A Wood-Strand Material for Wind Erosion Control: Effects on Total Sediment Loss, PM_{10} Vertical Flux, and PM_{10} Loss

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Fugitive dust from eroding land poses risks to environmental quality and human health, and thus, is regulated nationally based on ambient air quality standards for particulate matter with mean aerodynamic diameter ≤ 10 μm (PM_{10}) established in the Clean Air Act. Agricultural straw has been widely used for rainfall-induced erosion control; however, its performance for wind erosion mitigation has been less studied, in part because straw is mobile at moderate wind velocities. A wood-based long-strand material has been developed for rainfall-induced erosion control and has shown operational promise for control of wind-induced erosion and dust emissions from disturbed sites. The purpose of this study was to evaluate the efficacy of both agricultural straw and wood-strand materials in controlling wind erosion and fugitive dust emissions under laboratory conditions. Wind tunnel tests were conducted to compare wood strands of several geometries to agricultural wheat straw and bare soil in terms of total sediment loss, PM_{10} vertical flux, and PM_{10} loss. Results indicate that the types of wood strands tested are stable at wind speeds of up to 18 m s^{-1}, while wheat straw is only stable at speeds of up to 6.5 m s^{-1}. Wood strands reduced total sediment loss and PM_{10} emissions by 90% as compared to bare soil across the range of wind speeds tested. Wheat straw did not reduce total sediment loss for the range of speeds tested, but did reduce PM_{10} emissions by 75% compared to a bare soil at wind speeds of up to 11 m s^{-1}.

Arid conditions and persistent winds, characteristic of much of the western United States, promote conditions conducive to wind erosion. Wind-blown dust liberated from construction sites, burned areas, and agricultural fields is a widespread problem with both human health and environmental implications. In 1987 the United States Environmental Protection Agency (USEPA) began to regulate PM_{10} as a criteria pollutant. Since then, numerous epidemiological studies have shown a strong correlation between incidence of respiratory ailments, such as asthma, and atmospheric PM_{10} (Dockery and Pope, 1994; Koren, 1995; Peden, 2001). Based on these and other findings, National Ambient Air Quality Standards have been set regulating PM_{10} on a 24-h basis (USEPA, 2006). Aside from the health issues directly related to particulate matter, PM_{10} also represents the most chemically active portion of the soil, and thus has the potential to transport heavy metals, pesticides, and microbes (Garrison et al., 2003; Whicker et al., 2006a). In addition to these potentially harmful compounds, PM_{10} may also transport nutrients necessary for plant growth, reducing soil productivity (Van Pelt and Zobeck, 2007).

Once fine-sized particles are in suspension, they can remain in the atmosphere for long periods of time before being redeposited. This long residence time allows impacts of particulate matter to be felt in areas distant from the actual dust source. For instance, suspended particulates originating from dust storms in the Columbia Plateau region of the U.S. Pacific Northwest have been shown to affect air quality in eastern Washington and the Idaho Panhandle, with ambient PM_{10} concentrations exceeding air quality standards numerous times since monitoring began in 1985 (Sharratt and Lauer, 2006). Influxes of dust originating from events as far away as Asia have been measured on the Columbia Plateau (Vaughan et al., 2001) and it is estimated that hundreds of millions of tonnes of dust from Africa are deposited in the Caribbean each year (Moulin et al., 1997).

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Abbreviations: PM_{10}, particulate matter with mean aerodynamic diameter ≤ 10 μm; SLRs, soil loss ratios.

Traditional management practices for wind erosion control have included implementation of wind breaks, shelterbelts, irrigation, applied surface cover material, conservation tillage practices, and crop residue handling techniques. Newer approaches have also included the application of soil binding agents and stabilizers, such as polyacrylamides (Armbrust, 1999; Van Pelt and Zobeck, 2004). These techniques, in principle, apply to all land types; however, wind erosion research efforts have primarily focused on agricultural lands, and control technologies developed for agricultural lands may not be equally suitable or readily adaptable for use in other ecosystems such as grasslands, shrublands, forests, and the built environment. Little information is available regarding wind erosion protection in nonagricultural lands, although they have been shown to be important sources of dust emissions (Whicker et al., 2006a, 2006b).

Perhaps the most widely used material for erosion control has been agricultural straw. Straw, however, may not be entirely effective in controlling wind erosion. Straw is a lightweight material and, unless it is anchored or crimped into the soil, lacks stability during high-wind events. Other drawbacks to the use of straw arise when it is applied on wildlands or forest ecosystems. One of these drawbacks is the concern over the introduction of noxious weeds and non-native species to forested areas (Robichaud et al., 2000). Straw itself carries fine dust particles that may be liberated when the straw elements are shattered, posing a health hazard to workers involved in the application process (Kullman et al., 2002). Straw is also a raw material for other potentially high-value uses such as energy production (Gorzell, 2001). Value-added products derived from straw may reduce the supply for erosion control.

Forest Concepts, LLC (Auburn, WA) has developed a wood-based straw analog made from the byproducts of forest thinning and veneer manufacturing. The wood-strand materials (WoodStraw) are heavier than straw, and thus less likely to be blown away when exposed to high winds. Wood strands also have favorable mulching characteristics for decomposing into environment-friendly duff, offer long-term resistance to erosion, and do not introduce noxious weeds, pesticides, or non-native materials to forest wildlands (Forest Concepts, LLC, 2007). Additionally, the manufacturing of wood strands uses what were previously considered waste materials. The use of wood strands as an alternative material for water erosion control has previously been investigated. Foltz and Dooley (2003) and Yanosek et al. (2006) reported that agricultural straw and wood strands were equally effective on two soil types in reducing rainfall-induced erosion by more than 98% as compared to bare soil.

