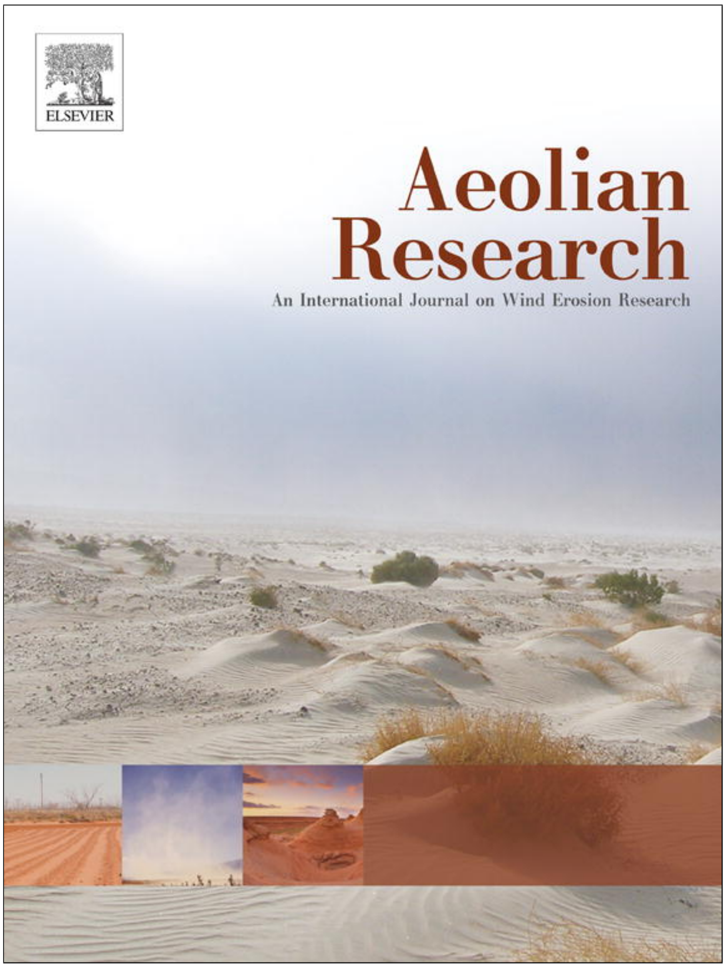
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Threshold friction velocity of soils within the Columbia Plateau

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ABSTRACT

Wind erosion only occurs when the friction velocity exceeds the threshold friction velocity (TFV) of the surface. The TFV of loessial soils found across the Columbia Plateau region of the U.S. Pacific Northwest is virtually unknown even though these soils are highly erodible and a source of atmospheric particulates that reduce air quality. The TFV's of a sandy loam and four silt loams collected from field sites in eastern Washington were determined by systematically measuring the temporal variation in wind speed, saltation activity, and PM10 (particles with an aerodynamic diameter of $\leqslant$10 μm) and TSP (total suspended particulate matter) concentrations above the soil surface inside a wind tunnel. The erodible fraction of each soil, obtained by drying and screening the soil, was placed in a tray inside the wind tunnel. The TFV for the sandy loam was 0.139 m s^{-1} whereas the TFV for the four silt loams ranged from 0.180–0.239 m s^{-1}. The sandy loam was aerodynamically smoother than that of the silt loams, possibly due to a smaller size fraction of larger soil aggregates or particles on the surface of the sandy loam. The TFV's measured in this study were lower than those previously observed in the field in the Columbia Plateau and also lower than the minimum TFV required to initiate erosion in some wind erosion models. While these TFV's are representative of the erodible soil fraction, the low TFV's may contribute to the occasional poor performance of wind erosion models in the region.

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1. Introduction

The Columbia Plateau is a 70,000 km^2 region that spans across northern Idaho, north-central Oregon, and eastern Washington of the Inland Pacific Northwest in the United States. The Plateau is a Basalt Plain bordered by the Okanogan Highlands on the north, Bitterroot Mountains on the east, Blue Mountains on the south, and Cascade Mountains on the west. Soils in this region have been derived from loess and volcanic deposits (Busacca et al., 2004). These deposits are susceptible to wind erosion, particularly in the drier parts of the Columbia Plateau where agricultural fields are managed in a winter wheat-summer fallow rotation. Winter wheat – summer fallow is the conventional crop rotation used on more than 1.5 million ha of land in the low precipitation zone (annual precipitation <300 mm) of the Columbia Plateau. Land in summer fallow is very susceptible to wind erosion because multiple tillage operations during the fallow phase of the rotation degrades and exposes the soil to high winds. Winds sufficient to cause wind erosion occur primarily in the spring and autumn (Saxton, 1995). Wind erosion not only causes loss of topsoil and degradation of the soil resource, but also contributes to high atmospheric PM10 concentrations and poor air quality in the region (Saxton, 1995; Sharratt et al., 2007).

Models such as the Wind Erosion Prediction System (WEPS) can aid in identifying lands susceptible to wind erosion as well as identifying management strategies with the potential to control wind erosion. Feng and Sharratt (2009) used the WEPS model to simulate wind erosion and PM10 emissions from a silt loam that was managed in summer fallow using conventional and conservation tillage practices in the Columbia Plateau. They found the WEPS model failed to simulate erosion for all (four) high wind events that caused measurable erosion from both tillage practices over two years. In an earlier multi-year study, Feng and Sharratt (2007) found the WEPS model simulated erosion for only three of six high wind events that caused measurable erosion from a silt loam managed in conventional summer fallow in the Columbia Plateau. Feng and Sharratt (2009) speculated that the WEPS model failed to simulate erosion during these high wind events as a result of overestimation of the TFV. Erosion is simulated by WEPS only when the friction velocity exceeds the TFV.

