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An evaluation of three wood shred blends for post-fire erosion control using indoor simulated rain events on small plots

R.B. Foltz *, N.S. Wagenbrenner

USDA Forest Service, Rocky Mountain Research Station, 1221 South Main Street, Moscow, ID 83843, USA

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ABSTRACT

The assessment teams who make post-fire stabilization and treatment decisions are under pressure to employ more effective and economic post-fire treatments, as wild fire activity and severity has increased in recent years across the western United States. Use of forest-native wood-based materials for hillslope mulching has been on the rise due to potential environmental, erosion control efficacy, and economic incentives. One concern regarding use of woody materials prepared on or near burned sites is the wide range in the size distribution of the shredded materials. We tested three blends of shredded woody materials, each blend containing different amounts of fine (less than 2.5 cm in length) woody particles. The blends (AS IS with 24% fines, MIX with 18% fines, and REDUCED with 2% fines) were applied at 50 and 70% ground cover to 5-m^2 plots containing burned soil placed at 40% slope and evaluated through simulated rain events which consisted of a rain only, a rain plus low flow, and a rain plus high flow period. The REDUCED blend was the optimum for both runoff and sediment concentration reduction under conditions of rainfall and rainfall plus concentrated flow. There was no difference between application rates of 50 and 70% for either of the rainfall plus concentrated flows tested. Our recommendation was that 50% ground cover of the REDUCED blend was adequate for both rainfall and sediment reduction compared to a bare soil. The other two blends were effective in reducing runoff but not sediment concentration compared to a bare soil. The wood shred manufacturing and blending process resulted in two statistically different relationships between application rate and ground cover; relationships were controlled by the amount of fines.

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1. Introduction

Wildland fires have become larger and more severe in the western United States, with the 2004–2007 fire seasons being the largest on historical record in terms of acres burned, total number of fires, and suppression costs (USFS, 2008). Unlike undisturbed forest soils, burned forest soils are highly susceptible to runoff and erosion. Forest fires remove both above ground vegetative cover and below ground small roots, destroy the protective duff layer, and often induce soil water repellency, all of which contribute to lower infiltration rates, increased runoff, and increased sediment production (Benavides-Solorio and MacDonald, 2001, 2005; Johansen et al., 2001; Robichaud et al., 2000; Smith and Dragovich, 2008).

Burned Area Emergency Response (BAER) teams are responsible for estimating post-fire risks and, when necessary, administering post-fire rehabilitation treatments to mitigate these effects. Increased fire activity puts more pressure on BAER teams to employ the most effective and economically viable post-fire rehabilitation treatments available. Prompt application of protective ground cover is perhaps the most effective rehabilitation treatment available and studies have shown the efficacy of various types of ground cover materials (Cerda and Doerr, 2008; Foltz and Copeland 2009; Wagenbrenner et al., 2006). Cover materials protect the exposed soil from wind and raindrop impact, help to retain moisture at the soil surface by reducing evaporative heat transfer, slow and divert runoff, and trap erodable material entrained in runoff. If a cover material is to be used on a large scale, such as for post-fire rehabilitation, it must be: (1) cost-effective, (2) ecologically sustainable and environmentally benign, (3) widely available and easily transported, and (4) durable and stable enough to provide protection until natural ground cover has been reestablished. The current challenge is to identify effective ground covers that maximize these criteria.

Mulch application is an effective post-fire rehabilitation method that provides immediate ground cover to exposed burned soil. Agricultural straw is currently the most common mulching material for BAER treatments. It is reasonably effective in reducing erosion; however, straw is (1) not native to forested areas and may introduce non-native vegetation and residual pesticides, (2) not stable under high wind conditions, and (3) less effective for severe storms (Copeland et al., 2009; Robichaud et al., 2000; Wagenbrenner et al., 2006). Also, the increasing cost and decreasing availability of straw may impact its use as a post-fire treatment (Gorzell, 2001). There is a growing consensus

* Corresponding author. Tel.: +1 208 883 2312; fax: +1 208 883 2318.
E-mail addresses: rfoltz@fs.fed.us (R.B. Foltz), nwagenbrenner@fs.fed.us (N.S. Wagenbrenner).

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among land managers that a mulch product derived from native forest materials would be preferable to agricultural straw.

Work has recently been done to evaluate forest-native mulching materials (Foltz and Copeland, 2009; Foltz and Dooley, 2003; Yanosek et al., 2006). Yanosek et al., (2006) found wood strands, an engineered material produced from veneer waste, to be a good alternative to agricultural straw. The wood strands reduced erosion by over 90% compared to bare soil from two different soil types during rainfall simulation tests (Yanosek et al., 2006). These results were comparable to those from agricultural straw treatments (Burroughs and King, 1989). Additionally, mulches made from woody materials may offer other benefits such as nitrogen immobilization which reduces the adverse impact on water quality (Homyak et al., 2008). Wood strands are currently manufactured at a single facility and are a more expensive treatment than agricultural straw.

Mulch derived from on-site woody materials could reduce manufacturing and transportation costs, and thus, provide a more cost-effective alternative. Wood shreds are one such product and have shown promise as an effective mulching material (Foltz and Copeland, 2009). Wood shreds are created by shredding on-site woody materials such as tree limbs and small-diameter trees. Wood shreds were developed by the USDA Forest Service Missoula Technology and Development Center to provide an alternative to traditional mulching materials such as agricultural straw, hydromulch, and wood chips. Groenier and Showers (2004) discussed the advantages of using portable shredding equipment to produce wood shreds for on-site erosion control.

While wood shreds have demonstrated operational promise as an erosion control alternative, further evaluation is necessary to optimize wood shreds for large-scale post-fire erosion control. Wood shreds have not been evaluated on burned soils and their post-fire erosion reduction efficacy is difficult to extrapolate from studies done on unburned soil, as erosion and runoff mechanics differ for burned and unburned soils (Cerda and Doerr, 2008; Robichaud et al., 2007; Robichaud, 2000; Smith and Dragovich, 2008). For example, fire activity can alter hydrologic structure through deposition of a wettable ash layer at the soil surface and creation or enhancement of soil water repellency due to volatilization of organic compounds just below the soil surface.

Additionally, standard shred manufacturing produces a mixture that contains a large proportion of fine (less than 2.5 cm in length) material (Foltz and Copeland 2009). We hypothesize that these fine materials have little effect on erosion and are likely to be washed downslope during the first runoff event. Further, application costs may increase because the fines add to the overall weight of the material and more weight must be applied in order to achieve an effective ground cover. A material with fewer fines may be more cost-effective for large-scale application if (1) it can be produced with little extra cost or alteration to existing equipment and (2) a low fines shred material is equally effective in reducing erosion.