The current study was intended to evaluate wood strands in terms of wind erosion mitigation and air quality protection. Specific objectives of this study were: (i) to evaluate the effectiveness of wood strands in reducing total sediment loss, PM_{10} vertical flux, and PM_{10} loss compared to bare soil and soil covered with agricultural straw; and (ii) to identify dimensional characteristics impacting the erosion reduction and dust reduction efficacy of the wood strands.

Materials and Methods

Experimental Design

Wind tunnel experiments were performed at the U.S. Department of Agriculture Agricultural Research Service (USDA ARS) Palouse Conservation Field Station in Pullman, WA. The experiments were performed in a nonregulated climate facility using a portable wind tunnel (Pietersma et al., 1996) with a working section 1.0 m wide, 1.2 m tall, and 7.3 m long. Wind was generated by a 1.4-m diam. Joy Series 1000 axivane fan driven by a Ford industrial type gasoline engine. A bell infuser and curvilinear guiding vanes were employed to ensure smooth transitions at the upwind and downwind edges of the fan. The flow was passed through a diffuser and honeycomb-screen combination to reduce turbulence. Sand-coated plywood (for fixed surface roughness) was used for the floor of the tunnel and allowed for establishment and stabilization of a boundary-layer characteristic of a smooth, bare soil surface upwind of the test surface.

The experiment consisted of 11 different surface treatment combinations of two surficial material types (agricultural straw or wood strands) and three coverages (0, 50, or 70%) (Table 1). Treatments were randomly assigned to the test plots, and each treatment combination was replicated four times at three wind speeds of 6.5, 11, and 18 m s^{-1}. The low wind speed, 6.5 m s^{-1}, was chosen as the lower limit for this wind erosion investigation because it is near threshold velocity (i.e., the minimum velocity required to move soil particles) for the type of soil used in this study (Sharratt et al., 2006) and is a commonly achieved sustained wind speed throughout the year in the northwestern United States (U.S. Bureau of Reclamation Agrimet System, 2006). The middle wind speed, 11 m s^{-1}, was chosen to represent a common wind event, as this speed is achieved frequently as a peak wind gust or several times within a season as a sustained wind event in the northwestern United States (U.S. Bureau of Reclamation Agrimet System, 2006). The 18 m s^{-1} wind speed was chosen to represent a high-wind event, as this speed occurs as a 1-min average wind speed about once every 2 yr in many parts of the northwest, including the Columbia Plateau region (Wantz and Sinclair, 1981). Each soil treatment was subjected to the wind for 5 min, as much of the erodible size material was depleted from the test surface within this time period.

Surface treatments included a bare soil, soil covered with air-dried wheat straw at either 50 or 70% cover, and soil covered with air-dried wood strands of varying dimensions at either 50 or 70% cover. Wood strands were classified by their length, depth (thickness), and width. There were four types of wood-strand treatments including long strands (240 mm) of two thicknesses (4.8 and 2.5 mm) and a mixture of short (64 mm) and long strands of the same two thicknesses (Fig. 1). Mixes were created on a 50:50 mass basis (long and short of designated thickness). All wood strands had a standard width of 4.5 mm. Forest Concepts, LLC produced the wood strands used in this experiment from Douglas fir [*Pseudotsuga menziesii* (Mirbel) Franco] clear wood blocks.

A Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) collected from the top 10 cm of the soil profile at a field site near Lind, WA, was selected for the study due to the soil's high potential to erode and emit PM_{10} (Chandler et al., 2004). Before testing, the soil was air-dried and sieved to remove aggregates larger than 2 mm in diameter. Nondispersed aggregate-size analysis indicated that more than 70% of the soil was comprised of suspendible particles, or PM_{100} (particulate matter ≤ 100 μm in diameter), with nearly 4% of this fraction as PM_{10}. Aluminum trays (1 m long, 0.5 m wide, and 0.04 m deep) were filled with soil in three layers. After the addition of each soil layer, the sides of the trays were tapped to ensure even settling. Following the addition of the third layer, the trays were overfilled with soil and then leveled with a screed. Cutouts in the plywood floor of the wind tunnel were made 5 m downwind from the flow conditioning section so that the soil surface was flush with the tunnel floor.

Cover treatments were applied by hand to the soil before transfer of trays to the tunnel. The treatments were applied in a random manner to the plots (although evenly distributed over the plot area), such that individual elements did not lay in exactly the same orientation relative to one another, but rather overlapped and intertwined with one another to form a matrix-like cover. This application method was intended to simulate field application of the cover treatments. Actual percent cover was determined by a point count method using a 48-point grid overlay on digital pictures of the trays. Average cover height was measured before each run.

Measurements

Measurements made during the wind tunnels tests included: (i) loss of saltating and suspended sediment and surface creep to determine total sediment loss from the tray and (ii) PM_{10} concentrations to assess the impact on air quality. Saltating and suspended sediment were measured using a vertically integrating isokinetic slot sampler (modified Bagnold type, Stetler et al., 1997) connected in series with a high efficiency cyclone and vacuum. A 10-cm wide collection tray was attached to the downwind edge of the soil tray to catch surface creep. Total sediment loss was calculated by summing the masses caught by these two devices.

Table 1. Treatment combinations and average measured cover height.

Cover type	Percent cover	Dimensions†	Avg cover height
			cm
Bare	0	–	–
Agricultural straw	50	–	2.7
	70	–	3.3
Wood strands	50	Long/Thick	2.5
		Mix/Thick	2.3
		Long/Thin	2.0
		Mix/Thin	1.3
	70	Long/Thick	3.3
		Mix/Thick	2.7
		Long/Thin	2.3
		Mix/Thin	1.8

† Long: 240 mm, short: 64 mm, thick: 4.8 mm thin: 2.5 mm.

