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Soil properties influenced by summer fallow management in the Horse Heaven Hills of south central Washington

B. Sharratt and W.F. Schillinger

Abstract: The Horse Heaven Hills (HHH) is the world's driest rainfed wheat (*Triticum aestivum* L.) region where soils are highly susceptible to wind erosion due to use of tillage during the fallow phase of the winter wheat–summer fallow (WW-SF) cropping system. Wheat straw residue biomass and cover, surface roughness, soil water content and strength, and aggregate size distribution of no-tillage fallow (NTF), undercutter-tillage fallow (UTF), and traditional-tillage fallow (TTF) were measured after primary tillage of UTF and TTF in late April and after sowing winter wheat in late August of 2007 at two sites in the HHH. Residue cover and silhouette area index were at least two times greater and penetration resistance and shear stress were at least five times greater for NTF than TTF in spring and late summer at both sites. Random roughness was typically lower for NTF as compared with UTF in spring and late summer at both sites. Summer fallow treatments influenced soil aggregation whereby geometric mean diameter was greater and erodible fraction was lower for NTF than TTF. Based upon the Revised Wind Erosion Equation (RWEQ), sediment flux was lowest for NTF and at least 70% lower for UTF as compared with TTF. Thus, soil loss due to wind erosion can be reduced by using NTF and UTF rather than TTF for WW-SF rotations in the HHH.

Key words: aggregate size—crop residue—soil strength—tillage—wind erosion

Wind erosion of agricultural land is a concern in the Inland Pacific Northwest (PNW) United States due to its impact on the long-term sustainability of the soil resource and air quality. This concern is particularly acute in the Horse Heaven Hills (HHH) of south central Washington, which is considered the driest rainfed wheat (*Triticum aestivum* L.) producing region in the world (Schillinger and Young 2004). Annual precipitation in this region ranges from 150 to 215 mm (Rasmussen 1971). Fragile soils, low biomass production, tillage-based summer fallow, meager precipitation, and high winds contribute to wind erosion of agricultural land. Wind erosion causes the emission of fine particulate matter into the atmosphere, which degrades visibility and air quality in the region. Indeed, ambient concentration of particulate matter ≤10 μm in aerodynamic diameter (PM10) frequently exceed National Ambient Air Quality Standards due to windblown dust (Sharratt and Lauer 2006).

The dominant crop rotation practiced on 1.5 million ha in the low precipitation (<300 mm) zone of the PNW is winter wheat–summer fallow (WW-SF) where winter wheat is grown every other year. Wind erosion occurs primarily during the summer fallow phase of the rotation, which begins after wheat harvest in July and ends 13 to 15 months later when wheat is sown in late August (if adequate seed-zone moisture is available for deep-furrow sowing) or mid-October or later (date of sowing dependent on commencement of autumn rains). Wind erosion events primarily occur in spring and late summer when high winds coincide with partially denuded and disaggregated soil conditions that are a result of tillage and sowing operations. Indeed, the soil is exposed to the forces of wind initially after primary tillage in spring and after sowing winter wheat in late summer.

Tillage-based summer fallow has been a proven method for profitable winter wheat production compared to alternate management practices for more than a century in the low precipitation zone of the PNW. Annual spring crops (e.g., spring wheat) are generally not grown in the HHH as grain yields tend to be low and variable compared to WW-SF (Schillinger and Young 2004). In a WW-SF rotation, the land typically remains undisturbed after harvest until the following spring when primary tillage is performed with a tandem disk, field cultivator, or undercutter sweep implements. The tandem disk causes greater disturbance and buries more residue compared to the field cultivator. The undercutter sweep is a conservation tillage implement that does not invert the soil, resulting in minimal residue burial. Primary spring tillage is often critical to the success of establishing newly sown winter wheat in the low precipitation zone because tillage disrupts soil capillary continuity and thus liquid water flow to the soil surface, thereby minimizing evaporative loss during summer as compared with no-tillage fallow (NTF) (Papendick et al. 1973; Lindstrom et al. 1974; Hammel et al. 1981). After spring tillage and before sowing, weeds are controlled with one or two rodweeder operations. If adequate seed-zone moisture is available at the end of the fallow phase of the rotation in August, wheat is sown with deep-furrow drills. Establishment of winter wheat in late August or early September is extremely important because grain yield is reduced by 30% or more when sowing is delayed until the onset of rains in mid-October (Donaldson et al. 2001; Higginbotham et al. 2011).

Due to wind erosion and blowing dust associated with tillage-based fallow, NTF has become increasingly popular among many farmers, especially in the drier western portion of the HHH where adequate seed-zone moisture for wheat seed germination and seedling establishment is only rarely available in late-August (Schillinger and Young 2014). With NTF, weeds are controlled with herbicides and the only soil disturbance occurs during the winter wheat sowing operation. High-disturbance tillage operations on weakly structured soils degrade aggregates

Brenton Sharratt is a soil scientist with the USDA Agricultural Research Service, Pullman, Washington, and **William F. Schillinger** is a professor in the Department of Crop and Soil Sciences at Washington State University, Pullman, Washington.