The purpose of this study was to test several blends of wood shreds through small-scale laboratory rainfall simulation experiments to determine the most appropriate blend for use in post-fire BAER treatments. This study served as a preliminary step to identify the optimal wood shreds blend for further testing in a larger field experiment at the hillslope scale. The goals of this study were to (1) determine differences in the material size distribution of three wood shred blends and the impact of those differences on the required mass application rates to achieve a desired ground cover, (2) determine the statistical significance of each wood shred blend in reducing runoff, sediment concentration, and rill formation from a burned soil, and (3) determine which wood shred blend best reduces runoff and sediment concentration.

2. Methods and materials

Rainfall events were simulated with an indoor simulator between August 2007 and April 2008 at the U.S. Department of Agriculture (USDA) Forest Service, Rocky Mountain Research Station in Moscow, Idaho. We tested the erosion control efficacy of three blends of wood shreds applied at 50 and 70% ground cover. The study used a completely randomized design with six replications of each treatment combination, including a bare soil treatment as a control, which gave a sample size of 42 rainfall simulations. Wood shreds effectiveness was assessed based on runoff, sediment concentrations, and rill formation during the simulated storms.

2.1. Simulations: plot preparation

A burned sandy loam soil collected from the Tripod Fire Complex near Winthrop, Washington, USA was used for the simulations (Table 1). The soil was collected from an area of high burn severity six months after the fire. The top 20 cm of surface soil included a layer of ash approximately 4 cm thick, and had neither duff nor small roots. The parent material was granitic-based glacial till that was overlain with volcanic ash. The collected soil was sieved through a 3/8-in mesh screen, well-mixed, and air-dried prior to simulations.

A steel-framed plot 1.24 m wide, 4 m long, and 0.2 m deep was filled with the burned soil and leveled with a trapezoidal-shaped screed (80 mm wide and 5% side slopes) to eliminate edge effects. Drainage of the plot was achieved with a metal screen with 12-mm openings covered by geotextile fabric that allowed water to penetrate the bottom face of the plot. Soil bulk density was measured prior to rainfall using a Troxler Model 3440 nuclear gauge. Gravimetric soil water content was measured before and after rainfall by oven drying soil samples at 110 ºC for 24 h (ASTM Standard D4959, 2007).

The plots were pre-wet using a rain intensity of 51 mm h^{-1} for 5–10 min, until the soil surface became saturated, but before ponding occurred. The plots were pre-wet at a slope of 0% to facilitate settling of the soil and to prevent mass failure due to the steep slope used for the simulations. Prepared soil plots were attached to a steel frame at 40% slope for rainfall and overland flow simulations (Fig. 1). This slope was chosen to be representative of the steep hillslopes commonly found in forested areas of the western U.S.

A pre-determined mass of wood shreds, based on trial cover count experiments for each blend, was applied to the plot by hand to achieve the desired cover amount of either 50 or 70% cover. Actual wood shred coverage was determined from point-count measurements made with a clear grid that contained 605 points spaced 25 mm apart. Wood shreds were then added or removed as necessary to ensure that the actual cover amount on the plot was within five percentage points of the desired cover amount. A relationship of the form

$$F_c = 1 - e^{-A_m M} \quad (1)$$

was predicted from the observed data based on Gregory (1982), where F_c is the fraction of soil covered, M is the application rate, and A_m is the area covered by one average wood shred per mass of one average wood shred.

Table 1
Soil physical properties.

Parameter	Units	*n*	Mean	*s*
Sand fraction	%	9	66	3.0
Silt fraction	%	9	35	3.1
Clay fraction	%	9	0.18	0.32
D_{84}	mm	9	1.1	0.17
D_{50}	mm	9	0.14	0.02
D_{16}	mm	9	0.02	0.00
Bulk density	g cm^{-3}	42	1.1	0.03
Gravimetric water content (pre-rain)	%	42	12	2.8

s = standard deviation, *n* = sample size.
Soil particle size analyses performed by wet sieving (ASTM Standard D422-63 (2007)).

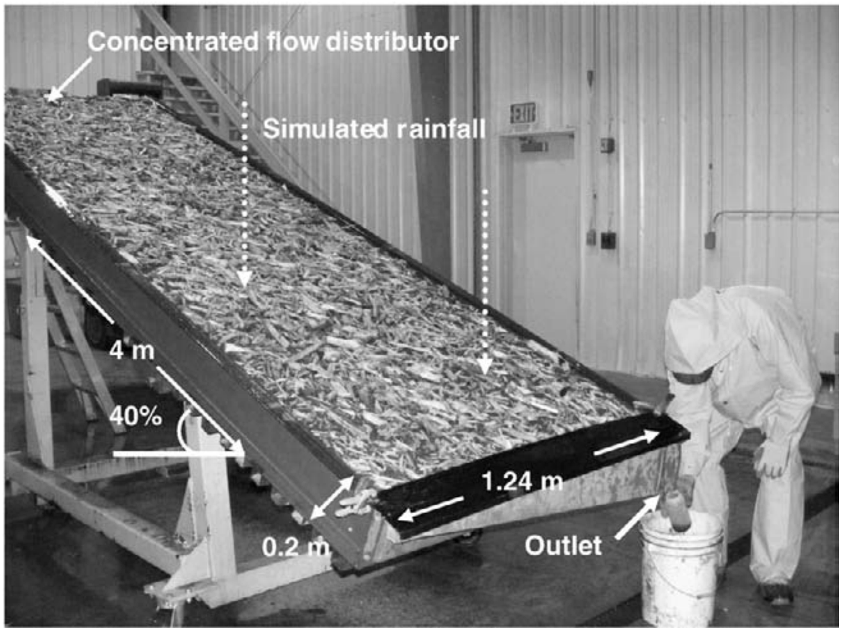

Fig. 1. Plot setup for rainfall and overland flow simulations.

