EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms **34**, 1323–1332 (2009)

(www.interscience.wiley.com) DOI: 10.1002/esp.1812

Windblown dust influenced by conventional and undercutter tillage within the Columbia Plateau, USA†

B. S. Sharratt[1]* and G. Feng[2]
[1] USDA-Agricultural Research Service, Pullman, Washington, USA
[2] Washington State University, Department of Biosystems Engineering, Pullman, Washington, USA

Received 29 September 2008; Revised 12 January 2009; Accepted 16 February 2009

* Correspondence to: B. Sharratt, USDA-Agricultural Research Service, 213 LJ Smith Hall, Washington State University, Pullman, WA 99164, USA. E-mail: Sharratt@wsu.edu
† The contribution of B. S. Sharratt to this article was prepared as part of his duties as a United States Federal Government Employee.

Earth Surface Processes and Landforms

ABSTRACT: Exceedance of the US Environmental Protection Agency national ambient air quality standard for PM10 (particulate matter ≤10 μm in aerodynamic diameter) within the Columbia Plateau region of the Pacific Northwest US is largely caused by wind erosion of agricultural lands managed in a winter wheat–summer fallow rotation. Land management practices, therefore, are sought that will reduce erosion and PM10 emissions during the summer fallow phase of the rotation. Horizontal soil flux and PM10 concentrations above adjacent field plots (>2 ha), with plots subject to conventional or undercutter tillage during summer fallow, were measured using creep and saltation/suspension collectors and PM10 samplers installed at various heights above the soil surface. After wheat harvest in 2004 and 2005, the plots were either disked (conventional) or undercut with wide sweeps (undercutter) the following spring and then periodically rodweeded prior to sowing wheat in late summer. Soil erosion from the fallow plots was measured during six sampling periods over two years; erosion or PM10 loss was not observed during two periods due to the presence of a crust on the soil surface. For the remaining sampling periods, total surface soil loss from conventional and undercutter tillage ranged from 3 to 40 g m^{-2} and 1 to 27 g m^{-2} while PM10 loss from conventional and undercutter tillage ranged from 0·2 to 5·0 g m^{-2} and 0·1 to 3·3 g m^{-2}, respectively. Undercutter tillage resulted in a 15% to 65% reduction in soil loss and 30% to 70% reduction in PM10 loss as compared with conventional tillage at our field sites. Therefore, based on our results at two sites over two years, undercutter tillage appears to be an effective management practice to reduce dust emissions from agricultural land subject to a winter wheat–summer fallow rotation within the Columbia Plateau. Copyright © 2009 John Wiley & Sons, Ltd.

KEYWORDS: wind erosion; air quality; PM10; particulates

Introduction

Wind erosion degrades soil productivity as a result of removing fertile topsoil. As the rate of soil erosion exceeds the rate of soil regeneration, biomass production cannot be sustained as a result of depletion of the soil resource. Therefore, development of control strategies that will mitigate wind erosion is imperative to conserving the soil resource. Wind erosion is initiated when the friction velocity exceeds the threshold friction velocity at the surface. Threshold velocity is governed by soil surface characteristics such as soil moisture, soil texture, soil crust cover, and surface roughness whereas friction velocity is strictly influenced by wind velocity and the protrusion of roughness elements above the soil surface.

Wind erosion can also impair crop vigor and visibility. Indeed, crop vigor can be impaired as a result of saltating particles sandblasting seedlings (Fryrear, 1986a), erosion exposing newly sown seeds or tubers, or deposition of eroded sediment burying seedlings emerging in the furrow of seed rows. Lack of visibility caused by windblown dust has resulted in vehicular accidents and loss of life (Hudson and Cary, 1999). The process of eroding soil by wind can also liberate fine soil particulates into the atmosphere that adversely affects human health. Stetler and Saxton (1996) found a positive relationship between mass of soil eroded from an agricultural field and mass of PM10 (particulate matter ≤10 μm in aerodynamic diameter) in the atmosphere during high wind events on the Columbia Plateau. In the western US, emission of fine particulates into the atmosphere caused by high winds has contributed to the exceedance of the US Environmental Protection Agency ambient air quality standard for PM10. In fact, PM10 emitted from agricultural lands in the Columbia Plateau region of the Pacific Northwest is a major contributor to poor air quality (Saxton, 1995; Sharratt and Lauer, 2006).