PM_{10} concentrations were measured using TSI DustTrak Aerosol Monitors (TSI, Inc., St. Paul, MN). The DustTrak is a constant-flow portable laser photometer capable of measuring particle sizes in the range of 0.1 to 10 μm. The PM_{10} measurements were made at a frequency of 1 Hz with aerosol inlets placed at 0.5, 1, 2, 3, 4, and 10 cm above the cover surface at the downwind edge of the soil tray. These heights were chosen to measure concentrations within and above the boundary layer. Background PM_{10} concentrations were monitored with two additional aerosol monitors located at the upwind end of the tunnel. Wind speeds were measured at a frequency of 1 Hz and averaged over 60 s using pitot tubes connected to differential pressure transmitters (Series 606, Dwyer Instruments, Inc., Michigan City, IN) at heights corresponding to DustTrak inlet heights. Free stream velocity was measured with an additional pitot tube at a height of 1 m inside the wind tunnel. Soil water potential was measured before each wind tunnel run using a dew-point meter (WP4-T, Decagon Devices, Pullman, WA).

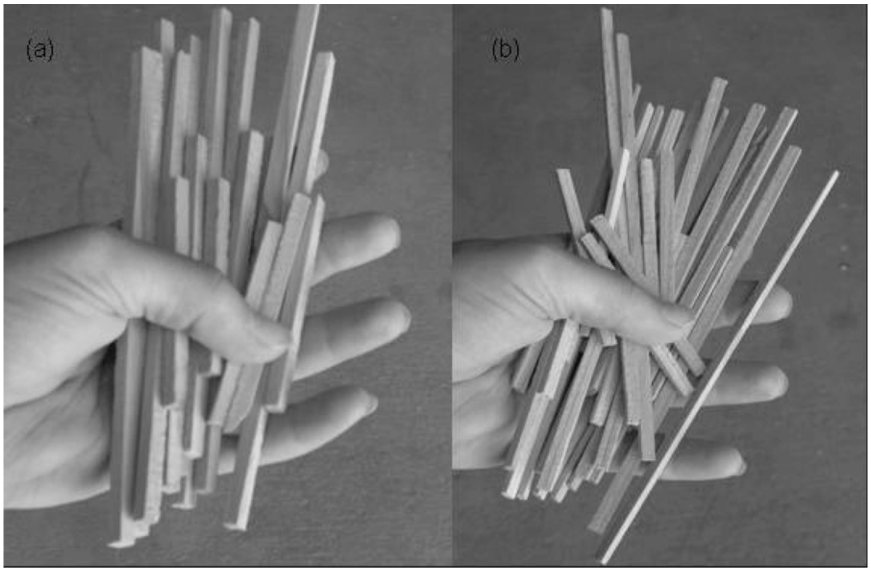

Fig. 1. Two types of wood strand treatments used in this study: mixtures of long and short (240 and 64 mm) wood strands with thicknesses of (a) 4.8 mm and (b) 2.5 mm.

PM_{10} Vertical Flux and Loss

Treatment effectiveness was assessed based on total sediment loss, vertical flux of PM_{10}, and PM_{10} loss. The wind velocity profile above the test surface was characterized to determine PM_{10} flux from the tray. When airflow encounters a change in surface conditions, such as the edge of the soil tray, the air begins to adjust to the new surface. An internal boundary layer with thickness δ develops and grows thicker with increasing fetch. Boundary layer thickness (δ) was approximated by (Munro and Oke, 1975):

$$\delta(x) = 0.1x^{(4/5)} z_0^{(1/5)} \qquad [1]$$

where x is the distance downwind from leading edge (m) and z_0 is the roughness parameter of new underlying surface (m), estimated by:

$$\log_{10} z_0 = 0.997 \log_{10} h - 0.883 \qquad [2]$$

where h is crop height (m). Crop height was estimated as the average cover thickness for each of the wood strand and straw treatments and as the diameter of a coarse sand particle for the bare soil treatments. This estimation allowed for approximation of boundary layer depth to provide guidelines for instrumentation setup.

Wind speed and PM_{10} concentrations were measured within and above the boundary layer. Airflow within the internal boundary layer was assumed to be fully adjusted to the new surface, and a logarithmic relationship was applied to characterize the wind velocity profile (Campbell and Norman, 1998):

$$U(z) = \frac{u^*}{\mathrm{k}} \ln \frac{z-d}{z_0} \qquad [3]$$

where $U(z)$ is mean wind speed at height z (m s^{-1}), k is the von Karman constant, taken as 0.4, u^* is friction velocity (m s^{-1}), z_0 is the roughness parameter (m), and d is zero-plane displacement (m). Friction velocity and the roughness parameter were determined from linear regressions of log-linear plots of (z-d) vs. $U(z)$ based on Eq. [3]. Friction velocity, u^*, is a characteristic velocity in a turbulent boundary layer and is defined as:

$$u^* = \sqrt{\frac{\tau_0}{\rho}} \qquad [4]$$

where u^* is friction velocity (m s^{-1}), τ_0 is Reynold's stress (Pa), and ρ is air density (kg m^{-3}). Therefore, friction velocity is an indication of shear stress at the surface. The roughness parameter (z_0) is directly related to height (h) of the roughness elements. Wind speed was measured at six heights above the soil surface; however, u^* was determined from best-fit linear regression based on three to four of these heights that fell within the boundary layer ($R^2 > 0.90$ in all cases). High degrees of linearity further ensured that measurements were made within the boundary layer. The zero-plane displacement (d) is an important parameter for rough surfaces and is an indication of the mean level at which momentum is absorbed by individual roughness elements. It was calculated as a function of roughness element height (h) by the following relationship (Stanhill, 1969):

$$\log_{10} d = 0.979 \log_{10} h - 0.154 \qquad [5]$$

where h is roughness element height (m) and d is the zero-plane displacement (m).

