., 2010a). Some short-term (12–24 months) post-fire treatment effectiveness studies have reported 48–99% lower sediment yields from research hillslope plots or swales treated with agricultural straw mulch as compared to untreated controls (Badia and Marti, 2000; Dean, 2001; Wagenbrenner et al., 2006; Rough, 2007; Groen and Woods, 2008).

Aerial application techniques for agricultural straw mulch have made it possible to apply mulch more efficiently and to treat inaccessible burned areas (Napper, 2006). With increasing use of agricultural straw mulch as a post-fire hillslope treatment, some of the drawbacks have become apparent. These include redistribution by wind, possible hindrance of native vegetation regrowth, and weed contamination (Robichaud et al., 2003; Beyers, 2004; Bautista et al., 2009). Other dry mulches made from native forest materials, have been developed, tested, and in some cases, applied as post-fire hillslope treatments. However, agricultural straw remains the most commonly used post-fire mulch because it is generally available from agricultural lands near many fires, less costly than wood-based mulches, and lighter-weight and therefore, less expensive to transport and aerially apply than wood-based mulches.

Wood mulches have been developed from wood manufacturing waste (e.g., wood strands such as WoodStraw®, Forest Concepts, Inc., Auburn, WA), wood shreds or wood chips made from burned trees or forest thinning operations, and shredded forest floor material from nearby unburned areas (Bautista et al., 2009; Robichaud et al., 2010a). Although these wood-based mulches are unlikely to harbor non-native seeds, their greater density can increase the cost of transportation to the site and aerial application as compared to straw mulch (i.e., necessitate more round trips from the staging area and/or the use of aircraft with larger payload capacities). Laboratory studies established that wood strands have greater resistance to wind displacement as compared to agricultural straw (Copeland et al., 2009), and both wood strands and wood shreds provide equal or greater protection from erosion as compared to agricultural straw mulch at equal areal coverage rates (Yanosek et al., 2006; Foltz and Wagenbrenner, 2010). Foltz and Wagenbrenner (2010) reported that a 50% cover of wood shred mulch, with small (<25 mm length) pieces removed by sieving, reduced sediment yields nearly as well as 70% cover when it was tested using indoor rainfall and overland flow simulations.

In a recent field study, manufactured wood strands and agricultural (wheat) straw were tested on burned hillslope plots at two sites—the Colorado Front Range and south-central Washington (Robichaud et al., 2013). Although both mulch treatments increased total ground cover to more than 60% immediately after application, the wheat straw mulch cover decreased nearly twice as fast as the wood strand mulch. Wood strand mulch significantly reduced sediment yields at both sites and the wheat straw mulch significantly reduced sediment yields at the Washington site but not at the Colorado site. In addition, wood strands reduced sediment yields for up to 4 years (Robichaud et al., 2013).

Given that the post-fire erosion potential is greatest immediately after the fire and decreases over time, field tests of post-fire treatments are best accomplished immediately after a wildfire. Yet results from post-fire experiments can be inconclusive if the natural rainfall characteristics during the first few years of the experiment are significantly below normal—a common occurrence as drought cycles often coincide with increases in wildfire ignitions. The use of simulated rainfall and concentrated flow (rill) experiments to field-test post-fire treatments provides opportunities for researchers to garner comparable runoff and erosion information while controlling the timing of the experiments and the characteristics of the rainfall and/or overland flow applied to the plots (Robichaud et al., 2010b). In addition, the inter-rill and rill erodibility parameters (K_i and K_r, respectively) of the burned soil can be calculated from rainfall and rill simulations and these values are used in predictive post-fire erosion models (Robichaud et al., 2007; Wagenbrenner et al., 2010). Although the information from simulations is useful, runoff and erosion from natural rainfall cannot be fully captured in simulations. Thus we used two simulation experiments (rainfall and rill) to individually evaluate treatment effects on inter-rill and rill erosion. We also examined treatment effectiveness on the combined processes of hillslope erosion by measuring sediment yields from natural rainfall on hillslope plots.

This study was initiated immediately following the 2009 Terrace Mountain wildfire in southern British Columbia to compare the effects of wood shred and agricultural straw mulches on post-fire hydrologic responses on hillslopes with high soil burn severity. Specific objectives were to determine the effects of wood shred and agricultural straw mulches on post-fire: 1) runoff and sheet erosion rates generated from rainfall simulations on small plots; 2) runoff velocities, rill geometry, and rill erosion rates generated from simulated concentrated flow experiments; 3) sediment yields from natural rainfall on planar hillslope plots; and 4) discern changes in post-fire responses, treatment effectiveness, and the characteristics of the wood shred and straw mulches over time for 2 years after the fire.

2. Methods

2.1. Site description

The Terrace Mountain fire in south-central BC started on 18 Jul 2009 and was deemed contained (15 Sep 2009) in the same week we established our study site (14–18 Sep 2009) on a 2-ha area classified as mostly high soil burn severity (Fig. 1, based on the criteria of Parsons et al., 2010). Plots for rainfall simulation, rill simulation, and natural rainfall (hillslope silt fence plots) experiments were established in close proximity, but not overlapping, on a large planar west-facing hillslope at an elevation of 1000 to 1200 m (mean of 1070 m) with slopes of 25–50% (Fig. 1).

The continental climate that dominates south-central BC is generally mild in the summers with cold winters at higher elevations where the study plots are located. The annual average precipitation at the Kelowna Airport weather station (20 km away and 600 m lower than the study site) is 381 mm, which is divided fairly equally between summer and winter with maxima occurring in the months of June (rain) and December (snow) (Fig. 2). The study area is usually snow covered from late October to late April. The dominant forest overstory species are Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and trembling aspen (*Populus tremuloides*) with an understory dominated by pinegrass (*Calamagrostis rubescens*) and birch-leaved spirea (*Spiraea betulifolia*) (Lloyd et al., 1990; Meidinger and Pojar, 1991).

The soil in the study area was derived from a shallow glacial till of mainly granitic origin—predominantly Eutric Brunisols of the Connaly soil series (BC Ministry of Environment, 1978), which corresponds to Eutrocryept in the USDA soil classification system. In 2009, when the experimental sites were established, nine core samples were taken at each of two depths (0–5 and 5–10 cm) at four locations near the rill plots. The mean soil bulk density measured at the control plots

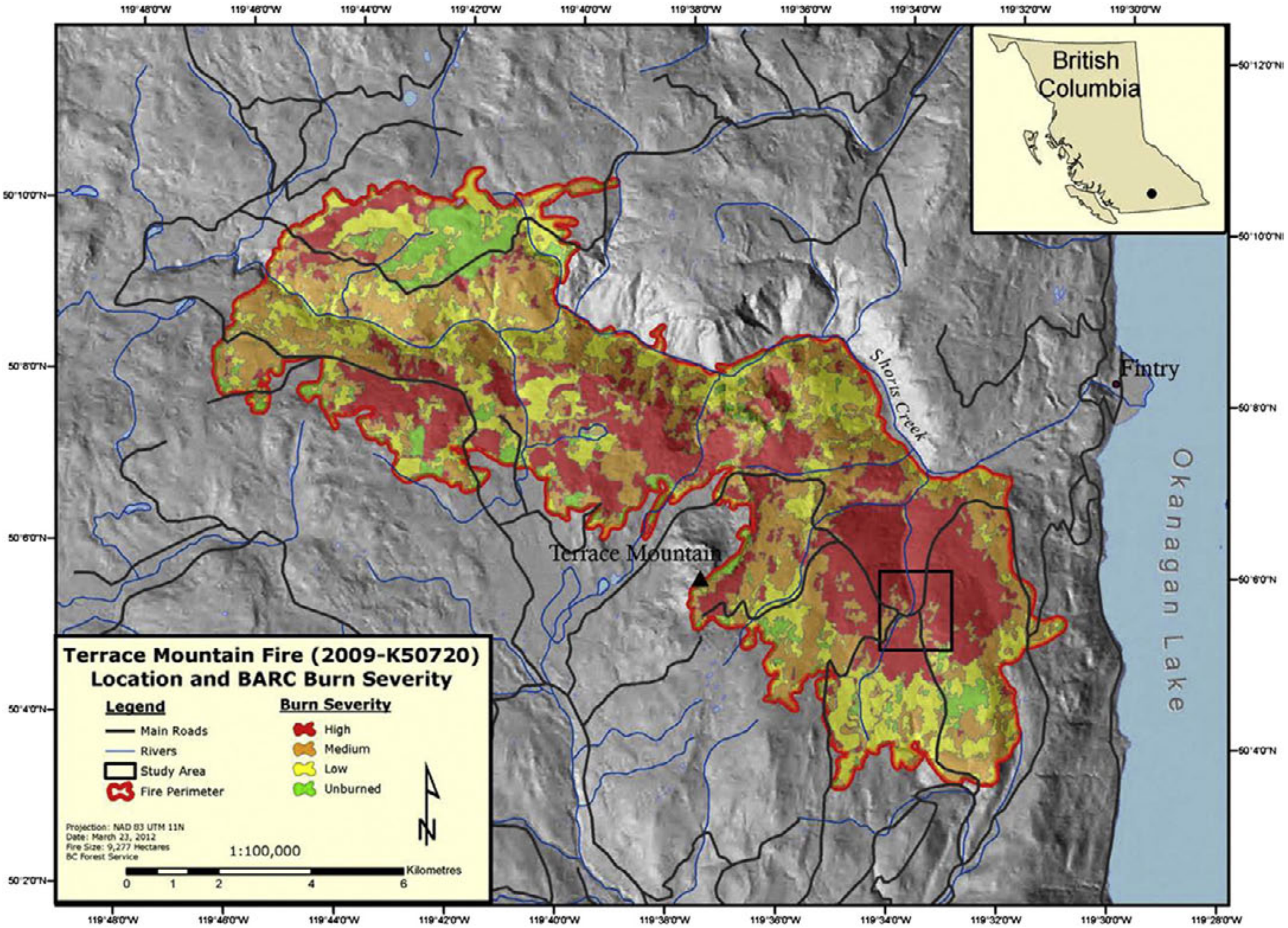

Fig. 1. The Terrace Mountain burn severity map with the study area delineated by the rectangle.