Agricultural lands maintained in a winter wheat–summer fallow rotation (about 1·5 million ha) are particularly vulnerable to wind erosion and are the primary source of atmospheric PM10 during high wind events on the Columbia Plateau. During the summer fallow phase of the rotation, soils are very susceptible to erosion due to a lack of vegetative cover, little surface roughness, and small aggregate size as a result of multiple tillage operations. Few options have been developed as an economic alternative to the conventional winter wheat–summer fallow rotation. During the 13-month summer fallow phase of the rotation, soils are usually tilled with sweeps, disks, or cultivators after wheat harvest in late summer and again the following spring and then rodweeded to control weeds during summer (Schillinger, 2001). Every tillage operation tends to reduce crop residue cover (Wagner and Nelson, 1995) and surface roughness (Romkens and Wang, 1986; Zobeck and Onstad, 1987). Crop residue cover and surface roughness greatly affect soil erosion. In fact, wind erosion decreases exponentially with an increase in residue cover (Chepil, 1944; Fryrear, 1985). Wind erosion also decreases with an increase in surface roughness (Chepil and Milne, 1941; Fryrear, 1984). Horning *et al.* (1998) also found an exponential decrease in wind erosion with residue cover and roughness of soils within the Columbia Plateau. These studies suggest that alternative tillage practices that enhance residue cover or roughness could reduce wind erosion and possibility PM10 emissions from soils in summer fallow on the Columbia Plateau.

Management of agricultural land to reduce PM10 emissions within the Columbia Plateau region of the Pacific Northwest US has been the focus of a multidisciplinary research program since the early 1990s (Saxton, 1995; Sharratt and Schillinger, 2005). Land management options are sought as an alternative to the conventional winter wheat–summer fallow rotation for reducing PM10 emissions during high wind events. The US Department of Agriculture (USDA)-Natural Resources Conservation Service has recently implemented a cost-sharing program with growers for acquiring an undercutter tillage implement with the goal of reducing wind erosion and PM10 emissions (Burnham, 2007). The undercutter implement consists of wide, over-lapping, V-shaped blades mounted on a tool bar; these blades minimize soil inversion that otherwise occurs with a plow, sweep, or disk. No previous studies have examined the impact of the undercutter conservation tillage implement on both erosion and PM10 emissions from agricultural soils during high wind events. Therefore, the objective of this study was to assess wind erosion and PM10 emissions from soils subject to conventional and undercutter tillage during the summer fallow phase of a winter wheat–summer fallow rotation.

Materials and Methods

This two-year study was conducted on land owned and operated by wheat growers. The physical location of the field sites differed between years, but both sites are located within the low precipitation zone (<300 mm annual precipitation) of the Columbia Plateau region (Figure 1) where agricultural land is predominately in a winter wheat–summer fallow rotation. The fallow phase of the rotation began after harvest of wheat in July of 2004 and 2005. In 2004, the field site (46°51′N, 118°39′W; elevation 505 m) was located 12 km southwest of Lind, Washington on a Shano silt loam (Andic Aridic Haplustoll). The site has a 2% east slope and an annual precipitation of 220 mm. In 2005, the field site (46°53′N, 118°26′W; elevation 525 m) was located 14 km southeast of Lind, Washington on a Ritzville silt loam (Andic Aridic Haplustoll). The site was level and receives 250 mm of annual precipitation. Dispersed particle size analysis (measured using a Malvern Mastersizer S laser diffractometer) indicated that Shano silt loam had a mass median diameter of 36 μm, sand (>50 μm) content of 34%, and clay (<2 μm) content of 10% while Ritzville silt loam had a mass median diameter of 24 μm, sand content of 21%, and clay content of 14%. Both soils have an organic matter content of 1% and $CaCO_3$ content of 0% in the upper 3 cm of the profile.

Tillage

Soil and PM10 loss were measured from adjacent field plots during high wind events, with the plots subject to either conventional tillage or undercutter tillage during the fallow phase of a winter wheat–summer fallow rotation. Data collected from these non-replicated field plots were used to validate field-scale wind erosion processes as simulated by the Wind Erosion Prediction System (Feng and Sharratt, 2009). Field plots were 200 m × 100 m in 2004 and 200 m × 200 m in 2005. The longer plot dimension in 2004 was oriented east–west. Conventional tillage in this study constituted those management practices typically employed by the grower.

In 2004, the field plots (in wheat stubble) were not disturbed until the following spring when the conventional tillage plot was disked (double disk with a spring tooth harrow) to a depth of 0·1 m on 2 May 2005. The undercutter tillage plot was tilled to a depth of 0·1 m using an undercutter implement and spring tooth harrow on 5 May 2005. The undercutter implement had 0·81 m wide V-blades. Fertilizer was incorporated into the soil on both plots using a shank applicator on 6 May. Both field plots were rodweeded on 10 May (to establish a uniform subsurface interface at a depth of 0·1 m for conserving soil moisture) and 21 July prior to sowing winter wheat on 31 August 2005 with a deep furrow drill.

