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Wind erosion and PM10 emission affected by tillage systems in the world's driest rainfed wheat region

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ABSTRACT

The Horse Heaven Hills of south-central Washington is the driest rainfed wheat growing region in the world. Low precipitation, high winds, poorly aggregated soils, sparse residue cover, and a tillage-based winter wheat (*Triticum aestivum* L.) – summer fallow (WW-SF) cropping system often combine to create soil surfaces which are susceptible to wind erosion. No-tillage summer fallow (NTF) and conservation tillage fallow (CTF) with an undercutter sweep implement were examined as alternative practices to traditional tillage fallow (TTF) with a tandem disk implement for reducing wind erosion and PM10 (particulate matter ≤10 μm in aerodynamic diameter) emissions during the fallow phase of the WW-SF rotation. Wind erosion and PM10 emissions were assessed with a wind tunnel after primary spring tillage in mid-to-late April and after sowing winter wheat in August. Sediment loss and PM10 vertical flux and loss were generally less for NTF than with TTF, likely due to retention of surface residue and maintaining a soil crust in NTF. Sediment and PM10 loss increased after sowing wheat in both the TTF and CTF treatments. Although NTF abated the loss of sediment and PM0 compared with TTF, NTF is not yet an economical option for most growers in the region. Conservation tillage fallow using the undercutter sweep is an economically viable alternative to TTF for reducing windblown sediment and PM10 loss from agricultural soils in the Horse Heaven Hills.

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1. Introduction

High winds, poorly aggregated soils, low biomass production, tillage-based summer fallow, and extended time periods without precipitation promote wind erosion of agricultural lands in the Columbia Plateau region of the US Pacific Northwest. Wind erosion impacts air quality in this region due to the emission of fine sediment or dust into the atmosphere during high winds. The sediment-laden air sometimes forces road closures due to zero visibility and is enriched in PM10 (particulate matter ≤10 μm in aerodynamic diameter), an air pollutant that adversely affects human health (Dockery and Pope, 1994; Paden, 2001). Based on the linkage between high PM10 concentration and respiratory ailments, air quality standards have been set for PM10 (USEPA, 2006). PM10 represents the chemically active portion of soil and has the potential to transport heavy metals, pesticides, and microbes (Garrison et al., 2003; Whicker et al., 2006). In addition, PM10 can also transport nutrients and organic matter that will affect soil productivity (Van Pelt and Zobeck, 2007). Zhang et al. (2003) suggested that fine particulates represent the most fertile part of the soil resource.

Wind erosion has long been a problem in the western United States. In the drier (<300 mm annual precipitation) zone of the Inland Pacific Northwest, where rainfed winter wheat is produced every other year on land managed in a WW-SF rotation, controlling wind erosion to maintain air quality is a major challenge for growers (Saxton et al., 2000). Wind erosion, mainly occurring from March through October, is a major cause of soil loss and also significantly degrades air quality.

Low precipitation, with the majority of precipitation occurring in winter, necessitates the use of summer fallow to store a portion of over-winter precipitation in the soil for successful establishment and profitable production of winter wheat. Average annual precipitation in the Horse Heaven Hills of south-central Washington, where 120,000 hectares is devoted to WW-SF production, ranges from a high of 200 mm in the east to a low of 150 mm in the west (Fig. 1). The western portion of the Horse Heaven Hills is considered the driest rainfed wheat producing region in the world (Schillinger and Young, 2004).

Summer fallow is necessary for profitable wheat production compared to alternate management practices such as no-tillage annual cropping in the low precipitation zone of the Inland Pacific

Abbreviations: CTF, conservation tillage fallow; NTF, no-tillage fallow; TTF, traditional tillage fallow; WW-SF, winter wheat-summer fallow.

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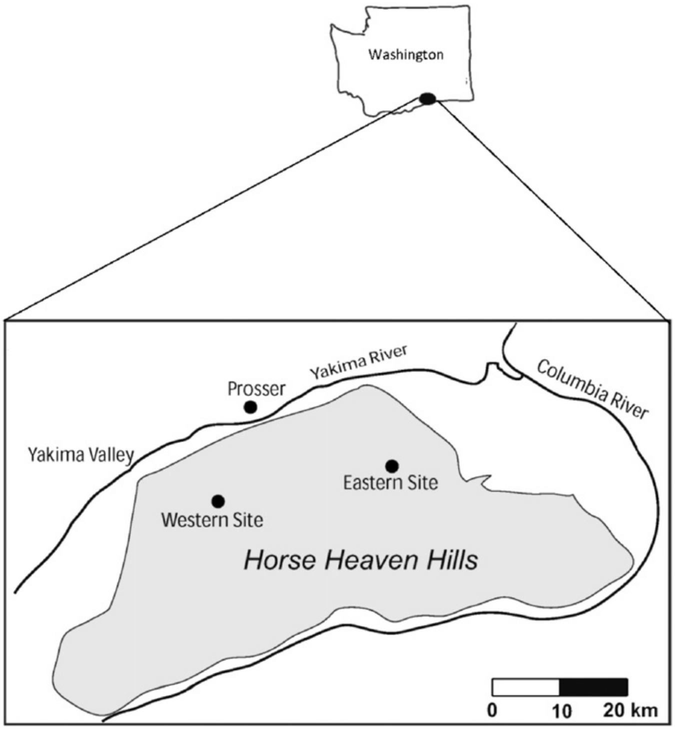