Friction velocity is a parameter used to describe the shear stress near the surface. Shear stress, or the stress exerted on the surface by wind shear, is influenced by winds aloft as well as surface roughness. Rough surfaces exert drag upon the wind which enhances wind shear. Wind shear and friction velocity are therefore dependent upon roughness cast by aggregates, ridges, vegetation,

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and other irregularities (e.g. tillage tool marks) on the soil surface. Threshold friction velocity is the minimum friction velocity that is required to initiate movement of an aggregate or particle resting on the soil surface; movement occurs when drag and lift forces overcome gravitational and inter-particle cohesive forces acting on the soil aggregate or particle. Therefore, TFV is governed by the size, shape, and mass of aggregates or particles. Threshold friction velocity is also affected by soil surface water content and crusting, surface roughness, and biomass cover (Shao, 2000). Soil surfaces that are wet, rough, aggregated, crusted, and partially covered with crop residue generally have a higher TFV than surfaces that are dry, smooth, single-grained, non-crusted, and bare.

Little field or laboratory information is available on the TFV of soils found within the Columbia Plateau. Kjelgaard et al. (2004) and Sharratt and Feng (2009) measured wind velocity profiles above a Ritzville silt loam managed in conventional summer fallow in eastern Washington and found the TFV to be 0.35–0.4 m s^{-1}. Saxton et al. (2000) estimated the TFV of soils within the Columbia Plateau was 0.33 m s^{-1}. This estimation was based upon the velocity required to cause saltation of 0.5-mm diameter particles according to Bagnold's theory (Bagnold, 1941). We are not aware of other studies that report TFV's of soils found within the Columbia Plateau. Knowledge of TFV is critical for predicting regional transport of PM10 in the atmosphere that affects air quality in the Columbia Plateau (Sundram et al., 2004). Therefore, the objective of this study was to measure the TFV of selected agricultural soils that are highly erodible or could potentially affect air quality within the Columbia Plateau.

2. Methods and materials

Threshold friction velocities of five soils of loess origin found across the Columbia Plateau were measured inside a wind tunnel. These five soils represent a composite of 29% of the land area within the Columbia Plateau, based upon the USDA-Natural Resources Conservation Service soil series database (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm). Samples of each soil were taken from agricultural fields managed in conventional crop rotations. The sampling location for the five soils is illustrated in Fig. 1.

Threshold friction velocities were determined for Athena silt loam, Palouse silt loam, Ritzville silt loam, Walla Walla silt loam, and Warden sandy loam. Ritzville silt loam and Warden sandy loam are commonly found in the low precipitation zone (<300 mm annual precipitation), Walla Walla silt loam is found in the intermediate precipitation zone (300–450 mm precipitation), and Athena silt loam and Palouse silt loam are found in the high precipitation zone (>450 mm precipitation) of the Columbia Plateau. Soils in the low precipitation zone are more susceptible to erosion than soils in the intermediate and high precipitation zones while soils in the high precipitation zone have more PM10 potentially available for emissions than soils in the low and intermediate precipitation zones (Chandler et al., 2004). Athena silt loam (fine-silty, mixed, superactive, mesic pachic Haploxerolls) was obtained near Colfax, WA (46°47′N, 117°26′W) in summer during the chemical fallow phase of a winter wheat-spring wheat-fallow rotation. This soil occurs on 3.5% of the land within the Columbia Plateau and was sampled from an area that receives 490 mm of annual precipitation. Palouse silt loam (fine-silty, mixed, superactive, mesic pachic ultic Haploxerolls) was obtained near Pullman, WA (46°45′N, 117°12′W) during the spring barley phase of a continuous cereal rotation. This soil occurs on 2.8% of the land comprising the Columbia Plateau and was sampled from an area that receives 540 mm of annual precipitation. Ritzville silt loam (coarse-silty, mixed, superactive, mesic calcidic Haploxerolls) was obtained near Ritzville, WA (47°08′N, 118°28′W) during the summer fallow phase of a winter wheat-fallow rotation. This soil is more commonly found across the Columbia Plateau than the other four soils tested in this study; this soil occurs on 9.7% of the land and was sampled from an area that receives 280 mm of annual precipitation. Walla Walla silt loam (coarse-silty, mixed, superactive, mesic typic Haploxerolls) was obtained near Waitsburg, WA (46°15′N, 118°09′W) during the summer fallow phase of a winter wheat-spring wheat-fallow rotation. This soil occurs on 5.6% of the land that comprises the Columbia Plateau and was sampled from an area that receives 400 mm of annual precipitation. Warden sandy loam (coarse-silty, mixed, superactive, mesic xeric Haplocambids) was obtained near Paterson, WA (46°01′N, 119°37′W) during the summer fallow phase of a winter wheat-fallow rotation. This soil occurs on 3.1% of the land within the Columbia Plateau and was sampled from an area that receives 200 mm of annual precipitation.