The vertical flux of PM_{10} represents the portion of the total PM_{10} emitted from the surface that is transported vertically into the atmosphere and is directly proportional to friction velocity. Vertical flux of PM_{10} into the atmosphere was calculated as (Gillette, 1977):

$$F_v = -\mathrm{k}u^* \frac{dC}{\ln\left(\frac{z_2}{z_1}\right)} \qquad [6]$$

where F_v is vertical flux of PM_{10} (mg m^{-2} s^{-1}), k is the von Karman constant, u^* is friction velocity (m s^{-1}), C is PM_{10} concentration above background concentration (mg m^{-3}), and z is height as previously defined. Change in concentration with height was determined by plotting PM_{10} concentration against the natural log of height to generate a linear trend (Fig. 2) with slope equal to $dC/(\ln z_2 - \ln z_1)$. Vertical flux was not constant over the entire 5 min of testing, likely due to the absence of saltating particles to continuously liberate PM_{10} from the surface. Since PM_{10} concentrations decreased rapidly within the first 60 s of testing (Fig. 3), vertical flux was only calculated for this time period.

Friction velocity, the roughness parameter, and PM_{10} vertical flux were not calculated for the straw treatments at 11 or 18 m s^{-1} due to straw mobility and measurement constraints. Calculation of these parameters required that wind speed and PM_{10} measurements be made within the boundary layer. The bottom of the boundary layer was approximated based on average height of the cover material (e.g., for a straw treatment, the lowest sampling height was 0.5 cm above the average cover height for that treatment). Once the straw was blown away, the instrumentation was no longer within the boundary layer, prohibiting calculation of friction velocity, and thus calculation of vertical flux.

The emission rate of PM_{10} (E) was calculated based on the following relationship (Houser and Nickling, 2001; Shao et al., 1993).

$$E = \frac{1}{L}\int_0^{z_b} Cu\,dz \qquad [7]$$

where E is PM_{10} emission rate (mg m^{-2} s^{-1}), L is length of the eroding surface (m), z_b is height at which PM_{10} concentrations reached background concentrations (m), C is PM_{10} concentration above background concentration (mg m^{-3}), and u is wind speed at height z (m s^{-1}).

Equation [7] was evaluated from the lowest sampling height to z_b by plotting PM_{10} horizontal flux as a function of height (Fig. 4). Sampling height was plotted as a function of PM_{10} concentration and fit with a logarithmic function to determine the height at which background concentration was achieved. Soil loss ratios (SLRs) were calculated as the soil loss from a given treatment divided by soil loss from the bare treatment.

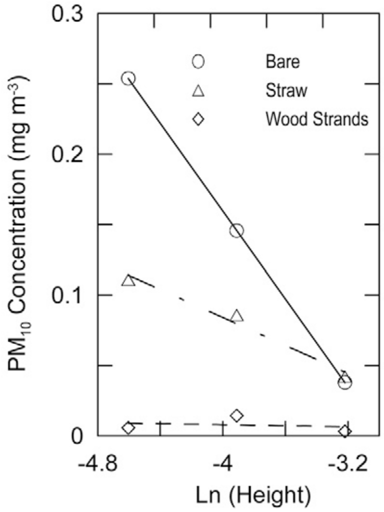

Fig. 2. Composite trends of particulate matter with mean aerodynamic diameter ≤ 10 µm (PM_{10}) concentration averaged over the first 60 s of testing vs. natural log of height at a wind speed of 6.5 m s^{-1}.

Statistical Analyses

Statistical analyses were performed on total sediment loss, friction velocity, the roughness parameter, PM_{10} vertical flux, and PM_{10} loss using mixed-model ANOVAs in SAS (Littell et al., 1996; SAS, 2003). Analyses were first made across wind speeds, with wind speed treated as a continuous variable. Three-way ANOVAs were conducted with "treatment", "percent cover", "wind speed", and "wind speed*treatment" and "wind speed*percent cover" interactions as the treatment effects. Percent cover was nested within treatment in the model statement, and thus, the "treatment*percent cover" interaction was not included in the model. Multiple pairwise comparisons were made using Tukey's procedure. Two-way ANOVAs were performed within wind speed groups with treatment and percent cover as the treatment effects. All results are reported at the $\alpha = 0.05$ level of significance.

Residuals from the mixed-model were not normally distributed in all cases; transformations were therefore performed on the data to satisfy the normality assumption necessary for the ANOVA. Log transformations were performed on total sediment loss, friction velocity, PM_{10} vertical flux, and PM_{10} loss data for all ANOVAs. Square-root transformations were performed on the roughness parameter data for two-way ANOVAs at 6.5 and 11 m s^{-1}; no transformation was necessary for the ANOVAs at the 18 m s^{-1} wind speed. Log and square-root transformations were performed on PM_{10} vertical flux data for the three-way and two-way ANOVAs, respectively.

Straw treatments were not considered in the analysis of friction velocity, the roughness parameter, or PM_{10} vertical flux at the 11 or 18 m s^{-1} wind speed due to previously mentioned measurement constraints. A within-wind speed evaluation was conducted to investigate differences in friction velocity, the roughness parameter, and vertical flux among treatments. All three treatments were examined at the 6.5 m s^{-1} wind speed and the bare and wood strand treatments were compared at the 11 and 18 m s^{-1} speeds.