between 0 and 5 cm (upper) was 1.1 g cm^{-3} and that from 5 to 10 cm (lower) was 1.3 g cm^{-3}. Basic soil texture was determined from six soil samples (three samples taken at each of two depths: 5 and 10 cm) near six of the hillslope silt fence plots. The soil had 30–40% coarse fragment (>2 mm) content and 4–6% organic matter content. The remaining soil was composed of about 45% sand, 45%

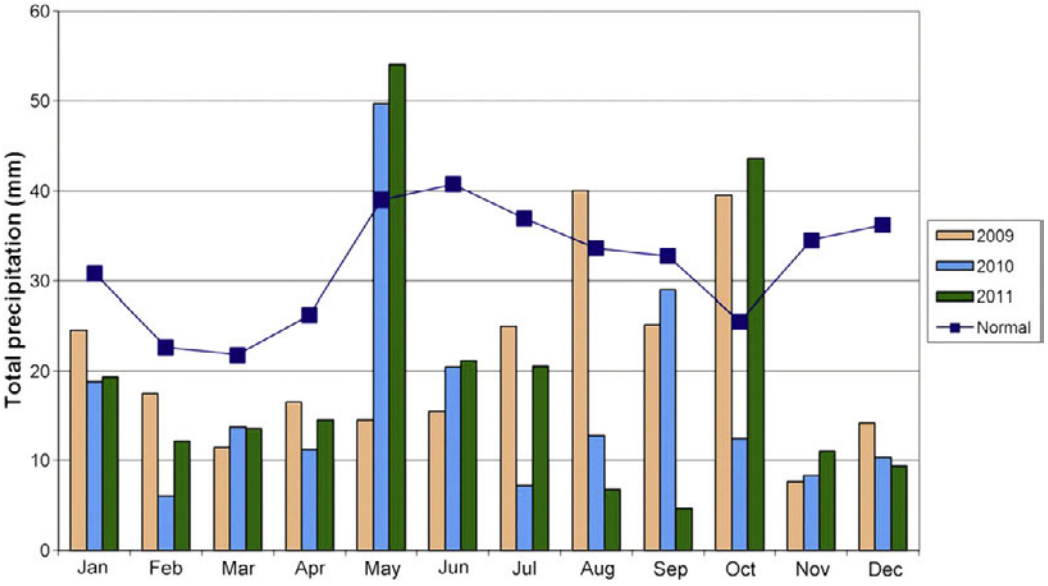

Fig. 2. Monthly precipitation during the study as reported at the Kelowna Airport weather station near the study area.

silt, and 10% clay, which classified it as a loam in the USDA soil classification system.

2.2. Experimental designs, measurements, and analyses

Ground cover was assessed each year within or in close proximity to the plots used in each experiment. In general, ground cover was assessed using a 1-m^2 frame containing a 100-point-intercept grid. The ground cover type (e.g., treatment mulch, litter, woody debris, rock [>25 mm], and live vegetation) at each intersection of the grid was identified (after Chambers and Brown, 1983). The percentage of each type of ground cover was summed to estimate total ground cover (excluding ash), and bare soil was assumed to be the remaining "uncovered" proportion. The mean proportions of applied mulch treatment and live vegetation cover were often analyzed separately to determine mulch longevity and vegetative recovery rates.

Soil water repellency was assessed using the water drop penetration time (WDPT) test (DeBano, 1981) and the soil infiltration rate as measured with a mini-disk infiltrometer (MDI) using the protocol described in Robichaud et al. (2008). Other site data were collected as needed in each experiment and are described in the individual experiment subsections below.

2.2.1. Rainfall simulation

Each year a set of 1-m^2 rainfall simulation plots (18 in 2009 and 15 in 2010) were established in areas that were relatively free from boulders or roots which would prevent the installation of the metal-edged plot frame and collection trough (Table 1). A 1-m^2 steel plot border was pounded into the soil approximately 5 cm deep with 5 cm above ground to prevent inflow and outflow of water from the plot. The down slope edge of the border was level with the ground surface so the runoff and sediment flowed over it and into a trough which funneled into a single point for collection into 1-L sample bottles.

In September of 2009, 15 plots were installed and the three treatments (control, agricultural straw, and wood shreds) were randomly applied to five plots each (Table 1, Figs. 3 and 4a). Agricultural straw was applied at a rate of 0.2 kg m^{-2} (2 Mg ha^{-1}) and wood shreds were applied at 1.3 kg m^{-2} (13 Mg ha $^{-1}$) with fines (wood shreds that were smaller than 25 mm) removed as suggested by Foltz and Wagenbrenner (2010). An additional three plots were installed in an area with a thick cover of ash, to test the effect of ash on runoff and sheet erosion. In August 2010, 15 new plots were installed in a different location within the study area and five replicates of the three treatments were randomly applied at the same rates as in 2009. This was necessary due to the plot damage that occurred during the first round of rainfall simulations.

Before each simulation, ground cover, soil moisture and water repellency were measured adjacent to the plot; soil moisture was also measured in the plot after each simulation. Ground cover was assessed on a 1-m^2 area within each rainfall simulation frame. Soil moisture was measured at the soil surface and at 5 and 15 cm depths using a soil moisture probe (Theta Kit, Delta-T Devices, Burwell, Cambridge, UK). Soil water repellency was determined using the Water Drop Penetration Time (WDPT) test (10 or more drops of water were placed on the soil surface and the time for the drops to infiltrate was measured; after DeBano, 1981) at the mineral soil surface and repeated for several depths between 1 and 3 cm. The depth at which the greatest soil water repellency was found was used to characterize the soil water repellency of the plot. This depth was usually 1 cm. The percentage of water drops that infiltrated in the following time ranges was recorded: <10, 10–40, and >40 s, which corresponded to the respective soil water repellency classifications of None, Moderate, and Strong. This classification of repellency is used by post-fire assessment teams in the USA (USDA-FS, 1995; Robichaud et al., 2008; Parsons et al., 2010). To reduce these data to a single number for analyses, an index of water repellency (WDPT index) was calculated (% Strong + % Moderate / 2) such that the percentage of water drops classified as Moderate influences the WDPT index value half as much as the percentage of water drops classified as Strong. For example, if all 10 water drops infiltrated after more than 40 s (100% Strong) the index would be 100; if all 10 water drops infiltrated in between 10 and 40 s (100% Moderate) the index would be 50. The index provides a spatially averaged measure of water repellency on each plot and reduces the plot-scale variability inherent in water repellency measurements (Woods et al., 2007).

Rainfall simulations were done on the plots using a portable rainfall simulator. The simulator, based on the nozzle-type simulator developed by Edwards et al. (2002), was set at 3 m above the plot. A wind screen was used when winds affected rainfall patterns. Nominal rainfall intensity for this experiment is 65 mm h^{-1} for 20 min; however, actual measured rainfall intensities, corrected for slope, averaged 80 mm h^{-1}. Runoff samples were taken for 30 s of each minute during the simulation. The rainfall simulator and these post-fire rainfall simulation experiments have been described in detail by Covert and Jordan (2009). Each 30-s runoff sample was weighed and dried to determine the amount of runoff and sediment. Time to the start of runoff (min), time to peak runoff (min after runoff start), runoff depth (mm), and total sediment yield (kg m^{-2}) were calculated for each 20-min simulation.

