

Windblown Dust Potential from Oilseed Cropping Systems in the Pacific Northwest United States

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ABSTRACT

The volatility of petroleum reserves and prices coupled with concerns about greenhouse gas emissions and climate change has created worldwide interest in renewable fuels. Little is known, however, about the impact on natural resources of growing oilseed crops for biofuel. This study examined the impact of growing oilseed crops in winter wheat (*Triticum aestivum* L.) rotations on wind erosion and emissions of particles $\leq 10 \mu\text{m}$ in aerodynamic diameter (PM₁₀) in eastern Washington, where atmospheric PM₁₀ is an acute environmental concern. Wind erosion and PM₁₀ emissions were measured immediately after sowing winter wheat in a winter wheat–summer fallow (WW-SF) rotation, a winter wheat–camelina [*Camelina sativa* (L.) Crantz]–summer fallow (WW-C-SF) rotation, and a winter wheat–safflower (*Carthamus tinctorius* L.)–summer fallow (WW-S-SF) rotation. Best management practices were implemented during the 13-mo fallow phase of the rotation, which included undercutting and fertilizing the soil in spring and rodweeding during summer to control weeds. A wind tunnel was used to assess horizontal sediment and PM₁₀ flux after sowing wheat because this is the time when the soil is most susceptible to wind erosion. Horizontal sediment and PM₁₀ flux were as much as 250% higher after sowing winter wheat in the WW-C-SF and WW-S-SF rotations than the WW-SF rotation. Vertical PM₁₀ flux was higher in the WW-C-SF and WW-S-SF rotations, in part due to the aerodynamically smoother surface of these rotations compared with the WW-SF rotation. Farmers must be especially judicious in protecting the soil from wind erosion during the fallow phase of the WW-C-SF and WW-S-SF rotations.

In an effort to reduce petroleum oil consumption and associated greenhouse gas emissions, which accentuate global warming and climate change, the United States has advocated the development of renewable energy sources since the creation of the Department of Energy in 1977. The Energy Independence and Security Act of 2007 mandates the use of 136×10^9 L of biofuel in the transportation industry by 2022. Of this, 57×10^9 L is required to come from cornstarch feedstock while 79×10^9 L must come from advanced biofuel derived using non-cornstarch feedstock such as sugar, cellulosic, or waste material (USDA, 2010). To meet this goal, the USDA recently developed a strategy that identified that 49.8% of the advanced biofuel would be produced in the Southeast, 43.3% in the Central, 4.6% in the Northwest, 2.0% in the Northeast, and 0.3% in the Southwest regions of the United States (USDA, 2010).

A large fraction of the biofuel to be produced in the western United States is anticipated to come from oilseed crops grown on arid and semiarid agricultural lands. Although oilseeds are not currently grown across the region, there is increasing interest

for including oilseeds into more traditional crop rotations. Oilseed crops such as canola (*Brassica napus* L.) and sunflower (*Helianthus annuus* L.) have been grown with success in the western United States. Canola is currently the most widely grown oilseed crop in Washington, Idaho, and Oregon, with 34,000 ha planted in these states in 2013 (National Agricultural Statistics Service, 2013). Other drought-tolerant oilseed crops such as camelina and safflower have the potential to be grown in the western United States. Adoption in the region will require agronomic and rotational practices that are equally or more profitable than current cropping systems. New cropping systems that incorporate oilseeds into the rotation should have no additional adverse impact on and preferably enhance the quality of environmental resources (Blanco-Canqui, 2010).

Air quality is a major environmental concern across the Columbia Plateau of the Inland Pacific Northwest due to windblown dust emitted from excessively tilled agricultural lands. The low-precipitation zone of the Columbia Plateau, delineated by <300 mm of annual precipitation, is particularly susceptible to wind erosion due to the occurrence of high winds, poorly aggregated soils, low crop biomass production, and excessive tillage during fallow. Winter wheat–summer fallow is the dominant crop rotation used on $>1.5 \times 10^6$ ha in the low-precipitation zone. Wind erosion occurs primarily during the fallow phase of the rotation and is particularly acute at the end of the fallow phase in late August or early September

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Abbreviations: C, camelina; PM_{10_h}, horizontal flux of particles $\leq 10 \mu\text{m}$; PM_{10_v}, vertical flux of particles $\leq 10 \mu\text{m}$; S, safflower; SF, summer fallow; WW, winter wheat.