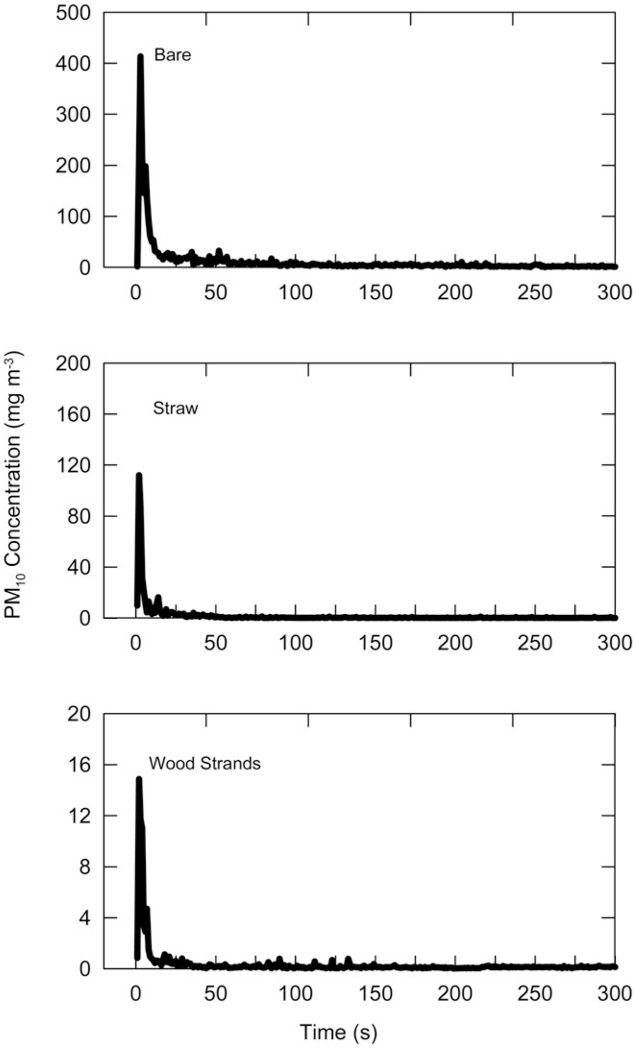

Fig. 3. Representative time series of particulate matter with mean aerodynamic diameter ≤ 10 µm (PM_{10}) concentration measured 0.5 cm above the surface of three different treatments at a wind speed of 11 m s^{-1}. Note the scale difference in the three panels.

Results and Discussion

Trends in PM_{10} concentration over time were characterized by a rapid increase to a peak concentration within the first 3 to 5 s of testing, followed by a rapid decay over the next 60 to 90 s (Fig. 3). The trends observed in this study were similar to the conceptual trend reported in Houser and Nickling (2001) and Loosemore and Hunt (2000) for nonabraded dust resuspension. In several cases, peak PM_{10} concentrations at the lower sampling heights exceeded the DustTrak capabilities during the first 5 s of testing. This outcome was of particular concern for bare and straw treatments at 18 m s^{-1}. Peak PM_{10} concentrations were estimated in these instances to obtain better estimates of PM_{10} loss. Peak PM_{10} concentration estimates were made by fitting the reliable data points before and after the exceedance with linear and power functions, respectively, and then extrapolating forward and backward in time.

Overall, there was little total sediment or PM_{10} loss at 6.5 m s^{-1}, and there were increasing amounts at 11 and 18 m s^{-1} (Fig. 5). Differences in treatment efficacy became more evident at higher

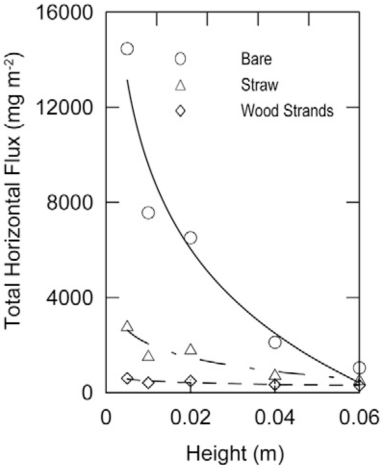

Fig. 4. Composite trends of total particulate matter with mean aerodynamic diameter ≤ 10 μm (PM_{10}) horizontal flux with height at a wind speed of 11 m s^{-1}. Total flux is for the 5-min time period.

wind speeds, with wood strands consistently outperforming straw in suppressing soil and PM_{10} loss (Fig. 5). There were also differences in cover stability among wind speeds. Straw was only semi-stable at 6.5 m s^{-1}, with some movement from the upwind edge to the middle of the tray during the first few seconds of testing. The straw then appeared to become intertwined and restabilize, resulting in little loss of straw elements from the tray. The straw was not stable at 11 or 18 m s^{-1}, and was completely blown from the test tray within the first few seconds of testing. Wood strands remained on the test plots at all wind speeds, although some reorientation of the wood strands occurred at 18 m s^{-1}, as the wood strands appeared to jostle slightly throughout the run in response to the higher wind speed.

Soil water potential ranged from −135 to −51.8 MPa, and was not significantly different among the treatments to warrant its use as a covariate. This result is in accordance with that reported in McKenna-Neuman and Nickling (1989) who found little variation in threshold velocity to initiate soil movement at water potentials < −10 MPa.

A paired *t* test indicated that applied covers were not statistically different from the intended covers of 50 or 70% so these nominal values were used in statistical testing and in all subsequent discussion.

No statistically significant differences were found in measured loss or flux among wood strand blends. With the exception of PM_{10} vertical flux, no significant differences were found due to percent cover of straw or wood strands. Consequently, results are discussed only in terms of the three treatments (bare, straw, and wood strands), except for the discussion on vertical flux, which also includes relevant information about material coverage.

