Friction velocity and aerodynamic roughness of conventional and undercutter tillage within the Columbia Plateau, USA

Brenton Sharratt [a,*], Guanglong Feng [b]

[a] USDA-Agricultural Research Service, 213 LJ Smith Hall, WSU, Pullman, WA 99164, United States
[b] Department of Biosystems Engineering, Washington State University, Pullman, WA, United States

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ABSTRACT

Friction velocity (u_*) and aerodynamic roughness (z_o) at the soil–plant–atmosphere interface affect wind erosion, but no attempts have been made to quantify these parameters as affected by tillage systems within the Columbia Plateau region of the Pacific Northwest United States. Wind velocity profiles above adjacent field plots (>2 ha), with plots subject to conventional or undercutter tillage during the summer fallow phase of a winter wheat–summer fallow rotation, were measured over 50 high wind events (wind velocities in excess of 6.4 m s^{-1} at a height of 3 m) during 2005 and 2006 near Lind, Washington to determine u_* and z_o of tillage treatments. Wheat stubble plots were subject to either conventional (disks) or undercutter (wide V-shaped blades) tillage in spring and then periodically rodweeded prior to sowing winter wheat in late summer. Prior to sowing, u_* for conventional and undercutter tillage respectively averaged 0.36 and 0.46 m s^{-1} in 2005 and 0.38 and 0.40 m s^{-1} in 2006 while z_o for conventional and undercutter tillage respectively averaged 2 and 7 mm in 2005 and 2 and 4 mm in 2006. The aerodynamically rougher surface of undercutter tillage was predicted to suppress vertical dust flux; this was collaborated with observations in the field where undercutter tillage reduced dust flux as compared with conventional disk tillage. Undercutter tillage, therefore, appears to be an effective management practice to roughen the surface and thereby suppress dust emissions from agricultural land subject to summer fallow within the Columbia Plateau.

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1. Introduction

Wind erosion removes fertile topsoil and is therefore a concern for global societies in maintaining food and fiber production for future generations. Wind erosion damages crops as a consequence of saltating particles sandblasting seedlings (Fryrear, 1986) and can impair visibility and human health as a result of increasing the atmospheric dust load through the emission of fine particulate matter from soils. In fact, windblown dust has caused vehicular accidents as a result of reduced visibility (Hudson and Cary, 1999) and has contributed to exceedance of the US Environmental Protection Agency ambient air quality standard for PM10 (particulate matter ≤10 μm in diameter) within the Columbia Plateau region of the Pacific Northwest United States (Sharratt and Lauer, 2006).

Wind erosion is initiated when friction velocity (u_*) exceeds the threshold friction velocity. Threshold friction velocity is the minimum friction velocity, at the height where momentum is absorbed by surface roughness elements, that is required to initiate movement of an aggregate or particle resting on the soil surface; aggregate or particle movement is achieved when drag and lift forces overcome gravitational and inter-particle cohesive forces acting on the aggregate or particle at the soil surface. While threshold friction velocity is governed by the size, shape, and mass of aggregates or particles at the soil surface, threshold friction velocity is also influenced by soil surface water content and crusting, surface roughness, and biomass cover. Friction velocity, however, is governed by the apparent roughness of the surface and atmospheric convection or stability (Stull, 2000). The apparent roughness of an agricultural field is comprised of roughness cast by aggregates on the soil surface, tool marks or ridges created by tillage implements, and vegetation protruding above the soil surface. Abatement of wind erosion of an agricultural field, therefore, can be attained by altering soil surface characteristics (e.g. size of aggregates, biomass cover).

Developing strategies to mitigate wind erosion is imperative to conserving the soil resource and improving air quality within the Columbia Plateau. In the drier part (annual precipitation <300 mm) of this region, about 1.5 million ha of land is managed in a winter wheat–summer fallow rotation. Conventional summer fallow generally entails cultivating soils with sweeps, disks, or cultivators after wheat harvest in late summer and again the

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following spring and then rodweeding the soil to control weeds prior to sowing winter wheat in late summer (Schillinger, 2001). Although conventional tillage practices are very effective in conserving soil water during the fallow phase of the rotation, soils are very susceptible to erosion during summer fallow because multiple tillage operations degrade soil aggregates and bury crop residue.