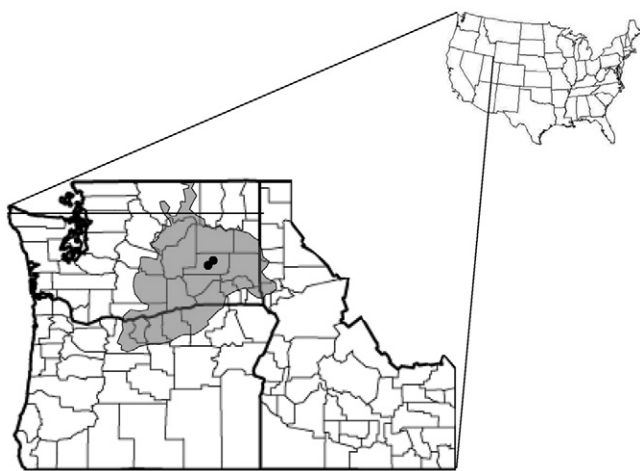


Fig. 1. Locations (black dots) on the Columbia Plateau (shaded area) where wind erosion was measured in winter wheat–summer fallow and winter wheat–camelina–summer fallow or winter wheat–saflflower–summer fallow rotations.

after winter wheat is sown and the soil is most exposed to the forces exerted by the wind. Soils in the region originated mainly from loess and contain a large fraction of fine particulate matter. Particulate matter $\leq 10 \mu\text{m}$ in aerodynamic diameter (PM₁₀) is emitted into the atmosphere during high wind events, occasionally resulting in exceedance of PM₁₀ air quality standards in communities downwind of eroding agricultural lands (Sharratt and Lauer, 2006).

The impact of growing oilseed crops on wind erosion is unknown across the western United States, including the Columbia Plateau region. The purpose of this study was to examine the effect of growing oilseeds in wheat-based crop rotations on wind erosion and PM₁₀ emissions from agricultural soils.

MATERIALS AND METHODS

The potential for wind erosion and PM₁₀ emissions from oilseed crop rotations in the Columbia Plateau was assessed in 2011 and 2012 at Lind and Ritzville, WA (Fig. 1). The dominant crop rotation used by farmers at both locations is winter wheat–summer fallow (WW-SF). The fallow phase of the rotation begins after harvest in late July or early August and continues until winter wheat is sown 13 mo later. The main purpose of fallow is to store a portion of the precipitation occurring during the winter in the soil to enable sowing and establishment of winter wheat. The average annual precipitation at Lind is 242 mm and at Ritzville is 290 mm. The soil at both locations is silt loam, but the Lind site contains more sand (34 vs. 30%) and less clay (9 vs. 11%). The mean size of the primary soil particles is 31 μm at Lind and 26 μm at Ritzville. The soil type at Lind is a Shano silt loam (a coarse-silty, mixed, superactive, mesic Xeric Haplocambid), and at Ritzville it is a Ritzville silt loam (a coarse-silty, mixed, superactive, mesic Calcic Haploxeroll according to U.S. soil taxonomy). Soils at both sites are >1.8 m deep and contain no rocks or restrictive layers. The soil texture is uniform throughout the profile at both sites, and the slope is $<2\%$.

Crop Rotations

Wind erosion was assessed from WW-SF and winter wheat–camelina–summer fallow (WW-C-SF) rotations at Lind. These rotations were initiated in 2008, with each phase of the rotation present every year. The experimental design was a randomized complete block with four replications, and individual plots were 9 by 75 m. Winter wheat (in the WW-SF rotation) and camelina (in the WW-C-SF rotation) were harvested in July 2010 and 2011. The soil and residue remained undisturbed after harvest until the following April, when glyphosate herbicide [*N*-(phosphonomethyl) glycine] was applied to the standing stubble to control weeds. In mid-April, the soil was tilled and fertilized in a single pass using an undercutter sweep implement. The undercutter is a low-disturbance, non-inversion tillage implement with overlapping 0.8-m-wide sweep blades designed to slice below the soil surface at a depth of 130 mm. The purpose of tillage in fallow soils in the spring is to sever capillary pores to restrict liquid water movement toward the soil surface in order to retain seed-zone moisture during the hot, dry summer months (Papendick, 2004). The undercutter method has been identified and promoted as a best management method for conservation tillage in the WW-SF region of the Inland Pacific Northwest (Young and Schillinger, 2012). The soil was rodweeded, with an implement having a square bar that rotates below the soil surface and opposite to the direction of travel, in July before sowing winter wheat on 2 Sept. 2011 and 28 Aug. 2012. These operations currently represent the best management system for retaining maximum quantities of surface residue and clods for successful tillage-based WW-SF farming in the Inland Pacific Northwest (Papendick, 2004).

