Fine Particle Emission Potential from Loam Soils in a Semiarid Region

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Fugitive dust emission from agricultural soils is a concern in the U.S. Inland Pacific Northwest because emission of particles with an aerodynamic diameter ≤10 μm (PM10) and ≤2.5 μm (PM2.5) are regulated by the U.S. Environmental Protection Agency (EPA) as air pollutants. The objective of this study was to characterize the PM10 and PM2.5 emission potential of soils in the region. Soil from the upper 3-cm layer of the profile was collected from five major soil types in southeastern Washington. Soil samples collected from the field were placed inside a wind tunnel to simultaneously measure PM10 and PM2.5 emissions at three wind speeds. Dispersed soil analysis indicated that the sand and silt content, respectively, ranged from 17 to 68% and 23 to 66% while nondispersed soil analysis revealed the PM10 and PM2.5 content averaged 3.7 and 1.2%, respectively, across the five soil types. Emissions of PM10 and PM2.5 were greatest for Warden sandy loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambids) and lowest for Walla Walla silt loam (coarse-silty, mixed, superactive, mesic Typic Haploxerolls). During the 5 min wind tunnel test at the highest wind speed (18 m s^{-1}), loss of sediment, PM10 and PM2.5 for the five soils ranged from 113 to 8039 g m^{-2}, 0.4 to 11.0 g m^{-2}, and 0.1 to 6.0 g m^{-2}, respectively. Although the PM10/sediment loss ratio differed among soils, there was no difference in the PM2.5/sediment loss ratio across soils. Our results suggest that the emission potential varies for windblown soils found across the Inland Pacific Northwest.

Abbreviations: EPA, U.S. Environmental Protection Agency; NAAQS, National Ambient Air Quality Standard; PM2.5, particulate matter ≤2.5 μm in aerodynamic diameter; PM10, particulate matter ≤10 μm in aerodynamic diameter; WEPS, Wind Erosion Prediction System; WEQ, Wind Erosion Equation.

Soil wind erosion and fugitive dust emission contribute to land degradation, loss of soil productivity, and poor air quality and visibility. Atmospheric dust also influences climate by altering the Earth's radiation balance (Tegen and Lacis, 1996). The potential for wind erosion is highest in arid and semiarid regions. The Columbia Plateau, located in eastern Washington, north-central Oregon, and northern Idaho, is a semiarid to arid region with annual precipitation ranging from 100 to 700 mm (Fig. 1) and extensive loess deposits as deep as 10 m (Stetler and Saxton, 1996). During high wind events, soil entrainment is dominated by suspension processes (Kjelgaard et al., 2004; Sharratt, 2011). Suspension of fine particulates from relatively small emission source areas can impact communities downwind. Soil and mineral particles with a diameter <60 μm are especially important to air quality because they contain significant amounts of soil nutrients (Zobeck and Fryrear, 1986) and contaminants (Pye, 1987). Of particular concern are those particles with a mean aerodynamic diameter ≤10 μm (PM10) and 2.5 μm (PM2.5) which are stringently regulated by EPA as air pollutants.

The 1990 Clean Air Act (USEPA, 1990) established PM10 standards and in 1997 the EPA promulgated a new standard for PM2.5. In the western United States, blowing dust can cause exceedance of the National Ambient Air Quality Standard (NAAQS) for PM10. Several locations within the Columbia Plateau region failed to achieve the NAAQS for PM10 in the late 1980s and early 1990s (Department

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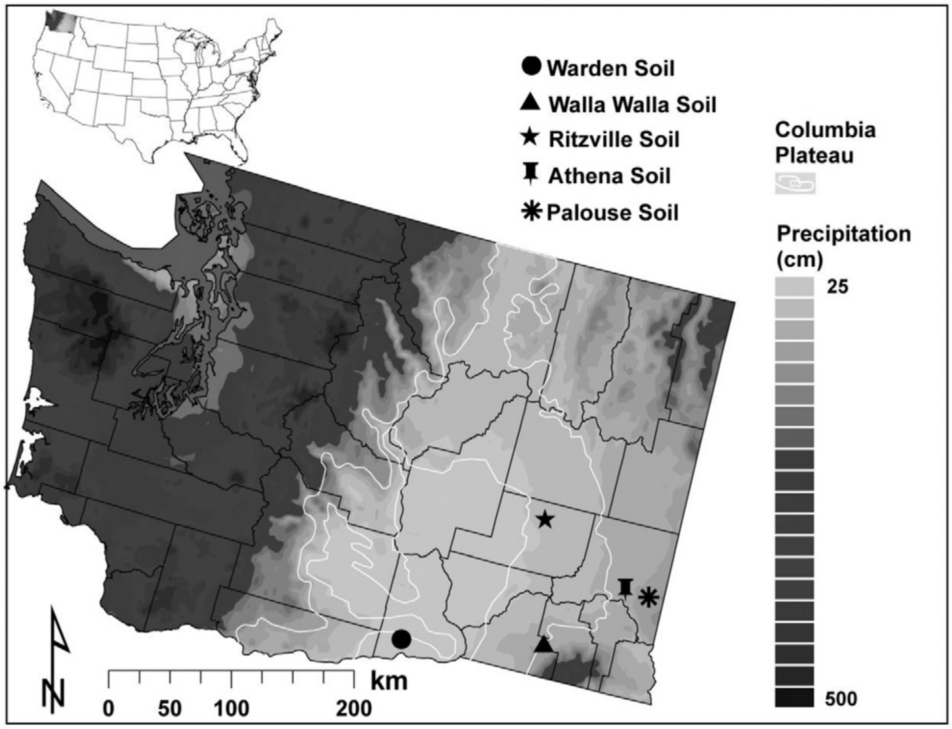

Fig. 1. Soil sampling sites and annual average precipitation within the Columbia Plateau of Washington state.

of Ecology, 2003). Sharratt and Lauer (2006) reported that the NAAQS PM10 standard at Kennewick, WA was exceeded on 38 d between 1987 and 2005 due to windblown dust. Hence, of importance is identifying the PM10 and PM2.5 contributions from soils that are susceptible to erosion during high winds for implementing control measures in the field and designing prediction tools to forecast air quality throughout the region.