(Hevia et al. 2007; Zobeck and Popham 1992), reduce residue cover (Wagner and Nelson 1995), and decrease surface roughness (Römkens and Wang 1986; Zobeck and Onstad 1987). Residue cover and surface roughness influence wind speed at the surface; wind speeds are lower over surfaces with greater residue cover or roughness (Fryrear 1984, 1985; Horning et al. 1998). Summer fallow practices in the HHH are therefore needed to enhance residue cover and surface roughness. At field sites with higher annual precipitation (220 to 250 mm) in the PNW, Sharratt and Feng (2009) found that undercutter-tillage fallow (UTF) reduced wind erosion and PM10 emissions by as much as 70% as compared with traditional-tillage fallow (TTF). They suggested UTF reduced wind erosion as a result of higher residue cover and more standing stubble as compared with TTF. Similarly, Sharratt et al. (2012) reported a decrease in wind erosion and PM10 emission from agricultural soils subject to lower tillage intensity or fewer tillage operations due to an increase in residue cover. While these and other studies (Kjelgaard et al. 2004; Sharratt et al. 2007; Stetler and Saxton 1996) focused on wind erosion in wetter areas (220 to 250 mm of annual precipitation) of the PNW, little is known concerning wind erosion in the HHH. The only known studies to assess wind erosion in the HHH were conducted by Saxton et al. (2000), who determined the relative erodibility of soils throughout the PNW, and Singh et al. (2012), who observed that sediment and PM10 flux were higher for TTF as opposed to UTF and NTF. Neither study, however, assessed the reason for differences in erodibility or emissions among soils or summer fallow treatments.

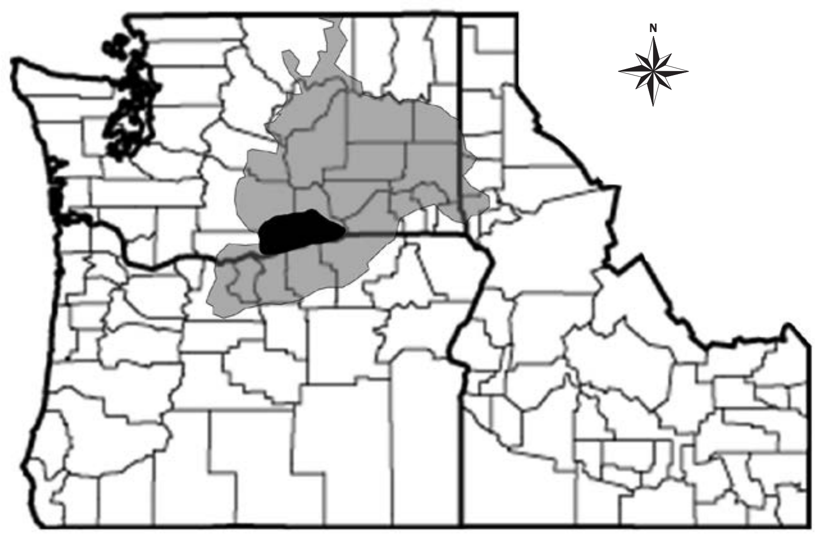
The objective of this study was to identify inherent crop residue and soil characteristics that govern differences in wind erosion and dust emissions of three tillage management methods imposed during the summer fallow phase of a WW-SF rotation in the HHH.

Materials and Methods

This study was conducted in the HHH of south central Washington (figure 1) where 120,000 ha are managed in a WW-SF rotation. Prevailing winds are from the southwest and can attain speeds over 18 m s^{-1} (Papendick 1998). Soil properties were assessed at two sites that were on the south-facing slope of an anticline located 15 km south of Prosser, Washington. Both sites

Figure 1

Location of Horse Heaven Hills (HHH) in the Pacific Northwest United States. The black shaded area is the HHH while the gray shaded area is the Columbia Plateau, which spans across Idaho, Oregon, and Washington.



had been in a traditional-tillage WW-SF rotation since farming began in the early 1880s. The Eastern site (46°08´ N, 119°28´ W and elevation of 440 m) is characterized by a Ritzville silt loam (coarse-silty, mixed, superactive, mesic Calcidic Haploxeroll) and annual precipitation of 211 mm. The Western site (45°59´ N, 119°51´ W and elevation of 240 m) is characterized by a Warden silt loam (coarse-silty, mixed, superactive, mesic Xeric Haplocambid) and annual precipitation of 153 mm. The soil at the Eastern site had 13% clay, 33% sand, 0.9% organic matter, and a mean particle size of 46 μm, while the soil at the Western site had 14% clay, 36% sand, 0.6% organic matter, and a mean particle size of 59 μm.

Summer Fallow Treatments. The Eastern and Western sites were in a traditional WW-SF rotation when summer fallow management treatments were established after harvesting winter wheat in July of 2006. The experimental design was a randomized complete block with four replications. Summer fallow treatments imposed after wheat harvest were (1) TTF in which plots were disked to a depth of 0.1 m in mid-April of 2007, fertilized with an applicator shank in June of 2007, and rodweeded to a depth of 0.1 m in June and July of 2007; (2) UTF in which plots were undercut to a depth of 0.1 m using overlapping 0.8 m wide V-blades in mid-April of 2007 and then rodweeded to a depth of 0.1 m in June and July of 2007; and (3) NTF in which plots remained undisturbed throughout the fallow period and weeds were controlled with herbicide applications beginning in mid-March of 2007. Individual experimental plots were 18 m wide and 61 m long. Additional details on soils, tillage implements, fertilizers, herbicides, and drills used to sow winter wheat in the experiment are provided by Schillinger and Young (2014).