2.2. Simulations: rainfall and overland flow

A simulated storm that generated both raindrop impact and concentrated flow was delivered to the prepared plots (Foltz and Copeland, 2009; Foltz and Dooley, 2003; Yanosek et al., 2006). Rain was applied at a continuous rate of 51 mm h^{-1} for a duration of 25 min using a Purdue-type rainfall simulator with VeeJet 80150 nozzles. An event of this intensity and duration has a return period of 50 years throughout much of the Intermountain Western United States (NOAA, 1973). The storm duration and intensity were chosen not to represent a particular design storm, but rather to exceed the infiltration rate and ensure that the entire plot area contributed to runoff. Concentrated inflow was added to simulate overland flow from upslope and was delivered to the plot at flow rates of 0.97 and 4.1 L min^{-1} (nominally referred to as 1 and 4 L min^{-1} and equivalent to 12.1 and 48.4 mm h^{-1} run-on rates, respectively) by a flow distributor box (rectangular outlet with width of 7.6 cm) located at the top and center of the plot. These added flows increased the hydraulic shear of the runoff water and simulated a plot with concentrated flow from upslope (Laflen et al., 1991). The 25-min simulations were divided into three cumulative simulation periods, each characterized with a different combination of rainfall and concentrated overland flows:

1. R: (0–15 min) rain only
2. R + 1: (0–20 min) R + rain and 1 L min^{-1} concentrated flow during minutes 15–20
3. R + 4: (0–25 min) R + R + 1 + rain and 4 L min^{-1} concentrated flow during minutes 20–25

Note that each period represents a cumulative time series and includes the prior simulation scheme(s) in the 25-min simulation. The simulation schemes were used to investigate differences in erosion that may be expected in the field due to location in the watershed (upland or lowland) and duration of the runoff event. For example, concentrated overland flow would be less likely to occur on a hillslope located high in the watershed or when the intensity does not greatly exceed the soil infiltration rate; these cases are represented by R. On the other hand, if storm duration or intensity is high enough to greatly exceed the infiltration capacity of the soil and there is sufficient upland area in the watershed, the hillslope would likely receive concentrated overland flow; this case is represented by R + 1 and R + 4. Each case would presumably result in different contributions of raindrop splash and concentrated flow erosion processes and thereby potentially require different levels of mitigation. Reporting results as R, R + 1, and R + 4 provides the reader with the expected runoff and sediment concentrations from a combination of raindrop splash and concentrated flow processes.

Timed grab samples were taken during each minute of the runoff period and used to calculate runoff rates and sediment concentrations. Rill formation was characterized by the number of rills that formed during the simulation period and the width and depth of the rills at an upper, middle, and lower location along the length of the plots. Rill widths and depths at each location in the plot were used to determine a plot average. Digital photos were taken before and after simulations to document changes in the plots.

2.3. Wood shreds characteristics

The wood shreds used in this study were produced from lodgepole pine (*Pinus contorta*) slash. We investigated shred blends containing different amounts of shreds less than 2.5 cm in length (referred to as “fines” in this paper), as we suspected that shreds of this size likely do not contribute to the erosion control efficacy of the shreds material, but do add to the overall weight of the material, and thus, to the cost of application. Three blends were tested in this study (Fig. 2).

1. AS IS: standard blend produced by a Vermeer horizontal grinder.
2. MIX: 50% fewer fines by count than the AS IS blend.
3. REDUCED: fines removed.

The REDUCED was produced by passing the AS IS over a 12-mm mesh screen to remove the fines. The MIX was created by adding fines back to the REDUCED mix to achieve a blend that had 50% fewer fines by count than the AS IS. Samples of each wood shreds blend were hand sorted to characterize the actual size distribution of each blend (Table 2). Moisture content (wet weight basis) of the shreds ranged from 6.8 to 13.1% with an average of 9.7% over the nine month duration of the study.

2.4. Statistical methods

Statistical analyses were performed using SAS (2002). Consistency of initial soil conditions were evaluated using separate one-way mixed model analyses of variance (ANOVAs) to test for differences in

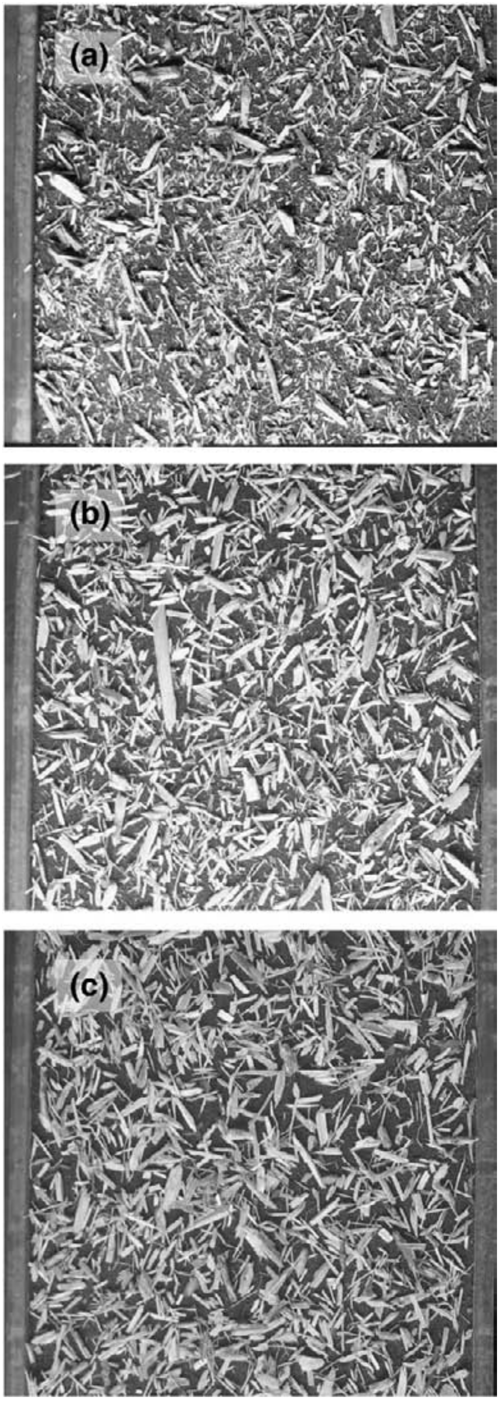

Fig. 2. (a) AS IS, (b) MIX, and (c) REDUCED wood shreds applied at 50% cover.

Table 2
Size characterization of three wood shred blends.

Blend	Target/description	Length (cm)	Percent by mass (%)	Percent by count (%)
AS IS	Standard, pre-screen blend	>5	80	58
		2.5–5	15	18
		<2.5	5	24
MIX	50% fewer fines (by count) than AS IS	>5	78	58
		2.5–5	18	24
		<2.5	4	18
REDUCED	~0% fines (by count), post-screen blend	>5	80	69
		2.5–5	19	29
		<2.5	1	2

pre-simulation soil water content and bulk density (Littel et al., 1996). A paired *t*-test was used to test for differences between applied and desired coverage amounts. A two-way mixed model ANOVA was used to test for differences in application rate among shred blends.

