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Evaluating the effectiveness of agricultural mulches for reducing post-wildfire wind erosion

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ABSTRACT

Post-wildfire soil erosion can be caused by water or aeolian processes, yet most erosion research has focused on predominantly water-driven erosion. This study investigates the effectiveness of three agricultural mulches, with and without a tackifier, on aeolian sediment transport processes. A wind tunnel was used to simulate post-wildfire wind erosion at three wind speeds (6, 11 and 18 m s^{-1}). Shallow trays containing soil collected after a wildfire were treated with chopped rice, wheat or chopped wheat mulch; mulch treatments were also compounded with liquid treatments, tackifier to water ratios of 1:6, 1:3 and water. The mulch treatments were generally easily moved at all wind speeds with cover reductions greater than 90% at the highest wind speed. As expected, sediment loss was greatest for the bare soil treatment, ranging from 6.5 g m^{-2} at the lowest wind speed which increases to 6258 g m^{-2} at the highest wind speed. Adding wheat or chopped wheat mulch significantly reduced sediment loss by an order or magnitude (698 and 298 g m^{-2}, respectively) at the highest wind speed. Adding chopped rice straw reduced sediment loss by a half to 3573 g m^{-2} at the highest wind speed, but the effect was not significant due to mobilization of the mulch. The most effective sediment loss mitigation was achieved with liquid tackifier treatments when applied to bare soil and when compounded with various mulch treatments, particularly at the highest wind speed. These results may aid management decisions when mitigating aeolian sediment transport after wildfires.

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1. Introduction

Over four million hectares burned in the United States in 2015, the most wildland area burned since 1960 (National Interagency Fire Center, 2016). Wildfires are likely to continue increasing in regions affected by fluctuating hydrologic regimes and other climate-change related phenomena (Liu et al., 2010; Miller et al., 2009; Westerling et al., 2006). Since post-fire watershed responses such as soil erosion and downstream sedimentation (i.e., deteriorated water quality from ash and sediment) tend to have a farther reaching impact than the actual burned area (Moody et al., 2013), it is necessary to consider the most successful and cost effective strategies for mitigating the widespread secondary effects of wildfire. Soil erosion may be driven by wind or water and its associated impacts are a high priority concern in the post-fire environment.

Burned landscapes are more susceptible to erosion, which can have dramatic effects on water quantity and quality (Smith et al., 2011), downstream infrastructure (Robichaud and Ashmun, 2012), and air quality (Sankey et al., 2009). While much attention has been given to determining appropriate strategies to control post-fire erosion from hydrologic processes (e.g., Robichaud et al., 2013a,b), treatments specific to addressing the consequences of wind erosion through aeolian sediment transport have received markedly less consideration (Field et al., 2009; Miller et al., 2012; Wagenbrenner et al., 2013). Wind erosion plays a major role in burned landscapes as a result of lower threshold velocities needed to transport sediment (Ravi et al., 2007), which negatively impacts nutrient availability and water-holding capacity (Field et al., 2010; Lyles and Tatarko, 1986). Additionally, increases in dust flux measured after wildfires can persist for years (Whicker and Breshears, 2006). Such increases have been known to impact snowpack melting regimes by altering the timing and availability of water resources (Painter et al., 2010) and change the natural biogeochemical balance in a given ecosystem (Field et al., 2010).

Management practices designed to moderate wind erosion include the use of windbreaks (e.g., Fryrear and Skidmore, 1985; Woodruff et al., 1972); and conservation tillage (Mannering and Fenster, 1983; Sharratt and Feng, 2009a,b). There is also substantial evidence that surface cover, such as surface residues and mulches,

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reduces wind erosion (Armbrust, 1977; Bilbro and Fryrear, 1994; Fryrear and Skidmore, 1985; Horning et al., 1998). Additionally, vegetative recovery after wildfire (Wagenbrenner et al., 2013) and vegetation cover and soil crusting can reduce wind erosion (Hupy, 2004; Sharratt and Vaddella, 2012). Although there have been recent investigations of the effectiveness of wind erosion control treatments, much of the literature is not specific to post-fire circumstances. For example, soil bonding agents such as polyacrylamides (PAM) have a demonstrated ability to reduce aeolian sediment transport (Armbrust, 1999; Genis et al., 2013; He et al., 2008), but most studies research PAM efficacy on unburned agricultural or pasture lands. Two notable exceptions have contrasting results in regard to PAM efficacy in reducing hydrologic erosion in post-fire environments (Inbar et al., 2015; Prats et al., 2014).

Few studies have focused on treatments to reduce wind erosion via land management after wildfires. For example, Miller et al. (2012) investigated the effect of seeding perennial plants on wind erosion in Utah after the 2007 Milford Flat Fire and found that decreases in sediment flux observed three years after the fire were primarily attributed to the establishment of exotic plants and not intentionally seeded perennials. Copeland et al. (2009) evaluated wood strands and agricultural wheat straw treatment efficacy in controlling wind erosion of an agricultural (Ritzville) silt loam soil. Results from their study demonstrated that both treatments reduced wind erosion when compared to bare soil at moderate wind speeds (11 m s^{-1}). At higher wind speeds (18 m s^{-1}), no difference was found between agricultural straw treatment (131 g m^{-2}) and bare soil (126 g m^{-2}), whereas wood strands (13.6 g m^{-2}) continued to reduce the amount of eroded soil. This suggests that wind erosion treatments should be tailored to anticipated wind events with consideration for local topography. While these studies contribute to needed investigations specific to wind erosion treatment effectiveness in an agricultural context, there is still a deficiency of studies focused on testing burnt soils and alternative treatment combinations.