The TTF and UTF plots were split lengthwise to facilitate sowing winter wheat with a deep-furrow drill on August 11, 2007, at the Eastern site and on August 23, 2007, at the Western site. The plots were split to simulate two schemes in sowing winter wheat in the HHH; these schemes are sowing wheat when subsoil moisture is adequate for plant establishment in mid-to-late August or delay sowing until autumn rains replenish surface soil moisture for wheat seedling establishment. These schemes will be referred to hereafter as seed treatments S and NS to denote sown and not sown, respectively, to winter wheat. The NTF plots at both locations were sown with no-tillage drills after rains moistened the soil in October. Since wind erosion is not a major concern after the arrival of autumn rains, an assessment of soil properties was not made any later than after sowing the TTF and UTF treatments to wheat in August.

Crop Residue and Soil Characteristics. Crop residue and soil characteristics of the summer fallow treatments were assessed to identify causal relations between these characteristics and wind erosion or PM10 emissions. Crop residue and soil characteristics were measured on April 23 and August 13, 2007, at the Eastern site and on April 30 and August 27, 2007, at the Western site. These dates correspond to 5 and 2 days, respectively, after primary spring tillage and sowing at the Eastern site and 21 and 4 days, respectively, after spring tillage and sowing at the Western site. More immediate assessment of crop residue and soil characteristics was not possible after spring tillage owing to rain showers 3 days after tillage at the Eastern site and 5 and 13 days after tillage at the Western site. Crop residue and soil characteristics were assessed as soon after primary spring tillage and sowing winter wheat as feasible because soils managed in a WW-SF rotation in the PNW are most susceptible to wind erosion during these times of the rotation. Indeed, high winds occur in spring (April to May) and late summer (September to October) when soils subject to tillage-based summer fallow are dry, friable, and partially denuded (Papendick 2004).

Crop residue and soil characteristics were assessed at three locations adjacent to the portable wind tunnel that was used to measure wind erosion (Singh et al. 2012) in each experimental plot. Separate assessments of prostrate and standing wheat residue were made by collecting, drying, and weighing the aboveground residue components within a 0.25 m^2 area. Stem density, height, and diameter were documented for determining silhouette area index (SAI), prior to collecting the residue, according to equation 1:

$$\mathrm{SAI} = \frac{\Sigma dh}{A} \ , \tag{1}$$

where A is soil surface area (m^2), d is stem diameter (m), h is stem height (m), and the summation is evaluated for all standing stems located within the measurement area. Crop residue cover, crust cover, and soil surface random roughness was measured using a pin meter. The pin meter had 40 equidistant pins that moved vertically through holes in a steel frame mounted above the soil surface. Residue and crust cover were calculated as the percentage of pins lying on respectively prostrate residue elements and soil crust after lowering the pins to the surface. A pin whose foot (diameter of the foot of each pin was 6.4 mm) protruded beyond both edges of a residue element or did not protrude beyond the edge of an underlying crust added to percentage cover. A soil crust had developed prior to our assessment of soil properties in spring of 2007 due to a 5 mm rain shower after tillage at the Western site. A 0.5 mm rain shower also occurred after spring tillage at the Eastern site, but resulted in no perceivable crust. Soil crust thickness was determined by fracturing the soil surface and measuring the thickness of the consolidated soil using a ruler. Surface random roughness was determined after removing residue from the soil surface; random roughness was equivalent to the standard deviation among pin elevations after correcting for slope (Currence and Lovely 1970).

Aggregate size distribution was determined on soil samples collected in the upper 0.03 m of the soil profile. The 1 kg soil samples were collected with a flat-bladed shovel, placed on a tray, air-dried in an oven maintained at 30°C, and then processed through a rotary sieve (Lyles et al. 1970) equipped with sieves having 0.42 to 19 mm openings. A sonic sieve (Advantech Manufacturing Inc., New Berlin, Wisconsin) was used to determine the size distribution of the <0.42 mm size fraction using sieves with 100 and 10 μm openings. The erodible fraction was the fraction of soil passing through the 0.84 mm sieve, and the PM10 fraction was the fraction of soil passing through the 10 μm sieve.

Soil surface water content was determined by inserting a 76 mm diameter steel ring assembly into the soil. The assembly consisted of two separate rings, the upper ring being 5 mm tall and the lower ring 30 mm tall. The assembly was inserted such that the top of the assembly was nearly level with the soil surface. A knife was used as a screed to level the soil across the surface of the ring. The assembly was extracted from the soil after which the upper ring was removed from the assembly. The 5 mm thick layer of the soil protruding above the lower assembly was then placed into a sealed container. The 30 mm tall ring was used to extract a soil core from the upper 30 mm depth using the above procedure, except that the soil protruding below the bottom of the ring was removed to create a planar surface across the surface of the ring. The soil in the ring was placed in a separate sealed container. Soil water content and water potential of the 5 mm sample were determined by gravimetric analysis and a potentiometer (WP4-T, Decagon Devices, Pullman, Washington), respectively. Volumetric water content and bulk density of the 30 mm sample were determined by drying the sample at 105°C.