The primary interest was to determine differences among the wood shred blends and coverage amounts for each of the three flow schemes representing varying contributions of the physical processes of raindrop splash and concentrated flow erosion. Two-way mixed model ANOVAs were performed within each flow period to determine differences among runoff and sediment response variables. Mixed model ANOVAs were performed to test for differences among treatments for runoff depth (RO), defined as the total runoff volume for a given simulation scheme divided by the plot area, and sediment concentration (SEDCON), defined as the average sediment concentration for a given simulation scheme. Model treatment effects included *run* (R, R + 1, R + 4), *type* (NONE, AS IS, MIX, REDUCED) and *cover* (0, 50, 70). The levels of *cover* were not equally distributed among the *type* effect (e.g., NONE represents a single coverage of 0%, AS IS includes both 50 and 70% cover) but rather were nested within the various levels of *cover*. Therefore, this effect was treated as a nested effect in the statistical modeling and was expressed as *cover (type)* to indicate the nested structure of *cover*.

Log and square-root transformations were necessary for R-period RO and SEDCON data, respectively, to satisfy the assumption of normally distributed residuals. Transformations were not needed for any of the response variables for analyses of the R + 1 or R + 4 periods. All reported mean values and standard deviations are from the raw data. Multiple pairwise comparisons were performed on all significant treatment effects using Tukey's procedure. Results are reported at the $\alpha = 0.05$ level of significance.

3. Results and discussion

The wood shred coverage amounts did not differ significantly from the desired values of 50 or 70% at any time during the study; thus, treatments are referred to by these nominal coverage values. Despite efforts to control initial soil conditions, pre-simulation soil water content values range from 6.7 to 20% and bulk density values ranged from 1.1 to 1.3 $g\,cm^{-3}$; however, these variations did not have a significant effect on the RO, or SEDCON responses.

3.1. Runoff and sediment concentration responses from bare burned soil

Average RO from NONE, the bare burned soil, increased from 1.5 to 3.3 to 8.7 mm from the R to R + 1 to R + 4 schemes, respectively (Table 4) indicating lower infiltration rates as concentrated flow became the dominate process. Average RO values from NONE were relatively low compared to previous studies on similar and coarser grained soils on smaller slopes of 15 and 30%. A typical rainfall runoff hydrograph from a burned soil peaks at a value controlled by the hydrophobic layer followed by a decrease in runoff due to the breakdown of the hydrophobic layer (Robichaud, 2000). None of the hydrographs (Fig. 3) displayed this behavior, perhaps due to soil mixing, which likely destroyed connectivity of the hydrophobic layer. Additionally, high ash content may have altered hydrologic properties of the soil. Previous studies have reported increased soil water holding capacity and hydraulic conductivity following small additions of ash material (Chang et al., 1977; Ghodrati et al., 1995). Cerda and Doerr (2008) reported post-fire reductions in runoff due to presence of a thick wettable ash layer at the soil surface. In the field, ash would be concentrated in a layer at the soil surface; however, in this study, the ash was well-mixed throughout the soil profile during plot construction, thus making it plausible that the ash may have altered soil structure and influenced hydraulic conductivity.

Average SEDCON from NONE increased from 130 to 240 to 450 $g\,L^{-1}$ from the R to R + 1 to R + 4 schemes, respectively (Table 4). Average

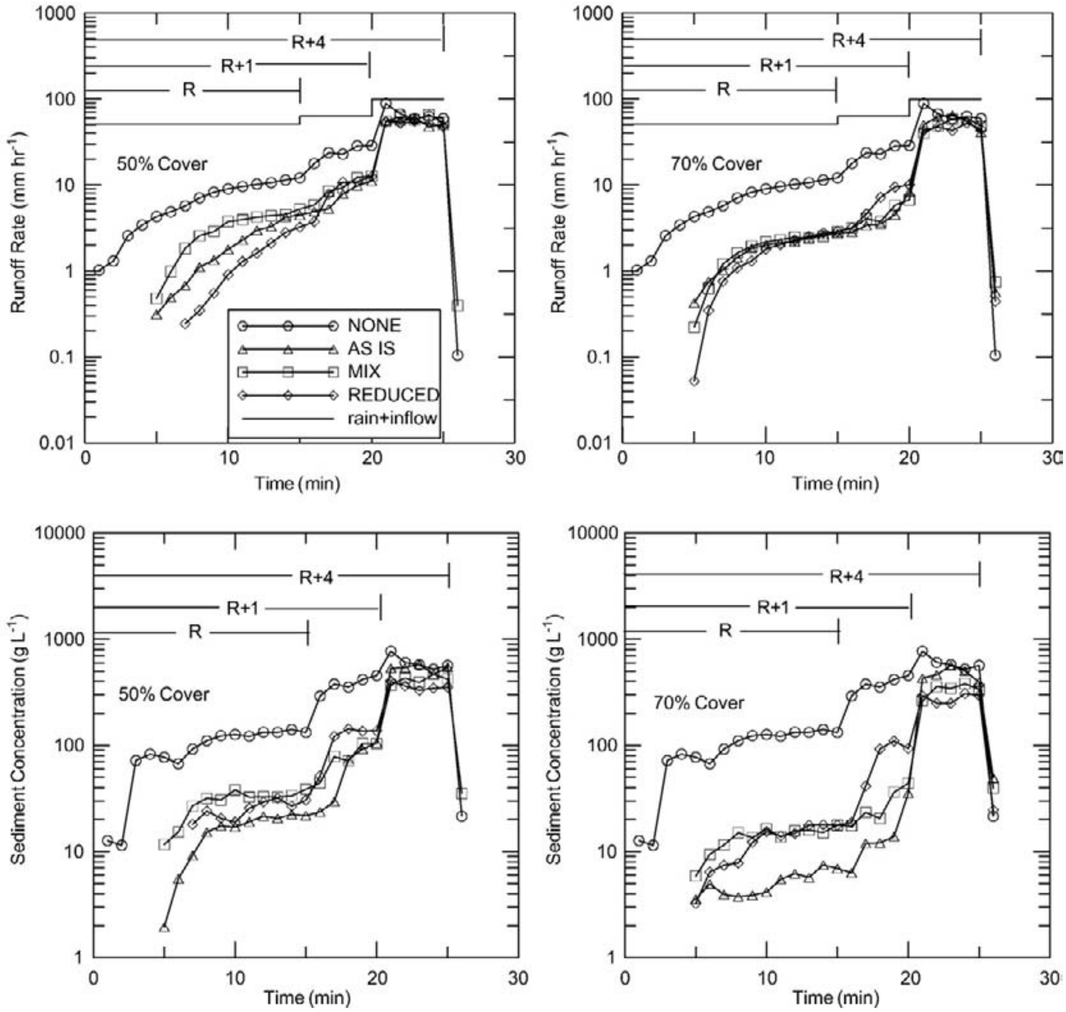

Fig. 3. Average runoff rates and sediment concentrations during three simulation periods for bare soil (NONE) and soil treated with three wood shred blends applied at 50 and 70% cover.