All statistical analyses were conducted using SAS statistical software (SAS Institute Inc., 2008). Non-parametric correlations (SAS Proc Corr Spearman) and scatterplots were used to evaluate the relative strength of controlling factors (ground cover, indexed water repellency, relative infiltration, and soil moisture) for the dependent response variables. The runoff and sediment yields showed some heteroscedasticity, so log (runoff) or fourth-root (sediment yield) transformations were used to make the model residuals more homoscedastic. Linear mixed statistical models (Littel et al., 2006) were developed using time since the fire and treatment as fixed effects, the plot-treatment replicate as a random effect, and the four response variables (runoff depth, sediment yield, time to runoff start, and time to peak runoff). A repeated measures structure was applied to each plot in the statistical model, and the year of the measurement was used as the period of repetition. Least-squares means with a

Table 1
Experimental designs of the three experiments. Number of plots and treatment reps, mean and range of plot areas (with plot length, the more relevant measurement, substituted in the rill simulations) and slopes, and experiment timing. Rainfall simulation plots were newly established in each of the two years. All experiments included three treatments—untreated control, wood shred mulch applied by hand at a nominal rate of 13.0 Mg ha^{-1} and agricultural straw applied by hand at a nominal rate of 2.0 Mg ha^{-1}.

	Total plots	Treatment reps	Plot area (m^2) [range]	Slope (%) [range]	Experiment timing	
					month year	Post-fire year
Rainfall simulation	15 + 3[a]	5	1	41 [34–50]	Sep 2009	0
	15	5		33 [24–41]	Aug 2010	1
Concentrated flow (rill) simulation	21	7	Plot length 9 m	44 [39–48]	Sep 2009	0
					Aug 2010	1
					Aug 2011	2
Sediment yields from natural rainfall	9	3	84 [69–105]	44 [38–51]	Sep 2009–Oct 2011	0–2

[a] In September of 2009, three plots with deep ash cover were added to the basic experimental design.

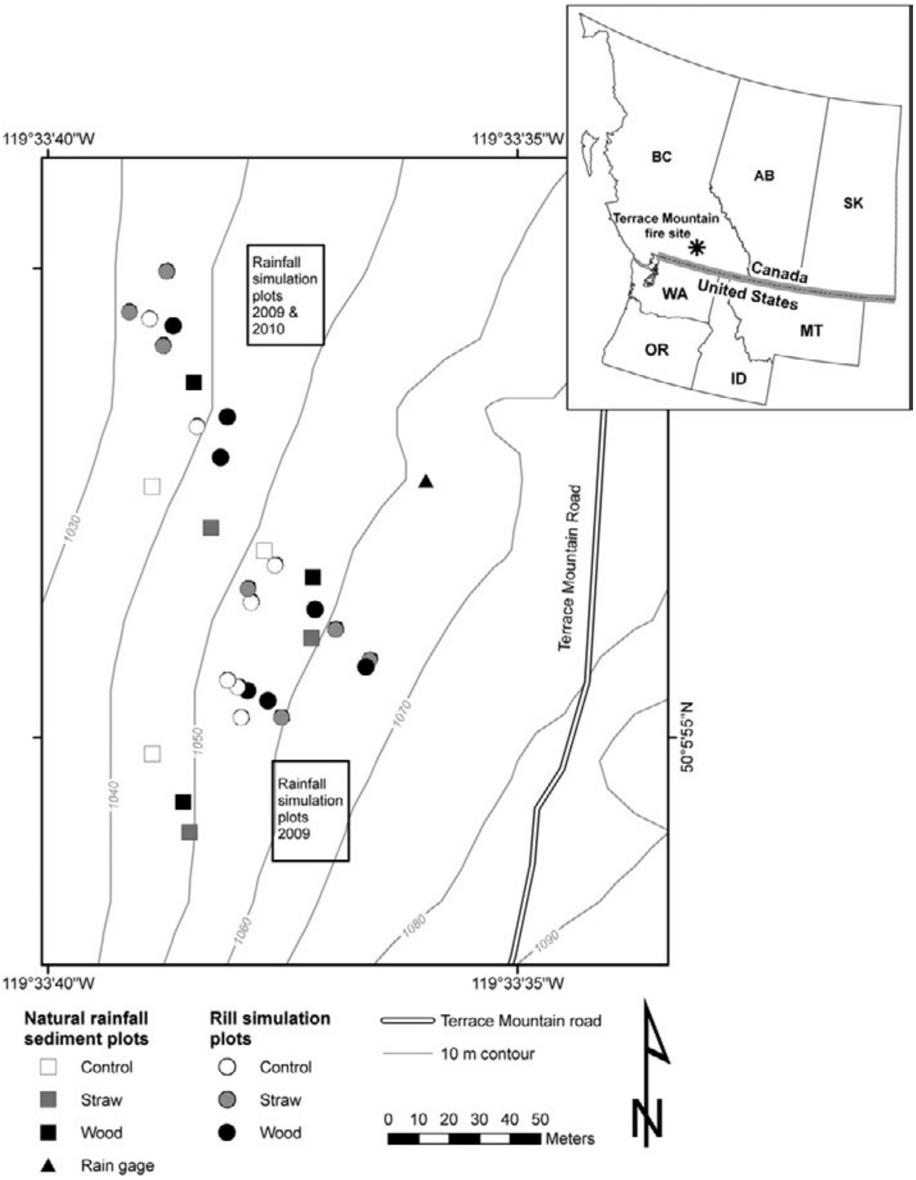

Fig. 3. Site map with two rainfall simulation experiment areas indicated by rectangles. Individual rill simulation and natural rainfall sediment yield hillslope plots are designated by symbols.

Tukey–Kramer adjustment were used to test the significance of multiple comparisons among treatments and years (Ott, 1993). The significance level was 0.05 for all statistical tests.

2.2.2. Rill (concentrated flow) simulations

Rill simulations were run on 21 randomly selected plots, seven of each treatment (control, agricultural straw mulch, and wood shred mulch), in September of 2009 (post-fire year 0) and in August of 2010 and 2011 (Table 1). The agricultural straw mulch and wood shred mulch were applied by hand at 2 and 13 Mg ha^{-1}, respectively. The 9-m long plots were unbounded on the sides, but if needed, Z-shaped sheet metal (10 × 70 cm) was used to funnel the flow to the sampling point at the bottom of the plot (Figs. 3 and 4b). The same plot locations were used for each subsequent year and no additional mulch was added. Before each simulation, ground cover measurements were completed at three locations in each plot and surface soil samples were taken for assessing soil moisture content (Gardner, 1986). In 2009, soil water repellency was assessed near each rill plot by measuring an infiltration rate with a mini-disk infiltrometer (Robichaud et al., 2008); however, negligible soil water repellency was found in subsequent years.

Each simulated runoff experiment (rill simulation) was conducted by releasing water through an energy dissipater at the top of each plot. The hour-long simulation included a sequence of five inflow rates (7, 22, 30, 15, and 48 L min^{-1}) that ran for 12 min each following the protocol established by Robichaud et al. (2010b). Overland flow velocity was measured using a dyed saline solution (Fig. 4b) and two conductivity probes placed in the flow 5 m apart (2 and 7 m from the top of the plot) during each inflow rate (King and Norton, 1992). The flow velocities were average by plot for analysis. The width and depth of flow in each rill were measured with a ruler at 2 and 7 m from the top of the plot during each inflow rate. The total width and average depth of all flows at each location were averaged to produce a mean flow width and depth for each inflow rate by plot. Six timed runoff and suspended sediment samples were collected at the bottom of the plot during each flow rate (30 samples total) and processed in the laboratory to determine runoff rates (L min^{-1}) and sediment flux rates (kg s^{-1}). Rill simulation experiments have been described in more detail in Robichaud et al. (2010b).

Linear mixed models (Littel et al., 2006) were developed using the treatment as a fixed effect, while the plot-treatment replicate was a random effect. Dependent variables were runoff rate, runoff velocity,