Thus, the purpose of this study was to examine three mulch-cover treatments (wheat straw, chopped wheat straw, and chopped rice straw), a new soil-bonding agent PineBind™ tackifier (National Land Management, Phoenix, AZ; http://www.ecodustcontrol.com; accessed 27 March 2017), and mulch-tackifier combinations to determine their efficacy at reducing soil loss from post-fire aeolian processes. The PineBind™ tackifier was originally designed to decrease dust transport on unimproved native material roads (National Land Management, 2016).

2. Methods and materials

2.1. Experimental design and equipment

Experimental trials with a portable wind tunnel were conducted at the US Department of Agriculture, Agricultural Research Service, Palouse Conservation Field Station in Pullman, Washington. The wind tunnel had working dimensions of 7.3 m long, 1.0 m wide and 1.2 m tall (Pietersma et al., 1996). Because soil moisture affects aeolian sediment transport (Mulumba and Lal, 2008) and the facility was not climate regulated, the experiment was conducted only when atmospheric humidity was <65%. Relative humidity was not expected to influence threshold friction velocity until liquid water bridges formed in the soil; these bridges can form at 65% relative humidity (Ravi et al., 2006) or soil water potentials of > −25 MPa (Sharratt et al., 2013).

A 1.4 m diameter Joy Series 1000 axivane fan powered via a Ford industrial gasoline engine generated winds from 2 to 20 m s^{-1}. Airflow into the tunnel was constricted using a bell infuser. Curvilinear guiding vanes were located immediately downwind of the fan blades to minimize vortices or swirling. Airflow then passed through a diffuser and honeycomb-screen to decrease flow turbulence. Upon entering the working section of the tunnel, the airflow passed through a shear-grid to generate shear boundary layer flow. Fully developed shear flow was achieved at a distance of about 3.6 m downwind of the shear-grid (Pietersma et al., 1996).

Plywood platforms were constructed and installed to form the floor of the wind tunnel. Cutouts to accommodate soil trays in these approach platforms were made 5 m downwind from the shear grid, which allowed the top of the trays to be flush with the plywood surface. The approach plywood platforms created a fixed surface roughness specific to each of the three mulch types and allowed for the establishment of an upwind boundary-layer prior to airflow reaching experimental plots. To achieve the desired experimental surface roughness, 70% cover for each mulch type – rice, wheat, and chopped wheat – were glued to three unique approach platforms, which were sequentially installed and specific to the treatment used within experimental runs. To create the bare soil approach platform, sand was glued in lieu of mulch.

To simulate soil in a post-fire environment, we used previously burned soil from the 2010 Jefferson Fire (43° 40′ N, 112° 35′ W) located in southeastern Idaho on the Snake River Plain. Soils in this region are predominantly loamy sand (USDA-NRCS Web Soil Survey, 2016). Soil samples were collected in 2010 from the top 5 cm of the soil and were classified as sand (sand 88%, silt 10%, and clay 1%). The soil was air-dried and stored in a climate-regulated facility until 2015, when the soil was then sieved to 2 mm and organic materials >2 mm were removed by hand. During experimental trials, aluminum trays (1 meter long, 40 cm wide, 1.5 cm deep) were overfilled with soil and leveled with a screed until soil was flush with the tray. Treatments were then applied at random to experimental trays.

In total, 19 different treatment combinations were applied to the experimental trays and consisted of: 1) control (bare soil); 2) three types of ground cover (chopped rice straw hereafter referred to as "rice straw", wheat straw, chopped wheat straw) at two cover percentages (10% and 70%); and 3) three liquid applications (PineBind™ tackifier agent at dilutions of 1:6 and 1:3; and water) (Table 1). Wheat and rice straw were selected for study because of their common or growing use in burned areas to mitigate hydrologic erosion (Napper, 2006; Robichaud et al., 2010). Baled rice straw is commonly chopped before aerial application because its high starch (amylopectin) content causes the rice to stick together

Table 1
Surface ground cover treatment types and combinations (19 total). Each of the 19 treatments was replicated four times at each of the three wind speeds (12 repetitions of each plot treatment, 228 total experimental runs).

Cover type	Ground cover (%)	Plot treatments
Bare soil (no cover)	0	Tackifier:water ratio (1:6 and 1:3), water only, and dry
Chopped rice straw	10	Tackifier:water ratio (1:6) and dry
	70	Tackifier:water ratio (1:6 and 1:3), water only, and dry
Wheat straw	10	Tackifier:water ratio (1:6) and dry
	70	Tackifier:water ratio (1:6 and 1:3), water only, and dry
Chopped wheat straw	70	Tackifier:water ratio (1:6), water only, and dry

and not spread uniformly. Chopped wheat and rice straw (pre-chop length 210 mm +/– 50 mm, post-length 71 +/– 50 mm) were obtained by cutting the straw using a Diamond Z Tub Grinder 1136B (Diamond Z, Caldwell, ID http://www.diamondz.com/#intro, accessed 15 October 2016). Rice and wheat mulches were applied to the tray surfaces at target rates of 10% or 70% cover; actual fractional cover (pre- and post-run% cover) were calculated from photographs of experimental trays using Cover Management Assistant software (available from: USDA Forest Service Region 6 Restoration Team, Western Forest Lands Highway Division, Vancouver, WA). Cover change during the experimental runs is defined as the percent change (loss in all cases) in cover, and was calculated by: (Pre-run cover – Post-run cover)/Pre-run cover * 100%.

Liquid application treatments were included to differentiate between the effects of the tackifier agent (diluted by water) and water alone in controlling for aeolian sediment transport. Water alone is not considered a viable post-fire treatment in field settings, however, the soil crust that forms as the water evaporates can influence erosion rates. Tackifier to water ratios were selected based on typical application dilutions used for road dust stabilization (National Land Management, 2016). Liquid treatments used 298 mL per experimental tray, which corresponds to the recommended 7.5-kiloliters ha^{-1} field application rate. Liquid treatments were applied using a spraying device normally employed for pesticide use to mimic wetting or spraying the liquid from a truck or aircraft. Trays selected for a liquid treatment were dried after application for 20–48 h, prior to testing, in a drying oven set at 55 °C. The drying temperature of 55 °C mimics regional summer soil surface temperatures (Bristow et al., 1986) as well as expected post-fire soil surface temperatures. Drying was done to mimic a typical field application process; a treatment would be applied, dried in place, then be exposed to a wind event.