Fig. 1. Location of the Eastern and Western field sites in the Horse Heaven Hills of Washington.

Northwest (Schillinger and Young, 2004). During the summer fallow phase of the rotation, growers do not typically disturb the standing wheat stubble that remains after grain harvest in July until April or May when primary spring tillage is conducted with a tandem disk, duck-foot cultivators, or undercutter sweeps. The tandem disk and cultivator partially invert the soil and bury considerable wheat residue whereas the undercutter sweep slices below the surface and lifts the soil with minimal residue burial. The purpose of primary spring tillage is to break soil capillary continuity by creating a loose, dry surface layer to retard evaporation of stored soil water during the dry summer months (Papendick et al., 1973; Lindstrom et al., 1974; Hammel et al., 1981). Weeds are controlled during late spring and summer with a rodweeder which consists of a square bar that rotates under the soil surface in the opposite direction of travel to uproot weeds. If adequate seed-zone water is available, growers sow winter wheat into moist sub-soil with deep-furrow drills in mid-to-late August. Timely winter wheat emergence through the loose, dry surface layer (generally >10 cm thick) is extremely important because grain yield is reduced by 30% or more when sowing is delayed until the onset of rains in mid October or November (Donaldson et al., 2001). No-tillage summer fallow is not widely practiced in the Horse Heaven Hills because soil drying occurs to a deeper depth compared with tilled fallow (Singh et al., 2011; Hammel et al., 1981) which does not allow sowing winter wheat into sub-surface soil moisture.

Despite the advantage of using tillage to conserve soil water, multiple tillage operations degrade soil aggregates and expose the soil to high winds. Tillage not only degrades the soil, but also reduces residue cover (Wagner and Nelson, 1995) and surface roughness (Römkens and Wang, 1986; Zobeck and Onstad, 1987). Residue cover and surface roughness affect the wind speed at the surface; an increase in cover or roughness reduces wind erosion (Fryrear, 1984, 1985; Horning et al., 1998). Alternate tillage practices are therefore sought that will enhance residue cover as well as surface roughness of soils during summer fallow in the Columbia Plateau. No-tillage summer fallow and CTF using the undercutter sweep method are two alternate practices that may enhance residue cover and surface roughness and reduce wind erosion. With NTF, herbicides are used to control weeds and thus retain residue and soil structure throughout the fallow period. Conservation tillage minimizes soil inversion by using wide-blade sweeps to undercut the soil. Sharratt and Feng (2009) found that CTF with the undercutter reduces wind erosion and PM10 emissions by as much as 70% as compared with TTF in eastern Washington where annual precipitation is >200 mm.

The objective of this study was to determine the effectiveness of alternative tillage practices in reducing wind erosion and dust emissions from soils during the summer fallow phase of a WW-SF rotation in the Horse Heaven Hills of south-central Washington. Of particular interest was comparing erosion and PM10 emissions from NTF, CTF, and TTF practices.

2. Materials and methods

The potential for wind erosion and PM10 emissions was assessed in 2007 on land owned and operated by two wheat growers located in the eastern and western portions of the Horse Heaven Hills (Fig. 1). The crop rotation practiced by both growers was WW-SF. The fallow phase of the rotation began after wheat harvest in July 2006 and continued until sowing winter wheat in August 2007.

The distance between the two sites was 30 km. The sites were characterized by a slope of <2% and soil depth of >1.5 m. Average annual precipitation is about 200 mm at the Eastern site and 165 mm at the Western site. The soil at the Eastern site (46°08′N, 119°28′W and elevation of 440 m) is a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) consisting of 33, 54, 13% sand, silt, and clay and at the Western site (45°59′N, 119°51′W and elevation of 240 m) a Warden silt loam (coarse-silty mixed, superactive, mesic Xeric Haplocambid) (Rasmussen, 1971) consisting of 36, 50, 14% sand, silt, and clay.