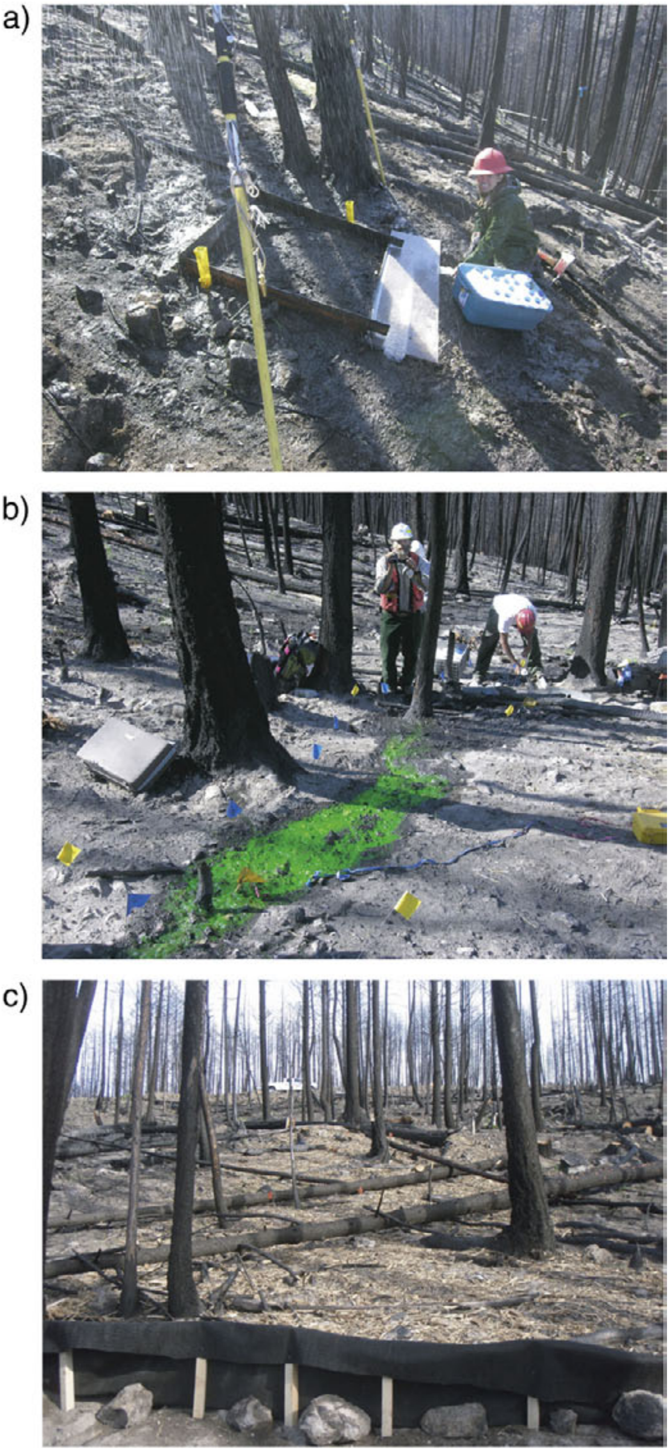

Fig. 4. Three experimental set-ups: a) rainfall simulation (without a windshield) on a 1-m^2 framed control plot; b) rill simulation on a 9-m long control plot during time when green dye (used for flow rate measurements) was present in the overland flow; and c) a hillslope plot treated with wood shreds with a silt fence sediment trap to collect sediment from natural rainfall. Photographs by P. Jordan (a, b), S.A. Covert (c).

sediment flux rate, and flow width and depth, which were all averaged by plot. In 2009, in the same year as the fire, the runoff and sediment flux rates approached a steady-state condition by the fourth sample in each experimental flow rate, so only samples 4–6 were used to compare treatments (Robichaud et al., 2010b). In the subsequent two years (post-fire years 1 and 2), runoff rarely made it to the bottom of plot, especially on the treated plots, and few samples were collected. When there was no runoff at the collection point, no data for the response variables were generated. Consequently, the statistical model was developed using the data from the year of the fire only. The runoff rates, sediment flux rates, and flow velocities showed some heteroscedasticity, so square-root (runoff rate and flow velocity) or fourth-root (sediment flux rate) transformations were used to make the model residuals more homoscedastic. Least-squares means with a Tukey–Kramer adjustment were used to test the significance of multiple comparisons among treatments (Ott, 1993).

2.2.3. Hillslope sediment yields from natural rainfall

Following Robichaud and Brown (2002), nine hillslope plots were installed at the study site on 17–19 September 2009 (Table 1, Fig. 1). Each plot had nominal dimensions of 5 m along the contour by 15 m upslope (Figs. 3 and 4c). At the upper end of each plot, two 20 cm deep diagonal trenches were dug to direct any overland flow from further upslope away from the plot. The three treatments (control, agricultural straw mulch, and wood shred mulch) were randomly assigned to the plots and the straw and wood shreds were spread by hand at the nominal rates of 2 and 13 Mg ha^{-1}, respectively. The plot areas had a range of 69–105 m^2 (mean 84 m^2) and plot slopes ranged from 38 to 51% (mean 44%) (Table 1).

Precipitation at the site was measured using a tipping bucket rain gage located near the sediment fences (Fig. 1). The recorded rainfall amounts and timing were used to determine storm amounts, durations, and 10-min maximum rainfall intensities during the study period. The storm with the highest 10-min rainfall intensity was assigned to the next clean out date while the rainfall amounts were cumulative for the same period. Ground cover measurements (three per plot) were made immediately after plot installation in mid-September 2009 and at the peak of the growing season in August 2010 and 2011. In 2011, cover was estimated from photographs of each plot, rather than direct measurements.

Sediment was collected from the plots in October 2009 before the first major snowfall. In subsequent years, sediment was collected three times—May or June, August, and October. Sediment was removed from inside the silt fence and weighed using a field scale. Any tree material that had obviously fallen or been blown into the sediment at the base of the plot (branches, cones, or bark) was discarded. Although rarely present, large stones that had been dislodged by wildlife were also discarded. If the collected sediment fit into a single sample bag (about 2 kg), the total sample was taken; however, if the accumulated sediment exceeded the capacity of a sample bag, the sample was spread on a piece of geotextile fabric, quartered, and a subsample was collected. This sampling procedure was needed in 2009 (the year of the fire) when the largest sediment yields occurred, but not in subsequent years. In the laboratory, the samples were weighed and oven-dried (100 °C for 24 h) to measure the moisture content and calculate the dry weight. In 2009, mulch material (wood shreds and agricultural straw) was discarded from the accumulated sediment at collection. In subsequent years, a portion of the collected material was grass and leaves, as well as some mulch material. At the lab, the total sample was passed through a 4-mm sieve and the vegetation which remained on the sieve was discarded. Any gravel that remained on the sieve was added to the soil which passed through. Some fine vegetative material (mostly grass seed) could not readily be separated from the sediment; but given the negligible weight of these organic particles, the calculated dry weights were considered as all eroded sediment.

Data analyses for the hillslope plot sediment yields measured from natural rainfall were similar to those used in Robichaud et al. (2013). The ground cover for each plot was averaged across quadrants by cover category. Each plot was then treated as an independent observation of ground cover and live vegetation for each treatment and site. Repeated-measures analyses were conducted using each plot as the subject, and the post-fire year as the period of repetition. Least significant differences were used to compare differences in least-squares means between total ground cover and live vegetation by treatment and year (Littel et al., 2006; SAS Institute Inc., 2008).

Again, a linear mixed model (Littel et al., 2006) was developed using the post-fire year and treatment as fixed effects, while the plot-treatment replicate as a random effect. The dependent variable was sediment yield, which was log-transformed to reduce residual heteroscedascity. The covariance structure of the repeated measures on each plot was modeled using a spatial power function and the number of days between the fire and the clean out event (Littel et al., 2006). Differences in the log-transformed sediment yields were compared using the least squares mean estimates for each treatment and post-fire year. A Tukey–Kramer adjustment was used for comparisons of multiple least-squares means.

3. Results

3.1. Rainfall simulation

3.1.1. Ground cover

Several soil characteristics related to runoff and sediment yield were measured prior to the rainfall simulation (Table 2). Immediately after the fire (September 2009), ground cover on the control plots averaged 10%. The "ash" plots had a mean cover of 96% ash and only 4% other ground cover. The agricultural straw plots had 85% cover (80% was treatment), and the wood shred plots had 71% cover (66% was treatment) (Table 2). In the following August (2010, post-fire year 1), new 1-m^2 rainfall simulation plots were established and treated with straw and wood shred mulches at the same rates as in the prior year (post-fire year 0). Newly applied straw mulches provided 53% of the total cover (75%) and newly applied wood shreds provided 49% of the 73% total ground cover (Table 2). In both years, the treated plots had at least twice as much ground cover as the control plots.

3.1.2. Soil properties

Immediately after the fire, the WDPT index of soil water repellency was similar across treatments and ranged from 24 to 38, indicating that less than 40% of the total plot area was classified as strong water repellency. In the following year (post-fire year 1), the WDPT index ranged from 4 to 10 indicating that strong water repellency had decreased to less than 10% on all plots (Table 2). Similarly, low MDI infiltration rates (1.3–4.9 mL min^{-1}) indicating high to moderate water repellency were measured in post-fire year 0 and higher MDI infiltration rates (11–14 mL min^{-1}) indicating no water repellency were measured in post-fire year 1 (Table 2; Robichaud et al., 2008). Soil moisture was measured at the soil surface and at 5 cm depth. Regardless of the depth or treatment, volumetric soil moisture ranged from about 0.05 to 0.09 in the year of the fire and was even lower (0.01–0.03) in the following August (post-fire year 1) (Table 2).

3.1.3. Runoff and sediment response

Analyzing both years of data simultaneously, the response variables, runoff and sediment yield, were analyzed to determine significant correlations with several soil covariates. Runoff was significantly correlated to only one covariate—surface soil moisture—with a fairly weak positive relationship (the Spearman rank correlation coefficient $\rho = 0.36$) (Fig. 5). In contrast, sediment yield was strongly correlated to several of the covariates. Significant positive correlations were found between sediment yield and water repellency (WDPT index) ($\rho = 0.65$) and surface soil moisture ($\rho = 0.62$); significant negative correlations were found with MDI infiltration rates ($\rho = -0.59$) and ground cover ($\rho = -0.52$) (Fig. 5). Significant covariates from the correlation and regression analyses were tested in the mixed model, but none of the soil factors were statistically significant in predicting runoff or sediment yield in the model.