Surface penetration resistance and shear stress were determined using a pocket penetrometer and shear vane device, respectively. Oriented or ridge roughness was only apparent after sowing wheat; ridges created by the deep-furrow drill were characterized by roughness associated with height and spacing of ridges according to Zingg and Woodruff (1951) using equation 2:

$$\mathrm{RR} = \frac{4H^2}{D} \ , \tag{2}$$

where RR is ridge roughness (mm), H is ridge height (mm), and D is ridge spacing (mm).

Crop and Soil Characteristics Affecting Sediment Transport. The Revised Wind Erosion Equation (RWEQ; Fryrear et al. 1998b) was used to estimate the influence of crop residue and soil characteristics on horizontal sediment transport capacity or the maximum horizontal sediment flux (Q_{max}) of each summer fallow treatment according to equation 3:

$$Q_{max} = 109.8 \times \mathrm{WF} \times \mathrm{EF} \times \mathrm{SCF} \times \mathrm{K} \times \mathrm{COG}, \tag{3}$$

where Q_{max} is in kg m^{-1}, WF is the weather factor (kg m^{-1}), EF is the erodible fraction, SCF is the soil crust factor, K is the soil roughness factor, and COG is the ground-cover factor. The WF is computed for a single day (24 hours) or erosion event using equation 4 (Fryrear et al. 1998a):

$$\mathrm{WF} = \frac{\sum_{i=1}^{N} (\frac{\rho}{g}) u(u - ut)}{N} \ , \tag{4}$$

where ρ is air density (kg m^{-3}), g is gravitational acceleration (m s^{-2}), u is wind speed, ut is the threshold wind speed, and N is the number of wind speed observations in one day or during an erosion event. We estimated WF based upon ut equaling 5 m s^{-1} as specified by Fryrear et al. (1998b). Furthermore, u was assumed to remain constant at 15 m s^{-1} for each observation in a day as this wind speed occurs once every two years in the Columbia Plateau (Wantz and Sinclair 1981). Although WF is also dependent on soil wetness and snow cover, neither of these parameters suppressed wind erosion and thus were not considered in the derivation of WF.

The SCF was set to a value of 1.0, except for NTF since a soil crust developed in response to more than 12 mm of precipitation in both spring and late summer at each experimental site. The K was determined from random roughness and ridge roughness where ridge roughness was adjusted for orientation of ridges in relation to wind direction. The COG was determined from crop residue cover and silhouette area.

Statistical Analyses. Soil properties and surface characteristics of summer fallow treatments were analyzed for differences using analysis of variance (ANOVA). Homogeneity of variance across treatments and normalcy of distribution within treatments were examined prior to performing the ANOVA. Homogeneity of variance was tested using Bartlett's test statistic (Snedecor and Cochran 1989), and normalcy of distribution was tested using the standardized *t*-test. Although crop residue and soil characteristics were normally distributed, heterogeneity of variance was found for residue collected in late summer and SAI, penetration resistance, and geometric mean diameter assessed in spring and late summer at both the Eastern and Western sites. Therefore, residue data collected in late summer and SAI, penetration resistance, and aggregation data obtained in spring and late summer were log transformed to equalize variances prior to performing an ANOVA. In the event that significant F-values ($p \leq 0.05$) were found, differences among treatment means were separated using Tukey's honest significant difference (HSD) test.

Results and Discussion

Surface residue and soil water content are two of the most important biophysical factors that govern wind erosion (Feng and Sharratt 2005). While surface residue influences wind characteristics at the soil surface, water content of soil particles influence the threshold wind velocity at which particles move at or along the surface. Indeed, standing residue exerts a drag on the wind and thereby reduces wind speed at the surface while prostrate residue provides cover to soil particles and reduces the surface area susceptible to erosion. Soil water facilitates binding of soil particles, and only when capillary forces exceed adsorption forces is the threshold velocity of particles substantially influenced by soil water (McKenna-Neuman and Nickling 1989; Sharratt et al. 2013).

Summer fallow treatments during summer fallow influenced residue characteristics in this study. Total residue was higher for NTF than for UTF and TTF immediately after tillage in spring and sowing of winter wheat in late summer (table 1). Surface residue ranged from 75% to 1,420% higher in NTF than the other summer fallow treatments. Total surface residue for UTF was 145% to 500% higher than for TTF. Total residue was low after sowing wheat in TTF (<30 g m^{-2} or 300 kg ha^{-1}). Retaining residue on the surface is extremely important for protecting the soil surface (Blanco-Canqui and Wortmann 2017), especially in the HHH where average winter wheat grain yield may not exceed 1,200 kg ha^{-1} (Schillinger and Young 2014). Differences in total residue were largely a result of differences in prostrate residue versus standing residue. For example, differences in total surface residue among summer fallow treatments in spring reflected differences in prostrate residue at both sites. While both total and prostrate residue were highest for NTF, no differences were found between standing residue for NTF and UTF during spring at the Eastern and Western sites. Differences in total residue among summer fallow treatments in late summer, however, reflected differences in both prostrate and standing residue at both sites.