The PM10 or PM2.5 production potential of soils has been characterized in some wind erodible areas of the United States (Table 1). Mirzamostafa (1996) indicated that the PM10 content of 11 Kansas soils ranged from 0.05 to 0.39%. Slightly larger PM10 contents were reported for several soil types in California; PM10 content ranged from about 0.25 to 0.42% when soils were suspended inside a chamber (Carvacho et al., 2001). Likewise, a chamber experiment revealed that PM10 content was generally larger for nondispersed soils from the Columbia Plateau in Washington than soil obtained from Texas; PM10 content for the Washington soils ranged from 1.7 to 5% while PM10 content for the Texas soil was 0.6%. Dispersed soil particle size analyses showed that the PM10 composition of the Washington soils ranged from 19 to 38% while the PM10 composition of the Texas soil was 16% (Chandler et al., 2002). Soils of eastern Washington appear to have a high potential to release PM2.5 and PM10 compared with soils in other states.

The PM2.5 to PM10 emission ratio has been determined for some soils in the U.S. Agricultural soils in California were observed to have a PM2.5 to PM10 emission ratio of between 0.08 and 0.12 (Ashbaugh et al., 2003). Ono (2005) reported that the PM2.5/PM10 emission ratio from a dry lake bed during high winds in California to be about 0.1. Carvacho et al. (2004) reported a PM2.5/PM10 ratio of 0.1 for soils in the San Joaquin Valley, California. The PM2.5/PM10 ratio for ambient samples collected at sites of the Interagency Monitoring of Protected Visual Environments program averaged 0.11, but in the San Joaquin Valley was 0.06. In 1996, the Midwest Research Institute recommended the PM2.5/PM10 ratio for agricultural wind erosion be 0.15 (Cowherd and Kuykendal, 1997). Matsumura et al. (1996) found a PM2.5/PM10 ratio of 0.18 for a field undergoing harvest and land preparation in California.

Table 1. PM10 emission potential and PM2.5/PM10 emission ratio of wind erodible soils found across the world.

Reference	Location/soil type	Method of analysis	PM10 (%)	PM2.5/PM10
Mirzamostafa et al. (1996)	Kansas, 11 soil types	Nondispersed, chamber	0.05–0.39	
Carvacho et al. (2001)	California, unknown	Nondispersed, chamber	0.25–0.42	
Carvacho et al. (2004)	California, 44 soil types	Nondispersed, chamber		0.10
		ambient		0.11
		ambient		0.06
Sharratt and Lauer (2006)	Washington, unknown	ambient		0.04–0.07
Chandler et al. (2002)	Washington, sand/silt loam	Nondispersed, chamber	1.7–5	0.33–0.55
		Dispersed, laser diffraction	19–38	
	Texas, unknown	Nondispersed, chamber	0.6	
		Dispersed, laser diffraction	16	
Ashbaugh et al. (2003)	California, 19 soil types,	Nondispersed, fluid bed		0.08–0.12
Ono (2005)	California, unknown	Nondispersed		0.10
Cowherd and Kuykendal (1997)	unknown	unknown		0.15
Matsumura et al. (1996)	California, unknown	ambient		0.18
Singer et al. (2002)	Aral Sea Basin	Non-dispersed, dust generator		0.20–0.48
Hagen and James (1998)	Nevada, 9 soil types	Non-dispersed, chamber		0.03–0.1

Soils from the south Aral Sea Basin placed inside a dust generator produced a PM2.5/PM10 ratio of 0.2 to 0.48 (Singer et al., 2002). The PM2.5/PM10 ratio for ambient samples collected at Kennewick, WA was 0.04 to 0.07 (Sharratt and Lauer, 2006). However, chamber experiments on the suspendible fraction of soils tested within the Columbia Plateau in Washington indicated that the PM2.5/PM10 ratio ranged from 0.33 to 0.55 (Chandler et al., 2002).