Soil samples collected at each sampling location were processed prior to ascertaining TFV. The sampling location for each soil was chosen based upon the recommendation of the local USDA-Natural Resources Conservation Service office. Soil samples were collected from multiple sites within a 20-m radius and then consolidated at each location. Soil representative of near-surface conditions was collected from the upper 30 mm of the soil profile using a flat-bladed shovel. The upper 150 mm of the soil profile is uniformly mixed as a result of tillage and sowing operations that are conducted over the course of the season. In fact, conventional tillage in winter wheat – summer fallow rotations can necessitate eight or more tillage operations to create a 150-mm layer of dust mulch that conserves soil moisture during summer fallow (Schillinger and Young, 2004). The soil was air dried inside a laboratory at 30 °C and hand sieved through a 2-mm screen to obtain the erodible fraction. Threshold friction velocity and select physical properties were determined on the erodible fraction. Particle size percentages were determined on dispersed soil samples using a Mastersizer laser diffraction analyzer (Malvern Instruments Ltd.) and are reported in Table 1. Aggregate size distribution was determined by processing subsamples through a rotary sieve (Chepil, 1962) equipped with sieves having 0.42, 0.84, and 2.0 mm openings. A sonic sieve was used to determine the size distribution for the <0.42 mm size fraction. Soil aggregate geometric mean diameter, or size at which 50% of the soil mass passed through a sieve, was determined based upon a log-normal distribution (Zobeck et al., 2003).

The wind tunnel, used to assess TFV, was located inside a non-regulated climate facility. The climate of the facility was characterized by a range in temperature and relative humidity of respectively 22–35 °C and 14–66% during this study. The wind tunnel had a working section 1.0-m wide, 1.2-m tall, and 7.3-m long and can generate free stream wind velocities from 2 to 20 m s^{-1} (Pietersma et al., 1996). Winds generated by a 1.4-m diameter fan, which was powered by a gasoline engine, are conditioned with a diffuser and honeycomb-screen before passing through a grid assembly and into the working section of the tunnel. The conditioning process was used to achieve shear flow characteristics similar to those that occur naturally in the field. The design and operation of the wind tunnel and aerodynamic characteristics of the shear flow are discussed in detail in Pietersma et al. (1996) and Sharratt (2007). The tunnel was set up over a wooden floor that was coated with fine sand to mimic a boundary layer characteristic of a smooth, bare soil surface. A section of the floor was removed 5 m downwind from the grid assembly for insertion of a 15-mm deep tray filled with soil. Soil, air dried at 30 °C, was added to the 0.2-m wide by 1-m long tray and then leveled with the upper edge of the tray using a metallic screed. The soil tray fit snuggly into the floor of the wind tunnel such that the gap between the tray and wooden floor was ∼1 mm and the soil surface was level with the tunnel floor.

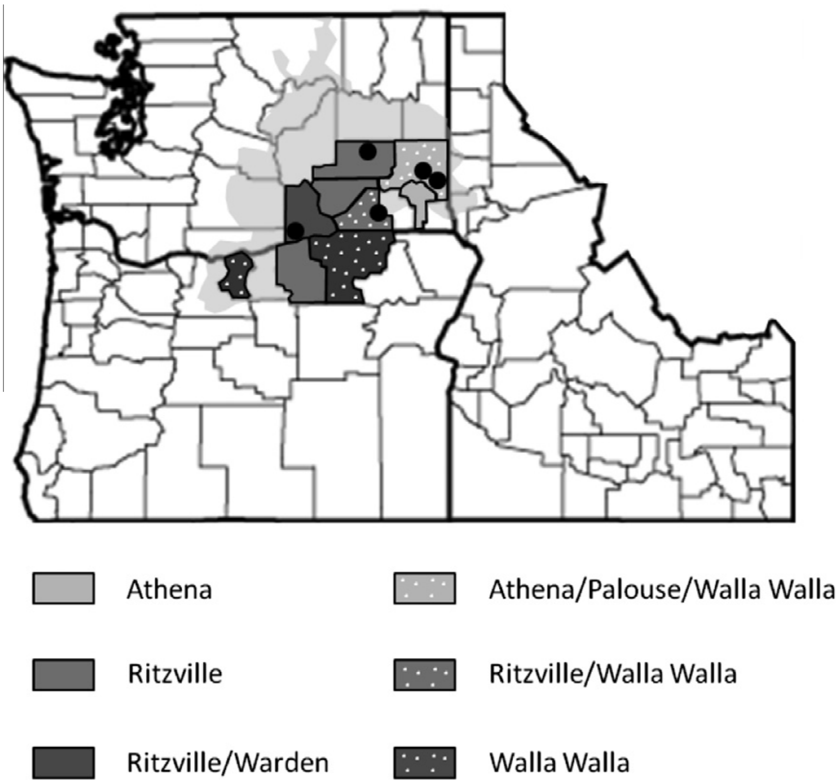

Fig. 1. Location of soil sample sites (solid black circles) across the Columbia Plateau (light shaded region) of Idaho, Oregon, and Washington in the US Pacific Northwest. Counties with over 40,000 ha of Athena silt loam, Palouse silt loam, Ritzville silt loam, Walla Walla silt loam, and Warden sandy loam are highlighted according to the legend below the map.

Table 1
Total hectares, percent of total hectares, and percentage of various particle sizes of five soils found in the Columbia Plateau.

Soil	Hectares	% Total	PM10 (%)	Sand[a] (%)	Silt (%)	Clay (%)	Mean size (D50) (μm)
Athena silt loam	203,560	3.5	38.7	17.2	65.8	17.0	17.1
Palouse silt loam	164,310	2.8	34.0	21.1	63.3	15.6	21.1
Ritzville silt loam	569,010	9.7	27.8	30.5	58.1	11.4	28.0
Walla Walla silt loam	326,190	5.6	38.0	20.2	63.5	16.3	18.5
Warden sandy loam	180,090	3.1	17.3	67.2	23.2	9.6	77.1
LSD[b]			2.3	2.6	1.9	1.5	3.1

[a] Sand >50 μm in diameter.
[b] LSD is least significant difference at the 0.05 level of probability.