2.1. Tillage treatments

Traditional tillage fallow, CTF, and NTF treatments were established in 2007 at both the Eastern and Western sites. The design of the experiment was a randomized complete block with four replications. Individual plot size was 61 m × 18 m. For the TTF treatment, glyphosate [*N*-(phosphonomethyl) glycine] herbicide was applied in early April. The soil was disked to a depth of 13 cm on 18 April at the Eastern site and 9 April at the Western site. Liquid aqua NH_3–N fertilizer was injected with shanks spaced 30 cm apart in June. The soil was subsequently rodweeded at a depth 10 cm in June and July at the Eastern site and June and early August at the Western site. For the CTF treatment, glyphosate herbicide was applied in April. The plots were undercut and fertilized with aqua NH_3–N to a depth of 13 cm in one pass with overlapping 0.7-m-wide V-blades on 18 April at the Eastern site and 9 April at the Western site. The soil was rodweeded to a depth of 10 cm in June and July at the Eastern site and June and early August at the Western site. In the NTF treatment, the soil remained undisturbed throughout the 13-month fallow period. Weeds in NTF were controlled with application of glyphosate herbicide in April and June at the Eastern site and April and July at the Western site.

One-half of the TTF and CTF plots were sown to winter wheat on 11 August and 23 August at the Eastern and Western sites, respectively. The purpose of sowing one-half of the plots was to simulate two scenarios that typically occur when sowing winter wheat in the Horse Heaven Hills. In years with adequate seed-zone water, growers sow winter wheat in mid-to-late August to maximize grain yield. In years with insufficient seed-zone water, sowing is delayed until the arrival of autumn rains in mid October or November. In NTF, wheat is sown at a shallow depth (i.e. 2 cm) after the arrival of autumn rains. Since wind erosion and PM10 emissions are not a concern after the arrival of autumn rains, an assessment of erosion and emissions was not made any later than after sowing the TTF and CTF treatments to wheat in August.

2.2. Wind tunnel

A portable wind tunnel was used to assess the potential for wind erosion and PM10 emissions from treatments. The wind tunnel is 13.4 m long with the working section dimension of 7.3 m × 1.2 m × 1.0 m. A 1.4 m diameter fan was used to generate the desired wind speed. Wind was 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). Wind erosion and PM10 emissions from TTF, CTF, and NTF treatments were assessed with the wind tunnel beginning 23 April and 13 August at the Eastern site and 30 April and 27 August at the Western site. Erosion and emissions could not be assessed immediately after spring tillage at both sites due to rain. Rain occurred three days after tillage (21 April) at the Eastern site and 5 and 13 days after tillage (14 and 22 April) at the Western site.

Sediment and PM10 fluxes were observed within the working section of the tunnel. Horizontal sediment flux was measured using a Bagnold-type slot sampler (Stetler et al., 1997). This sampler was used to catch sediment being transported by saltation and suspension within 0.75 m of the surface. The width of slot sampler is adjustable and therefore, isokinetic conditions can be achieved for a wide range of wind velocity. Prior to the field experiment, the slot sampler was calibrated for isokinetic conditions at a free-stream wind velocity of 15 m s^{-1}. This wind speed was chosen to represent a sustained high wind event that occurs about once every 2 years in the Columbia Plateau region (Wantz and Sinclair, 1981). Horizontal sediment flux is defined as the amount of sediment moving through a vertical plane over a period of time. The flux is determined as the ratio of sediment collected by the slot sampler to the sampling period and width of the sampler (~0.003 m). PM10 concentration was measured at heights of 4, 6, 9, 15, 30, and 60 cm above the surface using DustTrak aerosol monitors (TSI, St. Paul, MN). The DustTraks optically measured PM10 concentration at a frequency of 1 Hz and were factory calibrated prior to the field studies. The PM10 sampling inlets were constructed of stainless steel tubing with the inlets attached to the monitors using tygon tubing. The diameter of the inlet was adjusted to achieve isokinetic sampling of PM10 at a height of 0.2 m within the boundary layer. Aerosol monitors at greater heights would undersample PM10 concentrations while monitors at lower heights would oversample PM10 concentrations. No adjustments were made to account for differences in sampling efficiency of monitors with height in the boundary layer. At the leading edge of the working section, background PM10 concentration was measured using a DustTrak monitor. Pitot tubes were mounted adjacent to and at heights corresponding to aerosol monitor inlets to measure the wind speed. In addition, ambient air temperature, relative humidity, and atmospheric pressure were measured at a height of 1.5 m to aid in computing wind speed.