Prediction tools have been developed for estimating PM10 emission during high winds. One tool involves using the Wind Erosion Equation (WEQ) to estimate total soil loss and then assigning a fraction of the loss as PM10 (California Air Resources Board, 1991). The fraction can be determined by sieving dispersed or nondispersed soils (Mirzamostafa, 1996; Stetler and Saxton, 1996) or using chamber techniques for nondispersed soils (Chandler et al., 2002; Carvacho et al., 2003, 2004; Hagen, 2004). A second tool for estimating PM10 emission involves assigning an aerodynamic roughness and threshold friction velocity to various surfaces to estimate total dust emissions (Gillette and Passi, 1988) and then multiplying dust emissions by some fraction to obtain PM10 generation. The above procedures may assume that the PM10 generation for similar erosive losses does not vary among soils. The third tool for estimating PM10 emissions uses physical-based models like the Wind Erosion Prediction System (WEPS) (Hagen et al., 1995). These models require estimates of parameters that are related to the PM10 generation process such as the reservoir of loose PM10 at the soil surface created by weathering and mechanical forces, fraction of PM10 in the suspension component created by abrasion and breakage, and the ratios of PM2.5 to PM10 in the loose soil or created during abrasion and breakage (Hagen, 2004). To improve prediction of PM10 generation in WEPS, Hagen (2004) designed a chamber to measure these parameters for a range of soils from nine states across the United States (soils from the Columbia Plateau were not tested). His results revealed the fraction of PM10 in the suspension component created by breakage averaged 0.049 over all soils. The average ratio of PM2.5/PM10 created by breakage was 0.154. Tests on four Kansas soils showed that PM10 in the portion of the suspension component from abrasion of immobile clods ranged from 0.3 to 1.1%. The PM10 in the suspension component from breakage of saltation-size aggregates was larger and ranged from 1.1 to 3.6%. Chandler et al. (2002) observed breakage of the suspendible soil fraction from the Columbia Plateau inside a chamber and found that breakage caused a 2.2% increase in PM10 emission.

Few prediction tools, if any, are available to estimate PM2.5 emissions from field soil during high winds. There is a need to develop such tools since PM2.5 is an air pollutant regulated by EPA. To estimate the impact of wind erosion on air quality and to aid in developing control measures and prediction capabilities of atmospheric PM10 and PM2.5 concentration in the Columbia Plateau of the U.S. Pacific Northwest, knowledge must be acquired of the potential release of PM10 and PM2.5 from soils. The objective of this study was to characterize the PM10 and PM2.5 emission potential of five major soil types in the region.

MATERIALS AND METHODS

The Columbia Plateau encompasses an area of about 150,000 km^2. Five major soils found across the Columbia Plateau include Warden soil series, Ritzville soil series (coarse-silty, mixed, superactive, mesic Calcidic Haploxerolls), Palouse soil series (fine-silty, mixed, superactive, mesic Pachic Ultic Haploxerolls), Athena soil series (fine-silty, mixed, superactive, mesic Pachic Haploxerolls), and Walla Walla soil series. These soil series cover an area of nearly 1.5 million hectares, or about 10% of the area of the Columbia Plateau (U.S. Department of Agriculture, 2011). The Ritzville series is most dominant (570,000 ha) while the Warden Series is the least dominant (195,000 ha) of the five soil series examined in this study. The Ritzville and Warden series are found in the drier part (annual precipitation of <300 mm) of the Plateau and thus are by far the most susceptible to wind erosion. These soils are susceptible to erosion because dryland crop production in this region necessitates using summer fallow in the rotation to conserve soil water. Multiple tillage operations during summer fallow create a partially denuded and fragile soil surface that is susceptible to erosion. The Athena, Palouse, and Walla Walls series are found in the wetter part of the Plateau (>300 mm of annual precipitation) where crops are grown every year or 2 out of 3 yr. Soils in the wetter part of the Plateau are much less susceptible to wind erosion as a result of employing annual or more intense cropping systems (i.e., less fallow) that enhance biomass cover and soil aggregation.

Soil samples were collected from the upper 3-cm layer of the soil profile at field sites as illustrated in Fig. 1. Warden soil was collected during the summer fallow phase of a winter wheat–summer fallow rotation near Paterson, WA (46° 1′9″ N, 119°37′29″ W). Ritzville soil was collected during the summer fallow phase of a winter wheat–summer fallow rotation near Ritzville, WA (47°8′18″ N, 118°28′14″W). Palouse soil was collected after sowing a continuous spring barley rotation near Pullman, WA (46°45′38″ N, 117°12′1″ W). Athena soil was collected during the fallow phase of a 3-yr no-tillage winter wheat–spring wheat–chemical fallow rotation near Colfax, WA (46°47′25″ N, 117°27′23″ W). Walla Walla soil was collected during the fallow phase of a 3-yr winter wheat–spring wheat–summer fallow rotation near Waitsburg, WA (46°14′59″ N, 118°9′51″ W). The soil samples were air-dried and hand sieved through a 2-mm sieve to remove large aggregates and plant residue. The large aggregates were mechanically fractured to facilitate passage through the 2-mm sieve. Soil passing through the 2-mm sieve was used for dispersed soil particle size analysis, nondispersed aggregate size analysis, and examining emissions in a wind tunnel.

Dispersed and nondispersed size analyses were performed on the soil samples. Dispersed size analysis represents the primary particle composition of the soil whereas nondispersed size analysis is used to assess the state of aggregation of soil particles in the field. Dispersed particle size distribution was measured using a Malvern Mastersizer S laser diffractometer (Malvern Instrument, Malvern, England) which determines the volume percent of particles in 64 size classes from 0.5 to 850 μm. Samples were pretreated before analysis using sodium acetate to dissolve carbonates and hydrogen peroxide to oxidize organic matter.

Samples were rinsed with deionized water, centrifuged, and excess supernatant was decanted. Each sample was dispersed with sodium hexametaphosphate by agitation for 16 h and analyzed in a deionized water suspension with no sonication.

Nondispersed soil aggregates 2000–840, 840–420, 420–100, 100–45, 45–32, 32–10, and <10 μm in diameter were measured using a rotary and sonic sieve (Gilson, Worthington, OH). The sonic sieve is not capable of measuring particles <2.5 μm, thus soil samples were placed inside a rotating canister to simultaneously measure the PM10 and PM2.5 fractions of the samples using DustTrak Aerosol Monitors (TSI model 8520, Inc., St. Paul, MN).