Sensors were used to detect the emission of particles from the soil surface in this study since the unaided human eye cannot detect particles smaller than 50–100 μm in diameter. Small particles, typically 11–32 μm in diameter, comprise the bulk of windblown sediment emitted from agricultural soils in the Columbia Plateau (Sharratt, 2011). Sensors were installed immediately downwind of the soil tray to measure wind velocity, saltation activity, and concentration of PM10 and TSP. Wind velocity, PM10, and TSP were measured at 5, 10, 20, 40, 60, and 100 mm above the soil surface. Saltation activity was measured with a Sensit (model H11-LIN, Sensit Company, Portland, ND) and wind velocity was measured using pitot tubes. The PM10 and TSP were respectively measured using Dusttrak aerosol monitors (TSI Incorporated, Shoreview, MN) and E-samplers (Met One Instruments, Grants Pass, OR). Aerosol monitors were also installed at the entrance of the working section of the tunnel to measure background dust concentration. Pitot tube differential pressures were monitored every 0.1 s and recorded every 1 s using a datalogger. Air temperature, relative humidity, and atmospheric pressure were also monitored near the entrance of the wind tunnel and used along with pitot tube data to determine wind velocity. The Dusttraks and E-samplers recorded dust concentrations every 1 s.

Threshold friction velocity was determined by systematically increasing wind velocity until we observed a consistent increase in saltation activity or above-background PM10 or TSP concentration. Wind velocity was systematically increased by increasing the throttle setting of the wind tunnel engine. The throttle setting of the engine was increased every 60 s until we observed saltation activity or above-background PM10 or TSP concentrations at more than one height. Saltation activity and above-background PM10 and TSP concentrations were then monitored for 60 s before engaging the next highest throttle setting of the engine. Saltation activity and above-background PM10 and TSP concentrations were observed for another 60 s after which the throttle setting of the engine was lowered to the previous setting. This process eliminated instantaneous increases or spikes in saltation activity or PM10 or TSP concentrations that periodically result from contamination (e.g. external dust) entering the wind tunnel or perched particles emitted from the soil surface. Preliminary experiments provided an estimate of wind velocities that initiated saltation activity or an increase in dust concentration for each soil. Wind velocities below and above these estimates allowed for the most expeditious determination of TFV.

Friction velocity was determined by:

$$u(z) = (u_*/k)ln(z/z_0) \quad (1)$$

where $u(z)$ is mean wind velocity at height z (m s^{-1}), k is the von Karman constant (0.4), u_* is friction velocity (m s^{-1}), and z_0 is the roughness parameter (m). The slope of the wind velocity versus natural log height within 40 mm of the surface was used to calculate friction velocity (Fig. 2). Coefficients of determination typically >0.98 ensured that observations were made within the inertial boundary layer. The friction velocity for the 60 s period following initiation of saltation activity or above-background PM10 or TSP concentrations defined the TFV.

Threshold friction velocity was determined on four replications of each soil. Water content and potential of the surface 3 mm of soil in the tray was measured both immediately prior to engaging the throttle of the engine (to generate wind) and after the wind subsided at the end of each replicate. Water content was measured gravimetrically while water potential was measured using a dew point meter (WP4-T, Decagon Devices, Pullman, WA).

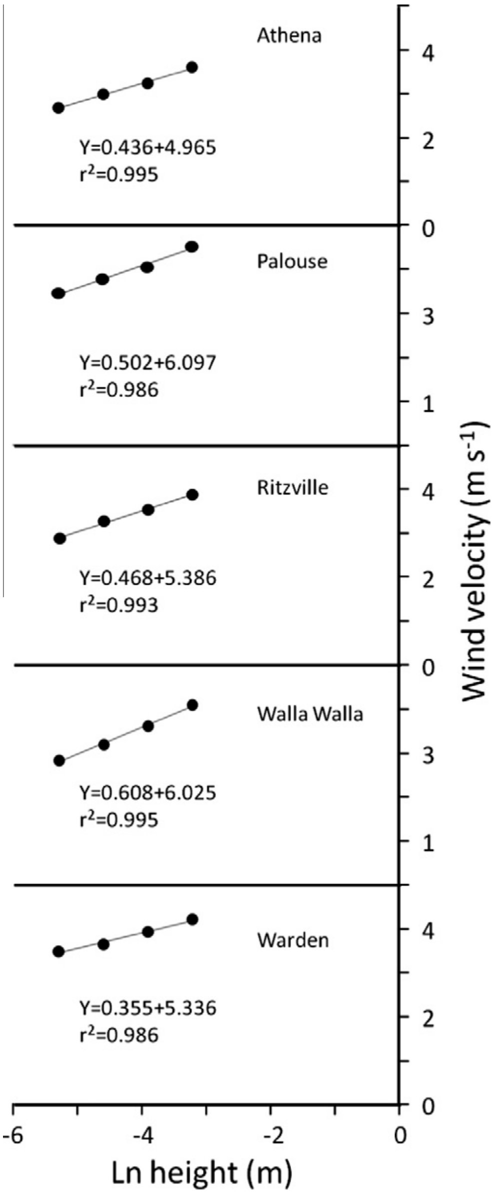

Fig. 2. Wind velocity as a function of the natural log of height above the surface of five soils. These data were collected inside a wind tunnel and used to assess friction velocity.