Residue cover and silhouette area index were higher for NTF than TTF in spring and late summer at both sites. In spring, residue cover was 3 to nearly 10 times greater for NTF than TTF, while in late summer residue cover was at least two times greater for NTF than TTF. Similar results were found for SAI, although SAI was greater for NTF than UTF and TTF and greater for UTF than TTF in late summer at both sites (table 1). Differences in residue cover and SAI among treatments have direct implications for wind erosion. For example, the relationship between soil loss ratio (SLR), which is the ratio of soil loss from a treated to bare soil, and residue cover (RC) can be expressed as equation 5 (Bilbro and Fryrear 1994):

$$\mathrm{SLR} = e^{-0.0438 \times \mathrm{RC}}. \quad (5)$$

Based upon this relationship and using values for residue cover in table 1, soil loss would be 80% less for NTF than TTF at the Eastern site and at least 55% less for NTF than TTF at the Western site. An exponential relationship also exists between SLR and SAI, but varies with wind speed according to equation 6 (Bilbro and Fryrear 1994):

$$\mathrm{SLR} = exp\,(a \times \mathrm{SAI}^{b}/u), \quad (6)$$

where *a* and *b* are regression coefficients, which are dependent on wind speed. Based upon regression coefficients provided by Bilbro and Fryrear (1994) and values for SAI in table 1, soil loss would be at least 99% and 80% less for NTF than TTF at wind speeds of 12 and 18 m s^{-1}, respectively, at both sites. Van de Ven at al. (1989) reported that soil loss (SL) was proportional to SAI according to equation 7:

$$\mathrm{SL} \propto \frac{u - ut}{\sqrt{\mathrm{SAI}}}\ , \quad (7)$$

where *ut* is the threshold wind speed. Based upon their equation and values for SAI in table 1, soil loss would be 91% to 97% and 82% to 89% less for NTF than TTF at wind speeds of 5 and 10 m s^{-1}, respectively, above threshold across sites. These differences in soil loss agree with findings of Singh et al. (2012) who observed at most a 95% reduction in soil loss for NTF as compared with TTF at these same experimental sites. They, however, also observed no reduction in soil loss for NTF as compared with TTF in spring at the Western site. This lack of any difference in soil loss may be attributed to a soil crust that was apparent in all treatments in spring at the Western site. Indeed, a 5 mm rain shower that occurred between spring tillage and assessment of wind erosion contributed to a 65 mm crust in the NTF treatment and 5 mm crust in the TTF treatment.

Little or no evidence was found to suggest that summer fallow treatments influenced soil water content or potential. Near-surface (0 to 5 mm) water content only differed among summer fallow treatments in the spring at the Western site when water content was higher in TTF than UTF or NTF (table 2). In contrast, near-surface water potential did not differ among summer fallow treatments in spring or late summer at either site. Near-surface soil water potentials of <−145 MPa were observed in this study and would have little impact on wind erosion since threshold friction velocity is not influenced by water potentials <−125 MPa for the soil types at the two sites (Sharratt et al. 2013).

Soil strength is governed by cohesive and adhesive forces that bind together soil particles. As such, soil strength is an indicator

Table 1
Residue characteristics affected by summer fallow management method in a winter wheat–summer fallow rotation in spring and late summer of 2007 at an Eastern and Western experimental site located in the Horse Heaven Hills of south central Washington.

			Location/season			
			Eastern site		Western site	
Residue characteristic	Fallow treatments*	Seed treatments†	Spring	Late summer	Spring	Late summer
Biomass (g m^{-2})	NTF	NS	189a	215a	155a	137a
	UTF	NS	106b	63b	78b	67b
		S		64b		40b
	TTF	NS	36b	21c	13c	14c
		S		26c		9c
Cover (%)	NTF	NS	51a	54 a	54a	34a
	UTF	NS	40a	35ab	21b	28ab
		S		26abc		16abc
	TTF	NS	13b	20bc	6b	14bc
		S		14c		7c
Silhouette area index (m^2 m^{-2})	NTF	NS	0.143a	0.103a	0.074a	0.107a
	UTF	NS	0.094a	0.024b	0.047a	0.013b
		S		0.026b		0.014b
	TTF	NS	0.005b	0.007c	0.003b	0.003c
		S		0.005c		0.002c

Note: Means followed by same letter within a column are not significantly different at $p = 0.05$.
*NTF = no-tillage fallow. UTF = undercutter-tillage fallow. TTF = traditional-tillage fallow.
†NS and S are not sown and sown, respectively, to winter wheat immediately before assessing characteristics in late summer.

Table 2
Soil gravimetric water content and water potential at 0 to 5 mm depth and volumetric water content and bulk density at 0 to 3 cm depth affected by summer fallow management method in a winter wheat–summer fallow rotation in the spring and summer of 2007 at an Eastern and Western experimental site in the Horse Heaven Hills of south central Washington.