The individual treatment effects on responding variables were scattered. In the year of the fire (post-fire year 0), sediment yields were significantly less on the agricultural straw (0.23 kg m^{-2}) and wood shred plots (0.18 kg m^{-2}) as compared to the control plots (0.60 kg m^{-2}) but runoff was not significantly different (Table 2). The plots with high ash cover (96%) did not have significantly different sediment yields (0.37 kg m^{-2}) compared to the controls, but did have significantly lower runoff (5.7 mm) than both the control and treated plots. In the following year (post-fire year 1), sediment yield values were almost an order of magnitude smaller on the agricultural straw and wood shred plots (0.03 kg m^{-2}) as compared to the control plots (0.10 kg m^{-2}), but the difference was not significant (Table 2). Runoff values were similar to those measured in post-fire year 0 on all plots (~10–13 mm) and were not significantly different by treatment.

Because the agricultural straw and wood shred treatments had similar sediment yields and runoff amounts that were not significantly different (Table 2), they were combined into a single "treated" class and compared to the control plots. Similar to the individual results, the difference in runoff rates measured on the control (12.5 mm) and treated (13.7 mm) plots was not different in either year while the sediment yields from the treated plots (0.20 kg m^{-2}) were significantly smaller than on the controls (0.60 kg m^{-2}) in post-fire year 0 but not different in post-fire year 1 (Table 2).

In the year of the fire, the shortest runoff start time was on the control plots (2.1 min), followed by the wood shred plots and then the agricultural straw plots (2.5 and 3.0 min, respectively). Runoff start time was greatest on the ash covered plots (5.4 min), which was significantly different from that of the control (Table 2). Peak runoff occurred about 12 to 14 min after runoff started on all plots (Table 2). In post-fire year 1, runoff start times were similar to the

Table 2

Rainfall simulation results and statistical analysis. Mean values of response variables and the pre-simulation soil characteristics by year and by treatment. Soil water repellency was measured using the water drop penetration time (WDPT) test and reported as an index value, and a relative soil infiltration rate was measured using a mini-disk infiltrometer (MDI). Differences in superscript letters indicate significant differences ($\alpha = 0.05$) among the values within a column.

Post-fire year	Treatment [*n*]	Sediment yield (kg m^{-2})	Runoff (mm)	Runoff start time (min)	Runoff peak time (min)	Pre-simulation soil characteristics				
						Ground cover (%)	WDPT index (0–100)	MDI (mL min^{-1})	Soil moisture (vol.)	
									surface	5 cm depth
0	Control [5]	0.60^{a}	12.5^{a}	2.1^{a}	12.9^{a}	10	30	4.7	0.06	0.07
	Ash [3]	0.37^{ab}	5.7^{b}	5.4^{b}	12.8^{a}	4	38	1.3	0.05	0.06
	Straw [5]	0.23^{bc}	14.9^{a}	3.0^{a}	13.9^{a}	85	24	4.9	0.07	0.09
	Wood [5]	0.18^{bc}	12.6^{a}	2.5^{a}	11.6^{a}	71	32	3.7	0.06	0.07
1	Control [5]	0.10^{cd}	12.8^{a}	2.0^{a}	12.7^{a}	37	4	14	0.01	0.01
	Straw [5]	0.03^{d}	9.6^{ab}	2.9^{a}	9.4^{a}	75	6	14	0.02	0.01
	Wood [5]	0.03^{d}	10.0^{ab}	3.3^{ab}	11.7^{a}	73	10	11	0.01	0.03

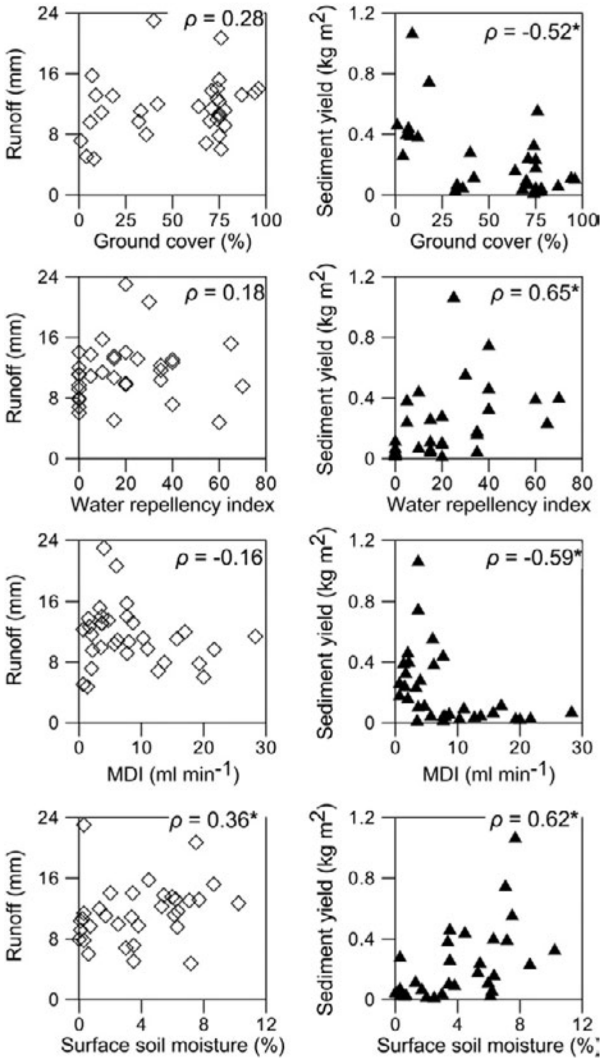

Fig. 5. Measured values of four variables (ground cover, water repellency index, MDI infiltration rate, and surface soil moisture) from all the rainfall simulation plots, individually plotted against runoff amount (left column of plots) and sediment yield (right column of plots). The Spearman rank correlation coefficient (ρ) for the plot variables is listed in the upper right corner. Statistically significant correlations ($p \leq 0.05$) are designated by *.

previous year (~2 to 3 min), and peak runoff occurred 9 to 13 min after runoff started, none of which were significantly different (Table 2).

3.2. Rill simulation

3.2.1. Ground cover

Similar to the rainfall simulation experiment, total ground cover on the rill simulation control plots was low in the year of the fire (19%) and consisted mostly of charred organic litter. Total cover was much higher on the treated plots due to the addition of the agricultural straw and wood shred mulches. Little to no live vegetation was measured on any of the plots. The straw mulch plots had 89% total ground cover, 82% of which was treatment cover and the wood shred plots had 76% total cover, 68% of which was treatment (Table 3). By August of 2010, the first post-fire year, total cover increased on the control plots (52%) and on the wood shred plots (87%), but total cover decreased on the straw mulch plots (71%). Live vegetation had increased on all plots, but the cover provided by the straw mulch had decreased by 46% while the cover provided by wood shred mulch had only decreased by about 20%. By August 2011, the second post-fire year, live vegetation provided about 50% cover on the plots regardless of treatment and total cover had increased to 84% on the control plots, 90% on the agricultural straw plots, and 98% on the wood shred plots. The cover provided by the straw mulch treatment decreased by nearly 65% during the study period compared to a 35% decrease in wood shred treatment cover in the same period (Table 3; Fig. 6).

3.2.2. Soil properties

Gravimetric soil moisture content, measured in late summer, varied little among treatment plots and years, and was overall fairly low. The mean moisture was 6.3% in 2009, the year of the fire, 4.2% in 2010, and 1.4% in 2011.

3.2.3. Flow velocity, runoff and sediment response

In the rill experiment, the inflow released at the top of a plot was collected as runoff samples at the bottom of the plot; however, if the overland flow infiltrated the soil prior to reaching the bottom of the plot no sample was collected. During the rill simulations, there were many uncollected samples due to the lack of runoff at the collection point at the bottom of the plot. In the year of the fire, runoff samples from the control plots were collected during 87% of the sampling periods as compared to about 70% of the sampling periods on the treated plots (Table 3). The proportion of runoff samples available declined in each of the next two years when the rill simulations were repeated. In post-fire year 2 (2011) when the third rill simulations were conducted, the control plots had runoff during 17% of the sampling periods and agricultural straw and wood shred plots had runoff during only 1% and 3% of the sampling periods, respectively (Table 3). Flow widths and depths decreased slightly over time; this is likely related to the general decrease in overland flow on all plots rather than a treatment effect (Table 3). When no runoff was available to be collected, no data were measured for the responding variables. Since there were significantly fewer data available for analyses in post-fire years 1 and 2 as compared to post-fire year 0, we only tested for treatment effects in post-fire year 0 (Table 4).