In 2005, the field plots (in wheat stubble) were harrowed twice in August to incorporate weed seed. No further tillage

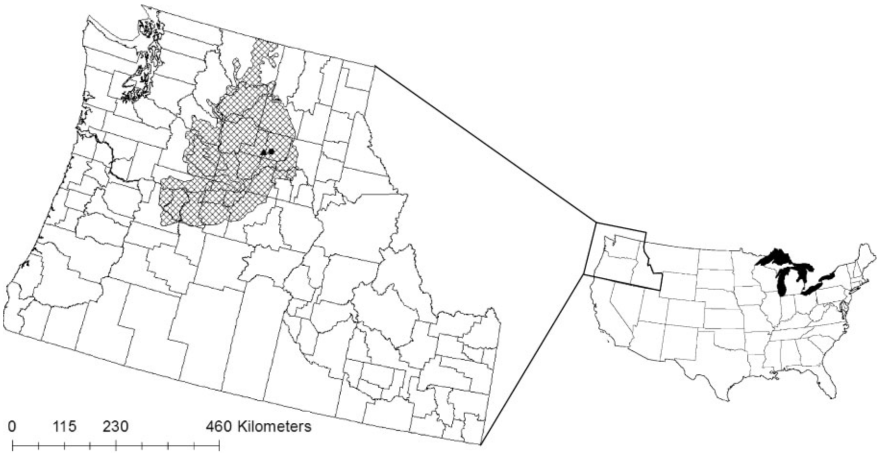

Figure 1. Location of field sites in 2005 (triangle) and 2006 (circle) within the Columbia Plateau region (shaded area) of the Pacific Northwest United States. The larger image includes county boundaries in Idaho, Oregon, and Washington.

DOI: 10.1002/esp

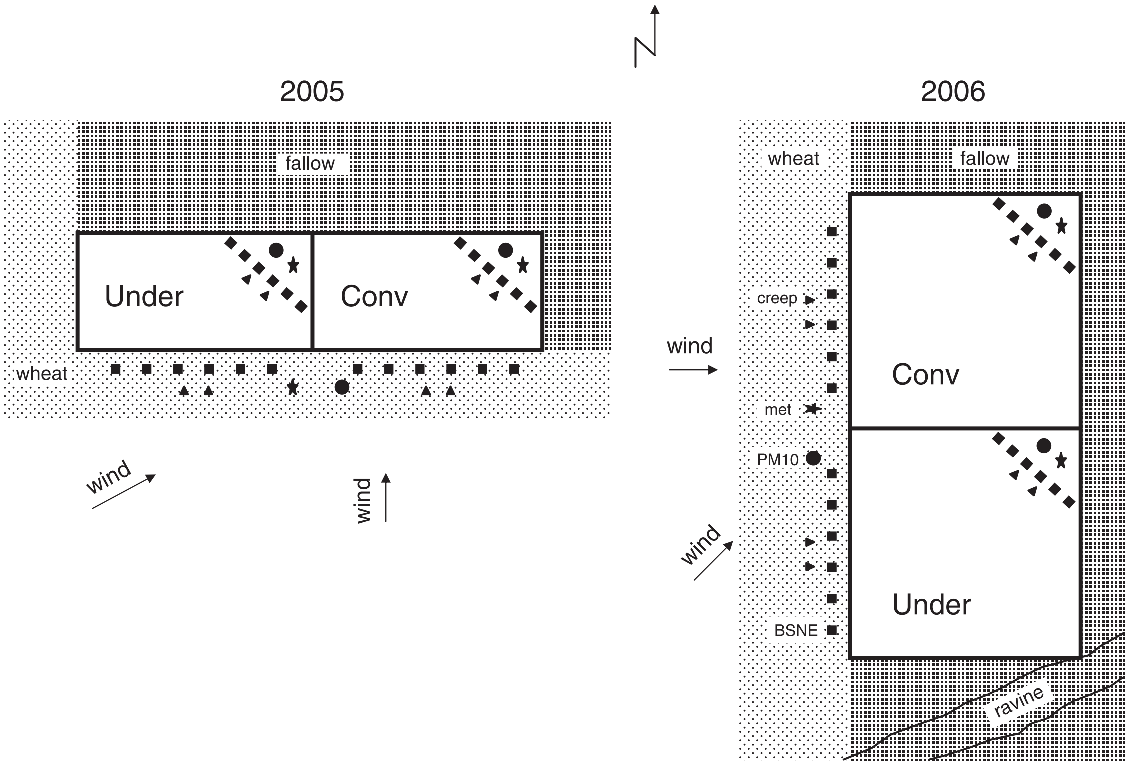

Figure 2. Layout of instrumentation in conventional (conv.) and undercutter (under.) tillage plots for measuring PM10 concentration, sediment flux using BSNE and creep samplers, and weather (met) in 2005 and 2006. Land surrounding the plots was either in wheat or summer fallow.

occurred until the following spring when the conventional tillage plot was disked (double disk with a spring tooth harrow) to a depth of 0·1 m on 30 April 2006. The undercutter tillage plot was tilled on 30 April 2006 to a depth of 0·1 m using the same undercutter implement and spring tooth harrow as the previous year. Both field plots were fertilized using a shank applicator on 2 June 2006, rodweeded on 24 June and 6 August, and sown to winter wheat on 27 August 2006 with a deep furrow drill.