The United States Department of Agriculture-Natural Resource Conservation Service has recently promoted the use of an undercutter tillage implement for reducing wind erosion within the Columbia Plateau (Burnham, 2007). The undercutter implement, with wide, over-lapping, V-shaped blades, minimizes soil inversion and disturbance that otherwise occurs with a plow or disk. Retention of crop residue or large aggregates on the soil surface as a result of less soil disturbance by the undercutter implement may better protect the soil surface against the forces of wind. No studies have examined the impact of this conservation tillage implement on aerodynamic surface characteristics that affect wind erosion and dust emissions from agricultural soils in the region. The objective of this study was to assess u_* and aerodynamic roughness (z_o) of soils subject to conventional and undercutter tillage during the summer fallow phase of a winter wheat–summer fallow rotation.

2. Materials and methods

This study was conducted at field sites located within the low precipitation zone (<300 mm annual precipitation) of the Columbia Plateau region of the Pacific Northwest United States (Fig. 1). Fields were in a winter wheat–summer fallow rotation when the fallow phase of the rotation began after harvest of wheat in July 2004 and 2005. Field sites were located 12 km southwest of Lind, Washington on a Shano silt loam (Andic Aridic Haplustoll) in 2004 and 14 km southeast of Lind, Washington on a Ritzville silt loam (Andic Aridic Haplustoll) in 2005. Shano silt loam is comprised of 34% sand, 56% silt, and 10% clay whereas Ritzville silt loam is comprised of 21% sand, 65% silt, and 14% clay. Organic matter content of both soils was 1%. Adjacent plots were established at the field site after wheat harvest each year with plots subject to either conventional tillage or undercutter tillage during the fallow phase of a winter wheat–summer fallow rotation. Conventional tillage practices were those used by the wheat growers who owned and managed the field sites. Field plots were 200 m × 100 m in 2004 and 200 m × 200 m in 2005.
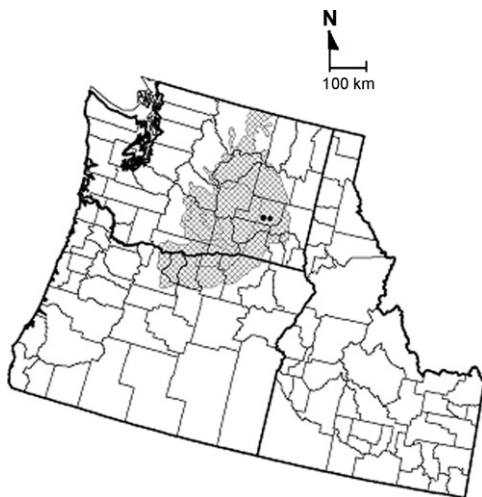

Fig. 1. Location of field sites in 2005 and 2006 (dots) within the Columbia Plateau region (shaded area) of the Pacific Northwest United States.

Table 1
Dates of field operations and precipitation during the 2005 and 2006 field campaigns.

Year	Calendar date	Day of year	Field operation	Precipitation[a] (mm)
2005	May 5	125	Tillage	
	May 6	126	Fertilize	
	May 10	130	Rodweed	
	May 15	135		2.3
	May 20	140		3.6
	May 21	141		6.4
	June 5	156		4.6
	July 8	189		9.9
	July 9	190		1.8
	July 21	202	Rodweed	
	August 17	229		2.0
	August 31	243	Sow	
2006	April 30	120	Tillage	
	June 2	153	Fertilize	
	June 13	164		1.5
	June 14	165		5.6
	June 24	175	Rodweed	
	August 6	218	Rodweed	
	August 27	239	Sow	
	September 21	264		2.5
	October 16	289		3.6

[a] Days with precipitation ≥1.3 mm during the period of high wind observations in 2005 (12 May to 18 October) and 2006 (6 June to 20 October).

The wheat stubble plots remained undisturbed after harvest in 2004 while wheat stubble plots in 2005 were harrowed twice after harvest to incorporate weed seed. In early May 2005 and late April 2006, stubble plots were tilled to a depth of 0.1 m using either a double disk or undercutter implement. The undercutter implement had 0.81-m wide V-shaped blades spaced 0.7 m apart. After tillage, fertilizer was injected at a depth of 0.1 m into the soil with shanks spaced 0.45 m apart on 6 May 2005 and 2 June 2006. In 2005, both plots were rodweeded at a depth of 0.1 m on 10 May and 21 July prior to sowing winter wheat in rows spaced 0.45 m apart with a deep furrow drill on 31 August. In 2006, both plots were rodweeded on 24 June and 6 August prior to sowing winter wheat on 27 August with a deep furrow drill. Field operations during 2005 and 2006 are summarized in Table 1.