In the first rill simulations (September 2009, post-fire year 0), all plots produced runoff during all or part of the simulation and there were no statistical differences in mean runoff rates (ranging from 9.0 to 12.0 L min^{-1}) among the treatments (Table 4). In post-fire year 1, the control plots produced measureable runoff in two-thirds of the sampling periods and the mean runoff value was slightly less than that of the previous year. The lack of runoff at the bottoms of the treated plots in post-fire years 1 and 2 and from the control plots in post-fire year 2 (median values of 0) prevented statistical comparisons of means over time (Tables 3 and 4). Similarly, the mean sediment flux rates (0.43–0.88 g s^{-1}) were not significantly different among the three treatments in the year of the fire and comparisons by year were precluded by lack of runoff samples (Table 4). In contrast, flow velocity did show a treatment effect. In 2009, the year of the fire, the mean flow velocity on the control plots (0.21 m s^{-1}) was significantly greater than 0.10 m s^{-1} measured on both the straw and wood shred treated plots (Table 4). Because of the similarities of the flow velocities, runoff rates, and sediment flux rates on the straw and wood shreds plots in the year of the fire (Table 3 and Set A in Table 4), they were combined into a single "treated" class to compare to the control plots. Combining the treatments increased the sample size used in analysis, and resulted in an observed treatment effect in flow velocity and sediment flux rate, but not in runoff rate (Table 4).

3.3. Hillslope sediment yields from natural rainfall events

3.3.1. Rainfall

The years of 2009–2011 were generally drier than the average in the Okanagan Valley, based on the total annual precipitation at Kelowna (Fig. 2). Weather conditions are typically consistent throughout the

Table 3
Rill simulation results. Mean total ground cover and treatment ground cover, the number and percentage of samples that were available to be collected shown by post-fire year and treatment. There were 105 potential samples to be taken for each treatment in each year; however, many samples were not collected because overland flow did not reach the end of the plot. When no runoff was collected, the value of the response variable was listed as 0. The median values of the rill simulation response variables (flow velocity, runoff rate, sediment flux rate, flow width, and flow depth) are reported by treatment and year. "Nm" indicates that the variable was not measured.

Post-fire year	Treatment	Ground cover		Runoff samples taken		Median values				
		Total (%)	Treatment (%)	(#)	(%)	Flow velocity ($m\ s^{-1}$)	Runoff rate ($L\ min^{-1}$)	Sediment flux ($kg\ s^{-1} \times 10^{-3}$)	Flow width (m)	Flow depth (m)
0	Control	19	0	91	87	0.17	11	0.42	0.54	0.005
	Straw	89	82	74	70	0.08	6.8	0.11	0.46	0.005
	Wood	76	68	75	71	0.08	6.0	0.06	0.77	0.005
1	Control	52	0	72	69	0.14	4.8	0.05	0.34	0.005
	Straw	71	36	16	15	0	0	0	0.17	0.002
	Wood	87	49	6	6	0	0	0	0.17	0.002
2	Control	84	0	18	17	Nm	0	0	0	0
	Straw	90	18	1	1	Nm	0	0	0	0
	Wood	98	33	3	3	Nm	0	0	0	0

Okanagan Valley, and the Kelowna Airport weather station provides a good index for the entire valley. In the spring and early summer of 2009, the rainfall was well below the average and, coupled with greater than average temperatures, contributed to the high fire hazard that existed when the fire started in mid-July. However, greater than normal precipitation, which included several major rain events, occurred in August through October of 2009 (Fig. 2). The month of May in 2010 and 2011 also had greater than average precipitation that included higher intensity events (Fig. 2; Table 5). The highest intensity rain event in the first post-fire year occurred on 23 Jun 2010 with peak 10-min intensity (I_{10}) of 47 mm h^{-1} (Table 5). For durations of 10 and 30 min, this maximum intensity had a return period of about 5 years as compared to the Environment Canada Kelowna Airport rainfall intensity–duration–frequency curve. All other rainfall events had maximum intensities with return periods of 2 years or less (Table 5).

3.3.2. Ground cover

In 2009, the year of the fire, total ground cover on the control plots (14%) was significantly lower than either the agricultural straw or the wood shred plots and significantly lower than the control plots in post-fire years 1 and 2 (Table 6). Almost no live vegetation cover (≤1%) was measured on any plots in the year of the fire. The straw mulch plots had 74% (67% of which was treatment) the wood shred plots had 65% (61% was treatment) in post-fire year 0 (Table 6, Fig. 6). In the first post-fire year, cover increased to 26% on the control plots, decreased to 74% on the straw plots, and remained the same (69%) on the wood shred plots, but the control plots still had significantly less total cover compared to either agricultural straw or wood shred mulched plots. In the second post-fire year, total cover ranged from 67 to 70% on all plots regardless of treatment (Table 6). The changes in total ground cover over time were generally the result of live vegetation (and litter) increasing and mulch treatment decreasing (Fig. 6). Straw mulch decreased more rapidly than the wood shred mulch during the study and by the end of the second post-fire year (2011) straw mulch was only 3% of the total ground cover compared to wood shred mulch being 19% of the total ground cover. However, vegetation increased more rapidly on the straw mulch plots than on control or wood shred plots and by the end of the second post-fire year live vegetation constituted 61% of the total cover on the straw mulch plots, 40% on the control plots, and 45% on the wood shred plots (Fig. 6).

3.3.3. Sediment response

In 2009, the year of the fire, the hillslope plots were cleaned out once about 6 weeks after they were installed. During that interval, the rain event with the maximum 10-minute rainfall intensity (I_{10}) was 13.7 mm h^{-1}, and the sediment yields of 697, 60, and 77 kg ha^{-1} that were measured from the control, agricultural straw, and wood shred plots, respectively, were attributed to that event (Table 5). In the following year (post-fire year 1), the highest sediment yields were attributed to a storm with an I_{10} of 47.2 mm h^{-1} which was also the highest 10-minute rainfall intensity measured during the study period. Sediment yields on the control plots averaged 174 kg ha^{-1}, and on the agricultural straw and wood shred plots, 37 and 53 kg ha^{-1}, respectively (Table 5). These sediment yields were only exceeded by the

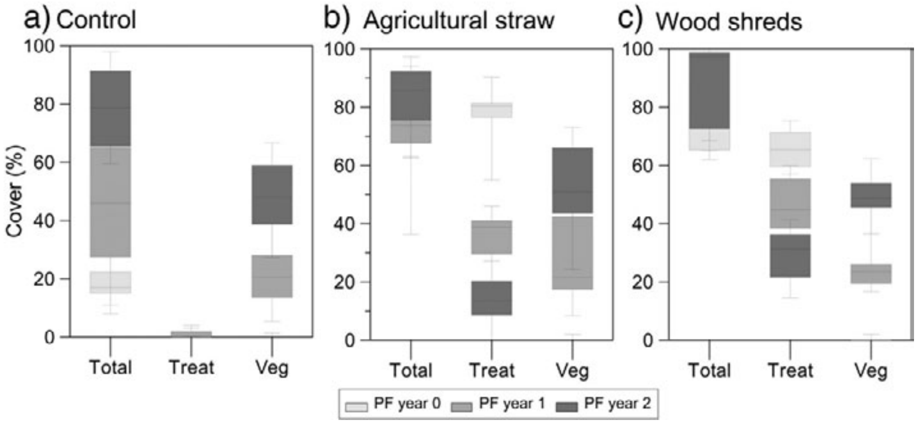

Fig. 6. Ground cover data from the rill simulation and hillslope sediment plots, shown using box and whisker plots for the data range, median, and quartiles by treatment (control, agricultural straw, and wood shreds) and year. Three ground cover categories, total ground cover (Total), mulch treatment (Treat), and live vegetation (Veg), were plotted. Since total ground cover included litter, woody debris, and rock in addition to mulch treatments and live vegetation, a Total plot may show a larger percent cover than the sum of the related Treat and Veg plots.

Table 4
Rill simulation statistical model results. Mean and standard deviation (in parenthesis) for flow velocity (m s^{-1}), runoff rate (L min^{-1}), and sediment flux (kg s^{-1} × 10^{-3}) by treatment in the year of the fire (Set A). Data and analyses are repeated with agricultural straw and wood shreds combined into a single "treated" category (Set B). Differences in superscript letters indicate significant differences ($\alpha = 0.05$) among the three values in a column in Set A or between the two values in a column in Set B. The [n] listed in the "Treatment" column reflects the number of samples that were collected and applies to all variables with the exception of the runoff rate where $n = 105$ for all treatments.

Post-fire year [Set]	Treatment [n]	Flow velocity (m s^{-1})	Runoff rate (L min^{-1})	Sediment flux (kg s^{-1} × 10^{-3})
0 [A]	Control [91]	0.21 (0.07)^{a}	12 (11)^{a}	0.88 (0.98)^{a}
	Straw [74]	0.10 (0.03)^{b}	9.0 (9.3)^{a}	0.43 (0.52)^{a}
	Wood [75]	0.10 (0.04)^{b}	9.2 (9.7)^{a}	0.50 (0.71)^{a}
0 [B]	Control [91]	0.21 (0.07)^{a}	12 (11)^{a}	0.88 (0.98)^{a}
	Treated [149]	0.10 (0.04)^{b}	9.1 (9.5)^{ab}	0.47 (0.62)^{b}

Table 6
Analysis of hillslope sediment yields from natural rainfall. Mean, standard deviation (in parenthesis), and significance based on statistical model results for total ground cover (%) and sediment yield (kg ha^{-1}) by treatment (agricultural straw and wood shred treatments are combined into a single "Treated" category) and post-fire year with interaction included. The number of individual sediment yield measurements is a combination of the number of plots and the number of clean outs (measurements). Differences in superscript letters indicate significant differences ($\alpha = 0.05$) among the values within a column (i.e., for all years).