Each of the 19 treatment types were replicated four times at each of the three wind speeds of 6.5, 11 and 18 m s^{-1}, totaling 12 replications per treatment type. Experimental runs, whereby the effective surface was exposed to wind, were five minutes. The low wind speed (6.5 m s^{-1}) was selected because it is a common and sustained wind speed year-round in the northwest US (US Bureau of Reclamation Agrimet System, 2016), and is near the initial threshold required to initiate soil particle transport for recently burned soils (Wagenbrenner et al., 2013), but thresholds wind speed for often increase over time as the site recovers. The moderate wind speed (11 m s^{-1}) characterizes a regularly occurring wind event, which can occur as a wind gust or as a sustained wind event in the northwest US (US Bureau of Reclamation Agrimet System, 2016). The highest wind speed (18 m s^{-1}) was selected to simulate high-wind events, which commonly occur on ridge tops and can persist for hours or days, and should therefore be considered when applying treatments to lessen wind erosion in the post-fire environment.

2.2. Measurements

Sediment transport occurs by creep, saltation, and suspension. We measured horizontal creep with a collection tray (1.5 cm long, 10 cm wide, 1.5 cm deep) attached to the downwind edge of the soil tray. The creep tray was oriented such that the length (1.5 cm) extended beyond the experimental tray, and the width (10 cm) was perpendicular to the wind direction. The top of the collection tray was flush with the surface of the soil in the tray and platform floor. We measured horizontal saltation and suspension flux with a modified Bagnold-type slot sampler (Bagnold, 1941; Stetler et al., 1997). The slot sampler is comprised of a cyclone and vacuum to capture saltating and suspended soil particles across a 3-mm wide vertical plane in pre-weighed collection bags. To calculate total sediment loss from each experimental tray, we first divided the eroded sediment mass by the unit area of each collection device, the creep tray and the slot sampler. These quantities were then summed to reflect total sediment loss for each experimental tray.

Atmospheric humidity, pressure, and temperature were measured at a frequency of 1 Hz at the mid-height of the fan intake of the wind tunnel. Before the initiation of and after each experimental run, a dew-point meter was used to measure soil water potential (WP4-T, Decagon Devices, Pullman, WA). Since water potential is one of the most critical factors affecting wind erosion, we ensured all soil trays were below −25 MPa after drying so that any difference in water potential among trays would not influence erosion (Sharratt et al., 2013). Liquid treatments formed a soil crust after drying. The thickness of this crust was measured after each experimental run concluded using digital calipers; crust measurements were not taken prior to experimental runs because it would disturb the surface and bias results. Three evenly spaced crust thickness measurements were taken at approximately 50 cm from the leading edge of the tray while avoiding areas of abraded soil. Variation in crust thickness depends upon the uniformity of tackifier or water application. Because our application for liquid treatments was uniform, the variation in crust thickness was very small (i.e. fractions of a millimeter among sampled areas), and therefore we believe three measurements per experimental tray represented the mean across the width of the tray. Wind speed was measured at six heights (0.005, 0.01, 0.02, 0.03, 0.04, and 0.1 m) above the effective surface and at the downwind edge of the soil trays using pitot tubes connected to differential pressure transmitters (Series 606, Dwyer Instruments Inc., Michigan City, IN). The effective surface of the bare soil treatment was the soil surface, whereas the effective surface of rice and wheat mulch treatments was the top of the straw. The mulch surface was determined by laying a ruler horizontally on top of the rice or wheat straw and measuring the distance to the soil surface. For all mulch treatments, the mean mulch thickness was 0.015 m above the soil surface. Wind speeds were measured at a frequency of 5 Hz and averaged over 1 s. We assumed wind speed was measured within the internal boundary layer and was thus fully adjusted to the surface. Accordingly, a logarithmic relationship was applied to wind speed and height in agreement with (Campbell and Norman, 1998):

$$u(z) = \left(\frac{u^*}{k}\right) \ln\left[\frac{z}{z_0}\right] \tag{1}$$

where u(z) is wind speed (m s^{-1}) at height z (m), k is the von Karman constant (0.4), u^* is friction velocity (m s^{-1}), and z_o is aerodynamic roughness (m). Friction velocity and z_o were determined by plotting the natural log of (z) against u(z) using data collected at three to six measurement heights. A high degree of linearity ($R^2 > 0.95$) ensured that measurements were made in the boundary layer.

2.3. Statistical analyses

Statistics were performed on total sediment loss using a mixed model (Proc Mixed) in SAS (Littell et al., 2006; SAS, 2003). To meet the assumptions of parametric analyses, total sediment loss data were first log transformed which homogenized the variance of the residuals (Helsel and Hirsch, 2002) and resulted in a normal distribution. A three-way ANOVA with type III sum of squares errors was performed with treatment, pre-run cover, wind speed and the interactions between treatment and wind speed, and pre-run cover and wind speed as the treatment effects. Treatments were class variables, while wind speed and pre-run cover were continuous variables. Two-way ANOVAs were performed within each wind speed class with treatment, pre-run cover and the interaction of the two as the treatment effects. Tukey's pairwise comparisons were made between treatment classes; the significance level (α) was 0.05 for all statistical tests.