			Location/season			
			Eastern site		Western site	
Soil water characteristic	Fallow treatments*	Seed treatments†	Spring	Late summer	Spring	Late summer
Gravimetric water content (g g^{-1})	NTF	NS	0.024a	0.015a	0.013b	0.016a
	UTF	NS	0.021a	0.013a	0.014b	0.011a
		S		0.015a		0.016a
	TTF	NS	0.019a	0.013a	0.017a	0.011a
		S		0.015a		0.015a
Water potential (MPa)	NTF	NS	−160a	−267a	−209a	−226a
	UTF	NS	−154a	−220a	−164a	−242a
		S		−218a		−225a
	TTF	NS	−162a	−249a	−147a	−255a
		S		−229a		−206a
Volumetric water content (m^3 m^{-3})	NTF	NS	0.061a	0.008a	0.026a	0.015a
	UTF	NS	0.025b	0.010a	0.019a	0.012a
		S		0.012a		0.015a
	TTF	NS	0.032b	0.010a	0.020a	0.013a
		S		0.010a		0.016a
Bulk density (Mg m^{-3})	NTF	NS	1.18a	1.18a	1.20a	1.27a
	UTF	NS	0.96b	1.11a	1.07b	1.22a
		S		1.13a		1.26a
	TTF	NS	0.92b	1.10a	1.07b	1.22a
		S		1.12a		1.29a

Note: Means followed by same letter within a column are not significantly different at $p = 0.05$.
*NTF = no-tillage fallow. UTF = undercutter-tillage fallow. TTF = traditional-tillage fallow.
†NS and S are not sown and sown, respectively, to winter wheat immediately before assessing characteristics in late summer.

Table 3
Soil surface roughness and strength characteristics affected by summer fallow management method in a winter wheat–summer fallow rotation in the spring and late summer of 2007 at an Eastern and Western experimental site located in the Horse Heaven Hills of south central Washington.

			Location/season			
			Eastern site		Western site	
Soil characteristic	Fallow treatments*	Seed treatments†	Spring	Late summer	Spring	Late summer
Ridge roughness (mm)	NTF	NS	31a	11b	28a	8b
	UTF	NS	24a	14b	0b	5b
		S		85a		133a
	TTF	NS	0b	16b	0b	7b
		S		83a		128a
Random roughness (mm)	NTF	NS	8b	7b	8b	8b
	UTF	NS	28a	16a	15a	14a
		S		18a		13ab
	TTF	NS	24a	11ab	10ab	10ab
		S		14ab		10ab
Penetration resistance (kPa)	NTF	NS	2,498a	1,973a	640a	1,374a
	UTF	NS	7b	14b	14b	20b
		S		15b		13b
	TTF	NS	6b	17b	14b	20b
		S		13b		15b
Shear stress (kPa)	NTF	NS	7.2a	10.2a	8.9a	9.0a
	UTF	NS	0.2b	0.6b	1.2b	2.6b
		S		0.4b		0.7b
	TTF	NS	0.2b	0.8b	1.2b	1.9b
		S		0.3b		0.6b

Note: Means followed by same letter within a column are not significantly different at $p = 0.05$.
*NTF = no-tillage fallow. UTF = undercutter-tillage fallow. TTF = traditional-tillage fallow.
†NS and S are not sown and sown, respectively, to winter wheat immediately before assessing characteristics in late summer.

of the stability of soils to withstand stresses that would otherwise deform, deflate, or erode the soil. We characterized strength according to measures of bulk density, penetration resistance, and shear stress. Summer fallow treatments had little influence on bulk density (table 2), although bulk density was greater for NTF than UTF and TTF in the spring at both sites. The higher bulk density for NTF may be due to overwinter consolidation of the soil matrix. Penetration resistance and shear stress were also greater for NTF than UTF and TTF in spring and late summer at both sites (table 3). Although a crust had formed on the soil surface as a result of a rainfall event soon after spring tillage at the Western site, the thinner crust in UTF and TTF resulted in lower penetration resistance and shear stress as compared with NTF. Higher penetration resistance and shear stress for NTF suggests the soil surface is less vulnerable to abrasion as compared with UTF and TTF.