2.1. Estimating u_* and z_o

Friction velocity and z_o were estimated from wind velocity profiles obtained during high wind events capable of causing wind erosion. A high wind event was defined by a threshold wind velocity of 6.4 m s^{-1} at a height of 3 m; an event was initiated when wind velocity exceeded the threshold for 10 consecutive minutes and terminated when wind velocity was lower than the threshold for 10 consecutive minutes. The field plots were instrumented to monitor wind velocity and air temperature at heights of 0.1, 0.5, 1, 2, 3, and 6 m above the soil surface in each plot. Wind velocity was measured using 3-cup anemometers (model 014A, Met One, Grants Pass, Oregon). Air temperature was measured using non-aspirated, shielded, fine-wire thermocouples. Instrumentation was installed at the leeward position (northeast corner) in the plots. In 2005, land to the south of both plots and to the west of the undercutter tillage plot was cropped to winter wheat while the west end of the conventional tillage plot abutted the undercutter tillage plot. In 2006, land to the west of both plots was cropped to winter wheat while the southern boundary of the undercutter tillage plot bordered a ravine (10 m deep and 50 m wide) and the southern boundary of the conventional tillage plot abutted the undercutter tillage plot. Friction velocity and z_o were assessed only for high wind events that had prevailing winds between 190° and 260° to ensure a fetch, or length of field with known and similar surface characteristics, of at least 100 m in 2005

Table 2
Soil surface characteristics of conventional and undercutter tillage during the 2005 and 2006 field campaigns.

Soil characteristic	Tillage treatment	Date of sampling[a]						
		2005			2006			
		7 June	25 July	14 September	6 June	28 June	9 August	6 September
Standing stubble (g m^{-2})	Conventional	4	5	21	4	4	5	2
	Undercutter	38	68	31	13	12	17	5
Prostrate residue cover (%)	Conventional	35	30	9	22	18	15	12
	Undercutter	55	50	11	40	42	46	29
Silhouette area index (m^2 m^{-2})	Conventional	0.01	0.01	0.02	0.01	0.01	0.01	0.003
	Undercutter	0.04	0.08	0.02	0.02	0.02	0.03	0.006
Random roughness (mm)	Conventional	11.7	15.0	10.4	13.8	10.8	7.2	11.0
	Undercutter	18.1	14.9	8.8	13.8	10.7	10.0	8.3

[a] Date of sowing was 31 August 2005 and 27 August 2006.

and 200 m in 2006. Maximum fetch over this range of prevailing wind directions was 225 m in 2005 and 285 m in 2006. Sensors were monitored every 10 s with data averaged and recorded every minute during a high wind event. An automated weather station was also deployed at the leeward position in the conventional tillage plot to measure relative humidity, precipitation, and solar radiation.

Wind velocity within the inertial sublayer of the surface boundary layer can be described by the log wind profile:

$$u_z = \left(\frac{u_*}{k}\right) \ln\left(\frac{z}{z_o}\right) \qquad (1)$$

where u_z is wind velocity (m s^{-1}) at height z (m) and k is von Karman's constant (0.4). Estimation of u_* and z_o in Eq. (1) can be obtained from a knowledge of the wind velocity profile under conditions of neutral atmospheric stability. Although neutral stability typically occurs during high winds (Oke, 1987), we verified the existence of neutral stability using the Richardson's number (Stull, 2000):

$$Ri = \frac{(g/T)(\partial T/\partial z)}{(\partial u/\partial z)^2} \qquad (2)$$

where Ri is Richardson's number, g is the gravitational constant (9.8 m s^{-2}), T is air temperature (K), and ∂T and ∂u are the respective change in temperature (K) and wind velocity (m s^{-1}) with height ∂z (m). Stability conditions were classified according to Thom (1975) with neutral stability defined by Ri between -0.01 and 0.01. Both u_* and z_o were obtained under conditions of neutral stability from wind velocity measurements at no fewer than three heights that were resolved to lie within the logarithmic region of the inertial layer. These parameters were estimated by linear regression analysis of u versus $\ln(z)$; accordingly, u_* is the ratio of k to regression slope and z_o is the exponent of the regression intercept. For all profiles, the coefficient of determination of the relationship was >0.98.