Wind tunnel experiments were performed inside a nonregulated climate control 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. axivane fan driven by an industrial type gasoline engine. Plywood coated with epoxy resin and embed quartz sand (250–500 μm size fraction), 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.

Soil passing through the 2-mm sieve was placed in an aluminum tray (1 m long, 0.2 m wide, and 0.015 m deep). The tray was 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.

Four replications of each soil were tested in the wind tunnel at wind speeds of 11, 15, and 18 m s^{-1}. The two lower wind speeds were chosen to represent a typical high wind event within the Columbia Plateau. These speeds are frequently achieved as a peak wind gust or as a sustained wind several times during a season in the Inland Pacific Northwest. The 18 m s^{-1} wind speed was chosen to represent a high wind event with a reoccurrence of once every 2 yr in the Columbia Plateau region (Wantz and Sinclair, 1981). Each soil was subject to high winds for 5 min inside the wind tunnel. A 5 min period was chosen based on preliminary tests that indicated the erodible material was depleted from the test surface within this time period.

Measurements made during the wind tunnels tests included wind speed, flux of saltating and suspended sediment and surface creep, and PM10 and PM2.5 concentrations. Saltating and suspended sediment were measured using a vertically integrating isokinetic slot sampler (Stetler et al., 1997). A 10 by 0.5-cm 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. The PM10 and PM2.5 concentrations were measured using DustTrak Aerosol Monitors. The DustTrak is a constant-flow portable nephelometer capable of measuring particle sizes in the range of 0.1 to 10 μm. The PM 10 and PM2.5 measurements were made at a frequency of 1 Hz with aerosol inlets placed at 0.5, 2, and 5 cm above the soil surface at the downwind edge of the soil tray. These heights were chosen to measure concentrations within and above the boundary layer. Initial testing with Palouse soil indicated that PM10 and PM2.5 concentrations reached background concentration near the 5 cm height. The DustTrak inlet diameter and flow rate were adjusted to achieve a known face velocity across the inlet. A single face velocity was used to achieve isokinetic conditions at the 2-cm height. As a result, DustTraks at 5 cm would under sample PM10 while DustTraks at 0.5 cm would over sample PM10. No adjustments were made to PM10 concentrations despite these differences in sampling efficiency with height. Background concentration is the ambient concentration of PM10 and PM2.5 inside the wind tunnel before and after the test. Wind speeds were measured at a frequency of 1 Hz and averaged over 60 s using pitot tubes installed at heights corresponding to the heights of the DustTrak inlets. Free stream velocity was measured with an additional pitot tube at a height of 1 m inside the wind tunnel.

The emission rate of PM10 and PM2.5 was calculated based on the following relationship (Houser and Nickling, 2001; Shao et al., 1993).

$$E = \frac{1}{L}\int_0^{z_b}\left(C \times u \times dz\right) \qquad [1]$$

where E is PM10 and PM2.5 emission rate (mg m^{-2} s^{-1}), L is length of the eroding surface (m), z_b is height at which PM10 or PM2.5 concentrations reached background concentrations (m), C is the average PM10 or PM2.5 concentration above background concentration (mg m^{-3}) over 5 min, and u is wind speed at height z (m s^{-1}). The equation was evaluated from the lowest sampling height to z_b by plotting PM10 or PM2.5 horizontal flux as a function of height. Sampling height was plotted as a function of PM10 or PM2.5 concentration and fit with an exponential function to determine the height at which background concentration was achieved.

Two-way ANOVA was conducted on loss of total sediment and PM10 and PM2.5, ratio of PM10 and PM2.5 emission to total sediment loss, wind speed, and soil type × wind speed interactions. One-way ANOVA was performed to examine soil type effects on loss of total sediment and PM10 and PM2.5, ratio of PM10 and PM2.5 emission to total sediment loss at each wind speed, and particle size distributions of both dispersed and nondispersed soils. Multiple pairwise comparisons were made using Tukey's adjustment. All results are reported at the α = 0.05 level of significance.

Normality of the distributions was examined by the Shapiro–Wilk test. 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. Transformations were necessary only for two-way ANOVAs.

RESULTS AND DISCUSSION

The five soils tested in this study represent major soil series in the Columbia Plateau region. The texture of all soil types is silt loam except Warden soil which is sandy loam (Table 2). Dispersed sample analysis indicated the Warden soil particle size distribution was different from the other soils and has a higher percentage of sand (Table 2 and Fig. 2). The D50 and D90 represent the 50th and the 90th percentile of the particle size distribution, respectively, as measured by volume. The Warden soil had the largest D50 and D90 values. Sand, very fine sand, and silt content as well as the mean diameter and D90 are similar for the Palouse and Ritzville soils and for the Athena and Walla Walla soils (Table 2). PM10 and PM2.5 content of dispersed soils ranged from 20 to 11% and from 39 to 17%, respectively (Table 3). Athena and Walla Walla

Table 2. Soil particle size distribution and texture based on dispersed analysis of five soil types found within the Columbia Plateau.