SEDCON from NONE increased sharply with added inflow, but then leveled off during each scheme (Fig. 3). Average SEDCON values from NONE were markedly higher than those reported in previous studies (Fig. 4). The increasing trend in SEDCON with added inflow was also not consistent with previous studies conducted on unburned soils with similar textural classifications (Fig. 4). Additionally, sandy loam soils

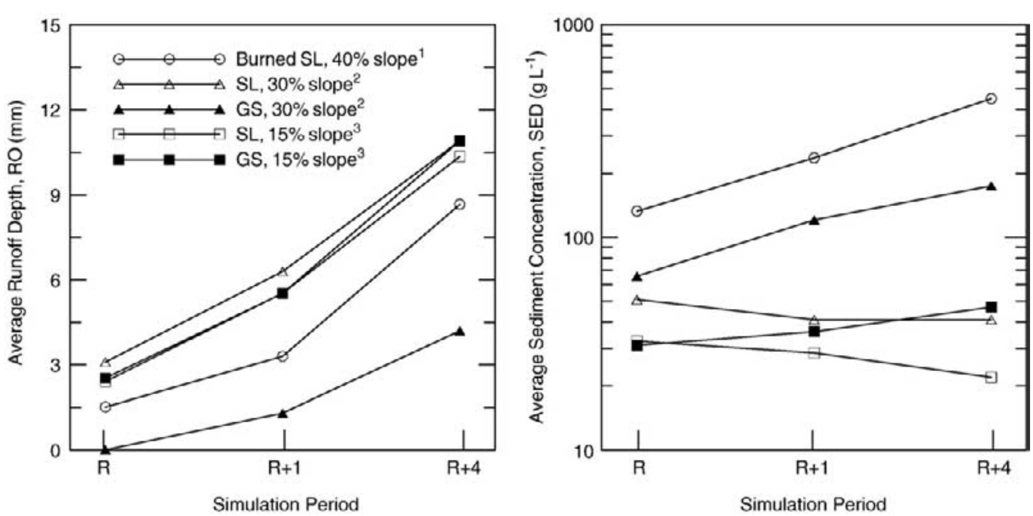

Fig. 4. Reported average runoff depths and sediment concentrations from sandy loam (SL) and gravelly sand (GS) soils at 15, 30, and 40% slopes during simulated overland flow experiments where R = rainfall only (51 mm h^{-1}); R + 1 = R + rainfall + 1 L min^{-1} added inflow; R + 4 = R + R + 1 + rainfall + 4 L min^{-1} added inflow. [1]this study; [2]Foltz and Copeland (2009); [3]Yanosek et al., (2006).

tested in previous studies exhibited decreased sediment concentrations with increased inflows (Fig. 4). Although sediment production increased with added inflows in the previous studies, the increase in sediment was not proportional to the increase in inflow, and SEDCON decreased. Conversely, the gravelly sand soils tested in previous studies had increasing trends in SEDCON, which means that their sediment production rate did increase in proportion to the added inflow. These differences can be attributed to textural classification. Movement of coarser gravelly sand would have caused the water to be more erosive, as larger gravel and sand-size particles became entrained in the flow and contributed to scouring of the soil surface. Additionally, smaller particles would have been exposed and available for entrainment as the larger particles were removed. Both processes would contribute to increased SEDCON.

SEDCON values from NONE in the current study, however, were actually higher than those measured from the gravelly sand soils in the previous studies and did not follow the same decreasing trend exhibited by the other bare sandy loam soils previously tested (Fig. 4). Rather, both sediment production and sediment concentration increased with added inflow. We attribute these anomalies to slope and burn characteristics. The steeper slope likely increased sediment production with respect to runoff, as the runoff would have imparted a greater shear stress on soil particles as it traveled at the steeper angle. Additionally, the soil particles would require less force to initiate movement on the steeper slope. Changes in soil structure due to increased ash content may have also contributed to the increase in sediment concentration between flow periods.

3.2. Wood shreds application rates

The AS IS required a statistically different application rate than the MIX and REDUCED to achieve a given F_c. Accordingly, two equations were used to predict F_c as a function of M, one for the AS IS, and one for the MIX and REDUCED (denoted MIX/REDUCED) (Fig. 5). We calculated mean A_m values of 1.1 and 0.71 $m^2\,kg^{-1}$ for the AS IS and MIX/REDUCED, respectively; these values were on the order of those reported for other surface residue covers in Gregory (1982). Values reported for straw range from 0.60 to 2.7 $m^2\,kg^{-1}$ and are dependant on the source of the straw (Gregory, 1982). Values estimated for different blends of wood shreds and wood strands are 0.71–1.22 and 0.93 $m^2\,kg^{-1}$, respectively (Table 3). We attribute the high variability

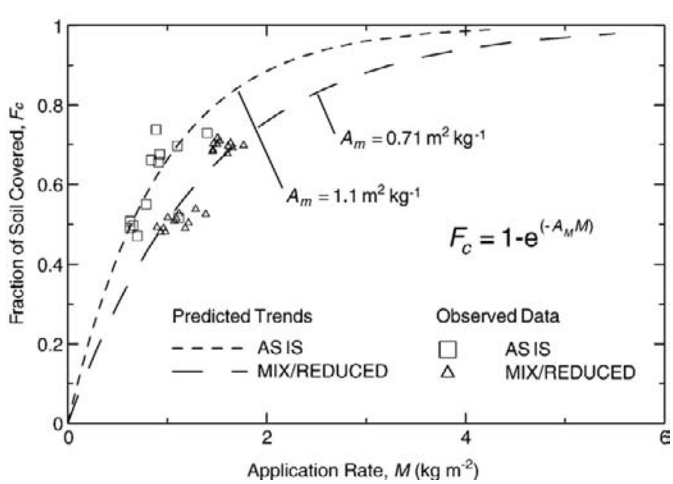

Fig. 5. Fraction of soil covered as a function of application rate in the form of Gregory's (1982) equation. Predicted curves were generated based on an average value of A_m, a physical property of the wood shreds, derived from observed data for the two groups of statistically different blends of shreds. A_m is the area covered by one average wood shred per mass of one average wood shred.