Free-stream wind velocities of ~15 m s^{-1} were sustained over two subsequent sampling periods in each treatment plot. Sediment flux and PM10 concentration were measured for the duration of each sampling period. The first sampling period represents field conditions with limited saltation. To avoid exceeding aerosol monitor capabilities at startup, treatments were subject to a free-stream wind velocity of ~10 m s^{-1} for the first 3 min of the first sampling period and then to a wind velocity of ~15 m s^{-1} for the last 7 min of the first sampling period. The lower wind velocity at startup allowed for the removal of perched particles from the soil surface. The second sampling period represents field conditions with active saltation. Saltation activity that mimics field conditions was achieved by introducing an abrader (quartz sand 250–500 μm in diameter) into the air stream at the leading edge of working section at a rate of 0.5 g m^{-1} s^{-1}. This abrader rate is representative of soil flux during extreme high winds in the Columbia Plateau (Sharratt et al., 2007).

In addition to measuring sediment flux and PM10 concentration, soil physical properties and surface characteristics of the tillage treatments were assessed adjacent to the wind tunnel in each plot to identify casual relations between wind erosion or PM10 emissions and soil attributes. Details of soil physical properties and surface characteristics measured at each site are not provided in this paper. For brevity, however, selected attributes measured included surface residue height, silhouette area index (SAI), soil water content, and soil crust thickness. Surface residue height and crust thickness were measured using a ruler or caliper. Silhouette area index was assessed from stem density, width, and height observed within multiple 0.25 m^2 areas in each plot. Soil volumetric water content in the 0- to 5-mm and 0- to 30-mm depth was determined by gravimetric sampling (Topp and Ferre, 2002).

2.3. PM10 flux

Wind speed and PM10 concentrations were measured within and above the boundary layer and perpendicular to wheat stubble rows in all treatments. 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 (Campbell and Norman, 1998):

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

where $U(z)$ is mean wind speed at height z (m s^{-1}), k is the von Karman constant (0.4), u^* is friction velocity (m s^{-1}), z_0 is roughness parameter (m), and d is zero plane displacement (m). Friction velocity and the roughness parameter were determined by plotting natural log of $(z - d)$ 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.

The fraction of PM10 transported vertically into the atmosphere represents vertical flux. Vertical flux is directly proportional to friction velocity and is calculated as (Gillette, 1977):

$$PM10_{vflux} = \frac{ku^* dC}{\ln(dz)} \quad (2)$$

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

PM10 loss was calculated as (Houser and Nickling, 2001):

$$PM10_{loss} = \frac{1}{L}\int_0^{z_b} Cu dz \quad (3)$$

where $PM10_{loss}$ is PM10 loss from the eroding surface (g m^{-2} s^{-1}), L is the length of eroding soil surface (m), z_b is height at which PM10 concentrations reached background concentrations (m), and u is wind speed at height z (m s^{-1}). Eq. (3) was evaluated by plotting horizontal PM10 flux (the product of C and u) as a function of height. PM10 loss was assessed by integrating Eq. (3) under the defined limits of the function.

2.4. Statistical analysis

Analysis of variance (ANOVA) was used to analyze differences in friction velocity, horizontal sediment flux, PM10 vertical flux, and PM10 loss of tillage treatments. Tukey's HSD test was used for comparisons between treatment means. Means were considered significantly different at $P < 0.10$.

3. Results and discussion

Our intention was to assess soil erosion and PM10 emissions immediately after tillage in spring and then after sowing winter wheat in the TTF and CTF treatments at both the Eastern and Western sites. However, rains occurring after primary spring tillage delayed this assessment. A 0.5 mm rain occurred 3 days after spring tillage at the Eastern site and a 5.1 and 0.3 mm rain, respectively, occurred 5 and 13 days after spring tillage at the Western site. Rainfall at both sites resulted in a soil crust during our wind tunnel campaign in spring. No rain occurred prior to assessing erosion and emissions after sowing winter wheat in the TTF and CTF treatments.