Soil series	Sand†	Very fine sand	Silt	Clay	Texture‡	Mean diameter§	D50	D90
	%					μm		
Warden	67.5a¶	30.6a	23.3c	9.2b	SL	98.3a	78.0a	217.2a
Athena	17.3c	12.1c	65.7a	17.0a	SiL	30.7b	17.1d	66. 0c
Palouse	23.4b	16.0b	62.2b	14.4a	SiL	42.7b	22.8c	88.9b
Ritzville	30.5b	21.2b	58.1b	11.4b	SiL	44.9b	28.0b	99.6b
Walla Walla	19.6c	14.7c	63.8a	16.6a	SiL	31.6b	18.2cd	70.7c
p value	<0.0001	<0.0001	<0.0001	<0.0001		0.0007	<0.0001	<0.0001

† Sand, 0.05–2 mm; Very fine sand, 0.05–0.1 mm; Silt, 0.002–0.05; Clay, <0.002mm.

‡ SL, sandy loam; SiL, silt loam.

§ Mean diameter by volume, D50 and D90 represent diameter of at least 50 and 90% of the volume.

¶ Values within a column followed by the same letter are not significantly different.

soils contained the largest amount of PM10 and PM2.5 while the Warden soil contained the lowest amount of PM10 and PM2.5. The percent of PM2.5 comprising PM10 ranged from 48 to 62% and was the same for all dispersed soils except the Warden soil. Coarse particulate matter, or particles between 2.5 and 10 μm in diameter (PM10–2.5), varied from 7 to 19% and was lowest for the Warden soil (Table 3).

Dispersed particle size analysis is routinely performed in the laboratory and thus efforts have been made to establish empirical relationships for predicting fine particle emissions from the dispersed particle size distribution (Carvacho et al., 2004; Pace, 2004). However, measurement of nondispersed aggregate size distribution could provide better representation of the fraction of the erodible component in the field. While dispersed particle size analysis represents the maximum potential for emission of PM10 and PM2.5 from our soils, this maximum is not likely to be achieved in the field because the PM10 and PM2.5 content of nondispersed soils was much lower than for dispersed soils (Tables 3 and 4, Fig. 2 and 3). The PM10 and PM2.5 content of the nondispersed erodible soil fraction ranging from 3.2 to 4.6% and 0.9 to 1.5%, respectively (Table 4). No significant differences in PM10 and PM2.5 content among soils were observed with the average PM10 and PM2.5 content of the five soils being 3.7 and 1.2%, respectively. Chandler et al. (2002) performed tests on the nondispersed, suspendible fraction of soils collected from 44 sites on the Columbia Plateau and found that the PM10 and PM2.5 content ranged from 1.7 to 5.0% and 0.7 to 2.4%, respectively. Their results are in agreement with those found in this study. Hagen et al. (1996) indicated that the PM10 content could reach 4% of the soil mass in the field within some semiarid regions. In comparison to our results, soils from field sites in the Great Plains of the United States contained <0.5% PM10 (Hagen, 2004), soils from field sites in Kansas contained 0.05 to 0.39% PM10 (Mirzamostafa, 1996), soils from field sites in California contained 0.25 to 0.42% PM10 (Carvacho et al., 2001), and soils from field sites in Texas contained 0.6% PM10 (Chandler et al., 2002). While we recognize that the method of sampling the soil and analyzing for PM10 can influence PM10 content, our data show that soils of the Columbia Plateau have an inherently high PM10 emission potential as compared with soils from other regions of the United States. The ratios of PM2.5 to PM10 for nondispersed soil ranged from 0.26 to 0.37 with Athena soil having a significantly lower ratio as compared with Walla Walla and Palouse soils (Table 4). Chandler et al. (2002) reported PM2.5/PM10 ratios of 0.3 to 0.55 for soils collected from 44 field sites within the Columbia Plateau, but their data are skewed by breakage of aggregates and testing only the suspendible fraction during analysis. In contrast, the PM2.5/PM10 ratio of nondispersed soils collected from field sites in California was 0.06 to 0.18 (Ashbaugh et al., 2003; Carvacho et al., 2001, 2004; Cowherd and Kuykendal, 1997; Matsumura et al., 1996).

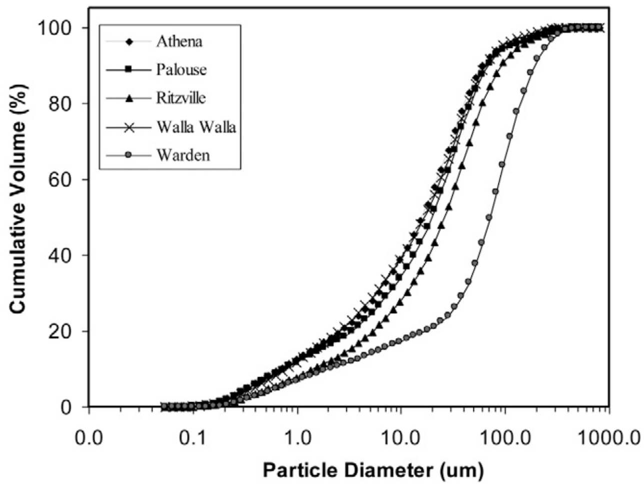

Fig. 2. Dispersed particle size distribution of five soil types.

Table 3. PM2.5 and PM10 content based on dispersed analysis of five soil types found within the Columbia Plateau.