Based on the initial results from the ANOVAs, we determined there was no difference in total sediment loss between the amount of mulch cover applied (10 or 70%) or the formulation of the two levels of tackifier (1:6 or 1:3 ratio of tackifier to water) that were applied as treatments. In order to reduce the number of treatment classes to clarify the results in subsequent statistical analyses, we combined pre-run cover classes into single "rice," "wheat," and "chopped wheat" classes. Similarly, the two formulations of tackifier were combined into a single "tackifier" class.

Sediment loss ratios were calculated for each treatment at each wind speed by dividing the treatment by the appropriate control treatment. Because treatments were compounded, the control (the divisor) changed depending on the level of treatment. Mulch treatments were compared to the bare soil control; mulch treatments plus water or tackifier were compared to the mulch-alone treatment, and the mulch plus tackifier treatments were additionally compared to the mulch plus water treatments (since tackifier is mixed with water). This aided in differentiating the effect of individual and compound treatments.

3. Results

3.1. Total sediment loss

The three-way ANOVA indicated treatment, wind speed, and the interaction between treatment and wind speed were significant effects for total sediment loss (Table 2). Two-way ANOVAs indicated differences in total sediment loss due to treatment at the two higher wind speeds (Table 2). Pre-run ground cover was not significant at any wind speed, thus was excluded from additional statistical analysis. The significant factors, treatment and wind speed, were further analyzed to differentiate their effects on sediment loss.

3.2. Friction velocity (u^*) and aerodynamic roughness (z_o)

We expected some difference in u^* by wind speed and treatment (Table 3). Indeed, we measured lower u^* for both the bare soil (0.43 m s^{-1}) and rice (0.46 m s^{-1}) treatments compared to the wheat (0.72 m s^{-1}) and chopped wheat (0.67 m s^{-1}) treatments over all wind speeds (Table 3). The difference in u^* between the smoother (bare and rice straw) treatments compared to the rougher (wheat and chopped wheat) treatments was more pronounced at the two higher wind speeds. Similarly, we measured lower z_0 values for bare soil and rice (Table 3); these differences were evident over all wind speeds.

Table 2
ANOVA results with corresponding p-values (bold values are significant at $\alpha = 0.05$). The response variable, total sediment loss, is Log$_{10}$ transformed to meet normality requirements for the ANOVA. All treatments are separate (cover and tackifier classes are not combined for this result, but are hereafter).

Model effect	Total sediment loss
3-way ANOVA	
Treatment	**0.0001**
Pre-run ground cover	0.24
Wind speed	**<0.0001**
Wind speed*Treatment	**<0.0001**
Wind speed*Pre-run ground cover	0.32
2-way ANOVA at 6.5 m s^{-1}	
Treatment	0.17
Pre-run ground cover	0.58
Treatment*pre-run ground cover	0.26
2-way ANOVA at 11 m s^{-1}	
Treatment	**<0.0001**
Pre-run ground cover	0.65
Treatment*pre-run ground cover	0.94
2-way ANOVA at 18 m s^{-1}	
Treatment	**<0.0001**
Pre-run ground cover	0.21
Treatment*pre-run ground cover	0.31

Table 3
Mean friction velocity (u^*) and aerodynamic roughness parameter (z_o) values the different surfaces at three wind speeds. Standard errors of the means are in parenthesis.

Treatment	Wind speed (m s^{-1})			All wind speeds
	6.5	11	18	
Friction velocity (m s^{-1})				
Bare soil	0.25 (0)	0.36 (0.01)	0.67 (0.03)	0.43 (0.05)
Rice	0.39 (0.02)	0.37 (0.02)	0.76 (0.02)	0.46 (0.04)
Wheat	0.54 (0.02)	0.65 (0.06)	0.98 (0.11)	0.72 (0.06)
Chopped wheat	0.46 (0.03)	0.60 (0.06)	0.93 (0.02)	0.67 (0.07)
Aerodynamic roughness (mm)				
Bare soil	0.05 (0)	0.03 (0)	0.08 (0.02)	0.05 (0.01)
Rice	0.69 (0.24)	0.04 (0.02)	0.25 (0.03)	0.36 (0.12)
Wheat	3.29 (0.41)	1.23 (0.32)	1.54 (0.70)	2.02 (0.36)
Chopped wheat	2.01 (0.66)	0.76 (0.29)	0.93 (0.09)	1.28 (0.29)

3.3. Treatment effects

3.3.1. Bare soil

At a wind speed of 6.5 m s^{-1}, sediment loss from the bare soil treatment was 6.5 g m^{-2} and increased exponentially to 182 g m^{-2} and 6258 g m^{-2} at wind speeds of 11 and 18 m s^{-1}, respectively (Table 4, Fig. 1). These sediment loss (flux) values are similar to sediment flux values Wagenbrenner et al. (2013) found during the first major wind event with similar wind speeds after the 2010 Jefferson Fire. The addition of water to the bare soil surface and the resulting soil crust was significantly effective at decreasing sediment loss over all wind speeds (Fig. 2a). The effectiveness was more pronounced as the wind speed increased, as indicated by sediment loss ratios of 0.82, 0.21 and 0.01 at wind speeds of 6.5, 11 and 18 m s^{-1}, respectively (Table 4). Tackifier was also a significant treatment across all wind speeds (Fig. 2a). Tackifier reduced sediment loss by more than half compared to bare soil at the lowest wind speed, and sediment loss was reduced by two orders of magnitude at the higher wind speeds. Similarly, tackifier at least doubled the effectiveness of sediment loss reduction compared to water at all wind speeds indicated by sediment loss ratios less than 0.5 (Table 4).