3.1. Friction velocity

Wind erosion is initiated when friction velocity exceeds the threshold friction velocity of a surface. Friction velocity is therefore an important parameter in assessing wind erosion. Friction velocity is in part governed by the roughness of a surface, thus friction velocity and aerodynamic roughness provide insight into aerodynamic properties of tillage systems examined in this study. Friction velocity and aerodynamic roughness were generated from profiles of wind speed (Fig. 2) at a free-stream wind velocity of ~15 m s^{-1} and are reported for the TTF, CTF, and NTF treatments in Table 1. Failure of data logging equipment resulted in no wind speed measurements at the Eastern site in summer. Friction velocity was generally higher for NTF than for TTF and CTF with friction velocities of NTF being >1 m s^{-1} and friction velocities of TTF and CTF being <1 m s^{-1} in spring at the Eastern site and in spring and summer at the Western site. Friction velocities of TTF and CTF were similar and varied from about 0.7 to 1.0 m s^{-1} across seasons, sowings, and sites. These values are higher than those observed in large-scale field studies conducted by Sharratt and Feng (2009) in the Columbia Plateau. They found that friction velocities ranged from 0.31 to 0.56 m s^{-1} for TTF and from 0.33 to 0.58 m s^{-1} for CTF. The higher friction velocities in this study may be due to rougher surface characteristics or a constricted boundary layer within the wind tunnel. For example, rougher surface characteristics are exemplified by taller crop residue height and greater SAI in this study with residue height and SAI of TTF and CTF treatments varying respectively from 0.04 to 0.16 m and 0.002 to 0.09 m^2 m^{-2} averaged across sites. In contrast, residue height and SAI of TTF and CTF varied respectively from 0.03 to 0.11 m and from 0.003 to 0.06 m^2 m^{-2} in the field study conducted by Sharratt and Feng (2009). Similarly, rougher surface characteristics are exemplified by greater surface random roughness in this study with values for TTF and CTF varying from 10 to 25 mm whereas random roughness for TTF and CTF varied from 8 to 12 mm in the field study conducted by Sharratt and Feng (2009). The aerodynamic roughness was an order of magnitude higher for NTF than for TTF and CTF at both the Eastern and Western sites. Aerodynamic roughness varied from 0.007 to 0.018 m for NTF and from 0.001 to 0.005 m for TTF and CTF across seasons, sowings, and sites (Table 1). Aerodynamic roughness of NTF generally conformed to parameterization of roughness of sparsely vegetated surfaces. For example, data of Hagen (1996) and Minivielle et al. (2003) indicate that aerodynamic roughness for a surface with a roughness density or SAI of 0.1 and stem height of 0.2 m (characteristic of NTF) is 0.01 m.

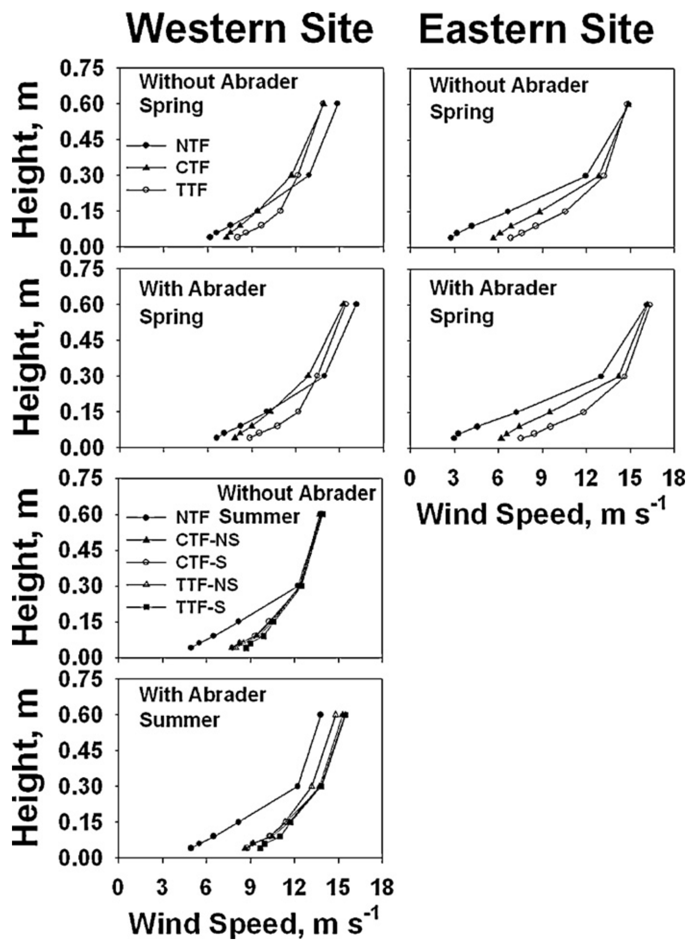

Fig. 2. Wind speed at various heights above the surface of no-tillage fallow (NTF), traditional tillage fallow (TTF), and conservation tillage fallow (CTF) in the spring and summer at the Western and Eastern sites in the Horse Heaven Hills of Washington. The TTF and CTF treatments remained undisturbed (NS) or were sown to winter wheat (S) in summer.

3.2. Sediment loss

Horizontal sediment flux and PM10 concentrations were measured under conditions of little and copious saltation in a wind tunnel. While saltation occurs to a limited extent in the loessial soils of the Columbia Plateau, suspension is the dominate process for the transport of sediment (Sharratt et al., 2007; Sharratt, 2011). Thus, sediment loss and PM10 vertical flux and loss are reported with and without abrader added to the airflow and which respectively represent a saltation-dominated and suspension-dominated transport process.