Total Sediment Loss

The three-way ANOVA indicated a significant difference in total sediment loss due to wind speed and wind speed*treatment (Table 2). Two-way ANOVAs indicated no significant differences among treatments at the 6.5 m s^{-1} wind speed, but indicated significant differences due to treatment at the 11 and 18 m s^{-1} wind speeds (Table 2). Tukey's procedure indicated no differences in total sediment loss among treatments at the 6.5 m s^{-1} wind speed, but grouped total sediment loss from the bare and straw treatments into a group statistically different from that of the wood strands at 11 and 18 m s^{-1} (Table 3).

The lack of differences among treatments at the 6.5 m s^{-1} wind speed was attributed to the small amount of total sediment loss observed at this wind speed (Table 3). Differences among treatments became evident at 11 m s^{-1}; at this wind speed the wood strands were effective in reducing total sediment loss compared to the straw and bare treatments (Fig. 5a). The straw appears to be effective at 11 m s^{-1}, with an average total sediment loss of about half of that from the bare treatment (Fig. 5a); however, due to the variability of the data, total sediment loss from the straw treatment was not significantly different from the bare treatment. This trend did not continue at the 18 m s^{-1} wind speed, at which the straw was not an improvement over the bare treatment, but the wood strands continued to reduce total sediment loss (Fig. 5a).

The SLRs demonstrate the effectiveness of cover treatments in reducing soil loss (Table 4). The SLRs were >1 at the 6.5 m s^{-1} wind speed (Table 4). This result was not unexpected, however, as there was no significant difference in soil loss among the three

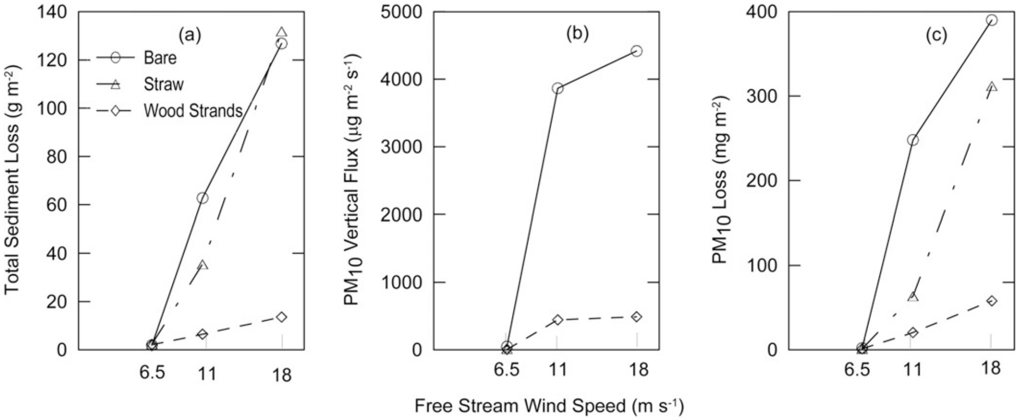

Fig. 5. (a) Average measured soil loss, (b) particulate matter with mean aerodynamic diameter ≤ 10 μm (PM_{10}) flux, and (c) PM_{10} loss from the test tray at three wind speeds. The PM_{10} vertical flux was not calculated for the straw treatment at wind speeds of 11 and 18 m s^{-1}.

Table 2. Response variables and model treatment effects used in ANOVAs with corresponding *P* values.†

	Response variable				
Model effect	Total sediment loss	Friction velocity‡	Roughness parameter‡	PM_{10} vertical flux‡	PM_{10} loss
Three-way ANOVA§					
Treatment	0.3029	**0.0001**	**0.0001**	**0.0001**	**0.0386**
Percent cover	0.9873	0.8794	0.8345	0.0724	0.4863
Wind speed	**0.0001**	**0.0001**	**0.0001**	**0.0001**	**0.0007**
Wind speed*Treatment	**0.0001**	**0.0056**	**0.0038**	**0.0001**	0.2974
Wind speed*Percent cover	0.8879	0.9568	0.9378	0.0759	0.4472
Two-way ANOVA§ at 6.5 m s^{-1}					
Treatment	0.9066	0.2972	0.1473	**0.0002**	**0.0269**
Percent cover	0.6890	0.8369	0.9135	0.1938	0.9671
Two-way ANOVA§ at 11 m s^{-1}					
Treatment	**0.0001**	**0.0001**	**0.0010**	**0.0001**	**0.0001**
Percent cover	0.9223	0.8152	0.7116	0.9116	0.1464
Two-way ANOVA§ at 18 m s^{-1}					
Treatment	**0.0001**	**0.0006**	**0.0006**	**0.0001**	**0.0001**
Percent cover	0.1208	0.9104	0.9634	0.1011	0.4865

† *P* values in bold font are statistically significant for α = 0.05.

‡ Friction velocity, the roughness parameter, and particulate matter with mean aerodynamic diameter ≤ 10 μm (PM_{10}) vertical flux were not calculated for straw treatments at the 11 or 18 m s^{-1} wind speeds.

§ Percent cover was nested within treatment in the model, thus eliminating the need for percent cover*treatment interactions in the ANOVAs.

treatments, and the overall mean sediment loss for the three treatments was relatively low (2.2 g m^{-2}, Table 3). The SLRs at 11 m s^{-1} showed that straw and wood strands both reduced total sediment compared to bare soil (SLRs of 0.57 and 0.11, respectively, Table 4). The effectiveness of the straw in reducing soil loss was not maintained at 18 m s^{-1} (SLR >1) while wood strands continued to maintain a reduction in total sediment loss (SLR of 0.11, Table 4). The diminishing effectiveness of straw in reducing soil loss at 18 m s^{-1} was due to the instability of the straw at this wind speed. The large SLR for the straw treatment at 18 m s^{-1} was attributed to the differences in surface creep between the bare and straw treatments at this wind speed (Table 5). As the straw was being blown from the tray, scouring of the soil surface carried larger particles as surface creep, thus producing a larger mean total sediment loss than from the bare treatment.