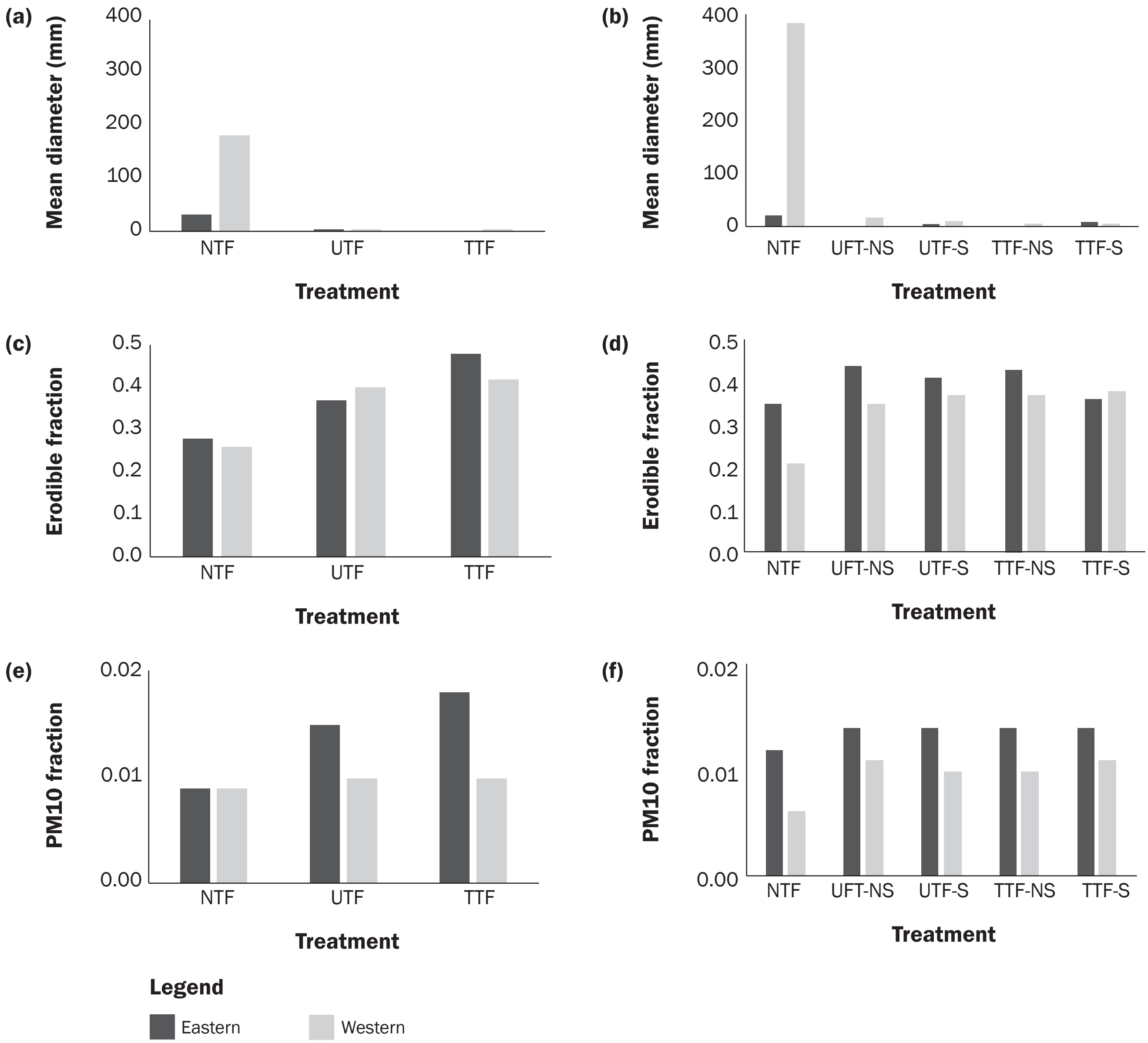
Like residue, other roughness elements such as ridges and aggregates that protrude above the soil surface exert a drag on the wind and thereby reduce wind speed at the surface. In general, ridge roughness is only effective at extracting momentum with a cross wind while random roughness is most effective at extracting momentum when winds are parallel to ridges (Fryrear et al. 1998b). Crop rows remaining after harvest in NTF or tool marks remaining after tillage with the undercutter implement created greater ridge roughness as compared with TTF in spring at both sites (table 3). After sowing winter wheat in late summer, ridges created by the deep-furrow drill resulted in greater ridge roughness for the S treatments as compared with NS treatments. Random roughness was typically lower for NTF as compared with TTF in the spring and late summer at both sites. Soil disturbance, either using tillage or sowing implements, appeared to leave larger aggregates on the soil surface as compared to undisturbed soil of NTF. Horning et al. (1998) expressed the proportional relationship between SLR and random roughness as equation 8:

$$SLR \propto e^{-0.052 \times RR}, \quad (8)$$

where random roughness (RR) is in mm. Based upon their equation and values for random roughness in table 3, soil loss would be 38% to 187% higher for NTF than UTF across seasons and sites and 128% higher for NTF than TTF in spring at the Eastern site. These differences in soil loss, however, do not agree with wind tunnel measurements from this same experiment where soil loss from NTF was 0% to 95% less than from both UTF and TTF across seasons and sites (Singh et al. 2012). In our study, both ridge roughness and random roughness influenced soil loss from NTF because the wind tunnel was oriented perpendicular to wheat stubble rows (Singh et al. 2012), whereas only random roughness influenced soil loss from UTF and TTF because the wind tunnel was oriented parallel to tillage direction and newly sown wheat rows. Soil loss is proportional to both ridge and random roughness according to equation 9 (Fryrear et al. 1998b):

Figure 2

Soil aggregation characteristics ([a and b] mean diameter, [c and d] erodible fraction, and [e and f] PM10 fraction) affected by summer fallow management methods in the (a, c, e) spring and (b, d, f) summer of 2007 at an Eastern and Western site in the Horse Heaven Hills of south central Washington. Summer fallow treatments included no-tillage fallow (NTF), undercutter-tillage fallow (UTF), and traditional-tillage fallow (TTF) either sown (S) or not sown (NS) to winter wheat immediately before assessing characteristics in late summer.



$$SL \propto exp\,(1.86RG - 2.41RG^{0.934} - 0.124RR), \qquad (9)$$

where RG and RR are in cm and RG equals zero when wind is parallel to ridges. Based upon this equation and values for ridge roughness and random roughness in table 3, soil loss would be 60% to 66% and 33% to 42% less for NTF than TTF and UTF in spring and late summer, respectively, across sites.