in wood shred A_m values to the production process. Although we intentionally altered the wood shred material through a screening process to generate three shred blends with different material size distributions in the current study, Foltz and Copeland (2009) found variation in A_m among separate batches of wood shreds produced from the same equipment. Field application of wood shred materials for erosion control would be improved by minimizing the variability in A_m. Logistics for reliable, effective field application necessitate this improvement, as the required application rate is a function of A_m. Rearranging Eq. (1) to solve for M, gives the following mass application rates,

$$M_A = -0.93\ln(1-F_c) \quad (2)$$

$$M_{MR} = -1.41\ln(1-F_c) \quad (3)$$

where M_A and M_{MR} are the application rates in kg m^{-2} for the AS IS and MIX/REDUCED, respectively, and F_c is the desired fraction of surface cover. These application rates are based on an average wood shred moisture content of 9.7% (wet weight basis). Ultimately, there is a statistical difference in the cover efficacy between the AS IS and the MIX/REDUCED blends, and on average, one representative piece of AS IS material will cover 34% more area per mass than one representative piece of the MIX/REDUCED material. This is explained by the large number of fines in the AS IS, which contribute to the F_c, but do not proportionately contribute to the mass.

Based on the predicted trends, differences in application rates between the AS IS and MIX/REDUCED are small at low F_c, but increase as the desired F_c increases (Fig. 5). For example, only 23% more mass is required to achieve 50% cover with the MIX/REDUCED versus the AS IS, but an additional 52% is required of the MIX/REDUCED versus the AS IS to achieve 70% cover.

3.3. Effect of wood shreds on runoff and sediment concentration

Average time to runoff (TTRO) for NONE occurred during minute one while for any amount of wood shred blend or coverage TTRO was delayed until at least minute five. Visual observations during the simulations suggested that wood shreds increased TTRO by the formation of mini check dams, which trapped and diverted overland flow. This attests to the increased surface roughness imparted by the wood shreds and suggests a decrease in the energy of the flow, and therefore, a decrease in the sediment transport capacity.

3.3.1. AS IS

The AS IS blend significantly reduced RO compared to NONE during the rain only period when the application rate was 70% (Table 4). When concentrated flow was added, having an AS IS blend was significant compared to NONE in terms of RO, but there were no differences between application rates (Table 4). RO reduction compared to NONE due to the AS IS blend decreased from a high of 81% when there was rain only to 40% at the highest rainfall and concentrated flow combination (R + 4) (Table 3).

The AS IS blend significantly reduced SEDCON compared to NONE during the rain only scheme for both 50 and 70% application rates (Table 4) (82 and 95% reduction, respectively; Table 3). For rainfall plus low concentrated flow (R + 1), having an AS IS blend was significant compared to NONE (83% reduction) in terms of SEDCON, but there were no differences between application rates (Table 4). For rainfall plus high concentrated flow (R + 4) there were no differences in SEDCON between a bare soil and one having any application rate of AS IS blend (Table 4).

The AS IS blend would be useful to reduce runoff when applied at 70% cover and useful to reduce sediment concentration when applied at either 50 or 70% cover under conditions dominated by rainfall only. For conditions dominated by concentrated flow, either of the two AS

Table 3
Reported application rates, A_m, and mean values for reductions in runoff volume and sediment loss compared to bare soil for different erosion control materials under similar simulated rain events.

Cover material	Slope (%)	Soil type	Type	A_m ($m^2 kg^{-1}$)	F_c	M ($kg\ m^{-2}$)	Runoff reduction (%)			Sediment concentration reduction (%)		
							R	R+1	R+4	R	R+1	R+4
Wood shreds[a]	40	Burned SL	AS IS	1.1	0.5	0.64	77	70	38	82	75	2.8
			MIX	0.71	0.5	0.98	65	62	30	73	70	25
			REDUCED	0.71	0.5	0.98	88	74	43	76	53	32
			AS IS	1.1	0.7	1.12	81	81	42	95	91	8.7
			MIX	0.71	0.7	1.70	85	81	44	84	79	35
			REDUCED	0.71	0.7	1.70	82	77	48	87	67	48
Wood shreds[b]	30	SL	Lot1	0.73	0.3	0.49	93	72	48	74	54	59
					0.5	0.95	100	94	69	100	70	72
					0.7	1.65	100	99	88	100	97	79
		GS	Lot2	1.2	0.3	0.29	97	39	20	92	72	59
					0.5	0.57	100	73	39	100	79	80
					0.7	0.99	100	84	44	100	85	90
Wood strands[c]	15/30	SL	LS/LM	0.93	0.3	0.38	94	42	35	66	55	56
					0.5	0.74	98	42	57	93	70	67
					0.7	1.29	100	83	74	100	77	66
		GS			0.3	0.38	69	46	48	63	66	67
					0.5	0.74	94	72	65	84	80	87
					0.7	1.29	99	85	68	94	83	92
Wood strands[d]	30	GS	W/N	NA	0.7	NA	100	97	81	98	91	92
Straw[d,e]	30	GS	Barley	4.3	0.7	0.22–0.45	98	92	72	94	91	94

Lot1/Lot2 = wood shreds delivered in two lots with different material characteristics.
LS/LM = blends with long (160 mm) and short strands (40 mm) and long and medium (80 mm) strands; width = 6 mm, thickness = 3 mm.
W/N = wide (16 mm) and narrow (4 mm) strands with lengths: 60, 120, and 240 mm; thickness = 3–4 mm.
SL = sandy loam ; GS = gravelly sand; NA = not available.
A_m = area covered by one representative piece of cover material per mass of one representative piece of cover material.
F_c = fraction of soil covered.
M = application rate.
R = rain only; R + 1 = R + rain + 1 L min^{-1} inflow; R + 4 = R + R + 1 + rain + 4 L min^{-1} inflow.
[a] This study.
[b] Foltz and Copeland (2009).
[c] Yanosek et al., (2006).
[d] Foltz and Dooley (2003).
[e] Gregory (1982).