Sediment loss, or amount of saltating plus suspended sediment emitted from the wind tunnel, was similar under conditions of limited saltation for the three tillage treatments after spring tillage at the Western site (Table 2). Indeed, sediment loss ranged from 12 to 17 mg m^{-2} s^{-1} across the three treatments. Differences in sediment loss among treatments, however, were apparent under condition of copious saltation. Sediment loss for NTF and CTF was respectively 50 and 30% smaller than for TTF. The similarity in sediment loss among treatments under conditions of limited

Table 1
Friction velocity and aerodynamic roughness of no-tillage fallow (NTF), traditional tillage fallow (TTF), and conservation tillage fallow (CTF) measured with a wind tunnel in the presence or absence of abrader in spring and summer at two sites in the Horse Heaven Hills of Washington. The TTF and CTF treatments remained undisturbed (NS) or were sown to winter wheat (S) in summer.

Site	Season	Tillage	Friction velocity		Roughness	
			No abrader ($m\,s^{-1}$)	Abrader ($m\,s^{-1}$)	No abrader (m)	Abrader (m)
Western	Spring	NTF	1.26c[a]	1.31c	0.008c	0.007b
		TTF	0.84b	0.96bc	0.001b	0.001b
		CTF	0.66b	0.75b	0.001b	0.001b
	Summer	NTF	1.11b	1.30b	0.015c	0.015c
		TTF-NS	0.77b	0.89b	0.001b	0.001b
		TTF-S	0.71b	0.80b	0.002b	0.002b
		CTF-NS	0.85b	0.98b	0.001b	0.001b
		CTF-S	0.79b	0.87b	0.001b	0.001b
Eastern	Spring	NTF	1.11b	1.28b	0.017c	0.018c
		TTF	0.86b	1.00b	0.002b	0.003b
		CTF	0.82b	0.93b	0.005b	0.005b
	Summer	NTF	ND	ND	ND	ND
		TTF-NS	ND	ND	ND	ND
		TTF-S	ND	ND	ND	ND
		CTF-NS	ND	ND	ND	ND
		CTF-S	ND	ND	ND	ND

ND indicates no data due to failure of data logging equipment.
[a] No abrader or abrader means at the Western or Eastern site followed by the same letter within a given season are not significantly different at $P = 0.10$.

Table 2
Total sediment loss and the ratio of PM10 loss to sediment loss from no-tillage fallow (NTF), traditional tillage fallow (TTF), and conservation tillage fallow (CTF) measured in spring and summer at two sites in the Horse Heaven Hills of south-central Washington. The TTF and CTF treatments remained undisturbed (NS) or were sown to winter wheat (S) in summer.

Site	Season	Tillage	Total sediment loss		PM10 loss/total sediment loss	
			No abrader ($mg\,m^{-2}\,s^{-1}$)	Abrader ($mg\,m^{-2}\,s^{-1}$)	No abrader (%)	Abrader (%)
Western	Spring	NTF	12b[a]	167b	0.8	0.1
		TTF	17b	313c	0.7	0.3
		CTF	13b	218b	0.8	0.2
	Summer	NTF	21b	190b	1.9	0.3
		TTF-NS	43b	316bcd	0.7	0.3
		TTF-S	351c	363c	1.6	1.0
		CTF-NS	21b	227bc	1.3	0.3
		CTF-S	408c	437cd	0.8	0.5
Eastern	Spring	NTF	5b	132b	0.3	0.0
		TTF	64c	325c	1.2	0.6
		CTF	19b	137b	2.1	0.8
	Summer	NTF	17b	106b	0.3	0.1
		TTF-NS	109bc	340de	0.4	0.5
		TTF-S	325d	387e	0.7	0.5
		CTF-NS	81bc	225c	0.5	0.3
		CTF-S	144c	278cd	0.7	0.3

[a] No abrader or abrader means at the Western or Eastern site followed by the same letter within a given season are not significantly different at $P = 0.10$.

saltation illustrates the protective role of soil crust in suppressing particle emissions from soil. During the spring field campaign at the Western site, a <1 and 5 mm soil crust was respectively apparent in the TTF and CTF treatments. In contrast, a >50 mm soil crust was apparent in NTF due to limited disturbance to the soil surface during fallow. The larger difference in sediment loss between treatments under conditions of copious saltation in spring illustrates the fragility of the soil crust in the TTF and CTF treatments. Similar trends in sediment loss were observed at the Eastern site in spring, with loss from TTF being greater than loss from the CTF and NTF under conditions of limited and copious saltation.