At Ritzville, wind erosion was assessed from WW-SF and winter wheat–saflflower–summer fallow (WW-S-SF) rotations. These rotations were established in 2009, with each phase of the rotation present every year. The experimental design was a randomized complete block with four replications, and individual plots were 9 by 150 m. Field operations at Ritzville were exactly the same as at Lind except that primary spring tillage and fertilization were performed in mid-May. Winter wheat in both the WW-SF and WW-S-SF rotations was sown into summer fallow on 8 Sept. 2011 and 11 Sept. 2012.

Wind Erosion Assessment

Wind erosion was assessed using a portable wind tunnel on 14 Sept. 2011 and 30 Aug. 2012 at Lind and on 20 Sept. 2011 and 11 Sept. 2012 at Ritzville. The soil is most vulnerable to erosion at this time in the rotation. Although wind erosion assessments were delayed 12 d after sowing wheat at both locations in 2011, no precipitation occurred during this time period. Wind erosion assessments at Lind were delayed 2 d after sowing wheat in 2012, during which time a 0.5-mm precipitation event resulted in the development of a very thin (<0.5 mm) and weak (<15 kPa) but perceivable soil crust.

The working section of the portable wind tunnel was 7.3 m long, 1.2 m tall, and 1.0 m wide. Wind was generated by a 1.4-m-diameter fan and was conditioned by passing through a diffuser, honeycomb screen, and grid assembly before entering 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 (Pietersma et al., 1996; Sharratt, 2007).

Horizontal sediment flux and PM10 concentrations were observed within the working section of the tunnel. Horizontal sediment flux was measured using a Bagnold-type slot sampler (Stetler et al., 1997) that caught sediment being transported by saltation and suspension within 0.75 m of the surface. The width of the opening of the sampler was adjusted to achieve isokinetic conditions across the face of the sampler at a free-stream wind speed of 15 m s⁻¹. This wind speed, which was maintained in the wind tunnel, typifies a sustained high wind event that occurs about once every 2 yr in the Columbia Plateau region (Wantz and Sinclair, 1981). Horizontal sediment flux is the mass of sediment moving across a vertical plane during a period of time and was determined as the ratio of sediment mass collected by the slot sampler to the sampling period and width of the sampler (~0.003 m). The PM10 concentrations were measured at a frequency of 1 Hz using factory-calibrated aerosol monitors (DustTrak, TSI Inc.). Monitor inlets were mounted at heights of 0.04, 0.06, 0.09, 0.15, 0.30, and 0.60 m above the surface. These inlets were constructed of stainless steel tubing with a diameter of 2 mm to achieve isokinetic sampling of PM10 at a height of 0.2 m within the wind tunnel. Aerosol monitor inlets at greater heights would underestimate PM10 concentrations, while monitor inlets at lower heights would overestimate PM10 concentrations. No adjustments were made to account for differences in the sampling efficiency of the monitors with height. The background PM10 concentration was measured at the leading edge of the working section of the tunnel. Pitot tubes were mounted adjacent to and at heights corresponding to the aerosol monitor inlets to measure the wind speed. Ambient air temperature, relative humidity, and atmospheric pressure were measured at a height of 1.5 m outside the wind tunnel to aid in computing the wind speed.