2.2. Estimating dust flux

Friction velocity influences vertical dust flux (F) according to (Gillette and Passi, 1988):

$$F = \gamma u_*^3 (u_* - u_{*t}) \qquad (3)$$

where γ is an empirical dust coefficient and u_{*t} is the threshold friction velocity (m s^{-1}). Vertical flux of dust occurs only when u_* exceeds u_{*t}. The u_{*t} of tillage treatments was estimated based upon known soil surface characteristics (Table 2) and empirical equations described by Shao (2000).

Soil surface characteristics measured after tillage, fertilizing, and sowing at three random locations in each tillage treatment included biomass of standing stubble and prostrate (i.e. flat) residue, silhouette area index (SAI), prostrate residue cover, and ridge and random roughness. Biomass of stubble and residue was assessed by collecting, drying, and weighing above-ground stubble and prostrate residue from 0.25 m^2 areas within each plot. SAI was determined according to:

$$SAI = \frac{1}{A} \Sigma (dh) \qquad (4)$$

where the summation is for all standing stubble elements of height h and diameter d within the sampling area A. A pin or roughness meter was used to measure prostrate or flat residue cover and soil surface random roughness. The pin meter was comprised of 40 equidistant pins (spacing of 25 mm) that protruded and moved vertically through holes in a steel frame mounted on the soil surface (Wagner and Lindstrom, 1996). The pins were in a retracted position until lowered to the soil surface for measuring residue cover and random roughness. Residue cover was calculated as the percent of pins whose feet (6-mm diameter) overlaid prostrate residue elements. Random roughness was determined as the standard deviation among pin elevations after correcting for slope (Currence and Lovely, 1970). 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).

Threshold friction velocity was estimated from standing stubble and prostrate residue biomass of tillage treatments prior to sowing because differences in crop residue characteristics were more apparent and consistent than differences in other surface characteristics between treatments prior to sowing (Table 2). According to Shao (2000):

$$u_{*t} = u_{*tss} f(\lambda) f(\text{rc}) \qquad (5)$$

where u_{*tss} is the threshold friction velocity of a smooth, dry, unconsolidated, and bare soil surface and $f(\lambda)$ and $f(\text{rc})$ are respective correction functions for standing stubble and prostrate residue cover. The correction function for standing stubble is:

$$f(\lambda) = \sqrt{\{(1 - m\alpha\lambda)(1 + m\beta\lambda)\}} \qquad (6)$$

where m is a constant (~ 0.5) that accounts for non-uniformity in shear stress caused by roughness elements, α is the ratio of stubble element basal area to stubble element frontal area, β is the ratio of stubble to soil surface drag coefficients, and λ is silhouette area index (total stubble frontal area to soil surface area). Stubble height prior to sowing was ~ 0.1 m for both treatments. The drag coefficient for stubble was 0.45 (Campbell, 1986) and for a smooth soil surface was 0.0033 (Raupach et al., 1993). Data presented by Hagen (1996) were used to derive the correction function for

prostrate residue cover as:

$$f(\mathrm{rc}) = (1 + 1.92\mathrm{rc} - 2.092\mathrm{rc}^2 + 0.866\mathrm{rc}^3)^2 \tag{7}$$

where rc is the fraction of soil surface covered by prostrate residue. The u_{*tss} was estimated to be 0.15 m s^{-1} based upon Bagnold's scheme (Bagnold, 1941) for a surface comprised of particles with a mean diameter of 100 μm.

2.3. Statistical analysis

Regression analysis and paired t-tests were performed to compare u_* and z_o of conventional and undercutter tillage. Each pair of u_* or z_o determinations obtained during a high wind event was used to test (paired t-test) whether significant differences existed between the mean u_* or z_o obtained for conventional disk and undercutter tillage across all high wind events.