Table 4
Sample size, mean value, and standard deviation for statistically significant treatment effects within the runoff depth (RO), and sediment concentration (SEDCON) responses during three simulation periods.

Treatment effect	Treatment level	RO (mm)			SEDCON ($g\ L^{-1}$)		
		n	Mean	s	n	Mean	s
		R period					
cover(type)	0 (NONE)	6	1.5[a]	0.70	6	130[a]	56
	50 (AS IS)	6	0.34[ab]	0.25	6	24[bc]	11
	50 (MIX)	6	0.52[ab]	0.19	6	36[b]	8.3
	50 (REDUCED)	6	0.18[b]	0.15	6	32[b]	22
	70 (AS IS)	6	0.29[b]	0.46	6	6.9[c]	6.5
	70 (MIX)	6	0.23[b]	0.17	6	21[bc]	4.2
	70 (REDUCED)	6	0.27[b]	0.24	6	17[bc]	11
		R + 1 period					
type	NONE	6	3.3[a]	1.0	6	240[a]	100
	AS IS	12	0.81[b]	0.67	12	40[b]	44
	MIX	12	0.95[b]	0.42	12	61[b]	49
	REDUCED	12	0.81[b]	0.42	12	96[b]	72
		R + 4 period					
type	NONE	6	8.7[a]	1.2	6	450[a]	190
	AS IS	12	5.2[b]	1.6	12	420[a]	130
	MIX	12	5.5[b]	1.0	12	320[ab]	94
	REDUCED	12	4.7[b]	1.2	12	270[b]	110

s = standard deviation, n = sample size.
The *cover(type)* factor was significant for the R period ANOVA; thus, each combination is shown.
Letters denote statistical groupings from pairwise comparisons within a simulation period and treatment effect.

IS blend coverage amounts would be better than a bare soil from a runoff viewpoint. From a sediment concentration viewpoint, the AS IS blend offers little to no improvement over a bare soil.

3.3.2. MIX

The MIX blend performed similar to the AS IS blend. The MIX blend significantly reduced RO compared to NONE during the rain only period when the application rate was 70% (Table 4). When concentrated flow was added, having a MIX blend was significant compared to NONE in terms of RO, but there were no differences between application rates (Table 4). RO reduction compared to NONE due to the MIX blend decreased from a high of 85% when there was rain only to 37% at the highest rainfall and concentrated flow combination (R + 4) (Table 3).

The MIX blend significantly reduced SEDCON compared to NONE during the rain only scheme for both 50 and 70% application rates (Table 4) (73 and 84% reduction, respectively; Table 3). For rainfall plus low concentrated flow (R + 1), having a MIX blend was significant compared to NONE (74% reduction; Table 3) in terms of SEDCON, but there were no differences between application rates (Table 4). For rainfall plus high concentrated flow (R + 4) there were no differences in SEDCON between a bare soil and one having any application rate of MIX blend (Table 4).

The MIX blend would be useful to reduce runoff when applied at 70% cover and useful to reduce sediment concentration when applied at either 50 or 70% cover under conditions dominated by rainfall only. For conditions dominated by concentrated flow, either of the two MIX blend coverage amounts would be better than a bare soil from a runoff viewpoint. From a sediment concentration viewpoint, the MIX blend offers little to no improvement over a bare soil.

3.3.3. REDUCED

The REDUCED blend performed better than either the AS IS or the MIX blends. The REDUCED blend significantly reduced RO compared to NONE during the rain only period when the application rate was 50 or 70% (Table 4) (88 and 82% reduction, respectively; Table 3). When concentrated flow was added (R + 1 and R + 4), having a REDUCED blend was significant compared to NONE in terms of RO, but there were no differences between application rates (Table 4). RO reduction compared to NONE due to the REDUCED blend decreased from a high of 88% when there was rain only to 45% at the highest rainfall and concentrated flow combination (R + 4) (Table 3).

The REDUCED blend significantly reduced SEDCON compared to NONE during the rain only scheme for both 50 and 70% application rates (Table 4) (76 and 87% reduction, respectively; Table 3). For both rainfall plus low and rainfall plus high concentrated flow (R + 1 and R + 4), having a REDUCED blend was significant compared to NONE (60 and 40% reduction, respectively; Table 3) in terms of SEDCON, but there were no differences between application rates (Table 4).

The REDUCED blend would be useful for runoff and sediment reduction when applied at either 50 or 70% cover under conditions dominated by rainfall only or concentrated flow. The REDUCED blend was the only blend tested that demonstrated significant reductions in both runoff and sediment concentration for the three rainfall and concentrated flow schemes used in this study. We suggest that the improvement in both runoff and sediment reduction is due to the larger average shred size of the REDUCED blend compared to the AS IS and MIX blends. The larger materials were more stable during concentrated flows than the smaller materials which constituted a large proportion of the AS IS and MIX blends (Fig. 6). Blend size differences did not impact effectiveness during the rain only or the rain plus low flow schemes, but did impact effectiveness during the rain plus high flow scheme.

The finding that REDUCED was the best wood shred blend in terms of runoff and sediment reduction confirms our prior suspicion that the shreds less than 2.5 cm in length do not contribute to the erosion efficacy of the shreds material. If the relatively simple screening procedure used at the laboratory scale can be adapted to production scale, the REDUCED blend could be commercially viable.

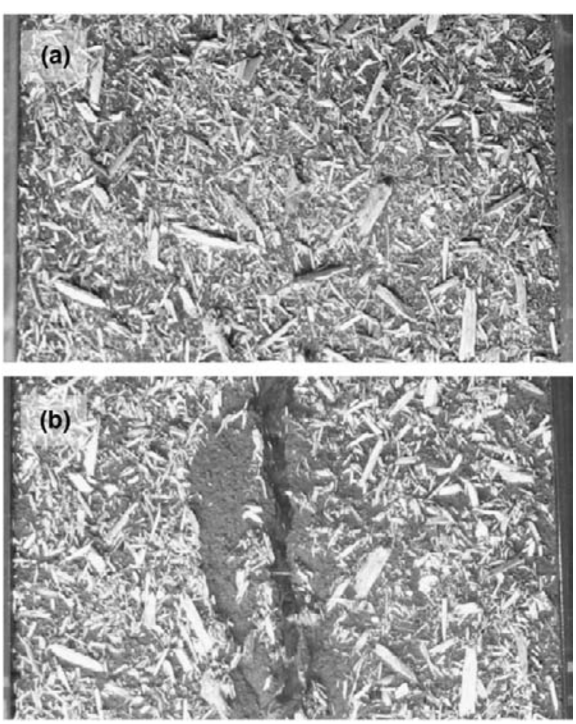

Fig. 6. (a) Pre-simulation and (b) post-simulation pictures of the AS IS wood shreds blend applied at 70% cover.