3.3.2. Dry mulch treatments

At the lowest wind speed, soil with rice straw unexpectedly produced about 1.5 times greater low sediment loss (9.6 g m^{-2}) compared to the bare soil, whereas wheat straw and chopped wheat straw reduced sediment loss by a quarter to half (to 5.0 g m^{-2} and 3.1 g m^{-2}, respectively). At 11 m s^{-1}, all three dry mulch treatments significantly reduced sediment loss by an order of magnitude compared to bare soil treatment (182 g m^{-2}). The addition of rice straw at the highest wind speed reduced sediment loss by half, but the effect was not significant (Fig. 2b). At the same high wind speed, wheat straw and chopped wheat straw significantly reduced sediment loss by an order of magnitude or more compared to bare soil (Table 4, Fig. 2b). These results indicate the efficacy of mulch on aeolian sediment transport.

Table 4
Mean total sediment loss for different treatments by wind speed. The sediment loss ratio, in parenthesis, allows for comparing the individual effects of a treatment as well as the compound effects of mulch and liquid treatments on sediment loss. The control (the divisor) changes depending on the treatment (sediment loss ratio = treatment/control). For example, a sediment loss ratio of 0.01 is equivalent of a 99% decrease in sediment loss compared to the control.

		Total sediment loss (g m^{-2})		
		Wind speed (m s^{-1})		
Treatment	Control	8 Treatment mean	11 Treatment mean	18 Treatment mean
Bare soil	Bare soil	6.5 (1.0)	182 (1.0)	6258 (1.0)
Bare soil + water	Bare soil	5.4 (0.82)	38 (0.21)	83 (0.01)
Bare soil + tackifier	Bare soil	2.6 (0.39)	1.2 (0.006)	12 (0.002)
Bare soil + tackifier	Bare soil + water	2.6 (0.48)	1.2 (0.03)	12 (0.14)
Rice	Bare soil	9.6 (1.48)	17 (0.09)	3573 (0.57)
Rice + water	Rice	4.9 (0.51	15 (0.91)	520 (0.15)
Rice + tackifier	Rice	2.9 (0.31)	4.7 (0.28)	49 (0.01)
Rice + tackifier	Rice + water	2.9 (0.60)	4.7 (0.31)	49 (0.09)
Wheat	Bare soil	5.0 (0.77)	27 (0.15)	698 (0.11)
Wheat + water	Wheat	3.2 (0.63)	8.3 (0.31)	350 (0.50)
Wheat + tackifier	Wheat	7.4 (1.46)	11 (0.41)	36 (0.05)
Wheat + tackifier	Wheat + water	7.4 (2.33)	11 (1.31)	36 (0.10)
Chopped wheat	Bare soil	3.1 (0.48)	14 (0.08)	298 (0.05)
Chopped wheat + water	Chopped wheat	5.7 (1.81)	20 (1.46)	345 (1.16)
Chopped wheat + tackifier	Chopped wheat	4.8 (1.53)	17 (1.27)	23 (0.08)
Chopped wheat + tackifier	Chopped wheat + water	4.8 (0.84)	17 (0.87)	23 (0.07)

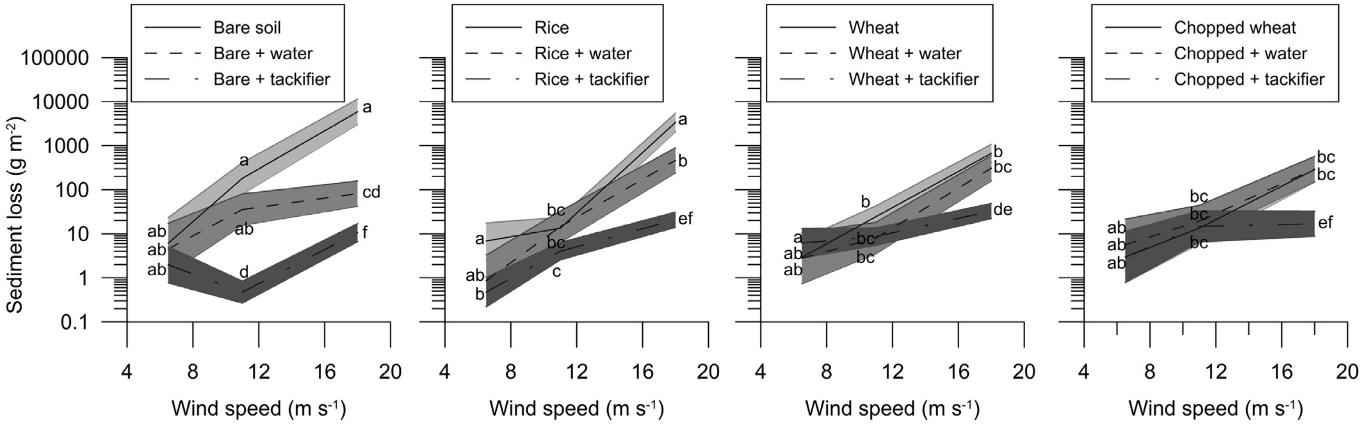

Fig. 1. Modeled total sediment loss at three wind speeds (6.5, 11 and 18 m s^{-2}), across all treatments. The y-axis scale is the same for all four figures; y-axis values represents the inverse-transformed sediment loss data for interpretability. Different letters within a wind speed (not over all wind speeds) indicate significantly different sediment loss at $\alpha = 0.05$.

3.3.3. Mulch treatments plus water

The addition of water and the formation of the soil crust under the rice straw treatment significantly decreased sediment loss over all wind speeds compared to dry rice straw (Fig. 2a), although the magnitude of effectiveness was not consistent across wind speeds (Table 4). There was only a non-significant reduction in sediment loss when compared to bare soil treated with water at the 6.5 and 11 m s^{-1} wind speeds (Fig. 1), and significantly greater sediment loss (520 g m^{-2}) on these plots than measured on bare soil plots treated with water (83 g m^{-2}) at the highest wind speed attributed to the instability of the rice (Fig. 2b).