Instrumentation

The field plots were instrumented after disking or undercutting in spring 2005 and 2006 to monitor horizontal soil flux and PM10 concentration at the windward and leeward positions. Layout of the instrumentation within the landscape encompassing the plots is illustrated in Figure 2. The windward boundary (south end of tillage plots in 2005 and the west end of tillage plots in 2006), and extending at least a distance 1 km upwind, was maintained in winter wheat during the 2005 and 2006 growing seasons. An ancient ravine (10 m deep and 50 m wide) extended along the south boundary of the undercutter plot in 2006. Instruments were installed at the leeward position (northeast corner) of the field plots. Soil and PM10 loss were assessed only for those high wind events that had prevailing winds between ~180–250° during the summer of 2005 and between ~225–270° during the summer of 2006; this ensured that a non erodible boundary was maintained upwind of the plots and that sediment captured at the leeward position in the field plot originated from the plot area. A high wind event was initiated when 1-minute average wind speeds at a height of 3 m exceeded 6·4 m s^{-1} for 10 consecutive minutes. This wind speed defines the threshold of movement for denuded, non-crusted, and finely aggregated soils (Saxton *et al.*, 2000) and appears to be a conservative estimate of the threshold velocity for PM10 within the Columbia Plateau (Kjelgaard *et al.*, 2004a). The high wind event terminated when the 3-m wind speed subsided to ≤5·0 m s^{-1} for 15 consecutive minutes.

Horizontal soil flux was measured using creep and BSNE (Big Spring Number Eight) collectors (Custom Products & Consultants LLC, Big Spring, Texas) commonly employed in wind erosion research (Zobeck *et al.*, 2003). Two creep collectors and six sets of BSNE collectors were installed along the windward boundary and at the leeward position in the plots (Figure 2). The creep collectors trapped sediment discharge below a height of 0·025 m while BSNE collectors trap sediment in saltation and suspension. The BSNE collectors typically have an efficiency of 0·4 for suspension-size particles (Goossens *et al.*, 2000) and 0·9 for saltation-size particles (Fryrear, 1986b). A set of BSNE collectors consisted of five BSNE collectors mounted on a pole at heights of 0·1, 0·2, 0·5, 1·0 and 1·5 m. Our goal was to retrieve sediment from the collectors after one high wind event or a series of high wind events with persistent southwest winds (prevailing wind direction); however, due to the remoteness of the field sites, sediment was not always obtained after a singular wind event or series of events with persistent southwest winds. In those instances when winds were not persistently from a southerly direction in 2005 or westerly direction in 2006 between days of data retrieval from the field (sample period), data were not collected and all instruments were cleaned and re-initialized for the next sample period. For those high wind events characterized by persistent southwest winds, sediment obtained from the collectors was placed in a plastic bag and air dried prior to weighing and separating into 10, 45 and 100 μm diameter fractions using a sonic sieve (Advantech Manufacturing Inc., New Berlin, Wisconsin). Approximately 0·3 g of the sediment (which was well mixed prior to extracting from the bag using a spatula) was screened through the stack of sieves for 15 minutes. Hagen *et al.* (2007) have also used sonic sieves to separate out PM10 from windblown sediment. Larger sieve diameters were not used to separate the sediment because >90% of sediment eroded from silt loams on the Columbia Plateau is <100 µm in diameter (Sharratt *et al.*, 2007).

Sediment mass in each BSNE collector was corrected to account for sampling inefficiency of the collector. Catch efficiency of the BSNE collector for suspended sediment (particles <100 µm in diameter) and PM10 was determined for both Shano silt loam and Ritzville silt loam in a wind tunnel at a wind speed of 3, 6 and 8 m s^{-1} as described by Sharratt *et al.* (2007). Over this range of wind speed, catch efficiency of the BSNE collector for suspended sediment varied from 0·65 to 0·70 for Shano silt loam and from 0·60 to 0·70 for Ritzville silt loam. For the same range in wind speed, the catch efficiency for PM10 varied from 0·10 to 0·25 for Shano silt loam and from 0·15 to 0·25 for Ritzville silt loam. Catch efficiency of the BSNE collector as a function of wind speed was estimated for Shano silt loam as:

$$\mathrm{CE100} = 0{\cdot}754u^{-0{\cdot}057};\ R^2 = 0{\cdot}987 \quad (1)$$

$$\mathrm{CE10} = 1{\cdot}184u^{-1{\cdot}188};\ R^2 = 0{\cdot}999 \quad (2)$$

and for Ritzville silt loam as:

$$\mathrm{CE100} = 0{\cdot}796u^{-0{\cdot}119};\ R^2 = 0{\cdot}993 \quad (3)$$

$$\mathrm{CE10} = 0{\cdot}531u^{-0{\cdot}581};\ R^2 = 0{\cdot}999 \quad (4)$$

where CE100 and CE10 are the catch efficiencies of the BSNE collector for suspended sediment and PM10, respectively, and u is wind speed (in m s^{-1}) at the opening of the BSNE collector.