Post-fire year	Treatment	Sediment yield measurements (#)	Total ground cover (%)	Sediment yield (kg ha^{-1})
0	Control	3 [3 plots/1 clean out]	14 (4.8)^{b}	697 (823)^{a}
	Treated	6 [6 plots/1 clean out]	70 (8.2)^{a}	69 (75)^{abc}
1	Control	9 [3 plots/3 clean outs]	26 (7.2)^{b}	104 (98)^{ab}
	Treated	18 [6 plots/3 clean outs]	72 (7.4)^{a}	26 (35)^{bc}
2	Control	9 [3 plots/3 clean outs]	67 (6.8)^{a}	5.2 (5.1)^{cd}
	Treated	18 [6 plots/3 clean outs]	70 (4.3)^{a}	1.7 (2.0)^{d}

first clean out in the year of the fire. In the second post-fire year, the greatest sediment yields were attributed to a rain event with an I_{10} of 13.7 mm h^{-1}, which was the event with the greatest I_{10} for the period between clean out, but not the event with the greatest I_{10} measured in post-fire year 2 (32.0 mm h^{-1}). Sediment yields in the second post-fire year were one to two orders of magnitude smaller than those in the previous two years, with a range of 9.7 kg ha^{-1} from the control plots to 0.3 kg ha^{-1} from the agricultural straw mulch plots (Table 5).

The effect of time was highly significant for predicting sediment yields in the statistical model (Table 7); sediment yields decreased significantly each post-fire year. However, there were no statistical differences among model sediment yield predictions for the control, straw, and wood shred plots (no treatment effect), and similarly, there were no significant differences among the post-fire year and treatment interactions (Table 6). As with the other experiments, we combined agricultural straw and wood shreds into a single "treated" class and compared sediment yield predictions for the treated plots to the control plots. The effect of time (post-fire year) was again significant, and the interaction between time and treatment was not significant. However, with the data combined into just two classes, treated and control, the treatment effect alone was significant ($p = 0.04$; Table 8).

4. Discussion

4.1. Site factors

All three experiments were influenced by natural rainfall. The sediment yields from hillslope plots were, of course, directly driven by natural rainfall, but the rainfall and rill simulation experiments were also impacted by the post-fire vegetative response to the natural rainfall. In the months after the fire, the total rainfall was high (an estimated 53 mm in the last days of the fire in August and 109 mm in September and October, 2009), but the rainfall intensities were low (13.7 mm h^{-1}). During field work in the burn area several days after the August rain event, only isolated instances of localized soil erosion were observed. During the installation of the hillslope sediment fence plots in September, small soil pedestals and transported ash that had accumulated in low spots were noted, but no significant rilling was observed except in one plot. During May of both 2010 and 2011, rainfall was well above normal (Fig. 2) and vegetation responded well to the early spring rains. In the first post-fire year (2010), live vegetation cover ranged from 17 to 28%, and in the second post-fire year, an unusually late snowmelt combined with the above normal May rainfall supported a robust early season growth of vegetation in the burned area.

Soil water repellency may have had some minor impact on the experiments. Moderate soil water repellency was measured at various locations within the research site immediately after the fire, but subsequent measurements in the first and second post-fire years found little evidence of water repellency remaining in the soil. As soil water repellency decreased, it is likely that infiltration increased and contributed to the reduced overland flow rates observed in post-fire years 1 and 2.

4.2. Rainfall simulation

Although only small plot runoff and sheet erosion were evaluated with rainfall simulation, it provides an insight into the effects of the two mulches on infiltration and easily detached soil. Immediately after the fire, runoff amounts were not affected by the mulch; since wood shreds and agricultural straw have little water holding capacity, there was little additional storage of water by the mulches. The mulch appeared to have slowed the runoff, probably by increasing the roughness, such that the runoff took longer to get to the bottom of the plot. The plots with the thick ash layer on the surface had significantly less runoff, 5.7 mm as compared to 12.5 mm on the control,

Table 5
Hillslope sediment yields from natural rainfall. Clean out date, time since previous clean-out, date and characteristics of the 10-min maximum rainfall intensity (I_{10}) rain event to which the mean sediment yields (kg ha^{-1}) were attributed. The sediment yields from the agricultural straw and wood shred plots were combined and shown in a separate column as "Treated".

Clean out date [post-fire year]	Time between clean out (days)	Total rainfall in period (mm)	Maximum I_{10} event			Sediment yield (kg ha^{-1})			
			Date	Event rainfall (mm)	I_{10} (mm h^{-1})	Control ($n = 3$)	Straw ($n = 3$)	Wood ($n = 3$)	Treated ($n = 6$)
28 Oct 2009 [0]	39[a]	71.4	17 Oct 2009	37.3	13.7	697	60	77	69
17 Jun 2010 [1]	232	130.8	19 May 2010	9.9	10.7	110	21	25	23
11 Aug 2010 [1]	55	30.7	23 Jun 2010	10.2	47.2	174	37	53	45
17 Oct 2010 [1]	61	62.5	19 Sep 2010	12.7	7.6	28	9.4	9.2	9.3
18 May 2011 [2]	219	63.0	7 Nov 2010	10.7	13.7	9.1	2.8	4.6	3.7
16 Aug 2011 [2]	90	88.6	17 Jul 2011	9.1	32.0	2.2	0.8	1.1	0.9
11 Oct 2011 [2]	56	78.2	4 Oct 2011	27.2	7.6	4.3	0.3	0.4	0.3

[a] Days since plot installations.

Table 7
Analysis of hillslope sediment yields from natural rainfall. Mean, standard deviation (in parenthesis), and significance based on statistical model results for sediment yield (kg ha^{-1}) by post-fire year without regard to treatment. The number of individual sediment yield measurements is a combination of the number of plots and the number of clean outs (measurements). Differences in superscript letters indicate significant differences ($\alpha = 0.05$) among the values within a column.

Post-fire year	Sediment yield measurements (#)	Sediment yield (kg ha^{-1})
0	9 [9 plots/1 clean out]	278 (521)^{a}
1	27 [9 plots/3 clean outs]	52 (72)^{b}
2	27 [9 plots/3 clean outs]	2.8 (3.7)^{c}

and a significantly later time to the start of runoff (Table 2). These results corroborate similar findings by Cerdà and Doerr (2008) and Woods and Balfour (2008, 2010) who found that ash is very absorbent and is able to store water and increase infiltration when present on the soil.

In the year of the fire, sediment yields from the treated plots were significantly less and about one-third that of the untreated control plots (Table 2), yet runoff rates were essentially unchanged by the addition of the mulch treatments. The mulches presumably reduced the impact of the raindrop energy and provided physical obstructions that may hold soil in place, which substantially decreased the amount of sediment that was detached and available for transport compared to the control plots. However, the amount of rainfall that resulted in runoff was about the same on the treated as on the untreated plots. The moderate soil water repellency that was measured in the year of the fire likely influenced the slightly greater runoff rates measured that year as compared to later years. The application of mulch did not appear to influence soil water repellency as no correlation between water repellency and treatment was found. By the first post-fire year, water repellency and soil moisture were lower, and overall, runoff rates were slightly lower than in the previous year. Sediment yields in the first post-fire year were much lower, coinciding with the growth of vegetation and a decrease in runoff (Fig. 5).

4.3. Rill simulation

The maximum runoff response in the rill simulations was measured in the year of the fire when 87% of the control plots and 70% of the treated plots produced measurable runoff collected at the bottom of the 9-m plot. Runoff decreased dramatically in the first and second post-fire years with zero runoff being measured on the majority of the plots, indicating that a major portion of the inflow infiltrated prior to reaching the collection point at the bottom of the plot. The loss of soil water repellency between the year of the fire and the first post-fire year likely contributed to the increased infiltration; yet the change in soil water repellency alone seems insufficient to explain these unexpected results. Although Robichaud et al. (2010b) found that significant infiltration occurred over the 9-m plot length and that runoff and sediment flux rates decreased as plot length increased, the inflow rates applied during the hour-long rill simulations were high and in similar studies in the western US where these same inflow rates were applied, it was rare to have zero runoff from burned plots. In addition, sediment flux rates were lower on this site (0.88×10^{-3} kg s^{-1}) compared to a northwest US post-fire site (2.9×10^{-3} kg s^{-1}) with similar soil burn severity and slopes (Robichaud et al., 2010b). Although these noted differences in post-fire responses were likely due to disparities among the sites, we have questioned the high soil burn severity classification of the current study site.