Sediment loss after sowing wheat in the TTF and CTF treatments was greater from these treatments than from the NTF treatment at both sites. No differences were observed in sediment loss between TTF and CTF after sowing at the western site, but sediment loss was greater from TTF than CTF after sowing at the Eastern site. Sharratt et al. (2010) also reported greater sediment loss from TTF than CTF using the undercutter sweep method during high winds. Sowing wheat in August enhanced sediment loss from both TTF and CTF treatments because the deep-furrow drills cause considerable movement of surface soil that enables sowing wheat into subsurface moisture. Sediment loss as a result of the sowing operation increased by an order of magnitude at the Western site and by 100% at the Eastern site, at least under conditions of limited saltation.

3.3. PM10 vertical flux and loss

PM10 vertical flux and loss were determined from PM10 concentration profiles above the soil surface as illustrated in Fig. 3. In the spring, PM10 concentrations within 0.3 m of the soil surface were significantly higher for TTF compared to CTF under conditions of copious saltation. Under conditions of limited saltation, PM10 concentrations for TTF were also significantly higher than for NTF, but only at the Eastern site. In summer, PM10 concentrations were significantly lower in NTF compared to TTF under conditions of copious saltation. These differences in PM10 concentration were amplified after sowing wheat in the TTF treatment.

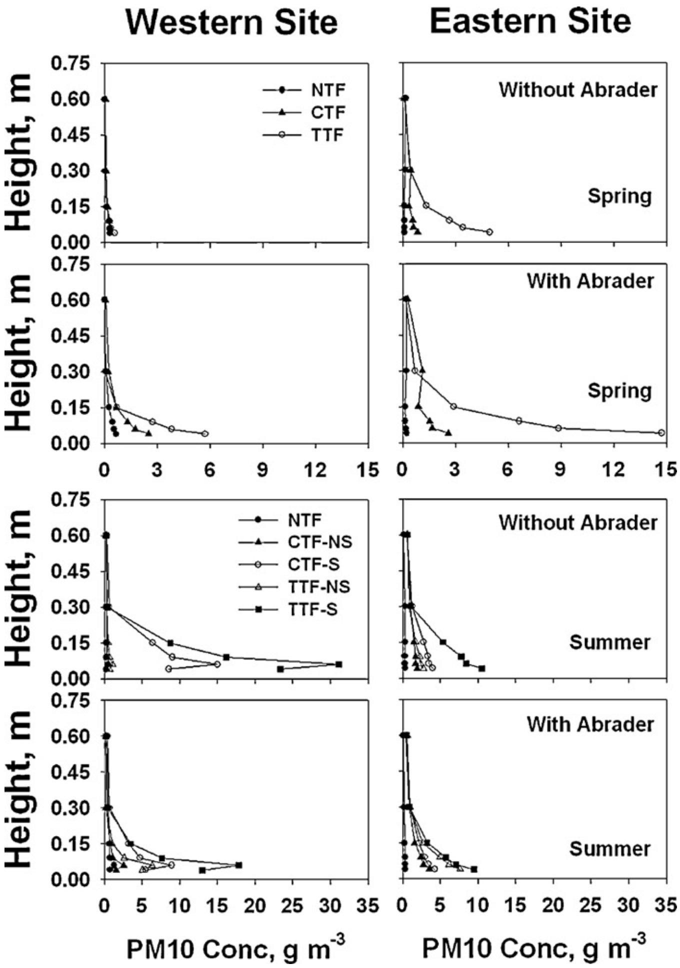

Fig. 3. PM10 concentration above the surface of no-tillage fallow (NTF), traditional tillage fallow (TTF), and conservation tillage fallow (CTF) in spring and summer at the Western and Eastern sites in the Horse Heaven Hills of Washington. The TTF and CTF treatments remained undisturbed (NS) or were sown to winter wheat (S) in summer.

Vertical PM10 flux ranged from 0.003 to 3.4 mg m^{-2} s^{-1} across tillage treatments, sites, and seasons (Table 3). Although the wind speed profile could not be ascertained after sowing wheat at the Eastern site due to data logger failure, vertical PM10 flux and loss were assessed using friction velocities and wind speeds obtained during spring. Friction velocity and aerodynamic roughness appeared to change little between spring and summer at the Western site (Table 1), thus similar results would be expected at the Eastern site. Vertical PM10 flux appeared to be higher for TTF than for CTF; these differences were significant in spring at the Eastern site and after sowing wheat at the Western site, the latter being a time when surface soils are particularly prone to wind erosion. Vertical flux was similar for NTF and CTF in spring and after sowing wheat at both sites. Sowing wheat appeared to enhance vertical PM10 flux and was most evident for the TTF treatment.