PM10 concentration was measured using High Volume PM10 samplers (model PM10, Graseby-Andersen, Village of Cleves, Ohio) and Esamplers (Met One, Grants Pass, Oregon). Although PM10 High Volume samplers may overestimate PM10 concentrations (Buser *et al.*, 2007), these samplers are used extensively by federal and state agencies in the US. One High Volume sampler and Esampler was deployed at a height of 1·5 and 6 m above the soil surface at the windward boundary of the plots and at the leeward position in the conventional and undercutter tillage plots. Esamplers were also deployed at a height of 3 m at the windward boundary and leeward position in both plots. The High Volume samplers served as a reference and basis for comparison of Esamplers. Flow rate of the High Volume PM10 samplers and Esamplers were checked prior to deployment. High Volume PM10 samplers were activated only during high wind events. The Esampler was programmed to perform a zero check and to record 5 minute average concentrations. As recommended by the manufacturer, periodic comparisons between Esampler gravimetric and optic PM concentrations were performed in the field. Filters for the High Volume samplers and Esamplers were equilibrated to standard laboratory conditions (air temperature of 20 °C and relative humidity of 45%) prior to weighing before deployment and after retrieval from the field which occurred on the day sediment was acquired from the BSNE and creep collectors.

An automated weather station was deployed at the windward and leeward position in the conventional tillage and undercutter tillage plots to measure relative humidity, wind speed, and temperature. Wind speed (model 014A, Met One, Grants Pass, Oregon) and air temperature (fine wire thermocouples) were measured at heights of 0·1, 0·5, 1, 2, 3, and 6 m. Sensors were monitored every 10 s with data recorded hourly except during high wind events when data were recorded every minute. Precipitation and solar radiation were also measured at the conventional tillage plot.

Vertical PM10 flux estimation

Vertical PM10 flux (F_v) within the boundary layer was estimated during each sample period by (Gillette, 1977):

$$F_v = ku^*[\delta C/\delta \ln(z)] \quad (5)$$

where k is von Karman's constant (0·4), u^* is friction velocity (in m s^{-1}), C is PM10 concentration (in µg m^{-3}), and z is height (in meters). Vertical flux was estimated from PM10 concentrations measured at heights of 1·5 and 3 m. The wind speed profile within the boundary layer is described by:

$$u_z = u^*\ln(z/z_o)/k \quad (6)$$

where u_z is wind speed (in m s^{-1}) at height z and z_o is the roughness height (in meters). Both u^* and z_o were obtained by regression analysis of u versus ln$z$ within the inertial layer.

Sediment and PM10 loss estimation

The vertical distribution of sediment captured by the BSNE collectors was described by a logarithmic function (our data, after correcting for catch efficiency, were better represented by a logarithmic function as compared with a power or exponential function). The function was integrated from 0·025 m to the height of the dust plume and the result added to the sediment trapped by the creep collector to obtain total horizontal sediment flux. Sediment loss (L_{sed}) from the plot was determined as:

$$L_{\mathrm{sed}} = (Q_l - Q_w)/d \quad (7)$$

where Q is total horizontal sediment flux at the leeward (subscript l) and windward (subscript w) positions in the plot and d is the distance across the plot in the direction of the prevailing wind.

PM10 loss was estimated from PM10 concentration profiles acquired using PM10 samplers and BSNE collectors. PM10 concentration at height z was determined from BSNE sediment catch at height z by correcting the BSNE PM10 mass for catch efficiency and dividing by the product of wind speed (in m s^{-1}) at height z, area of BSNE opening (in m^2), and duration of the wind event(s). PM10 concentration at height z was multiplied by wind speed at height z and duration of event to obtain horizontal PM10 flux at height z. Differences in PM10 concentration were observed between that estimated by BSNE sediment catch and that measured by PM10 High Volume samplers co-located at a height of 1·5 m above the soil surface, but those differences generally varied between 0·5% to 13% of that measured by the High Volume sampler. The vertical distribution of PM10 concentration or horizontal PM10 flux was described by a power function (our data were better represented by a power function as compared with a logarithmic or exponential function). Total horizontal PM10 flux was then determined by integrating PM10 flux from 0·025 m to plume height. Dust plume height was obtained by extrapolating the PM10 concentration profile at the leeward and windward positions in the plot and determining the height at which the top of the profiles intercepted as illustrated by Sharratt *et al.* (2007). Plume height varied from 6 to 7 m for the high wind events observed in this study. Loss of PM10 (L_{PM10}) was determined as:

$$L_{PM10} = (PM10_l - PM10_w)/d \quad (8)$$

where PM10 is total horizontal PM10 flux at the leeward (subscript l) and windward (subscript w) positions in the plot.