Adding water to the wheat and chopped wheat straw plots did not significantly reduce sediment loss compared to either the bare soil with water or to the dry mulch treatments at any wind speed (Figs. 1 and 2); in fact there were several instances where we measured an increase in sediment loss. At the 18 m s^{-1} wind speed, wheat straw and chopped wheat straw plus water had four-times greater sediment loss (~350 g m^{-2} each) than bare soil plus water (83 g m^{-2}) (Fig. 1).

3.3.4. Mulch treatments plus tackifier

The addition of tackifier to the rice straw treatment provided a significant sediment reduction compared to the dry rice treatment and to the rice plus water treatment over all wind speeds (Fig. 2a). At the two lower wind speeds, rice straw plus tackifier decreased sediment loss to about one-third compared rice straw alone, and by two orders of magnitude at the highest wind speed (6258 to 49 g m^{-2}, respectively) (Table 4). At the lowest wind speed, rice straw plus tackifier decreased sediment loss by nearly half compared to rice plus water, and greater sediment loss reductions were found at the 11 m s^{-1} and 18 m s^{-1} wind speeds, respectively (Table 4, Fig. 1).

There were more mixed results with the wheat straw plus tackifier treatments. Compared to the dry mulch treatments, wheat straw and chopped wheat straw plus tackifier produced just 5% total sediment compared to the bare soil treatment at the highest wind speed (Table 4; Fig. 2b). At the lowest wind speed, both wheat straw plus tackifier treatments had greater sediment loss than their respective dry mulch treatment

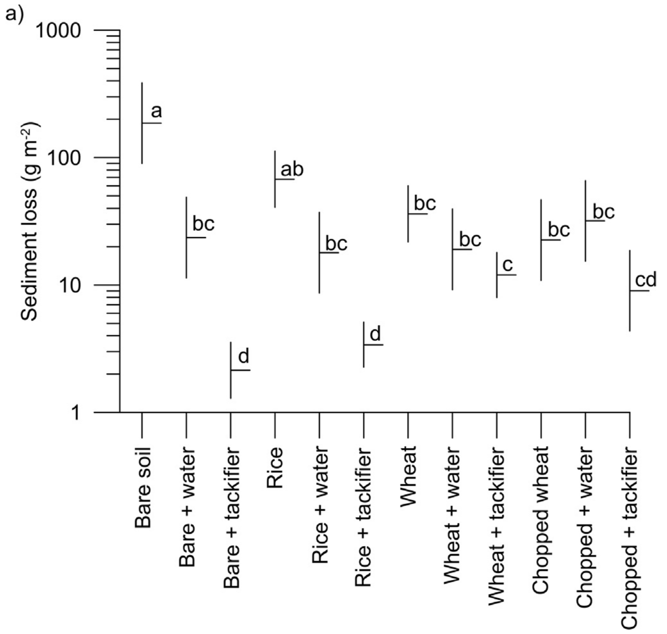

Fig. 2a. Least squares means estimates of total sediment loss over all wind speeds (result of 3-way ANOVA performed on Log_{10}-transformed sediment loss data, with grouped cover and tackifier treatments). The y-axis represents the inverse-transformed sediment loss data for interpretability. The vertical range of the bars represent the 95% confidence limits of the estimate, which is represented by the horizontal bar. The same letters indicate means are not significantly different at $\alpha = 0.05$.

(Fig. 1), which again can be attributed to minor sediment losses and the insignificance of the treatment effects at this low wind speed. Over all wind speeds, adding tackifier to the wheat and chopped wheat straw treatments did not provide significant additional sediment loss reduction compared to the respective wheat straw treatment plus water (Table 4, Fig. 2a). Interestingly, wheat straw plus tackifier and chopped wheat straw plus tackifier were either statistically equivalently effective or slightly less effective for reducing sediment loss than bare soil plus tackifier (Figs. 2a and 2b).

3.4. Cover changes and soil crusting

3.4.1. Cover change by wind speed and by topical treatment

At 6.5 m s^{-1} wind speed, cover change (loss) varied from 16 to 92% across all treatments (Table 5). Wheat plus tackifier and rice plus tackifier had the smallest cover change at 16%. Neither water nor tackifier significantly reduced cover loss for the wheat or chopped wheat treatments at any wind speed. Tackifier significantly reduced cover loss for the rice treatment at all wind speeds, and water added to the rice treatment reduced cover loss at 6.5 m s^{-1}. At 11 m s^{-1} wind speed, cover change varied from 61 to 100% across the treatments. At the highest wind speed, rice plus tackifier was the only treatment that had less than 90% cover loss (64%), and was the only significant treatment for reducing cover loss.

3.4.2. Crusting

The application of liquid to the soil surface, or to the mulch that was in contact with the soil surface resulted in a thin crust on the soil surface after the soils were dried in the oven which reduced sediment loss. The crust thickness was different than zero in all instances, yet there was no discernable difference in crust thickness between the water and tackifier treatments regardless of mulch (Table 6). The rice plus liquid treatments had the thickest