PM10 loss in spring ranged from 0.02 to 5.6 mg m^{-2} s^{-1} across treatments, seasons, and sites (Table 3). In spring, PM10 loss was higher from TTF than from NTF under conditions of copious saltation. Similar trends were apparent under conditions of limited saltation, although differences were only significant at the Eastern site. PM10 loss was greater in August than in spring. Sowing wheat appeared to amplify PM10 loss from the TTF and CTF treatments and was most evident at the Western site under conditions of limited saltation.

3.4. PM10 to sediment loss ratio

PM10 loss was compared to total sediment loss to identify tillage treatments in which the eroded sediment was enriched with fine particulate matter (i.e. PM10). The percentage of PM10 comprising total sediment loss is reported in Table 2. PM10 comprised from 0.04 to 2.1% of the total sediment loss across all treatments, seasons, and sites in this study. In the spring, the percent PM10 to total sediment loss was less than 1% under conditions of limited and copious saltation at the Western site. The percent PM10 to total sediment loss appeared to be higher in spring at the Eastern site as compared with the Western site, with percentages for the TTF and CTF treatments exceeding 1% under conditions of limited saltation. A thicker soil crust or aggregation of the fine particulate matter at the Western site may have suppressed fine particulate emissions as compared to the Eastern site in the spring. In August, PM10 comprised less than 2% of the sediment loss measured at both the Eastern and Western sites. Although no clear trends in the data can be distinguished, disturbing the soil by tillage or sowing wheat appeared to result in higher percentage loss of PM10. For example, TTF and CTF had a higher percentage of PM10 to sediment loss as compared with NTF

Table 3
PM10 loss and vertical flux from no-tillage fallow (NTF), traditional tillage fallow (TTF), and conservation tillage fallow (CTF) measured in spring and summer at two sites in the Horse Heaven Hills of Washington. The TTF and CTF treatments remained undisturbed (NS) or were sown to winter wheat (S) in summer.

Site	Season	Tillage	PM10 loss		Vertical PM10 flux	
			No abrader (mg m^{-2} s^{-1})	Abrader (mg m^{-2} s^{-1})	No abrader (mg m^{-2} s^{-1})	Abrader (mg m^{-2} s^{-1})
Western	Spring	NTF	0.097b[b]	0.159b	0.030b	0.120b
		TTF	0.115b	0.935c	0.121b	1.455c
		CTF	0.108b	0.505bc	0.034b	0.391bc
	Summer	NTF	0.394b	0.549b	0.058b	0.275b
		TTF-NS	0.298b	0.971bc	0.060b	0.855bc
		TTF-S	5.611d	3.490c	3.457c	2.743c
		CTF-NS	0.281b	0.593b	0.003b	0.258bc
		CTF-S	3.116c	2.068bc	0.871b	0.843bc
Eastern	Spring	NTF	0.016b	0.053b	0.014b	0.041b
		TTF	0.801c	1.838c	0.323c	1.377c
		CTF	0.394bc	1.081bc	0.087b	0.386bc
	Summer[a]	NTF	0.043b	0.114b	0.017b	0.051b
		TTF-NS	0.492bc	1.645ed	0.210b	1.327bc
		TTF-S	2.368d	2.007e	1.248c	2.027c
		CTF-NS	0.182bc	0.773bc	0.075b	0.396bc
		CTF-S	1.006c	0.940cd	0.324bc	0.532bc

[a] Values of PM10 loss and vertical PM10 flux were determined from measured wind speed data in spring.
[b] No abrader or abrader means at the Western or Eastern site followed by the same letter within a given season are not significantly different at $P = 0.10$.

in spring. In addition, sowing wheat in the TTF and CTF resulted in a higher percentage of PM10 to sediment loss under conditions of limited saltation at the Eastern site and copious saltation at the Western site. This suggests that disturbing the soil surface enriches the eroded sediment in PM10.

4. Conclusion

Sediment and PM10 loss measured under high winds were compared for three summer fallow management methods in the fallow phase of a WW-SF rotation in the Horse Heaven Hills of south-central Washington. Sediment and PM10 loss were enhanced by both primary spring tillage and sowing operations. Traditional tillage fallow with a tandem disk tended to have the highest sediment and PM10 loss while NTF resulted in the lowest loss. Although NTF can reduce sediment and PM10 loss, this method is not yet widely practiced in the region because accelerated loss of seed-zone water from NTF reduces the likelihood of sowing early to maximize grain yield. However, Singh et al. (2011) reported that NTF is likely a viable option for growers in the Western portion of the Horse Heaven Hills since adequate seed-zone water for August sowing of wheat cannot be achieved during most years even with tillage. Conservation tillage fallow using the undercutter sweep is much more desirable than TTF when early sowing can be successfully practiced. To reduce wind erosion and improve air quality in the region, agricultural management practices must be adopted that least disturb the soil during summer fallow while still allowing profitable wheat production.

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