Horizontal sediment flux and PM10 concentrations were measured during two subsequent sampling periods in each experimental plot. The first sampling period represented field conditions with limited saltation. To avoid exceeding the aerosol monitor capabilities at startup, a free-stream wind speed was maintained at 10 m s⁻¹ for the first 3 min and then at 15 m s⁻¹ for the last 7 min of the first sampling period. The lower wind speed at startup allowed the removal of perched particles from the soil surface. The second sampling period, which lasted 7 min, was characterized by a free-stream wind speed of 15 m s⁻¹ and field conditions with active saltation. Saltation activity that mimics field conditions was achieved by introducing an abraded (quartz sand 250–500 µm in diameter) into the air stream at the leading edge of the working section at a rate of 0.5 g m⁻¹ s⁻¹. This abraded rate is representative of soil flux during extreme high winds on the Columbia Plateau (Sharratt et al., 2007). Without the introduction of abraded into the air stream, emissions would be negligible during the second period.

Aerodynamic Parameters and Flux of Particles ≤10 Micrometers

Wind speed and PM10 concentrations were measured within and above the boundary layer and parallel to and between crop rows. It was assumed that wind speed in the internal boundary layer was fully adjusted to the surface, and a logarithmic relationship was applied to wind speed and height according to Campbell and Norman (1998):

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

where $U(z)$ is the mean wind speed (m s⁻¹) at height z (m), k is the von Karman constant (0.4), u^* is the friction velocity (m s⁻¹), and z_0 is a roughness parameter (m). Friction velocity and z_0 were determined by plotting the natural log of (z) against $U(z)$. To determine u^* , three to four heights within the boundary layer were used for best-fit linear regression. A high degree of linearity ($R^2 > 0.95$) ensured that measurements were made in the boundary layer.

Vertical PM10 flux represents the mass of PM10 transported vertically into the atmosphere. Vertical flux is directly proportional to u^* and is calculated as (Gillette, 1977)

$$\text{PM10}_{\text{vf}} = \frac{ku^* dC}{\ln(dz)} \quad [2]$$

where PM10_{vf} is the vertical flux of PM10 (g m⁻² s⁻¹) and C is the PM10 concentration above the background concentration (g m⁻³). Vertical flux was determined by plotting C vs. $\ln(z)$ to generate a linear trend, the slope of which represents $dC/\ln(dz)$.

Horizontal PM10 flux was calculated according to Sharratt et al. (2010) as

$$\text{PM10}_{\text{hf}} = \int C u dz \quad [3]$$

where PM10_{hf} is the horizontal PM10 flux (g m⁻² s⁻¹), and the integral is evaluated from the surface to the height at which PM10 concentrations reached background concentrations.

Statistical Analysis

Analysis of variance was used to determine whether differences in horizontal sediment flux, PM10_{vf} and PM10_{hf} existed among crop rotations. Horizontal sediment flux, PM10_{vf} and PM10_{hf} collected at Lind in 2011 and at Ritzville in 2012 required transformation before analysis due to heterogeneity of variance. In the event of finding differences in sediment flux, PM10_{vf} and PM10_{hf} among rotational treatments, least significant difference was used to compare means of treatments at $P < 0.10$.

RESULTS AND DISCUSSION

The loessial soils in the low-precipitation zone of the Columbia Plateau are susceptible to wind erosion due to their relatively fine soil particle size composition, low crop biomass production, and tillage practices that degrade soil aggregates and bury surface crop residues. These soils contain a high percentage of fine particles, with PM10 and silt contents as high as 40 and 65%, respectively (Sharratt and Vaddella, 2012). Wind erosion was assessed after sowing winter wheat when the soil is most vulnerable to erosion.

Wind speed increased and PM10 concentration decreased exponentially with height inside the wind tunnel during our assessment of wind erosion. Differences were apparent in the wind speed and PM10 concentration profiles between the rotational treatments, as illustrated for the mean of four