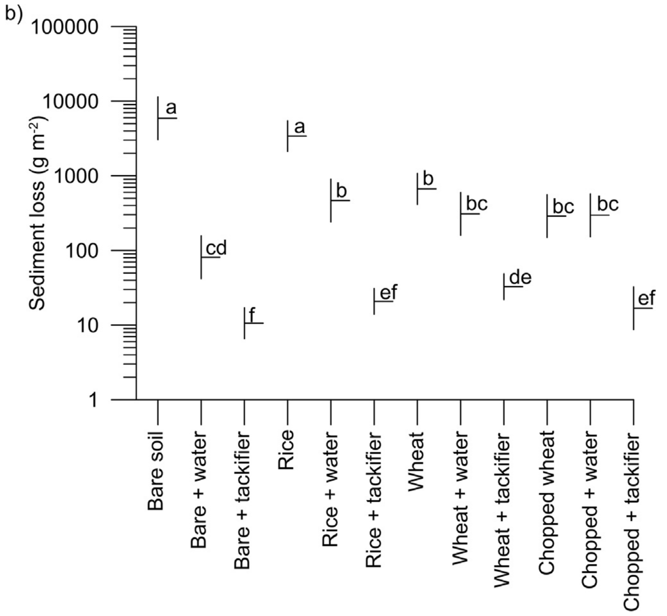

Fig. 2b. Least squares means estimates of total sediment loss at 18 m s^{-1} wind speed (result of 2-way ANOVA performed on Log_{10}-transformed sediment loss data). The y-axis represents the inverse-transformed sediment loss data for interpretability. The vertical range of the bars represent the 95% confidence limits of the estimate, which is represented by the horizontal bar. The same letters indicate means are not significantly different at $\alpha = 0.05$.

Table 5
Mean ground cover loss by treatment, standard errors are in parentheses. The same letters in a column (within a wind speed) indicate values are not significantly different at $\alpha = 0.05$. Either 10% or 70% cover was applied to the bare soil surfaces prior to the experimental runs. All cover change values are cover loss: (Pre-run cover − Post-run cover)/Pre-run cover*100%.

	Ground cover loss (%)		
	Wind speed (m s^{-1})		
Treatment	6.5	11	18
Rice	92 (6.9) a	98 (7.1) a	100 (6.8) a
Rice + water	45 (10.1) bc	99 (10.2) ab	100 (9.8) ab
Rice + tackifier	16 (5.4) c	61 (5.6) b	64 (5.3) b
Wheat	45 (6.9) bc	84 (7.1) ab	96 (6.8) a
Wheat + water	22 (10.1) bc	96 (10.2) ab	100 (9.8) ab
Wheat + tackifier	16 (5.4) c	73 (5.6) ab	94 (5.3) a
Chopped wheat	56 (10.1) ab	100 (10.2) ab	99 (9.8) ab
Chopped wheat + water	50 (10.1) bc	98 (10.2) ab	100 (9.8) ab
Chopped wheat + tackifier	67 (10.1) ab	85 (10.2) ab	91 (9.8) ab

Table 6
Mean soil crust thickness by treatment over all wind speeds; standard errors of the means are in parentheses.

Treatment	Crust thickness (mm)
Bare soil	0
Bare soil + water	3.4 (0.1)
Bare soil + tackifier	3.2 (0.1)
Rice	0
Rice + water	4.7 (0.3)
Rice + tackifier	4.4 (0.1)
Wheat	0
Wheat + water	3.9 (0.2)
Wheat + tackifier	3.9 (0.1)
Chopped wheat	1.1 (0.5)
Chopped wheat + water	3.9 (0.1)
Chopped wheat + tackifier	4.0 (0.1)

crust [4.7 mm (rice + water) and 4.4 mm (rice + tackifier)] of all treatment combinations.

Each mulch plus liquid treatment combination resulted in a crusted soil surface which reduced sediment loss. However across all wind speeds, crust thickness was initially tested as a covariate in the mixed model ANOVA and was not significant for predicting sediment loss. The data were also analyzed at the individual wind speeds and crust thickness was only significant at 6.5 m s^{-1} ($p = 0.03$) (not in tables), and not at the two higher wind speeds. Therefore, we concluded the presence of the crust due to the dried liquid treatments is important in reducing sediment loss, regardless of the measured thickness.

4. Discussion

Our experimental design allowed for direct comparison of treatments with minimal influence of ambient conditions on sediment transport. Relative humidity and soil water potential ranged from respectively 16 to 64% and −68 to −365 MPa across all experimental runs with the wind tunnel (data not shown), thus antecedent soil moisture likely had little or no influence on sediment transport in this study (Ravi et al., 2006; Sharratt et al., 2013). No additional saltation was introduced in the airstream thus our observations may not mimic transport processes under natural conditions where expected sediment loss might be amplified due to bombardment of the soil surface by saltating particles.

The u^* was low for bare soil and rice mulch since these were the smoother treatments. The wheat and chopped wheat were coarser, increasing the shear stress and therefore higher u^*. These u^* values were similar to what Wagenbrenner et al. (2013) found after the 2010 Jefferson Fire with similar natural wind speeds. At the lowest wind speed, u^* was more affected by the mulch treatments, while at the higher wind speeds the effect of the treatments on friction velocity were less. Much of the mulch treatments were removed, resulting in similar (smoother) surface conditions. The results of z_0 were comparable, as the main effects between the smooth (bare and rice straw) and coarse (wheat straw) treatments were more pronounced at the lower wind speed. The percent cover or amount of mulch applied (10 or 70%) did not significantly affect aeolian sediment loss, similar to what Copeland et al. (2009) found even though our sediment loss values were an order of magnitude greater with the burned soil used in this experiment as compared to the agricultural silt loam in their paper. We found that any amount of wheat straw cover significantly reduced sediment yields, both at the highest wind speed and when all wind speeds were considered. Therefore, we conclude any additional ground cover is beneficial for reducing wind-driven erosion. This finding is very different than what is typically found in post-fire water-driven erosion studies where at least 60% sustained cover is necessary to make a difference in reducing erosion (Robichaud et al., 2013a).

Sediment losses were low across all treatments (<10 g m^{-2}) at the lowest wind speed (Table 4, Fig. 1), which explains much of the variability and lack of significance in treatment effectiveness. For instance, the rice mulch treatment yielded slightly greater sediment loss than the bare soil at the 6.5 m s^{-1} wind speed (Table 4). This can likely be attributed to the rice straw detaching the soil as it moved across the soil surface dislodging the topmost soil particles, increasing soil loss. Since the wheat and chopped wheat were heavier they were not as easily moved at the lowest wind speed. This dislodging effect may have occurred with other treatments and wind speeds but since the bare soil sediment yields were relatively much greater, it did not reveal itself in the data.