Results and Discussion

A high wind event resulting in elevated dust concentrations across the Columbia Plateau typically occurs in association with the passage of a synoptic low pressure system to the north of the region. Southwesterly winds of ≥6 m s^{-1} can be sustained for more than 10 hours during the passage of these synoptic systems (Claiborn *et al.*, 1998). In this study, the duration of singular high wind events characterized by persistent southwesterly winds approached 15 hours in 2005 (29 September) and 20 hours in 2006 (21 August). South-southwest winds (3-m height) attained a velocity of 9 m s^{-1} on 29 September 2005 and 14 m s^{-1} on 21 August 2006.

Although one or more high wind events occurred during a sampling period in this study (Table I), one or more events also occurred within a single day. For example, although two high wind events were observed between 31 August and 14 September 2005, both events occurred on 9 September 2005. A total of 33 high wind events occurred on 29 days during the period of observation in 2005 (12 May to 18 October) and 49 high wind events occurred on 39 days during the period of observation in 2006 (6 June to 20 October). Of these wind events, only 12% were characterized by persistent south-southwest (180°–250°) winds in 2005 and only 8% were characterized by persistent west-southwest (225º–270°) winds in 2006 whereby a non-erodible boundary was maintained upwind of the experimental plots for the duration of the sampling period.

The maximum 1-minute wind speed recorded at a height of 3 m during the period of observation in successive years was 20·4 and 14·5 m s^{-1}. These maximum wind velocities, which are greater than those observed during the six sampling periods with persistent south-southwest or west-southwest winds (Table I), occurred on 21 June 2005 and 16 June 2006. Sediment loss, however, could not be assessed as a result of these extreme winds. Prevailing winds in excess of 6·4 m s^{-1} shifted from the north (28°) in the morning to the southwest (217°) in the afternoon of 21 June 2005; this shift in wind direction nullified our experimental design in maintaining a non-erodible boundary at the windward position in the field plots during the sampling period. In addition, sediment collected as a result of the high wind event that lasted from 11:00 to 22:20 on 16 June 2006 was confounded by southerly (202°) winds that attained velocities of ≥9 m s^{-1} during the morning of 17 June 2006.

The maximum 5-minute PM10 concentration observed at a height of 3 m over the six sampling periods reported in this study was 2580 µg m^{-3}. This concentration occurred on a Ritzville silt loam during the 29–30 August 2006 sampling period (Table II) and is much less than the 8535 µg m^{-3} previously reported above an eroding Ritzville silt loam in summer fallow by Sharratt *et al.* (2007). Although observations by Sharratt *et al.* (2007) were taken only 5 km distant from field plots used in this study, the higher PM10 concentration observed by Sharratt *et al.* may reflect dissimilarities in location characteristics between years. For example, Sharratt *et al.* (2007) measured PM10 concentrations at a height of 5 m above a 9-ha field during the second consecutive year of summer fallow. In addition, the higher PM10 concentration reported by Sharratt *et al.* (2007) may be due in part to the greater wind velocity (17·6 m s^{-1}) observed during the sampling period than in this study (12·0 m s^{-1} reported in Table I). Maximum and mean PM10 concentrations during high wind events were typically lower for undercutter than for conventional tillage (Table II). For those sampling periods in which erosion occurred from the tillage plots, mean PM10 concentration at a height of 3 m was 10% to 40% lower for undercutter tillage than for conventional tillage.

Horizontal flux of sediment to a height of 1·5 m above the soil surface at the leeward position in the field attained 1·9 kg m^{-1} for conventional tillage and 1·2 kg m^{-1} for undercutter tillage across the six sampling periods in this study (Table II). Although these fluxes are comparable to those observed previously in the Columbia Plateau (Saxton *et al.*, 2000; Sharratt *et al.*, 2007), Saxton *et al.* (2000) and Sharratt *et al.* (2007) have also observed horizontal fluxes approaching 25 kg m^{-1} for agricultural fields in summer fallow. Horizontal flux of sediment during high wind events on the Columbia Plateau, however, appear to be a magnitude smaller compared with fluxes observed during singular high wind events in the Great Plains region of the US. For example, a flux of 530 kg m^{-1} from a loam soil was observed in Indiana (Fryrear and Saleh, 1993) and a flux of about 350 kg m^{-1} was reported in Texas (Fryrear *et al.*, 1991). In this study, horizontal flux of sediment to a height of 1·5 m above the soil surface at the leeward position in the field was 20% to 75% smaller for undercutter tillage than for conventional tillage (Table II).