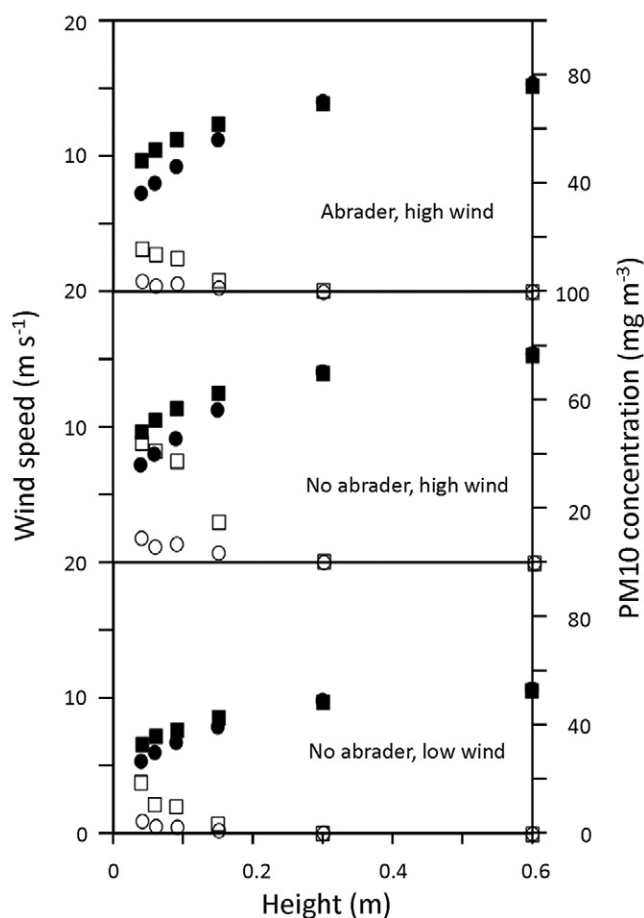


Fig. 2. Wind speed (solid symbols) and particles $\leq 10 \mu\text{m}$ in aerodynamic diameter (PM10) concentration (open symbols) measured at various heights inside a wind tunnel after sowing winter wheat into a winter wheat–summer fallow (circles) and winter wheat–camelina–summer fallow rotation (squares) at Lind, WA, in 2011. Wind speed and PM10 concentration were measured during two subsequent sampling periods—the first period with initially low wind speed followed by high wind speed under conditions of limited saltation (no abrader added to the air stream) and the second period with high wind speed under conditions of copious saltation (abrader added to the air stream).

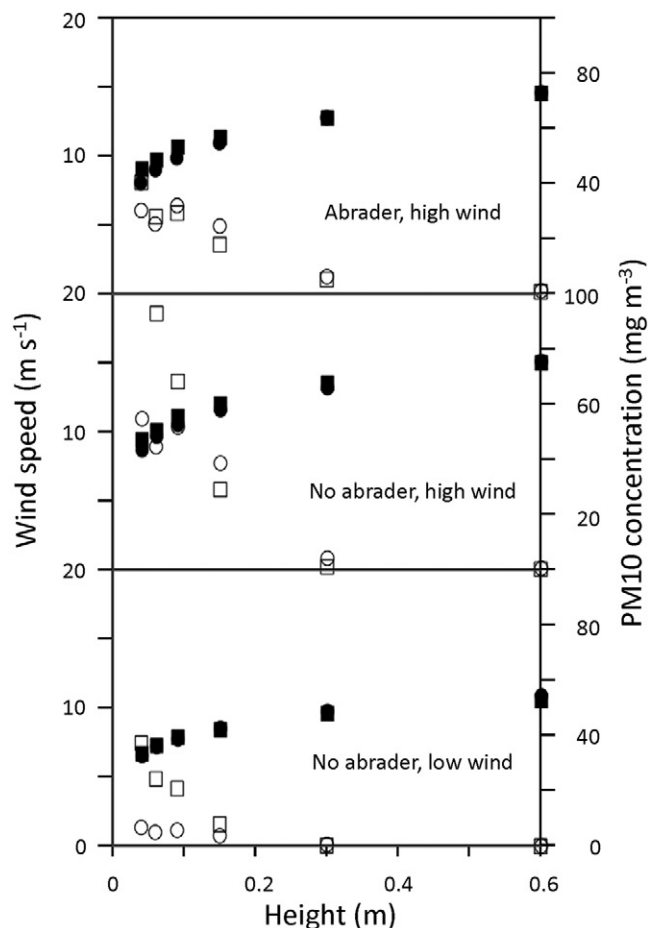


Fig. 3. Wind speed (solid symbols) and particles $\leq 10 \mu\text{m}$ in aerodynamic diameter (PM10) concentration (open symbols) measured at various heights inside a wind tunnel after sowing winter wheat into a winter wheat–summer fallow (circles) and winter wheat–safflower–summer fallow rotation (squares) at Ritzville, WA, in 2011. Wind speed and PM10 concentration were measured during two subsequent sampling periods—the first period with initially low wind speed followed by high wind speed under conditions of limited saltation (no abrader added to the air stream) and the second period with high wind speed under conditions of copious saltation (abrader added to the air stream).