At the highest wind speed, the crust formed by the addition of water to bare soil and to dry rice straw significantly reduced sediment loss; adding water to wheat straw or chopped wheat straw did not since the relative magnitude of sediment losses were much smaller (Table 4; Fig. 1). In addition, the effectiveness of the wheat mulch treatments were diminished at the high wind speed due to their instability (Table 5). While water alone is not an erosion mitigation treatment we would prescribe or recommend, it was evaluated discretely in this study as a way to account for the water in the tackifier as well as its effect of rainfall-induced consolidation and crusting of the surface soil (Table 6). After a wildfire, the time between the fire and the first wetting rainfall varies from days to months. If a low-intensity, wetting rainfall occurs and the soil subsequently dries prior to the next rainfall, our results indicate potential for some reduction in wind erosion due to the consolidation and crusting effect (Table 6) especially for post-fire ash and fine-grained soils. This water induced crusting is different than crypto biotic crusts by algae, fungi or soil bacteria that often forms in the interspace areas in rangelands which can be altered by fire (Ravi et al., 2007).

The surface cover loss from the plots treated with mulch averaged >80% (e.g. less than 15% cover remaining on a plot that started out with 70% cover) for nearly all treatments at the moderate and high wind speeds, with most of the mulch being removed in the first 30 s of the trial (by author observation). This cover loss likely explains why cover percentage was not a significant covariate in any of the statistical tests to predict total sediment loss (Table 2). Yet the remaining mulch cover was still able to reduce the overall sediment loss since greater sediment loss occurred earlier in the trial during the initial saltation of soil particles (by observation) while the cover was intact.

There was a non-significant additional reduction in wind erosion with a high concentration (tackifier to water ratio 1:3) of tackifier when coupled with the rice straw (results not shown), and mixed results with bare soil and the wheat straw treatments. Our results did not provide evidence of significant reduction to justify the additional expense in using the higher concentration, therefore under the conditions tested, using the tackifier to water ratio of 1:6 is appropriate. The addition of tackifier and subsequent crust formation provided a significant soil loss reduction when applied to bare soil and to dry rice straw. From the sediment loss ratios (Table 4), tackifier applied to bare soil at least doubled the effectiveness of sediment loss reduction compared to water at all wind speeds. These results could imply that where a liquid can be easily applied for dust control (e.g. truck mounted spray system), the tackifier may be beneficial. Results were more mixed with the wheat straw and chopped wheat straw; tackifier was most effective when compounded with these treatments only at the highest wind speed due to much small sediment loss at the lower wind speeds.

Chopped wheat straw tested in this study confirms that wheat straw does not clump as rice straw does due to the lower starch (amylopectin) content. Indeed, there was no difference between the effectiveness of wheat and chopped wheat straw at any wind speed, and both dry treatments were equivalent to rice straw except at the high wind speed (Fig. 1). Because sediment losses were small for all treatments and wind speeds (<40 g m^{-2}), wheat straw and chopped wheat straw plus tackifier were either statistically equivalently or slightly less effective at reducing sediment loss than bare soil plus tackifier. Thus for the conditions tested, we conclude there is little benefit to compounding either wheat-mulch treatment with tackifier at any wind speed. The results may be different for a combined wind and water erosion mitigation situation, in which the compounded treatments may provide effective treatment.

Based on this study alone, one would might infer that applying tackifier to bare soil is the most effective and simplest solution to reduce wind erosion. However, studies have shown that tackifier or other soil binding agents (polyacrylamide or PAM) unaccompanied by a mulch treatment have limitations (Hubbert et al., 2012; Foltz and Robichaud, 2013). Persistence and effective longevity may not last a full wet season (6 months) (Robichaud et al., 2010, 2013a). On a long burned hillslope, tackifier alone may not be effective for the full length of the slope (wind or water) based on observations on the 2003 Robert Fire, MT from the authors. Hydromulch is the most researched mulch often combined with a tackifier treatment (a water-based mixture of organic fibers, seeds, and a soil binding agent such as tackifier). Hydromulch has demonstrated mixed results at reducing runoff and sediment yields depending on the circumstances (Robichaud et al., 2010, 2013b; Hubbert et al., 2012; Rough, 2007; Wohlgemuth et al., 2011). On the 2003 Cedar Fire in southern California, hydromulch was found to be effective at reducing erosion immediately after the fire, with limited effectiveness after 2–4 months (Hubbert et al., 2012).

5. Conclusions

A wind tunnel experiment was used to determine effectiveness of various mulch and tackifier treatments at reducing aeolian sediment loss. A total of 19 different treatment combinations were applied to experimental burned soil trays at three wind speeds simulating potential post-wildfire conditions. As expected, sediment loss was greatest for the bare soil treatment which exponentially increased with wind speed. Two dry mulch treatments (wheat and chopped wheat straw) significantly reduced sediment loss in all cases, and the rice straw reduce sediment loss except at the low wind speed. Most of the mulch treatment cover was easily removed at the higher wind speeds, resulting in nearly a bare soil surface at the end of the run, yet the mulch still reduced total sediment loss as saltation of soil particles was greater at beginning of each trial while most of the cover was intact. Liquid treatments reduced sediment loss when applied to bare soil and when compounded with various mulch treatments, particularly at the high wind speed (18 m s^{-1}). These results suggest that tackifier may be useful to reduce aeolian sediment loss after wildfires and combining tackifier and mulch may also be beneficial. Dry wheat mulch treatments were more effective that dry rice mulch treatments. We anticipate these results will aid land managers when prescribing post-fire erosion mitigation treatments in areas of predicted high winds.

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