Horizontal sediment flux and PM10 concentration decreased rapidly with height above the soil surface for those sampling periods in which erosion occurred from the tillage plots. Profiles of sediment flux and PM10 concentration are illustrated in

Table I. Characteristics of high wind events observed at field sites near Lind, Washington in 2005 and 2006

Year	Sampling period[a]	Duration[b] (min)	Days/events[c]	Wind[d] Mean (m s^{-1})	Maximum (m s^{-1})	Direction
2005	23 June–8 July	1432	2/2	6·9	13·0	239–249
	31 August–14 September	438	1/2	5·7	9·7	221–235
2006	14–19 July	634	1/1	6·4	10·4	234
	19–25 July	381	1/1	5·6	9·3	262
	19–30 August	991	1/1	7·5	12·0	233
	30 August–6 September	664	1/1	7·7	11·6	231

[a] Dates corresponding to data collection at the field site.

[b] Total minutes of all high wind events (an event is defined by the time over which wind speed at a height of 3 m exceeded 6·4 m s^{-1}) occurring within the sample period.

[c] Number of days with high wind event and number of high wind events during sample period.

[d] Mean and maximum 3-m wind speed as determined from 1 minute averages and range in wind direction of all high wind events occurring within sample period.

Table II. Horizontal soil flux and PM10 concentration during high wind events for field sites subject to conventional (conv.) and undercutter (under.) tillage near Lind, Washington in 2005 and 2006

		Soil flux[a]		PM10 concentration[b]			
				Mean		Maximum	
Year	Sampling period	Conv. (kg m^{-1})	Under. (kg m^{-1})	Conv. (μg m^{-3})	Under. (μg m^{-3})	Conv. (μg m^{-3})	Under. (μg m^{-3}
2005	23 June–8 July	0	0	24	21	132	108
	31 August–14 September	0·7	0·5	305	232	2203	1800
2006	14–19 July	0·2	0·1	22	20	60	53
	19–25 July	0	0	12	12	24	36
	29–30 August	1·9	1·2	452	398	2580	1896
	30 August–6 September	1·4	1·1	238	145	1584	1188

[a] Horizontal soil flux integrated over a height of 0 to 1·5 m at the leeward position in the field as determined from BSNE sediment catch (data no adjusted for sampler inefficiency) during the sampling period.

[b] PM10 concentration at 3-m height above the soil surface at the leeward position in the field based upon 5-minute averages during the sampl period.

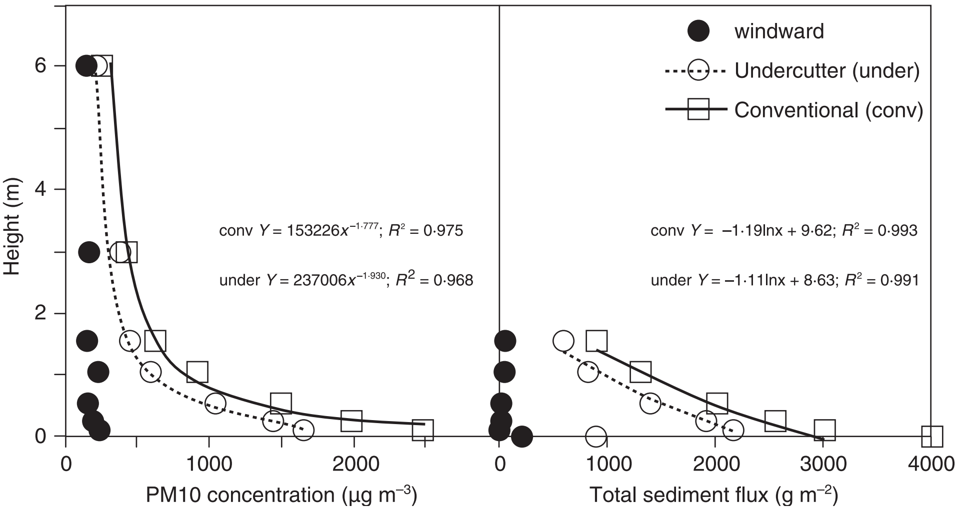

Figure 3. Total horizontal sediment flux and PM10 concentration measured above the windward boundary and adjacent eroding field plots subject to undercutter tillage or conventional tillage practices for the 29–30 August 2006 high wind event. Power and logarithmic functions were fit to data except at soil surface.