3. Results and discussion

3.1. High wind event characteristics

A total of 38 and 55 high wind events, with each event characterized by wind velocities at a 3-m height exceeding 6.4 m s^{-1}, occurred during the respective period of observation in 2005 (12 May to 18 October) and 2006 (6 June to 20 October). Persistent SW (190–260°) winds were observed during 45 and 87% of these events in subsequent years whereby a fetch with known surface characteristics of at least 100 m in 2005 and 200 m in 2006 was maintained upwind of the instrumentation for the duration of the high wind event. Power failures and plant debris lodged against sensors precluded obtaining quality wind data for three and six high wind events characterized by SW winds over the period of observation in successive years. In addition, neutral stability did not occur during six high wind events characterized by SW winds in 2006; for these events, Ri varied from -0.014 to -0.033. For high wind events characterized by SW winds and neutral stability in 2005 (14 events) and 2006 (36 events), the maximum 1-min wind velocity observed at a height of 3 m was 13.0 m s^{-1} in 2005 (occurred on 6 July) and 14.5 m s^{-1} in 2006 (occurred on 16 June). The maximum duration of a high wind event was 597 min in 2005 and 906 min in 2006 (these events occurred on 29 August in both years).

3.2. Friction velocity

Friction velocity ranged from 0.31 to 0.49 m s^{-1} for conventional tillage and from 0.43 to 0.58 m s^{-1} for undercutter tillage across all high wind events in 2005. In 2006, u_* ranged from 0.34 to 0.56 m s^{-1} for conventional tillage and from 0.33 to 0.56 m s^{-1} for undercutter tillage across all high wind events. Excluding the anomalously high wind events on 6 and 8 July 2005 (days 187 and 189) and 16 June 2006 (day 167), u_* was generally lower prior to sowing than after sowing both years (Fig. 2). For example, u_* for high wind events prior to and after sowing was respectively 0.36 (standard error or SE = 0.02) and 0.44 (SE = 0.01) m s^{-1} for conventional tillage and 0.46 (SE = 0.02) and 0.51 (SE = 0.01) m s^{-1} for conventional tillage in 2005. In 2006, u_* prior to and after sowing was respectively 0.38 (SE = 0.01) and 0.48 (SE = 0.01) m s^{-1} for conventional tillage and 0.40 (SE = 0.01) and 0.53 (SE = 0.01) m s^{-1} for undercutter tillage. Some variation in u_* occurred across high wind events prior to sowing as well as after sowing (Fig. 2). Changes in u_* prior to sowing were largely associated with changes in atmospheric flow characteristics (e.g. velocity, orientation to roughness elements) across high wind events as large variations in u_* occurred over periods of time in
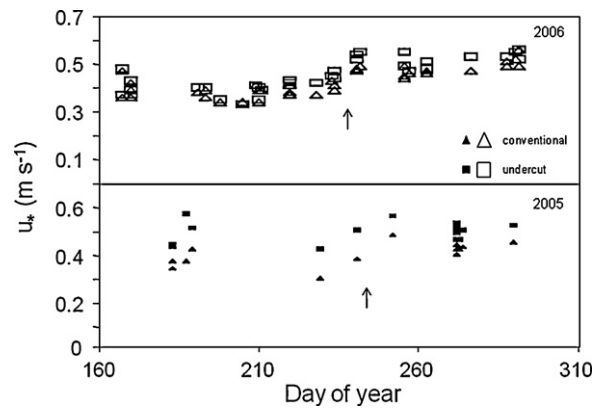

Fig. 2. Friction velocity (u_*) of conventional and undercutter tillage during high wind events in 2005 and 2006. The arrows indicate dates of sowing both years.

which the soil surface was not disturbed by field operations and precipitation. This is exemplified by differences in u_* of 0.03 m s^{-1} for conventional tillage and 0.14 m s^{-1} for undercutter tillage between days 183 and 187 in 2005 during which time there was no precipitation or tillage (Table 1). Similarly in 2006, differences in u_* of 0.11 m s^{-1} for both conventional and undercutter tillage occurred between days 167 and 170 and differences in u_* of 0.06 m s^{-1} for both conventional and undercutter tillage occurred between days 220 and 234 during which time there was no precipitation or tillage (Table 1).