Soil series	PM2.5	PM10	(PM10–2.5)†	PM2.5/PM10	(PM10–2.5)/PM10
	%				
Warden	10.8c‡	17.3c	6.5d	62.3a	37.7b
Athena	19.4a	38.7a	19.3a	50.2b	49.9a
Palouse	17.6ab	34.0b	16.4b	51.7b	48.4a
Ritzville	13.2bc	27.8b	14.6c	47. 6b	52.4a
Walla Walla	19.7a	38.9a	19.2a	50.6b	49.4a
p value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

† Coarse particulate matter percentage (PM10 minus PM2.5 content).

‡ Values within a column followed by the same letter are not significantly different.

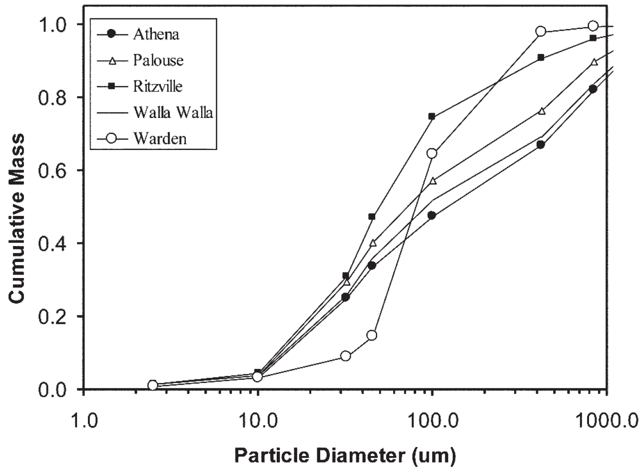

Fig. 3. Nondispersed particle size distribution of five soil types.

Table 4. PM2.5 and PM10 content based on nondispersed analysis of five soil types within the Columbia Plateau.

Soil series	PM2.5	PM10	PM10–2.5	PM2.5/PM10	(PM10–2.5)/PM10
				–%–	
Warden	1.0	3.3	2.2	31.8ab†	68.2ab
Athena	0.9	3.3	2.4	26.4b	73.6a
Palouse	1.4	3.8	2.4	36.3a	63.6b
Ritzville	1.5	4.6	3.2	31.5ab	68.5ab
Walla Walla	1.4	3.8	2.4	36.7a	63.3b
p value	ns‡	ns	ns	0.0021	0.0021

† Values within a column followed by the same letter are not significantly different.
‡ ns, no significant difference.

Hagen (1999) indicated that soil aggregates move by three modes during high wind events which can be separated by the size of aggregates; creep-size aggregates (0.84–2 mm diam.), saltation-size aggregates (0.1–0.84 mm diam.) and suspension-size aggregates (<0.1 mm diam.). Table 5 shows that more than half of the erodible mass of the five soils used in this study are composed of suspension-size aggregates, which implies that suspension may be the dominate mode of wind erosion in the region (Kjelgaard et al., 2004; Sharratt, 2011). The Ritzville and Warden soils had significantly higher amounts of suspension-size aggregates and are from a drier precipitation zone where winter wheat–summer fallow is the predominate crop rotation as compared with the other three soil types. No difference in the PM10, PM2.5, or PM2.5-PM10 to suspension ratios was observed in this study with ratios of PM10/suspension and PM2.5/suspension varying, respectively, from 0.051 to 0.073 and 0.016 to 0.024 across the five soils (Tables 5 and 6). A lower percentage of creep and saltation-size aggregates, compared with suspension-size aggregates, in the soils resulted in larger ratios of PM2.5 and PM10 to creep and saltation compared with suspension.

Horizontal sediment, PM10, and PM2.5 flux diminished with height and increased with wind speed (Fig. 4). As a result, sediment, PM10, and PM2.5 loss from each soil increased with wind speed (Table 7). Differences in the emission potential across the five soils were more evident at higher wind speeds (Table 7) and nearer the soil surface (Fig. 4 and 5).

Table 5. Percentage of creep-size (0.84–2 mm), saltation-size (0.1 to 0.84 mm), and suspension-size (<0.1 mm) aggregates constituting five soil types found within the Columbia Plateau. Creep, saltation, and suspension class is based on Hagen (1999).

Soil series	Total creep	Total saltation	Total suspension	PM10/Total creep	PM10/Total saltation	PM10/Total suspension
				%		
Warden	1c†	35a	64b	492.0a	9.1b	5.1
Athena	18a	34a	48c	18.4c	9.5b	6.9
Palouse	10b	33a	57bc	125.7c	11.7b	6.6
Ritzville	4c	22b	74a	23.7b	21.7a	6.2
Walla Walla	16a	32a	52c	23.7c	11.8b	7.3
p value	<0.0001	0.0008	<0.0001	<0.0001	0.0011	ns‡

† Values within a column followed by the same letter are not significantly different.
‡ ns, no significant difference.

Table 6. Percent PM2.5 and coarse particulates (PM10-PM2.5) in the creep, saltation, and suspension component that constitute five soil types found within the Columbia Plateau.

Soil series	PM2.5/Total creep	PM2.5/Total saltation	PM2.5/Total suspension	(PM10–2.5)/ Total creep	(PM10–2.5)/ Total saltation	PM10–2.5)/Total suspension
				%		
Warden	156.3a†	2.9b	1.6	335.7a	6.2b	3.5
Athena	4.9c	2.5b	1.8	13.5c	7.0b	5.0
Palouse	13.1c	4.2a	2.4	22.9c	7.4b	4.2
Ritzville	40.1b	6.8a	2.0	85.7b	14.8a	4.2
Walla Walla	8.7c	4.4ab	2.7	15.1c	7.5b	4.6
p value	<0.0001	0.0024	ns	<0.0001	0.0009	ns

† Values within a column followed by the same letter are not significantly different.
‡ ns, no significant difference.