Straw was not stable at the 11 or 18 m s^{-1} wind speeds; it did, however, reduce average total sediment loss as compared to the bare soil at 11 m s^{-1}. Although this reduction was not captured in the statistical analysis (due in part to large variance in the total sediment response), it is worth noting the marked decrease in average total sediment loss from the bare to the straw treatment (Fig. 5a). One possible explanation for observing a reduction in soil loss at this wind speed is that there was a slight delay in the straw transport at 11 m s^{-1} compared to the nearly instantaneous loss of straw at 18 m s^{-1}. Straw elements were then able to absorb certain initial momentum from the wind at 11 m s^{-1}, offering partial protection to the soil surface during start-up of the wind tunnel.

Friction Velocity, the Roughness Parameter, and PM_{10} Vertical Flux

Friction velocity, the roughness parameter, and vertical flux were not calculated for straw treatments at the 11 or 18 m s^{-1} wind speeds. Three-way ANOVAs indicated treatment, wind speed, and wind speed*treatment as significant effects for friction velocity and the roughness parameter (Table 2). Two-way ANOVAs indicated no significant differences in friction velocity or the roughness parameter at the 6.5 m s^{-1} wind speed (Table 2). Two-way ANOVAs indicated differences in friction velocity and the roughness parameter due to treatment at the 11 and 18 m s^{-1} wind speeds (Table 2). Tukey's procedure yielded identical groupings for the friction velocity and roughness parameter data, with all three treatments grouped together at the 6.5 m s^{-1} wind speed and the bare and wood strand treatments separated into different groups at the 11 and 18 m s^{-1} wind speeds (Table 6). Differences in the roughness parameter indicated differences in the surface roughness, and thus differences in friction at the wind-soil interface among the two treatments.

Additionally, Tukey's procedure indicated no significant differences in friction velocity or the roughness parameter among wind speeds within a given treatment. Therefore, we observed significant differences in friction velocity and the roughness parameter in response to the surface treatment effect, but not in response to the wind speed effect. The effect of surface treatment on friction velocity and the roughness parameter was dependent on wind speed, as there were differences among treatments at the 11 and 18 m s^{-1} wind speeds, but not at the 6.5 m s^{-1} wind speed (Table 6).

Table 3. Average total sediment and particulate matter with mean aerodynamic diameter ≤ 10 μm (PM_{10}) loss for three wind speeds.†

	Wind speed, m s^{-1}		
Treatment	6.5	11	18
Total sediment loss, g m^{-2}			
Bare	1.96a	62.7a	126a
Straw	2.37a	35.5a	131a
Wood strands	2.15a	6.45b	13.6b
PM_{10} loss, mg m^{-2}			
Bare	2.06a	248a	390a
Straw	1.24ab	63.6b	312a
Wood strands	1.22b	20.4c	58.0b

† a, b, and c denote statistically significant groupings of mean values within a wind speed. The same letters indicate means in that group are not significantly different at the significance level of 0.05.

Table 4. Total sediment and particulate matter with mean aerodynamic diameter ≤ 10 μm (PM_{10}) loss ratios† for straw and wood strand treatments at three wind speeds.

	Wind speed, m s^{-1}					
	6.5		11		18	
Treatment	Total sediment	PM_{10}	Total sediment	PM_{10}	Total sediment	PM_{10}
Straw	1.21	0.61	0.57	0.25	1.04	0.80
Wood straw	1.10	0.60	0.11	0.08	0.11	0.15

† Loss ratios were calculated as the total sediment or PM_{10} loss from the treatment divided by total sediment or PM_{10} loss from the bare soil.

The three-way ANOVA for PM_{10} vertical flux identified treatment, wind speed, and wind speed*treatment as significant effects (Table 2). A two-way ANOVA identified a significant difference in vertical flux due to treatment at 6.5 m s^{-1} (Table 2). Tukey's method grouped the straw and wood strands together in a group having a statistically lower vertical flux (average flux was 12.9 and 5.67 μg m^{-2} s^{-1}, respectively) than the bare treatment (average flux was 49 μg m^{-2} s^{-1}). This is different from the total sediment loss analysis, where there were not significant differences among the treatments at 6.5 m s^{-1}. Although overall soil loss at the 6.5 m s^{-1} wind speed was low, these differences in PM_{10} vertical flux have implications for air quality, as the amount of PM_{10} emitted into the atmosphere can be reduced from a bare soil even at wind speeds near the threshold velocity of the soil. Vertical flux at the 6.5 m s^{-1} wind speed was also affected by percent cover of material applied. Tukey's method indicated differences in vertical flux between the bare treatment and wood strands at both 50 and 70% cover; however, the straw was only effective in reducing vertical flux when applied at 70% cover.

Two-way ANOVAs indicated significant differences due to treatment for both the 11 and 18 m s^{-1} tests. In both cases Tukey's procedure identified wood strands at 50 and 70% cover as being different from the bare treatment. In other words, the wood strands were equally effective in reducing vertical flux as compared to bare soil at the 11 and 18 m s^{-1} wind speeds whether applied at 50 or 70% cover.

Additionally, a two-way ANOVA with wind speed and percent cover as the main effects indicated no significant difference between the 11 and 18 m s^{-1} wind speed for the wood strand treatment. The reduction in vertical flux from the bare soil by the wood strand treatments was large at 11 and 18 m s^{-1}, and wood strand effectiveness in reducing vertical flux increased from 11 to 18 m s^{-1} (Fig. 5b). Vertical flux is a function of both friction velocity and change in PM_{10} concentration with height as shown in Eq. [6]. The dominant variable in this case, however, was the concentration gradient, which varied by orders of magnitude among the treatments.