Table 1. Horizontal sediment flux measured after sowing winter wheat into the summer fallow of winter wheat–summer fallow and winter wheat–camelina–summer fallow rotations at Lind, WA, and winter wheat–summer fallow and winter wheat–safflower–summer fallow rotations at Ritzville, WA.

		Sediment flux†			
Location	Year	Without abrader		With abrader	
		Wheat	Oilseed‡	Wheat	Oilseed
		g m ⁻¹ min ⁻¹			
Lind	2011	75 a§	256 b	62 a	146 b
	2012	340 a	804 b	281 a	587 a
Ritzville	2011	376 a	778 b	311 a	569 b
	2012	338 a	615 a	196 a	653 b

† Horizontal sediment flux measured during two consecutive 10-min sampling periods, the first period without abrader and the second period with abrader added to the air stream.

‡ Oilseed at Lind was camelina and at Ritzville was safflower.

§ No abrader or abrader means followed by the same letter for the same location and year are not significantly different at $P = 0.10$.

Table 2. Horizontal flux of particles $\leq 10 \mu\text{m}$ (PM10) measured after sowing winter wheat into the summer fallow of winter wheat–summer fallow and winter wheat–camelina–summer fallow rotations at Lind, WA, and winter wheat–summer fallow and winter wheat–safflower–summer fallow rotations at Ritzville, WA.

Location	Year	PM10 flux†			
		Without abrader		With abrader	
		Wheat	Oilseed‡	Wheat	Oilseed
g m⁻¹ min⁻¹					
Lind	2011	0.91 a§	3.06 b	0.49 a	1.73 b
	2012	3.50 a	13.30 b	2.49 a	6.97 b
Ritzville	2011	4.19 a	10.29 b	3.80 a	5.15 a
	2012	5.80 a	6.01 a	0.66 a	1.57 b

† Horizontal PM10 flux measured during two consecutive 10-min sampling periods, the first period without abrader and the second period with abrader added to the air stream.

‡ Oilseed at Lind was camelina and at Ritzville was safflower.

§ No abrader or abrader means followed by the same letter for the same location and year are not significantly different at $P = 0.10$.

Table 3. Ratio of horizontal flux of particles $\leq 10 \mu\text{m}$ (PM10) to sediment flux measured after sowing winter wheat into summer fallow of a winter wheat–summer fallow and winter wheat–camelina–summer fallow rotation at Lind, Washington and a winter wheat–summer fallow and winter wheat–safflower–summer fallow rotation at Ritzville, Washington.

Location	Year	Ratio†			
		Without abrader		With abrader	
		Wheat	Oilseed‡	Wheat	Oilseed
Lind	2011	0.018 a§	0.019 a	0.009 a	0.014 a
	2012	0.011 a	0.018 a	0.010 a	0.014 a
Ritzville	2011	0.010 a	0.013 a	0.014 a	0.009 a
	2012	0.009 a	0.014 a	0.013 a	0.009 a

† Ratio of horizontal PM10 flux to sediment flux measured during two consecutive 10-min sampling periods, the first period without abrader and the second period with abrader added to the air stream.

‡ Oilseed at Lind was camelina and at Ritzville was safflower.

§ No abrader or abrader means followed by the same letter for the same location and year are not significantly different at $P = 0.10$.

replications of the WW-SF and WW-C-SF rotations at Lind (Fig. 2) and of the WW-SF and WW-S-SF rotations at Ritzville in 2011 (Fig. 3). Differences in wind speed and PM10 concentration between rotational treatments were most apparent below a height of 0.3 m; little difference was observed in wind speed and PM10 concentration between treatments at heights of ≥ 0.3 m above the soil surface.

Horizontal sediment flux at Lind appeared to be greater in 2012 than 2011 (Table 1), even though a thin and weak soil crust was present in 2012. This crust developed as a result of a 0.5-mm precipitation event that occurred on the day of sowing. The lower sediment flux in 2011 was probably due to the emergence of wheat seedlings before our assessment of wind erosion in 2011. The first leaf of the emerging wheat seedlings was 100 mm tall, with a leaf area index of $0.02 \text{ m}^2 \text{ m}^{-2}$, when we assessed erosion at Lind in 2011. Potential differences in other soil properties and surface characteristics, such as aggregate size distribution and crop residue cover, could also have influenced the sediment flux at Lind in 2011 and 2012. The sediment flux at Ritzville was similar in 2011 and 2012.