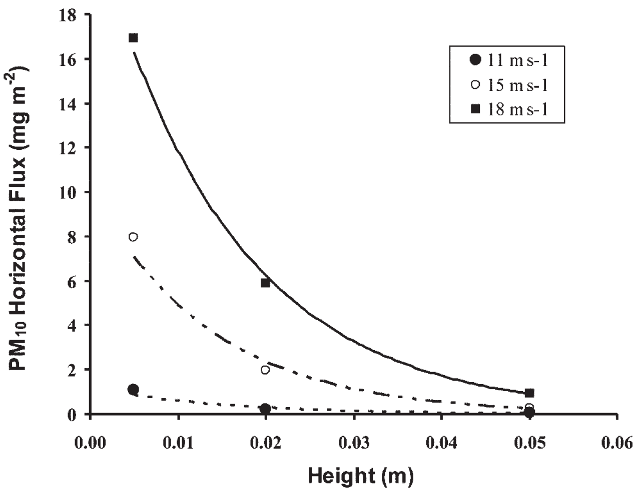

Fig. 4. PM10 horizontal flux of Walla Walla soil series as a function of height and three wind speeds over 5 min.

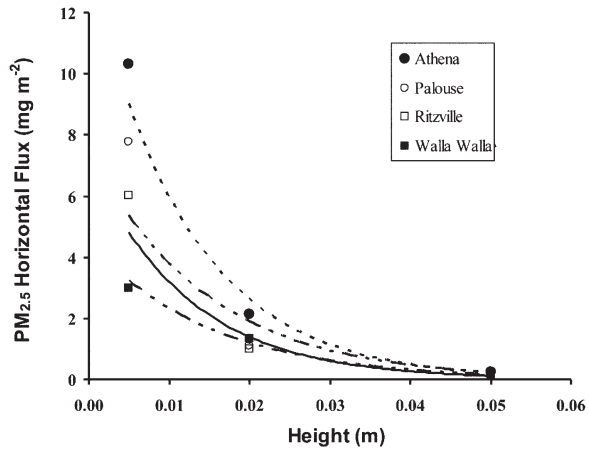

Fig. 5. PM2.5 horizontal flux as a function of height at a wind speed of 18 m s^{-1} over 5 min. Horizontal flux of Warden soil was too large (240 mg m^{-2} at 0.005 m height) to show in the figure.

The two-way ANOVA with soil type and wind speed as the main effects indicated significant differences in total sediment loss and PM10 and PM2.5 loss as well as their ratios due to soil type, wind speed, and wind speed × soil type interactions (Table 8). No significant differences in the ratios of PM10 and PM2.5 loss to total sediment loss were found in response to wind speed × soil type interactions (Table 8). A two-way ANOVA also indicated no significant difference in the ratio of PM2.5 loss to total sediment loss among soils at the 15 and 18 m s^{-1} wind speeds although there were significant differences in both total sediment and PM2.5 loss among soils (Tables 7 and 8). No statistically significant difference in the ratio of PM2.5 to PM10 loss was found based on soil type or wind speed and averaged 0.24, 0.19, and 0.27 at the three successive wind speeds (Table 7). The lack of difference in the PM2.5 to PM10 loss ratios was attributed to the variation of PM2.5 and PM10 loss.

The greatest loss of sediment, PM10, and PM2.5 was observed for the Warden soil at the three wind speeds (Table 7). This observation could not be collaborated by Warden soil having a higher PM10 and PM2.5 content compared to other soils because PM10 and PM2.5 content of both dispersed and nondispersed Warden soil was not higher than that found for the other four soils examined in this study (Tables 3 and 4). In comparison to other soils, the Warden soil had a significantly greater sand fraction (Table 2). Although the very fine sand fraction (particles 50–100 µm in diameter) is considered suspension by Hagen (1999), Goossens (1985) and Sharratt (2011) found that particles in the 50 to 100 µm diam. range are

Table 7. Total sediment, PM10, and PM2.5 loss from five soil types as observed at three wind speeds inside a wind tunnel.

Wind speed	Soil types	Total sediment loss	PM10 loss	PM2.5 loss	PM2.5/PM10 loss	PM2.5/Total sediment	PM10/Total sediment
m s^{-1}		——— g m^{-2} ———			——— % ———		
	Warden	215.3a†	0.141c	0.027a	18.9	0.012b	0.065b
	Athena	17.2bc	0.0223ac	0.006b	29.0	0.039a	0.136a
11	Palouse	21.9b	0.029a	0.008b	26.5	0.031ab	0.117ab
	Ritzville	26.3b	0.020ac	0.004bc	19.9	0.017b	0.079b
	Walla Walla	11.9c	0.010c	0.002c	24.5	0.021ab	0.084ab
	p value	<0.0001	<0.0001	<0.0001	ns‡	0.0093	0.0202
	Warden	3634.3a	3.814a	1.286a	32.5a	0.035a	0.105c
	Athena	135.7b	0.301c	0.046bc	15.5bc	0.045a	0.293b
15	Palouse	112.4b	0.553b	0.063b	11.3c	0.055a	0.491a
	Ritzville	49.1c	0.114d	0.024c	20.7b	0.048a	0.234bc
	Walla Walla	53.5c	0.128d	0.021dc	16.9b	0.047a	0.283bc
	p value	<0.0001	<0.0001	<0.0001	<0.0001	03274	0.0001
	Warden	8039.4a	10.769a	5.993a	55.7a	0.075	0.134b
	Athena	222.0b	0.878b	0.173b	19.9b	0.078	0.395a
18	Palouse	240.9b	0.702b	0.118c	16.9b	0.056	0.330a
	Ritzville	152.6bc	0.402c	0.091c	22.7b	0.062	0.272ab
	Walla Walla	112.7c	0.419c	0.083c	20.0b	0.074	0.378a
	p value	<0.0001	<0.0001	<0.0001	<0.0001	ns	0.0022

† Values within a column followed by the same letter are not significantly different.