3. Results and discussion

Particle size analysis indicated differences among the five soils used to assess TFV in this study (Fig. 3). Warden sandy loam had a higher percentage of larger diameter particles than Athena silt loam, Palouse silt loam, Ritzville silt loam, and Walla Walla silt loam. In fact, the percent of sand (>50 μm diameter) constituting the Warden soil was at least twice that of the other four soils (Table 1). Warden sandy loam had a lower percentage of clay as compared with the other four soils. The percent of PM10 composing the Warden soil was also low compared with the other four soils. Differences in percent sand, clay, and PM10 were also apparent among the four silt loams. Ritzville silt loam had a higher percentage of sand and lower percentage of clay and PM10 as compared with Athena silt loam, Palouse silt loam, and Walla Walla silt loam (Table 1). Differences in primary particle percentages are also reflected in differences in the mass mean particle diameter; the mass mean diameter was highest for Warden sandy loam (77 μm) and lowest for Athena silt loam, Palouse silt loam, and Walla Walla silt loam (about 20 μm).

Although our intent was to systematically increase wind velocity until saltation occurred, no saltation activity was recorded by the Sensit during this study. The lack of saltation activity is consistent with field observations for the loessial soils found within the Columbia Plateau (Kjelgaard et al., 2004; Sharratt et al., 2007). The lack of recorded saltation activity observed in this study may in part be due to the insensitivity of the Sensit to particles <100 μm in diameter (Stockton, 2009). Indeed, Van Pelt et al. (2009) found the Sensit unable to detect <100 μm particles in saltation except at very high wind velocities. The five soils were largely composed of aggregates and particles <100 μm in diameter (Fig. 4), with the composition ranging from 48% of the soil mass for Athena silt loam to 75% of the soil mass for Ritzville silt loam. Despite the five soils having a small percentage of large aggregates and particles (25–52% of the soil mass consisted of aggregates >100 μm in diameter), these large aggregates and particles are a potential source of saltators. The lack of recorded saltation activity of these large aggregates and particles may be due to either not

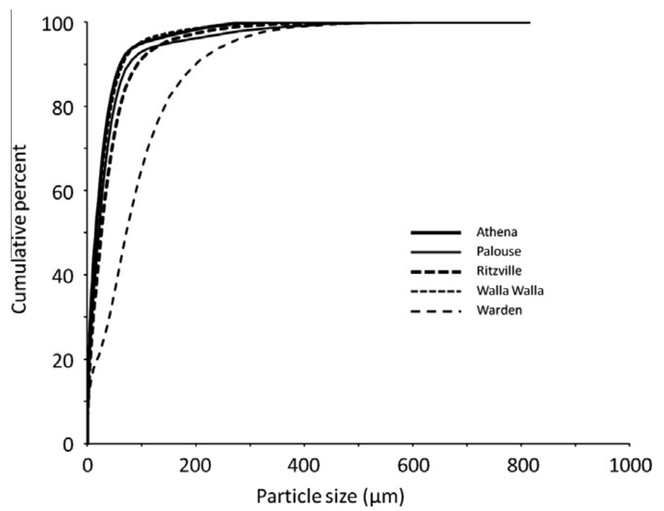

Fig. 3. Dispersed particle size analysis of five soils found across the Columbia Plateau.

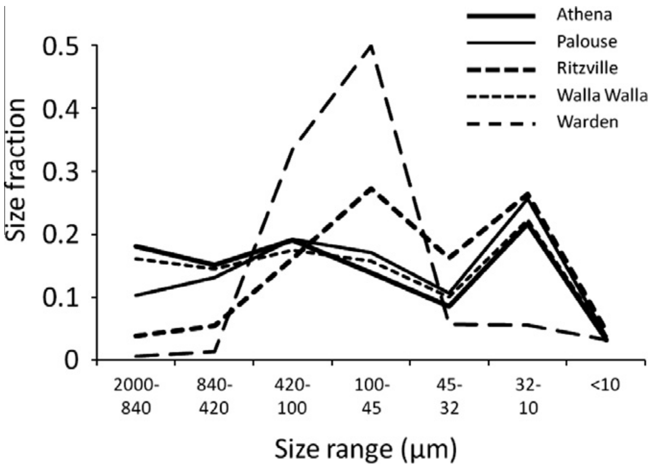

Fig. 4. Dry aggregate size distribution that characterized five soils for assessing threshold friction velocity inside a wind tunnel.

achieving threshold velocities of aggregates and particles >100 μm in diameter in this study or to the fragility of these aggregates. Indeed, degradation of fragile aggregates upon impact with the soil surface or sensor could result in no recorded saltation activity.

3.1. Observed threshold friction velocities and aerodynamic roughness

Time-series trends in PM10 and TSP concentrations with wind velocity inside the wind tunnel are illustrated for Palouse silt loam and Warden sandy loam in Fig. 5. Although instantaneous increases in PM10 and TSP concentrations near the soil surface resulted in some variation in one minute average concentrations as a function of wind velocity, we considered TFV to occur when the increase in PM10 and TSP concentrations were sustained over time and at multiple heights. This is exemplified in Fig. 5 where an increase in PM10 and TSP concentrations were observed at multiple heights at the eighth minute.