Table 8
Analysis of hillslope sediment yields from natural rainfall. Mean, standard deviation (in parenthesis), and significance based on statistical model results of sediment yield (kg ha^{-1}) by treatment (agricultural straw and wood shred treatments are combined into a single "Treated" category). The number of individual sediment yield measurements is a combination of the number of plots and the number of clean outs (measurements). Differences in superscript letters indicate significant differences ($\alpha = 0.05$) among the values within a column.

Treatment	Sediment yield measurements (#)	Sediment yield (kg ha^{-1})
Control	21 [3 plots/7 clean outs]	146 (356)^{a}
Treated	42 [6 plots/7 clean outs]	22 (41)^{b}

Mean and median flow velocities, runoff rates, and sediment yields on the treated plots were lower than their respective controls in all years, although differences were not always significant (Tables 3 and 4). The additional ground cover provided by the treatments increased surface roughness that slowed the flow velocity and diverted flow paths, which likely reduced the potential for overland flow to concentrate into rill flow. In addition, overland flow is often held behind mini debris dams that are created when mulch pieces (and other litter) interlock on the soil surface (Foltz and Copeland, 2008). These small ephemeral "pondings" of the flow may increase infiltration. Although it is difficult to determine the proportion of erosion reduction that can be attributed to slowing overland flow velocity (as opposed to increasing ponding, protecting soil from raindrop impact, etc.), it is clear that increased ground cover is effective in reducing erosion. For example, Benavides-Solorio and MacDonald (2005) reported that they found the dominant control on post-fire sediment yields was ground cover, and that the amount of (non-treatment) ground cover is strongly related to time since fire. In our study, the runoff and sediment flux rates measured on the control plots were nearly equivalent to the values measured on the treated plots in the previous year. In essence, the additional ground cover provided by the agricultural straw and wood shreds approximated an additional year of recovery (Fig. 7). This apparent trend observed in post-fire years 1 and 2 would likely be less observable in later years when ground cover was similar across all plots.

4.4. Hillslope sediment yields

This study found a very strong relationship between time since fire and sediment yields (Table 7) and less of a relationship between I_{10} and sediment yields, especially on the treated plots (Table 5). The effect of time passing is likely related to the natural increase in ground cover through vegetation recovery and accumulated litter. The highest sediment yields were in the year of the fire regardless of treatment or the lack of it. The event with the greatest I_{10} (47.2 mm h^{-1}) occurred in the first post-fire year and produced the greatest sediment yields on all plots (Table 5). However, the sediment yields from this event were much lower (75% less on the control plots and 35% less on the treated plots) than the sediment yields from a event with a much lower I_{10} (13.7 mm h^{-1}) in the previous year (Table 5). These results indicate that time since fire and rainfall intensity are both significant factors for predicting post-fire sediment yields and are not easily separable, which is consistent with Robichaud et al. (2010a).

4.5. Effectiveness of wood shred and agricultural straw mulch treatments

In the year of the fire, mean sediment yields from the treated plots were always less (although the differences were not always significant) than those from the control plots in all three experiments. However, there were no significant differences between the sediment yields from the agricultural straw and wood shred plots. In the rainfall simulation experiment, wood shreds produced slightly less sediment than the agricultural straw (Table 2), while in the rill simulation and the hillslope plot experiments the agricultural straw mulch plots produced slightly less sediment than the wood shreds plots (Tables 3 and 4). Runoff production followed the same trends in the rainfall and rill simulation experiments (Tables 2 and 3). However, there were no statistically significant differences between the agricultural straw and wood shreds plots in any experiment. By combining the straw and wood shred mulch treatments into a single treated category, we showed that the additional ground cover

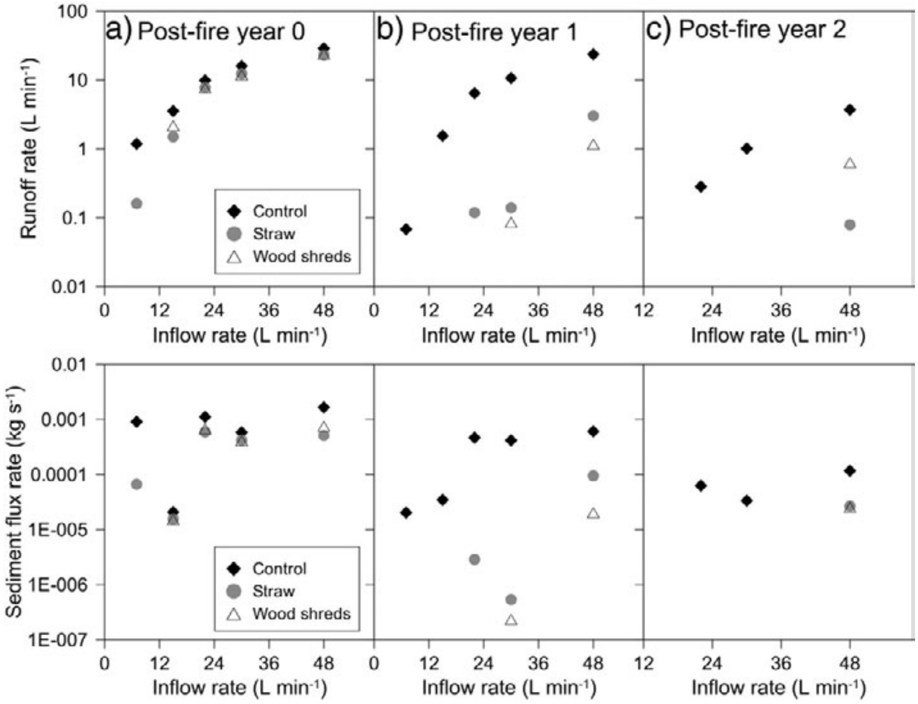

Fig. 7. Inflow rates during the rill simulation experiment plotted against runoff rates and sediment flux. Inflow rates are plotted separately by treatment (control, agricultural straw, and wood shreds) and year (post-fire years 0, 1, and 2). Data for post-fire years 1 and 2 are limited as runoff did not reach the collection point during many inflow sampling intervals.

provided by either mulch treatment significantly lowered overland flow velocities (in the rill experiment) and sediment yields (in all three experiments) in the year of the fire (Tables 2, 4, and 7).

In these experiments the vegetation recovery rates were similar regardless of treatment. Although the short duration of the study may have precluded seeing differences in later years, the wetter than normal spring weather in 2010 and 2011 provided ample moisture for natural vegetation growth; by post-fire year 2, the vegetation component of the cover ranged from 40 to 65% on the rill and hillslope sediment yield plots. The agricultural straw mulch cover decreased by nearly 80% during the study period whereas the wood shreds only decreased by about 50%. Some of the decrease is probably due to vegetation (e.g., pinegrass) obscuring the treatment mulch during cover measurements. In addition, the agricultural straw mulch is affected by decomposition and wind redistribution to a greater degree than the wood shred mulch (Foltz and Copeland, 2008). Generally, agricultural straw mulch remains visible for two years or less, while the wood mulches have remained in place for four or more years (Robichaud et al., 2010a, 2013). Nonetheless, the more rapid reduction in agricultural straw compared to wood shreds was of little importance in these experiments as the total ground cover in both treatment plots remained high throughout the study period.

Agricultural straw mulch is well established as an effective treatment for reducing post-fire sediment yields, but it has to be purchased and shipped to the area of use, may spread seeds of undesirable species, and may not provide adequate soil protection for the length of time needed. Wood shred mulch shows promise for being as effective as agricultural straw mulch at reducing post-fire hillslope sediment yields, with the added benefit of being created from a native forest material on or near the site where the mulch will be applied.

5. Conclusions

This study was initiated to determine the efficacy of using wood shred mulch as a post-fire hillslope treatment to reduce potential erosion and to compare the effectiveness of wood shred and agricultural straw mulches. Three experimental techniques (rainfall simulations, concentrated flow (rill) simulations, and hillslope plot sediment yields from natural rainfall) were used to assess treatment effects on raindrop impact (splash) and sheet (interrill) erosion, rill erosion, and the combination of erosion processes that impact hillslope sediment yields. Results varied by experiment and post-fire year, but when considering the results as a whole, we found that both treatments reduced sediment yields as compared to the controls. Additionally, in the rill simulation experiment we found that both treatments significantly reduced overland flow velocity and increased the proportion of overland flow that infiltrated the soil before reaching the outlet of the plot.

Time since fire, which is highly related to total ground cover due to the increase in vegetation over time, was a significant predictor of sediment yields. Vegetation cover responded similarly on all plots regardless of treatment, and averaged about 50% in the fall of the second post-fire year. Before vegetation had a chance to reestablish, however, the additional 40–80% ground cover provided by the agricultural straw and wood shred treatments in the year of the fire and the first post-fire year approximated the same erosion protection of an additional year of recovery. Although rainfall intensity, soil water repellency, and other rain event- and site-specific factors affect erosion rates, these effects may often be moderated by protecting bare soil with added ground cover.

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