3.4. Wood shreds effect on rill formation

Formal statistical analyses were not performed on rill formation data; however, means and standard deviations were determined for post-simulation rill depths and widths. Average rill depth decreased in the following order of shred blends: NONE, AS IS, MIX, REDUCED (Table 5). Average rill width and depth also decreased with increasing amounts of cover (Table 5). Typically, one rill formed down the center of the plot; however, in 12 out of the 42 simulations we observed formation of 2 or 3 rills in the plot. When multiple rills formed they tended to meander more across the plot and were less deep and incised than the single rills. Formation of multiple rills always occurred on wood shred treated plots (33% on AS IS, 17% on MIX, and 50% on REDUCED treatments). Formation of multiple rills suggested that the wood shreds split the concentrated flow paths and that larger-sized shreds caused this to happen more often. The results suggest that this hypothesis is true, as the REDUCED treatments, which contained the least amount of fines and the highest amount of large shreds, most often resulted in formation of multiple rills. The process of rerouting or splitting flowpaths resulted in individual flows with less energy and lower sediment transport capacity. This may explain why the REDUCED blend resulted in lower SEDCON during the high flow R + 4 periods compared to the other treatments, even though RO was the same across all wood shred treatments.

3.5. Wood shreds performance compared to results from previous simulation studies

The wood shreds tested in this study were less effective in reducing runoff and sediment concentrations than the wood shreds tested in Foltz and Copeland (2009), as compared to the respective untreated bare soils (Table 3). Since average RO was lower from the burned sandy loam used in the current study than from the sandy loam used in Foltz and Copeland (2009), we attribute the relative ineffectiveness in runoff reduction to the increased slope (40%) in the current study. Reductions in sediment loss were larger in Foltz and Copeland (2009) during all flow periods, and especially during the R + 4 period where average reduction was 95% from the sandy loam in the previous study and only 53% from the burned sandy loam in the current study (Table 3). Average SEDCON was higher in the current study (Fig. 4).

4. Conclusions

We received a batch of wood shreds produced from a horizontal grinder that had a 24% by count size distribution of less than 2.5 cm in length. We produced two other blends that had 18% and 2% by count size distribution of less than 2.5 cm in length. These three types of wood shreds fell into two representative A_m categories, and thus required two different application rates. There is a likelihood for high variability in A_m from batch to batch of wood shred materials due to the inherent variability in the production process. The application

Table 5
Average depth and width of rills after rain and overland flow simulations on bare soil and soil treated with three types of wood shreds at 50 and 70% cover.

Type	Cover (%)	Width (cm)		Depth (cm)	
		Mean	*s*	Mean	*s*
NONE	0	11	4.9	10	2.9
AS IS	50	8.5	3.7	9.2	3.8
MIX	50	14	12	5.6	3.8
REDUCED	50	8.4	4.8	5.9	4.6
AS IS	70	6.5	5.7	6.9	5.0
MIX	70	11	12	5.2	5.0
REDUCED	70	5.3	6.0	4.0	5.2

Sample size = 6 for each treatment combination.

rates required for 50 and 70% cover ranged from 0.64–0.98 kg m^{-2} and 1.12–1.70 kg m^{-2}, respectively. These application rates are three to eight times the frequently used straw application rate of 0.2 kg m^{-2}.

The AS IS and MIX blends performed similarly with respect to runoff and sediment concentration reduction. Each demonstrated a significant reduction in runoff when applied at 70% cover for rainfall only. For rainfall plus concentrated flow there was no difference between application rates, but there was less runoff compared to a bare plot. Both blends had a significant sediment concentration reduction for rainfall plus a low amount of concentrated flow with no difference between application rates. When the dominant process was concentrated flow, neither blend showed an improvement in sediment reduction compared to a bare plot.

The REDUCED proved to be the optimum blend for both runoff and sediment concentration reduction. For rainfall only, both 50 and 70% cover significantly reduced runoff and sediment concentration. When concentrated flow was added to the rainfall, the REDUCED blend significantly reduced both runoff and sediment concentration compared to a bare plot. Similar to the other two blends, there was no difference between the two application rates. The REDUCED also appeared to be more effective in diverting flow paths, as plots treated with REDUCED more often developed multiple and less incised rills than bare plots or those treated with other wood shred blends. Our recommendation is to use the REDUCED blend at 50% in order to minimize the amount of material required and to achieve significant reductions in both runoff and sediment concentrations under all conditions.

The REDUCED blend was easily produced at the laboratory scale using a simple screening procedure that could be done on-site, potentially without added significant cost or time to the production. Methods of screening for field-scale application would have to be developed and tested to confirm this.

Runoff and sediment loss reductions following application of wood shreds were smaller in this study than in previous wood shred evaluations on unburned soils at smaller slopes. Runoff reductions may have been smaller because average runoff in general was lower in this study. Average sediment concentrations, however, were higher in this study. Consequently, the smaller reductions in sediment loss is speculatively attributed to the steeper slope and changes in erosion mechanics due to altered soil structure from the incorporation of the ash layer from the burn.

Additional testing of burned soils at various slopes would help to identify which variable (slope or ash content) imparts the biggest impact on the runoff and sediment responses. Further rainfall simulation testing on burned soils could be used to investigate differences in runoff and erosion mechanics with the ash layer removed (i.e., burned soil with ash layer blown or washed away) and with the ash layer added at the soil surface during plot construction (i.e., immediate post-fire situation). Investigation of the effectiveness of wood shreds on burned soils of different textures, with different degrees of burn severity, and during different rainfall regimes would provide additional insight in regards to the changes in erosion mechanics and appropriate mitigation efforts. Incorporation of the surface ash layer via soil-ash mixing may have altered hydrologic and erosion processes from those typically observed in the field, and thus may have been a limitation in this laboratory investigation. Additional field evaluations are warranted to determine wood shred efficacy in the natural environment and on a large-scale basis. Large-scale application methods (e.g. aerial application) for wood shreds must also be evaluated to assess homogeneity of the application process.

5. Disclaimer

The use of trade or firm names in this paper is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

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