Threshold friction velocities of the five soils tested in this study ranged from 0.139 m s^{-1} for Warden sandy loam to 0.239 m s^{-1} for Walla Walla silt loam (Table 2). Threshold friction velocities decreased from Walla Walla silt loam > Palouse silt loam > Athena silt loam and Ritzville silt loam > Warden sandy loam. Although differences in TFV were observed among the five soils, differences in soil moisture (Table 3) likely had no impact of TFV. Soil water potentials observed either before or after exposing the soil to wind were <−100 MPa, which are far less than those (water potentials >−10 MPa) that reportedly cause a reduction in TFV (McKenna-Neuman and Nickling, 1989). Aerodynamic roughness corresponded closely with threshold friction velocities of the five soils in that roughness was smallest for Warden sandy loam and largest for Walla Walla silt loam (Table 2). Aerodynamic roughness decreased from Walla Walla silt loam > Palouse silt loam > Athena silt loam > Ritzville silt loam > Warden sandy loam. Since only the erodible fraction of the soil was used to ascertain TFV in this study, differences in roughness among soils are likely related to inherent differences in aggregate or particle size at the soil surface. Roughness cast by larger aggregates or particles on the soil surface would result in greater aerodynamic roughness (Sharratt and Feng, 2009).

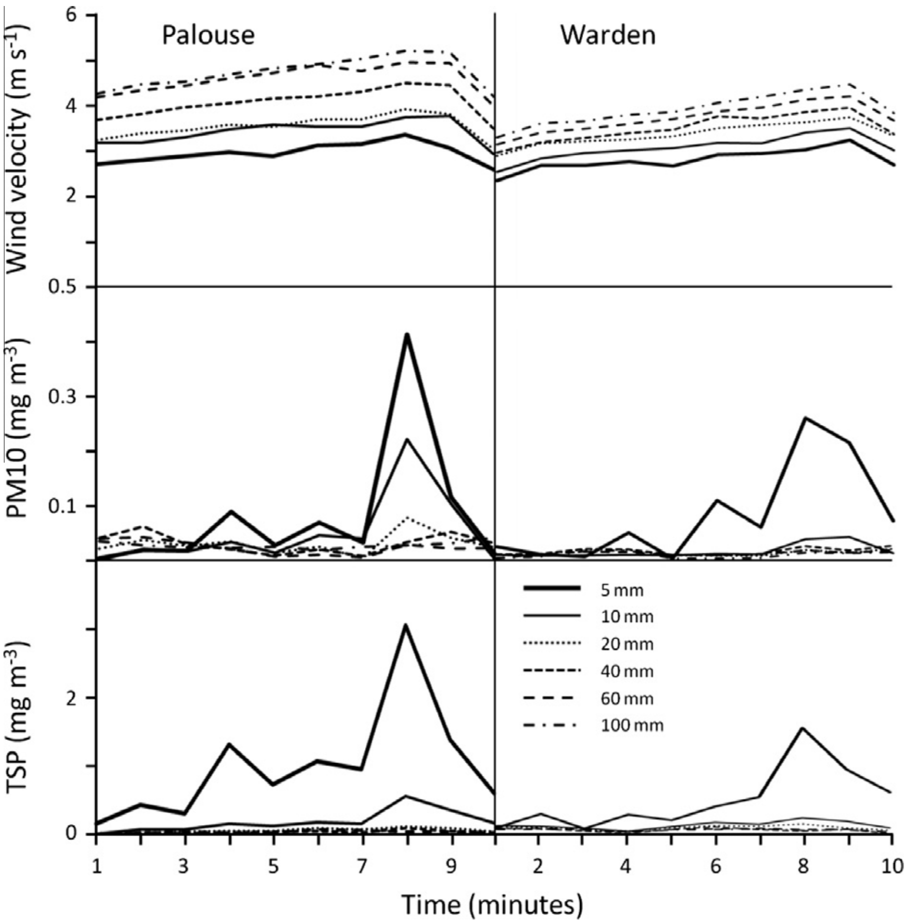

Fig. 5. One-minute time averages of wind velocity and PM10 and TSP concentrations at various heights above a Palouse silt loam and Warden silt loam inside a wind tunnel.

Table 2
Threshold friction velocity and aerodynamic roughness of five soils found within the Columbia Plateau.

Soil	Threshold friction velocity ($m\ s^{-1}$)		Aerodynamic roughness (mm)	
	Mean	SE[a]	Mean	SE
Athena	0.184	0.006	0.0128	0.0043
Palouse	0.210	0.011	0.0140	0.0056
Ritzville	0.180	0.006	0.0052	0.0018
Walla Walla	0.239	0.004	0.0370	0.0045
Warden	0.139	0.007	0.0007	0.0003
LSD[b]	0.020		0.001	

[a] SE is standard error.
[b] LSD is least significant difference at the 0.05 level of probability.

Table 3
Water content and potential of five soils immediately before and after exposing the soils to wind to assess threshold friction velocity inside a wind tunnel.

Soil	Water content (%)		Water potential (MPa)	
	Before	After	Before	After
Athena	2.55	2.77	−185	−167
Palouse	2.08	2.36	−182	−155
Ritzville	2.33	2.61	−118	−103
Walla Walla	2.01	2.64	−166	−123
Warden	1.70	1.67	−166	−169
LSD[a]	0.27	0.30	18	18

[a] LSD is least significant difference at the 0.05 level of probability.