Friction velocity for undercutter tillage prior to sowing in 2005 (Fig. 2) appeared anomalous for the 6 and 8 July (days 187 and 189) high wind events; these extreme u_* (0.58 and 0.52 m s^{-1}, respectively) were determined from wind velocity profile data containing the highest velocities (mean wind velocity at 6-m height was respectively 9.2 and 8.7 m s^{-1} during the events) of all events in 2005. After sowing in 2005, u_* of conventional and undercutter tillage appeared to decline with time; slope estimates of u_* versus day of year after sowing were $-0.0009 \text{ m s}^{-1} \text{ d}^{-1}$ for conventional tillage and $-0.0012 \text{ m s}^{-1} \text{ d}^{-1}$ for undercutter tillage. The apparent decline in u_* with time was contrary to our assumption that u_* would increase with time after sowing due to an increase in aerodynamic roughness of the surface and absorption of kinetic energy by the plant canopy during growth of winter wheat (wheat attained a height of 0.2 m at the end of the observation period both years). The decline in u_* with time after sowing in 2005 was not associated with any variation in mean wind velocities, as wind velocities at 6-m height ranged from 7.1 to 7.7 m s^{-1} across all high wind events after sowing. The decline in u_* with time after sowing, however, was likely influenced by a high u_* on 9 September (day 252). In fact, by omitting u_* on 9 September, u_* of conventional and undercutter tillage appeared to increase with time (slope estimates of u_* versus day of year were $0.0014 \text{ m s}^{-1} \text{ d}^{-1}$ for conventional tillage and $0.0015 \text{ m s}^{-1} \text{ d}^{-1}$ for undercutter tillage). The anomalously high u_* on 9 September was likely due to winds being more orthogonal to the NS ridges or seed rows on 9 September than on subsequent days. Winds on 9 September were from the WSW (239°) while winds for all events thereafter were more parallel to the ridges being from the SSW (191–216°).

Friction velocity of conventional and undercutter tillage prior to sowing in 2006 was highest for the 16 June (day 167) high wind event. The high u_* (0.47 m s^{-1} for conventional tillage and 0.48 m s^{-1} for undercutter tillage) corresponded with the highest wind velocities (mean wind velocity at 6-m height was 10.0 m s^{-1} during the event) observed across all high wind events in 2006. After sowing in 2006, u_* appeared to increase with time as the slope of the relationship between u_* and day of year was positive

for both conventional (0.0009 ± 0.0003 m s^{-1} d^{-1}) and undercutter tillage (0.0003 ± 0.0003 m s^{-1} d^{-1}). These temporal trends after sowing, however, were only significant ($P < 0.05$) for conventional tillage. An increase in u_* with time after sowing was likely due to continued development of wheat and not due to variation in mean wind velocity or wind direction across high wind events. Although the highest u_* for both tillage treatments (0.56 m s^{-1}) after sowing occurred in association with the highest wind velocities (mean wind velocity at 6-m height was 9.1 m s^{-1}) at the end of the period of observation on 19 October 2006 (day 292), temporal trends in u_* after removing this singular u_* from linear regression analysis remained significant for conventional tillage. Mean wind velocities at 6-m height across all other high wind events after sowing in 2006 ranged from 7.4 to 8.6 m s^{-1}, with higher velocities (>8.2 m s^{-1}) occurring within the first 20 d after sowing. In addition, an increase in u_* with time after sowing in 2006 was not imposed by a change in wind direction to a more orthogonal orientation to the NS ridges since there was no association between u_* and wind direction after sowing; in fact, there was a tendency for southwesterly winds to shift to a more southerly direction with time (slope of wind direction versus day of year was $-0.31 \pm 0.26°$ d^{-1}) after sowing.

Friction velocity was generally higher for undercutter tillage than for conventional tillage during high wind events in 2005 and 2006 (Fig. 4). Indeed, u_* was greater for undercutter tillage than for conventional tillage during all high wind events in 2005 and during 31 of the 36 high wind events in 2006. The slope estimate of the relationship between u_* for undercutter tillage and conventional tillage across all high wind events in 2005 and 2006 (Fig. 4) was not different from unity ($P < 0.05$) in both years, but the intercept of the relationship was significant ($P = 0.02$) in 2005. A paired t-test further indicated that differences in u_* between tillage treatments were significant ($P < 0.01$) both years. Although u_* was estimated from mean wind velocities during a high wind event, the variability or error in u_* was examined during singular high wind events (those that lasted >6 h) by computing u_* for each 1 min period during an event. These 1 min u_* values were then sorted by wind velocity categories of 6–7, 8–9, and 10–11 m s^{-1} at a height of 6 m. The standard error in u_* was then computed for each wind velocity category. Standard error in u_* varied little between tillage treatments, wind velocity categories, and years. For a singular high wind event, the standard error in u_* was about 0.005 m s^{-1}.