The horizontal sediment flux was higher after sowing wheat into summer fallow in the WW-C-SF and WW-S-SF rotations than the WW-SF rotation in 2011. Although similar results were obtained in 2012, sediment flux did not differ between treatments under conditions of limited saltation (without abrader) at Ritzville and under conditions of copious saltation (with abrader) at Lind (Table 1). In 2011, the sediment flux

under conditions of limited and copious saltation was 135 to 241% greater for the WW-C-SF rotation and 83 to 107% greater for the WW-S-SF rotation than the WW-SF rotation. In 2012, the sediment flux was 0 to 136% greater for the WW-C-SF rotation and 0 to 233% greater for the WW-S-SF rotation than the WW-SF rotation.

Similar to the horizontal sediment flux, $\text{PM}_{10\text{hf}}$ was generally higher from the WW-C-SF and WW-S-SF rotations than from the WW-SF rotation (Table 2). In 2011, $\text{PM}_{10\text{hf}}$ under conditions of limited and copious saltation was 236 to 253% greater from the WW-C-SF rotation and 0 to 146% greater from the WW-S-SF rotation than the WW-SF rotation. In 2012, $\text{PM}_{10\text{hf}}$ was 180 to 280% greater from the WW-C-SF rotation and 0 to 138% greater from the WW-S-SF rotation than from the WW-SF rotation.

The ratio of $\text{PM}_{10\text{hf}}$ to horizontal sediment flux did not differ between rotational treatments at either location in 2011 or 2012 (Table 3). This ratio, which was determined to identify treatments with eroded sediment enriched in PM10, varied from 0.009 to 0.019 across treatments. These ratios are similar to those previously reported for various tillage management practices at Lind. For example, Sharratt et al. (2010) found that the ratio of $\text{PM}_{10\text{hf}}$ to sediment flux varied from 0.006 to 0.226 across a range of tillage practices during the summer fallow phase of a WW-SF rotation. The lack of response in the ratio of $\text{PM}_{10\text{hf}}$ to sediment flux among the crop rotations examined in this study suggests that growing oilseeds in wheat-based crop rotations has no effect on the aggregation of the small particle size ($\leq 10\text{-}\mu\text{m}$) fraction. However, an oilseed crop grown in wheat-based rotations did influence the mass of material on the soil surface susceptible to erosion. The greater susceptibility of the WW-C-SF and WW-S-SF rotations to wind erosion and PM10 emissions is probably due to greater exposure of the soil surface to the forces of wind than the WW-SF rotation, as has been documented for various cropping and tillage systems around the world (Leys and Heinjus, 1992; Bilbro and Fryrear, 1994; Mendez and Buschiazzi, 2010).

Friction velocity and z_0 tended to be greater for the WW-SF rotation than the WW-C-SF and WW-S-SF rotations (Table 4). Differences in u^* and z_0 among the rotational treatments were significant under conditions of both limited and copious saltation at Lind but only in 2011. These differences are indicative of an aerodynamically rougher surface for the WW-SF rotation than the WW-C-SF rotation. Differences in u^*

Table 4. Vertical flux of particles $\leq 10 \mu\text{m}$ (PM10), friction velocity (u^*) and aerodynamic roughness (z_0) measured after sowing winter wheat into summer fallow of a winter wheat–summer fallow and winter wheat–camelina–summer fallow rotation at Lind, Washington and a winter wheat–summer fallow and winter wheat–safflower–summer fallow rotation at Ritzville, Washington.