Based upon the dry aggregate size distribution of the five soils (Fig. 4), Warden sandy loam had the smallest size fraction of large aggregates or particles as compared with the silt loams. Indeed, the fraction of 2000–840 μm diameter aggregates or particles decreased from Athena silt loam and Walla Walla silt loam > Palouse silt loam > Ritzville silt loam > Warden sandy loam (Least Significant Difference (LSD) was 0.030 at the 0.05 level of probability). Differences in aerodynamic roughness among soils did not appear to be related to differences in geometric mean diameter of aggregates or particles. Although aerodynamic roughness was smallest for Warden sandy loam and largest for Walla Walla silt loam, the geometric mean diameter did not differ between Warden sandy loam and Walla Walla silt loam. The geometric mean diameter of the soils used in this study were158 μm for Athena silt loam, 96 μm for Palouse silt loam, 67 μm for Ritzville silt loam, 118 μm for Walla Walla silt loam, and 109 μm for Warden silt loam (LSD was 33 μm at the 0.05 level of probability).

3.2. Comparison with field observations

The TFV's in this study are lower than those reported for agricultural soils in the southern Great Plains or the Columbia Plateau. Saleh and Fryrear (1995) found a threshold friction velocity of 0.31 $m\ s^{-1}$ for dry soils in the southern Plains while Kjelgaard et al. (2004) and Sharratt and Feng (2009) report threshold friction velocities of soil under conventional summer fallow in eastern Washington of 0.35–0.4 $m\ s^{-1}$. Kjelgaard et al. (2004) suggested, however, that the TFV may be 0.3 $m\ s^{-1}$ when particles are perched on the soil surface in the field.

Field measurements of TFV within the Columbia Plateau are limited to Ritzville silt loam (Kjelgaard et al., 2004; Sharratt and Feng, 2009). While these field studies report higher TFV's than measured for the Ritzville silt loam in this study, such differences may be expected as a result of dissimilarities in field and laboratory soil surface characteristics. Shao (2000) indicates that soil wetness, aggregate size distribution, soil surface roughness, and coverage of the soil surface with biomass influences TFV. Differences in TFV of Ritzville silt loam measured in the field and this study were not associated with differences in soil wetness. Threshold friction velocities of Ritzville silt loam in the field were observed at a soil water content of <0.02 $kg\ kg^{-1}$ (Feng and Sharratt, 2009) or a corresponding water potential of <−100 MPa (Feng et al., 2011) while TFV of Ritzville silt loam in this study were observed at soil water potentials of <−100 MPa (Table 3). Generally, little variation in TFV is found at soil water potentials <−10 MPa (McKenna-Neuman and Nickling, 1989). Differences in TFV of Ritzville silt loam measured in the field and this study, however, may have been related to differences in aggregate size distribution, soil surface roughness, and coverage of the soil surface. For example, dry aggregate geometric mean diameter, biomass flat cover, and silhouette area index (SAI defined as stem frontal area to soil surface area) were respectively 0.08–1.7 mm, 9–30%, and 0.003–0.02 $m^2\ m^{-2}$ in the field (Feng and Sharratt, 2009) as compared with respectively 0.07 mm, 0%, and 0 $m^2\ m^{-2}$ in this study. Soil surface roughness was not measured in this study, but we assume that random roughness of Ritzville silt loam reported in the field (8–12 mm) by Feng and Sharratt (2009) was greater than in this study (surface was leveled with a screed).

Threshold friction velocity of Ritzville silt loam measured in this study was used as the basis for estimating TFV in the field managed in conventional summer fallow. The field TFV (u_{*tf}) was estimated according to Shao (2000):

$$u_{*tf} = u_{*tss}\mathrm{f}(as)\mathrm{f}(bc)\mathrm{f}(\mathrm{SAI})\mathrm{f}(rr) \quad (2)$$

where u_{*tss} is the TFV of a smooth, dry, fine, unconsolidated, and bare soil surface (0.180 $m\ s^{-1}$ as measured in this study) and f(as), f(bc), f(SAI) and f(rr) are respective correction functions for aggregate size, biomass flat cover, SAI, and random roughness.

A correction function for aggregate size is difficult to obtain because TFV increases as the size of aggregates increases or decreases from ~0.1 mm in diameter (Chepil, 1945). However, based upon the relationship between TFV and aggregate size reported by Gillette et al. (1980), a correction function for aggregate size is:

$$\mathrm{f}(as) = 1 + 0.0002as \quad (3)$$

where as is aggregate size (mm). We assume that TFV attained a minimum for 0.07-mm diameter aggregates (mean aggregate size of Ritzville silt loam in this study).

Correction functions for biomass account for the influence of both prostrate and standing biomass on the soil surface on TFV. A correction function for biomass flat cover was derived based upon data of Hagen (1996) and is expressed as:

$$\mathrm{f}(bc) = (1 + 1.92bc - 2.092bc^2 + 0.866bc^3)^2 \quad (4)$$

where bc is the fraction of soil surface covered by prostrate residue. The correction function for SAI (Shao, 2000) is:

$$\mathrm{f}(\mathrm{SAI}) = \sqrt{\{(1 - m\alpha SAI)(1 + m\beta SAI)\}} \quad (5)$$

where m is a constant (~0.5) that accounts for non-uniformity in shear stress caused by standing stems, α is the ratio of stem basal area to stem frontal area, and β is the ratio of stem to soil surface drag coefficients. The drag coefficient for standing stems was 0.45 (Campbell, 1986) and for a smooth soil surface was 0.0033 (Raupach et al., 1993).