3.3. Aerodynamic roughness

Changes in the apparent roughness of the surface due to sowing winter wheat are distinguishable in the observed trend of z_o (Fig. 3). Aerodynamic roughness prior to and after sowing was respectively 2 (SE = 0.3) and 8 (SE = 0.6) mm for conventional tillage and 7 (SE = 0.5) and 15 (SE = 1) mm for undercutter tillage in 2005. In 2006, z_o prior to and after sowing was respectively 2 (SE = 0.2) and 7 (SE = 0.5) mm for conventional tillage and 4 (SE = 0.2) and 11 (SE = 0.6) mm for undercutter tillage. The greater z_o that was apparent after sowing wheat is likely due to an increase in ridge roughness in both treatments as a result of the sowing operation. Ridge roughness, defined according to Zingg and Woodruff (1951), was 0 mm prior to sowing and 89 and 108 mm after sowing in subsequent years. Enhanced random roughness did not contribute to the greater z_o after sowing because random roughness appeared to change very little as a result of the sowing operation (Table 2). After sowing in 2005, z_o declined with time; for example, the slope of the relationship between z_o and day of year was -0.14 mm d^{-1} for conventional tillage and -0.25 mm d^{-1} for undercutter tillage. Although these relationships were significant ($P < 0.05$), the high z_o observed on 9 September (day 252) influenced this trend. Opposite trends were
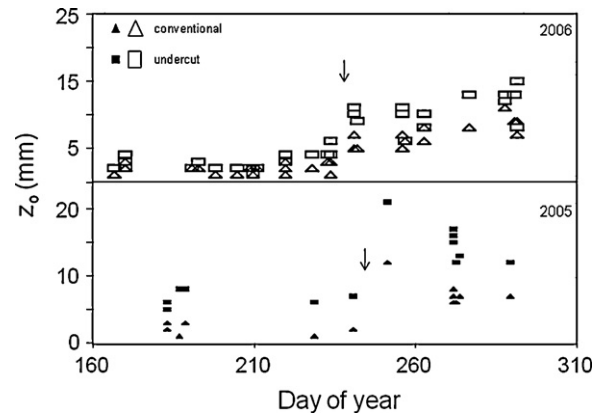
Fig. 3. Aerodynamic roughness (z_o) of conventional and undercutter tillage during high wind events in 2005 and 2006. The arrows indicate dates of sowing both years.

observed in 2006 as z_o increased with time after sowing. In fact, after sowing in 2006, the slope of the relationship between z_o and day of year was 0.08 mm d^{-1} ($P < 0.01$) for conventional tillage and 0.06 mm d^{-1} ($P = 0.07$) for undercutter tillage. The increase in z_o with time after sowing in 2006 was likely due to development of winter wheat.

Aerodynamic roughness was higher for undercutter tillage than for conventional tillage during high wind events in 2005 and 2006 (Fig. 5). The slope of the relationship between z_o of tillage treatments was significantly ($P < 0.05$) greater than unity both years while the intercept of the relationship was only significant in 2005. A paired t-test indicated that differences in z_o between tillage treatments were significant ($P < 0.01$) both years. The greater z_o of undercutter tillage was likely due to enhanced roughness of the soil surface created by the undercutter tillage implement. Indeed, silhouette are index was consistently greater for undercutter tillage than for conventional tillage both years (Table 2). Although z_o was estimated from mean wind velocities during a high wind event, the variability or standard error in z_o during singular high wind events was examined by computing z_o for each 1 min period and sorting by wind velocity categories (6–7, 8–9, and 10–11 m s^{-1} at a height of 6 m) during an event. Standard error in z_o was about 0.5 mm and varied little between tillage treatments, wind velocity categories, and years.