‡ ns, no significant difference.

Table 8. Statistical matrix of the effect of soil type and wind speed on loss of sediment, PM2.5, and PM10.

Model effect	Total sediment loss	PM10 loss	PM2.5 loss	PM2.5/PM10 loss	PM2.5/Total sediment	PM10/Total sediment
Two-way ANOVA						
Soil type	<0.0001	<0.0001	<0.0001	<0.0001	0.1852	<0.0001
Wind speed	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Wind speed × Soil type	<0.0001	<0.0001	<0.0001	<0.0001	0.0740	0.0882

subject to saltation. An abrader was not used in the wind tunnel, thus a possible explanation for the higher sediment loss from the Warden soil is the higher percentage of sand which might serve as a saltating agent to bombard suspension-size particles on the soil surface or break or abrade larger aggregates at high wind speeds. This abrading action could induce the release of more PM10 and PM2.5 from the soil surface. The abrasion and breakage process generally dominate the generation of PM10 from surfaces such as crusted lakebeds (Gillette et al., 1997), aggregated fields, and paved areas or desert pavement (Hagen et al., 1996). Hagen (2004) reported that 5% of PM10 in the suspension component was created by breakage. Chandler et al. (2002) also illustrated the importance of breakage in creation of PM10. The Warden soil is located in a lower precipitation area (annual precipitation about 200 mm) as compared with the other four soils, therefore efforts to stem wind erosion from this soil should target the control of the saltation process.

Our statistical analysis of comparing loss of sediment, PM10 and PM2.5; ratio of PM2.5 to PM10 loss; and ratio of PM2.5 or PM10 loss to total sediment loss indicated some similarity between Athena and Palouse soils as well as Ritzville and Walla Walla soils (Table 7). In general, loss of sediment, PM10, and PM2.5 was higher for Athena and Palouse as compared with Ritzville and Walla Walla soils. This finding suggested that Athena and Palouse soils have a higher PM10 and PM2.5 emission potential than Ritzville and Walla Walla soils, particularly at higher wind speeds. Chandler et al. (2002) also found that the PM10 emission potential increases in moving from west to east across the Columbia Plateau (Fig. 1). Athena and Palouse soils are found in the wetter or eastern part of the Columbia Plateau where wind erosion and dust emissions seldom occur. Thus, emissions characteristics reported in this study are contrary to those observed in the field. Emissions in this study, however, were measured from the erodible fraction of the soil and do not account for the protective role of nonerodible aggregates in the field. Although the emissions potential was high for the Athena and Palouse soils, these soils have a low erodible fraction that result in low emissions in the field (Chandler et al., 2002). PM10 and PM2.5 loss at any wind speed did not reach 3.5 and 1.0% of sediment loss as would have been expected from nondispersed particle size analysis (Table 4). Instead, the percentage of PM10 and PM2.5 loss to total sediment loss from the five soils at the highest wind speed was only 0.30 and 0.07% (Table 7). Copeland et al. (2009) also reported that PM10 flux was 0.31% of total sediment loss from a bare Ritzville soil at a wind speed of 18 m s^{-1}.

CONCLUSIONS

Five representative soils (Warden, Athena, Palouse, Ritzville, and Walla Walla) within the Columbia Plateau were examined for their potential to emit fine particulates during high winds. Dispersed soil particle size analysis indicated that the Warden soil is a sandy loam while the other four soils are a silt loam, PM10 content ranged from17 to 39%, PM2.5 content varied from 11 to 19%, and the ratios of PM2.5/PM10 ranged from 0.47 to 0.62. Nondispersed soil aggregate size analysis showed that there were no significant differences in the PM10 and PM2.5 content among the five soils, ranging from 3.25 to 4.61% and 0.87 to 1.46%, respectively. The percent of PM2.5 comprising PM10 ranged from 26 to 37%. Wind tunnel tests at a wind speed of 18 m s^{-1} indicated that the percentage of PM10 and PM2.5 loss to total sediment loss from the five soils was only 0.30 and 0.07%. This suggests that nondispersed soil particle size distribution may better represent the fine particulates emission potential in a field. Wind tunnel experiments revealed that the Warden soil is more erodible than the other four soils. No differences in the loss of total sediment, PM10 and PM2.5 flux, and PM2.5/PM10 ratios were observed between the Athena and Palouse soils and the Ritzville and Walla Walla soils at three wind speeds. Sediment, PM10, and PM2.5 loss from the Athena and Palouse soils were generally higher than from the Ritzville and Walla Walla soils. Farm management practices to curtail wind erosion should target the Warden and Ritzville soils located in the dry winter wheat–summer fallow region of the Columbia Plateau. In addition, differences in dispersed and nondispersed PM10 and PM2.5 content show that management practices play a significant role in coagulation of the fine particles onto larger, less erodible aggregates for reducing dust emission from farmland.

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