We are not aware of previous investigations that have examined the effect of random roughness on TFV. However, since soil loss is proportional to TFV, we used data of Horning et al. (1998) to estimate a correction function for random roughness. Horning et al. (1998) derived a relationship between soil loss ratio (ratio of soil loss from a rough surface to soil loss from a smooth surface) and random roughness for a Ritzville silt loam. The relationship between the inverse of the soil loss ratio and random roughness was used as the correction function:

$$\mathrm{f}(rr) = 1.0 + 0.0156rr + 0.0062rr^2 \quad (6)$$

where rr is random roughness (mm).

As mentioned previously, conventional summer fallow can be characterized by an aggregate geometric mean diameter of 0.08 mm, biomass flat cover of 9%, SAI of 0.003 $m^2\,m^{-2}$, and random roughness of 8 mm (Feng and Sharratt, 2009). Based upon these characteristics, the TFV for Ritzville silt loam in conventional summer fallow may be expected to be ~0.35 m s^{-1}. This threshold is similar to the TFV reported for Ritzville silt loam in the field by Kjelgaard et al. (2004) and Sharratt and Feng (2009). The good agreement between TFV derived using Eqs. (2–6) and measured in the field suggests the validity of these equations in estimating TFV's in the region once the TFV of the smooth, dry, fine, unconsolidated, and bare soil is known. The field-estimated and field-measured TFV's also closely approximate the minimum TFV (0.35 m s^{-1}) required to initiate wind erosion in WEPS. Indeed, occasional failure of WEPS to simulate erosion from loessial soils in the Columbia Plateau may be due to erosion occurring in the field at TFV less than 0.35 m s^{-1} (Feng and Sharratt, 2009). Threshold friction velocities lower than 0.35 m s^{-1} may occur in the field where the surface of a Ritzville silt loam has little biomass or roughness.

3.3. Particle diameters associated with threshold friction velocities

Particle diameter, mass and shape are important characteristics that affect the TFV. According to Bagnold's (1941) theory, the TFV of a sand particle (u_{*ts}) is directly related to particle density and diameter:

$$u_{*ts} = A\sqrt{(gd(\sigma - \rho)/\rho)} \quad (7)$$

where A is an empirical coefficient of turbulence equal to 0.1 for particle friction Reynolds number >0.35, σ is particle density (kg m^{-3}), ρ is air density (kg m^{-3}), g is acceleration due to gravity (m s^{-2}), and d is particle diameter (m). For comparative purposes, we assumed a particle density of 2650 kg m^{-3}, air density of 1.22 kg m^{-3}, and the acceleration due to gravity of 9.8 m s^{-2}. For the threshold friction velocities reported in Table 2, and according to Bagnold's theory, the particle diameter for the five soils was 159 μm for Athena silt loam, 207 μm for Palouse silt loam, 152 μm for Ritzville silt loam, 269 μm for Walla Walla silt loam, and 91 μm for Warden silt loam. The estimated diameters of the silt loams were generally twice as large as the geometric mean diameters measured in this study. This may suggest that the larger diameter aggregates or particles that comprise the silt loams in this study control particle emissions.

3.4. Model implications in specifying threshold friction velocity

Process-based wind erosion models typically predict sediment loss or flux based upon the difference between friction velocity and TFV. Wind erosion only occurs when the friction velocity exceeds the TFV. This scheme is used by models such as the Integrated Wind Erosion Modelling System (IWEMS), Texas Erosion Analysis Model (TEAM), Wind Erosion Assessment Model (WEAM), Wind Erosion on European Light Soils (WEELS), Wind Erosion Model (WEMO), and Wind Erosion Prediction System (WEPS). The parameterization of TFV varies among wind erosion models. For example, the WEELS and WEPS models estimate TFV from soil particle/aggregate properties, surface roughness, vegetation cover, and soil moisture (Hagen et al., 1996; Bohner et al., 2003). In addition, TEAM determines TFV from particle diameter and soil water content (Gregory et al., 2004) while IWEMS and WEAM determines TFV from particle diameter, surface roughness, and moisture content (Lu and Shao, 2001; Fratini et al., 2009). The WEMO estimates TFV by partitioning shear stress between a plant canopy and the soil surface (Okin, 2008). Although the TFV is an important parameter in simulating wind erosion, wind erosion models may set limits on TFV. For example, the WEPS model does not simulate sediment loss or flux until friction velocity exceeds a TFV of 0.35 m s^{-1} while WEMO simulates erosion only when the friction velocity exceeds a TFV of 0.24 m s^{-1}. Threshold friction velocities reported for our loessial and sandy loam soils (Table 2) are lower than those used in some wind erosion models to initiate erosion. Thus, wind erosion models that initiate erosion only after the friction velocity exceeds a TFV of ~0.2 m s^{-1} may not be applicable to agricultural soils in summer fallow that lack vegetative cover and roughness on the Columbia Plateau.

4. Conclusions

The TFV of five soils found across the Columbia Plateau was examined because little information exists on TFV of various soils and better estimates of TFV are needed for wind erosion models in the region. The TFV of a sandy loam was 0.139 m s^{-1} whereas the TFV of the four silt loams ranged from 0.180–0.239 m s^{-1}. These TFV's are lower than those previously observed in the field in the Columbia Plateau and lower than the minimum TFV required to initiate erosion of field surfaces in some wind erosion models. The low TFV of soils within the Columbia Plateau may contribute to the poor performance of wind erosion models such as the WEPS model in the region. Wind erosion models that initiate erosion only after exceeding a TFV of ~0.25 m s^{-1} may have limited application on agricultural soils in summer fallow that lack vegetative cover and roughness in the Columbia Plateau. The performance of these models may be improved by better estimating the TFV of dry, fine-grained, smooth, and bare loessial soil surfaces.

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