Summer fallow treatments influenced soil aggregation, but only in spring at the Eastern site and in late summer at the Western site (figure 2). Significant differences in geometric mean diameter and erodible fraction existed between NTF and TTF. Geometric mean diameter was greater and erodible fraction was lower for NTF than TTF. These results suggest that TTF is more susceptible to wind erosion than NTF. According to the classification of Shiyatyi (Zachar 1982), TTF was moderately erodible (erodible fraction between 0.4 and 0.5) in spring at both sites and in late summer at the Eastern site. UTF was also moderately erodible, but only in late summer at the Eastern site and in spring at

Table 4
Maximum horizontal sediment flux (Q_{max}) estimated from the Revised Wind Erosion Equation (RWEQ) for summer fallow treatments in the spring and late summer of 2007 at an Eastern and Western experimental site located in the Horse Heaven Hills of south central Washington.

				RWEQ parameters					
Site	Season	Fallow treatment*	Seed treatment†	WF (kg m^{-1})	EF	SCF	K	COG	Q_{max} (kg m^{-1})
Eastern	Spring	NTF	NS	222	0.28	0.47	0.12	0.003	1.1
		UTF	NS	222	0.37	1	0.10	0.011	9.3
		TTF	NS	222	0.48	1	0.13	0.371	542.1
	Late summer	NTF	NS	222	0.35	0.47	0.24	0.005	4.8
		UTF	NS	222	0.44	1	0.21	0.068	153.1
			S	222	0.41	1	0.18	0.095	167.6
		TTF	NS	222	0.43	1	0.30	0.246	785.9
			S	222	0.36	1	0.24	0.355	732.2
Western	Spring	NTF	NS	222	0.26	0.44	0.13	0.009	3.2
		UTF	NS	222	0.40	1	0.23	0.067	150.7
		TTF	NS	222	0.42	1	0.34	0.567	1,948.5
	Late summer	NTF	NS	222	0.21	0.44	0.25	0.011	6.1
		UTF	NS	222	0.35	1	0.25	0.134	281.0
			S	222	0.37	1	0.25	0.219	495.9
		TTF	NS	222	0.37	1	0.33	0.399	1,196.3
			S	222	0.38	1	0.32	0.582	1,708.9

Notes: WF = weather factor. EF = erodible fraction. SCF = soil crust factor. K = soil roughness factor. COG = groundcover factor.
*NTF = no-tillage fallow. UTF = undercutter-tillage fallow. TTF = traditional-tillage fallow.
†NS and S are not sown and sown, respectively, to winter wheat immediately before assessing characteristics in late summer.

the Western site. Fryrear et al. (1998b) suggest that soil loss is directly proportional to the erodible fraction. Based upon the erodible fractions in figure 2, soil loss would be 10% to 15% and 15% to 20% lower for NTF than UTF and TTF, respectively, across seasons and sites. Our results are similar to Hevia et al. (2007) who found a greater geometric mean diameter and lower erodible fraction for no-tillage versus conventional-tillage of a sandy loam in Argentina. No differences were found in the PM10 fraction among summer fallow treatments.

The above results, which describe differences or similarities in crop residue and soil characteristics among treatments, were based upon measurements taken during the first year after establishing summer fallow treatments. While we recognize the importance of long-term crop rotations in effecting change in soil characteristics, soils in the low precipitation zone of the PNW respond slowly to changes in management (Sharratt and Schillinger 2016; Gollany et al. 2011). For example, Schillinger et al. (2007) found little change in soil characteristics even after eight years of diverse crop rotations at a site with higher precipitation (301 mm). Thus, differences or similarities in soil characteristics among summer fallow treatments reported in this study likely extend to multiple cycles of the rotation.

We determined the combined influence of crop residue and soil characteristics on wind erosion potential from summer fallow treatments at each site using the RWEQ. The RWEQ parameter values and estimates of maximum horizontal sediment flux, based upon a wind speed of 15 m s^{-1} over a 24 hour period, for each treatment are tabulated in table 4. NTF resulted in the lowest sediment flux as compared with other treatments during both spring and late summer at both sites. Sediment flux from NTF was at most 10% of the flux estimated to occur from other treatments in either spring or late summer. In addition, UTF was estimated to reduce sediment flux by at least 250% as compared with TTF. These results in part agree with observations by Singh et al. (2012) at these same experimental sites in the HHH. They found sediment flux was generally lower from NTF than from UTF and TTF. Singh et al. (2012) also reported that sediment flux from UTF was the same or at most 135% lower than sediment flux from TTF.

Summary and Conclusions

Crop residue, surface roughness, and aggregate size distribution appeared to influence wind erosion from soils during the fallow phase of a WW-SF rotation in the HHH of south central Washington. Sediment flux was predicted to be lowest from NTF and highest from TTF after primary tillage in spring and sowing winter wheat in late summer. NTF was characterized by greater crop residue cover, stem silhouette area, and surface roughness and lower erodible fraction as compared with UTF and TTF. Summer fallow practices that retain more residue on the soil surface or that enhance surface roughness or aggregation will minimize soil loss in this highly erosive region. We are encouraged by farmers in the HHH who are increasingly adopting NTF and UTF management practices.

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