3.4. Impact on dust flux

The aerodynamically rougher surface of undercutter tillage should reduce sediment flux and dust emissions during high wind events as compared with conventional tillage. Indeed, Sharratt and Feng (2009) reported 15–70% less sediment flux and vertical dust
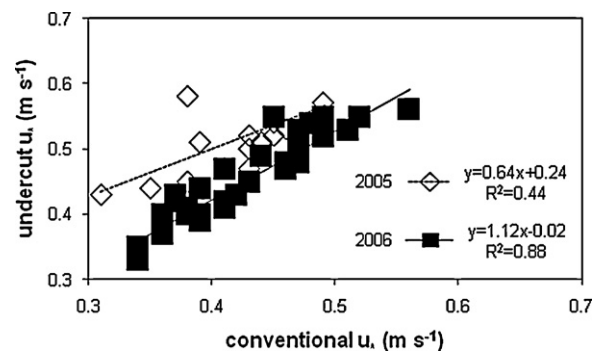
Fig. 4. Relationship between friction velocity (u_*) of conventional and undercutter tillage across all high wind events observed in 2005 and 2006.
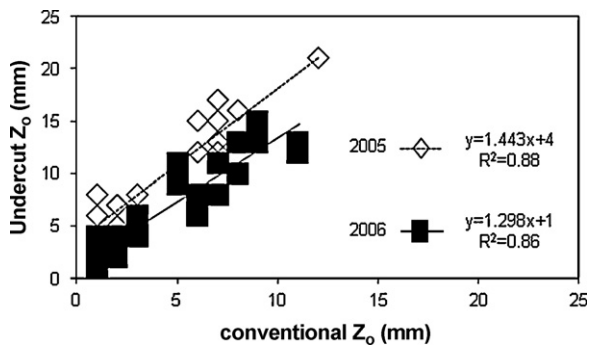
Fig. 5. Relationship between aerodynamic roughness (z_o) of conventional and undercutter tillage across all high wind events observed in 2005 and 2006.

flux from the undercutter tillage plot than from conventional tillage plot across four high wind events in 2005 and 2006. However, differences in sediment loss and dust flux between tillage treatments were not observed when the soil surface was completely covered with a crust. Since u_* was higher for undercutter tillage than for conventional tillage, the smaller F measured from undercutter tillage can only be possible if u_{*t} was also higher for undercutter tillage than for conventional tillage. Based upon silhouette area and prostrate residue cover measured prior to sowing both years (Table 2), u_{*t} estimated from Eq. (5) was 0.35 m s^{-1} for conventional tillage and 0.85 m s^{-1} for undercutter tillage in 2005 and 0.30 m s^{-1} for conventional tillage and 0.55 m s^{-1} for undercutter tillage in 2006. For undercutter tillage, the estimated u_{*t} exceeded the observed u_* both years; therefore, the estimated F was zero prior to sowing in 2005 and 2006. Dust flux, however, was observed from undercutter tillage during one high wind event prior to sowing in 2006 (Sharratt and Feng, 2009). This disparity in estimated and observed dust flux, although for one high wind event, may be due in part to inaccurately specifying the threshold friction velocity of unconsolidated soil particles (we assumed a mean particle diameter of 100 μm) in estimating u_{*t}. For conventional tillage, the estimated u_{*t} was less than the observed u_* both years; thus, the estimated F was >0 μg m^{-2} s^{-1} both years. Although γ in Eq. (3) varies between ∼0.001 and 0.01 g s^3 m^{-6} for the Columbia Plateau (Claiborn et al., 1998), γ was assumed to equal 0.001 g s^3 m^{-6} for the purpose of conservatively estimating flux in this study. According to Eq. (3), the estimated F from conventional tillage was 0.5 and 4.5 μg m^{-2} s^{-1} prior to sowing in subsequent years. Although Sharratt and Feng (2009) only observed F during one high wind event prior to sowing across both years, their observed F from conventional tillage in 2006 (9 μg m^{-2} s^{-1}) is comparable to that estimated in 2006. These findings suggest that the aerodynamically rougher surface of undercutter tillage likely increases the threshold friction velocity and thereby reduces sediment flux and vertical dust flux during high wind events as compared with conventional tillage.

4. Conclusions

Undercutter tillage has been promoted as a conservation tillage practice during the summer fallow phase of a winter wheat–summer fallow rotation to reduce wind erosion within the Columbia Plateau of the Pacific Northwest United States. Unknown, however, is the extent to which undercutter tillage affects soil surface characteristics that govern wind erosion. Friction velocity and z_o were greater for undercutter tillage than for conventional tillage, apparently due to enhanced roughness of the soil surface created by the undercutter tillage implement. Based upon estimates of u_{*t} from crop residue cover and silhouette area index prior to sowing both tillage treatments, vertical dust flux is expected, and was collaborated, to be lower from undercutter tillage than from conventional tillage. Undercutter tillage promotes retention of crop residue and roughness elements on the soil surface that reduces dust emissions from soils in the Columbia Plateau.

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