Location	Year	PM10 flux†				u^* ‡				z_0 ‡			
		Without abrader		With abrader		Without abrader		With abrader		Without abrader		With abrader	
		Wheat	Oilseed§	Wheat	Oilseed	Wheat	Oilseed	Wheat	Oilseed	Wheat	Oilseed	Wheat	Oilseed
		$\text{g m}^{-2} \text{ min}^{-1}$				m s^{-1}				m			
Lind	2011	0.11 a¶	0.36 a	0.09 a	0.26 a	0.96 a	0.82 b	1.00 a	0.76 b	0.002 a	0.0004 b	0.002 a	0.0003 b
	2012	1.11 a	6.71 b	0.97 a	4.20 b	0.89 a	0.86 a	0.96 a	0.86 b	0.0005 a	0.0005 a	0.0008 a	0.0006 a
Ritzville	2011	0.80 a	3.13 b	0.64 a	1.81 b	0.91 a	0.82 a	0.89 a	0.77 b	0.001 a	0.0005 b	0.001 a	0.0004 a
	2012	0.40 a	1.89 a	0.22 a	0.86 a	0.91 a	0.74 a	1.01 a	0.76 a	0.002 a	0.0006 a	0.002a	0.001 a

† Vertical PM10 flux measured during two consecutive 10-min sampling periods, the first period without abrader and the second period with abrader added to the air stream.

‡ u^* and z_0 at a free-stream wind speed of 15 m s^{-1} .

§ Oilseed at Lind was camelina and at Ritzville was safflower.

¶ No abrader or abrader means followed by the same letter for the same location and year are not significantly different at $P = 0.10$.

and z_0 also suggest an aerodynamically rougher surface for the WW-SF rotation than the WW-S-SF rotation at Ritzville but only in 2011. The $PM_{10_{vf}}$ under conditions of both limited and copious saltation was greater from the WW-C-SF rotation than the WW-SF rotation at Lind in 2012 and from the WW-S-SF rotation than the WW-SF rotation at Ritzville in 2011 (Table 4). The $PM_{10_{vf}}$ from the oilseed rotations was 0 to 504% greater than from the WW-SF rotation under conditions of limited saltation and 0 to 333% greater than from the WW-SF rotation under conditions of copious saltation across years. Although $PM_{10_{vf}}$ tended to be greater from the oilseed rotation at Lind in 2011 and at Ritzville in 2012, differences in $PM_{10_{vf}}$ were not statistically significant. The $PM_{10_{vf}}$ was compared with the horizontal sediment flux to assess the production rate of PM_{10} generated by the horizontal movement of sediment near the soil surface. No differences were found in the ratio of $PM_{10_{vf}}$ to horizontal sediment flux among rotational treatments, with the ratio ranging from 1×10^{-3} to 8×10^{-3} across all sites, treatments, and years. These ratios are similar to those found in field-scale studies conducted on the Columbia Plateau (Sharratt and Feng, 2009) and in Texas (Gillette, 1977). For example, Sharratt and Feng (2009) reported $PM_{10_{vf}}$ to horizontal sediment flux ratios of 1×10^{-3} to 3×10^{-3} , while Gillette (1977) observed ratios of vertical flux of 20- μm particles to horizontal sediment flux ranging from 5×10^{-1} to 1×10^{-5} .

Wind erosion and PM_{10} emissions from soils are governed by soil surface characteristics and properties during high wind events (Sharratt et al., 2012). Differences in horizontal sediment flux, $PM_{10_{hf}}$ and $PM_{10_{vf}}$ among the rotational treatments in this study were therefore a result of dissimilarities in soil surface characteristics and properties among treatments. Greater exposure of the soil surface to the forces of wind or increased erodibility of the soil caused by, for example, drying or aggregate breakdown, can enhance the flux of sediment and PM_{10} from soils. Future investigations will examine the influence of oilseeds in wheat-based crop rotations on soil characteristics and properties governing wind erosion.

CONCLUSIONS

Sediment and PM_{10} flux were greater after sowing winter wheat in the WW-C-SF and WW-S-SF rotations than the WW-SF rotation traditionally practiced in eastern Washington. Therefore, farmers must be cognizant in protecting the soil from wind erosion during the fallow phase of WW-C-SF and WW-S-SF rotations. While we measured sediment and PM_{10} flux during the time period when the soil is most susceptible to wind erosion, the soil is also susceptible to erosion at other times during the fallow phase of the rotations. Therefore, to determine the overall impact of growing oilseeds in wheat-based rotations on wind erosion and PM_{10} emissions, an assessment is required of the life cycle of emissions during the entire fallow phase of each rotation. The less frequent occurrence of fallow (i.e., once every 3 yr) in the WW-C-SF and WW-S-SF rotations may compensate for higher emissions than the WW-SF rotation, where fallow is present every other year.

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