Table 5. Average sediment lost as creep, saltation, and suspension at three wind speeds.

	Wind speed, m s^{-1}		
Treatment	6.5	11	18
Creep, g m^{-2}			
Bare	0.01	1.40	2.82
Straw	0.01	3.33	6.22
Wood strands	0.02	0.02	0.17
Saltation and suspension, g m^{-2}			
Bare	1.95	61.3	124
Straw	2.36	32.1	126
Wood strands	2.13	6.43	13.4

Table 6. Average friction velocity and roughness parameter for three surfaces at three wind speeds.†

	Wind speed, m s^{-1}		
Treatment	6.5	11	18
Friction velocity, m s^{-1}			
Bare	0.40a	0.55a	0.34a
Straw††	0.33a	NA	NA
Wood strands	0.48a	0.90b	0.64b
Roughness parameter, m			
Bare	9.69×10^{-4}a	9.56×10^{-4}a	1.62×10^{-5}a
Straw††	1.21×10^{-3}a	NA	NA
Wood strands	2.36×10^{-3}a	3.18×10^{-3}b	4.36×10^{-4}b

† a and b denote statistically significant groupings of mean values within a wind speed. The same letters indicate that means in that group are not significantly different at the significance level of 0.05.

†† Friction velocity and the roughness parameter were not calculated for straw at 11 or 18 m s^{-1}.

PM_{10} Loss

The three-way ANOVA indicated significant differences in PM_{10} loss due to treatment and wind speed (Table 2). All pairwise comparisons from Tukey's method were significant, which indicated that PM_{10} loss was different among the three surface treatments and also among the three wind speeds. Two-way ANOVAs indicated treatment as a significant effect at all three wind speeds (Table 2). Tukey's procedure grouped the bare and wood strand treatments into separate groups, with the straw treatment overlapping into both groups at the 6.5 m s^{-1} wind speed (Table 3). Little PM_{10} was lost from the three treatments at the 6.5 m s^{-1} wind speed (Fig. 5c). Although differences in PM_{10} vertical flux were found among all three treatments at 6.5 m s^{-1}, the lack of differences in PM_{10} loss is not surprising as loss was calculated for the entire five minute period. Vertical flux was determined for the initial 60 s period due to diminished emissions of PM_{10} with time (Fig. 3).

Tukey's procedure separated the treatments into three groups at the 11 m s^{-1} wind speed and grouped the bare and straw treatments into one that is different from the wood strands at the 18 m s^{-1} wind speed (Table 3). In other words, wood strands and wheat straw significantly reduced PM_{10} loss as compared to bare soil at the 11 m s^{-1} wind speed, although the wood strands reduced loss significantly further than the straw (Fig. 5c). The straw became ineffective in reducing loss from a bare soil surface at the 18 m s^{-1} wind speed, while wood strands continued to reduce PM_{10} loss. The straw's diminishing effectiveness can be attributed to the same reason as for the total sediment loss; that is, delayed movement of straw at the lower 11 m s^{-1} wind speed may have provided some initial protection to the bare soil surface, whereas instantaneous movement of straw at 18 m s^{-1} immediately exposed the soil surface to the forces of the wind.

PM_{10} loss did not comprise 4% of the total sediment loss as would have been expected from the particles size analysis.

Instead only 0.2 to 0.4% of total sediment loss from the 11 and 18 m s^{-1} wind speeds was PM_{10} (Table 3). We believe this is related to the direct suspension of particles by the wind. Gillette et al. (1974) discussed differences between direct and saltation-induced entrainment of soil particles. It has been shown that direct entrainment is a strong function of particle size, and that PM_{100} requires the minimum velocity for entrainment, with larger and smaller particles having greater threshold velocities (Chepil, 1945; Chepil, 1951). Chepil (1945) attributed the increased threshold velocity for smaller particles partly to cohesion effects but mainly to the fact that the smaller particles are not big enough to protrude above the laminar and viscous layers near the ground surface, and thus, require impacts from larger particles to become entrained.

Wood Strand Properties

Wood strands in the range of dimensions tested in this study were equally effective in reducing wind erosion, and were found considerably more stable than straw, especially at the 18 m s^{-1} wind speed. Lack of differences in total sediment and PM_{10} loss between 50 and 70% cover of the wood strands suggests that lower coverages than those tested in this study may also be effective. Wood strands may be less stable on the soil surface at a lower percent cover, however, as material stability is a function of cover due to material layering and interweaving. Layering increased with increasing percent cover because the wood strands laid on top of one another as more strands were applied. Layering thus increased both depth of cover and effective surface roughness. Layering also appeared to increase wood strand stability by promoting interweaving of the materials.

Conclusions

Wood strands were found to be a viable alternative to agricultural straw for wind erosion control. Wood strands reduced sediment loss and PM_{10} emissions from bare soil surfaces at wind speeds of up to 18 m s^{-1}, whereas agricultural straw only reduced sediment loss at the lower, 11 m s^{-1} wind speed tested. Wood strands were more stable at higher wind speeds than wheat straw. Wood strand effectiveness was not affected by the range of dimensional characteristics tested in this study. Additional testing of wood strands at lower coverage is needed to further investigate the cover-stability relationship of the wood strands. Wind tunnel testing with saltating agents used as abraders should also be of interest to explore the ability of the wood strands to prevent saltating grains from liberating erodible material from the soil surface. Further field-scale research may provide more insight into the erosion reduction efficacy of wood strands vs. agricultural straw, as microtopography will also play a role in the performance of cover elements in the field.

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