Figure 3 for the 29–30 August 2006 high wind event which resulted in the greatest soil loss reported in this study. Sediment flux profiles were best described by logarithmic functions while PM10 concentration profiles were best characterized by power functions with coefficients of determination (R^2) that varied from 0·90 to 0·99 for sediment flux and 0·81 to 0·98 for PM10 concentration across all high wind events and tillage treatments. Other investigators have also found that sediment flux above an eroding surface can be adequately described as a function of height (Fryrear *et al.*, 1991; Zobeck *et al.*, 1989). Indeed, Vories and Fryrear (1991) found that saltation flux with height was best described by an exponential function while suspension flux with height was best defined by a power function. These and other functions, however, cannot adequately describe the vertical distribution of eroded sediment above every type of surface. Zobeck *et al.* (1989), for example, found an R^2 of 0·99 using power functions to describe windblown sediment flux above a burned or tilled field and an R^2 of <0·5 using linear and non-linear functions to describe sediment flux above rangeland sites. Sediment flux, as determined by creep and BSNE sediment collectors positioned 0 to 1·5 m above the soil surface, was greater for conventional tillage than undercutter tillage. PM10 concentration, to a height of 6 m, was also greater for conventional tillage than for undercutter tillage. At the windward boundary of the tillage plots, lack of sediment flux near the soil surface (Figure 3) suggests no transport of sediment into the field plots from upwind sources while little variation in PM10 concentration with height is indicative of the regional background PM10 concentration. These observations suggest that the windward boundary was effective in minimizing influx of sediment from adjacent crop land into the tillage plots.

Soil loss

Sediment deposited in the creep or BSNE collectors, or horizontal flux of sediment, was not observed during the 23 June–8 July 2005 and 19–25 July 2006 sampling periods (Table II) despite winds attaining velocities sufficient to erode dry, unconsolidated, and fine soil particles. In fact, maximum wind velocities during the 23 June–8 July 2005 sampling period was greater than velocities attained during all other sampling periods in this study (Table I). Lack of soil movement was likely due to the presence of a crust on the soil surface during both sampling periods. A 9-mm thick soil crust was observed during the 23 June–8 July 2005 sampling period while a thin (<1 mm) and discontinuous crust (fraction of soil

DOI: 10.1002/esp

surface crusted was about 0·4) was observed during the 19–25 July 2006 sampling period (Feng and Sharratt, 2009). A thin (<1 mm) and sporadic soil crust was also measured during the 14–19 July 2006 sampling period, but winds were of sufficient duration or velocity to cause erosion from both the conventional and undercutter tillage plots. Although little is known about the effect of discontinuous crust cover on sediment transport and emissions, soil crusts can have a large impact on wind erosion processes. Gillette (1988), for example, found large differences in threshold friction velocities between crusted and non-crusted agricultural soils. Similarly, Woodruff and Siddoway (1965) assumed that a crust on the soil surface reduced soil loss by about 80% during high winds as compared with non-crusted soils. Soil erosion can occur from crusted soils as a result of saltation. Since saltation occurs only to a limited extent during high winds on the Columbia Plateau (Kjelgaard *et al.*, 2004b; Sharratt *et al.*, 2007), soil crustal material may be more stable in the absence of saltation and act as non-erodible elements on the surface. Fryrear (1984) observed that soil loss was reduced by nearly 90% when 60% of the soil surface was covered by non-erodible elements. Therefore, partial crust cover may substantially reduce soil loss in this study. The 9-mm thick crust observed during the 23 June–8 July 2005 sample period was caused by seven rainfall events (total precipitation equaled 17·8 mm) that occurred between rodweeding (10 May) and 23 June. Likewise, the thin and sporadic crust observed during the 14–19 July and 19–25 July 2006 sampling periods was caused by two rainfall events (0·8 and 0·2 mm) that occurred between rodweeding (24 June) and 14 July.

Soil loss from conventional tillage ranged from 3 to 40 g m^{-2} while loss from undercutter tillage ranged from 1 to 27 g m^{-2} across all but the 23 June–8 July 2005 and 19–25 July 2006 sample periods observed in this study (Table III). Soil loss from conventional tillage was much smaller than losses previously reported by Sharratt *et al.* (2007) on the Columbia Plateau where a loss of 230 g m^{-2} was observed during a single high wind event. This loss occurred from a non-crusted Ritzville silt loam subject to wind velocities that attained 17·6 m s^{-1} (Feng and Sharratt, 2007). Soil loss during high winds on the Columbia Plateau, however, appears much smaller than those reported in the Great Plains of the US. Hagen (2004), for example, observed soil loss of 7470 g m^{-2} from a sandy loam during a single high wind event in Kansas. For those periods in which erosion occurred by wind, undercutter tillage resulted in a 15% to 65% reduction in soil loss compared with conventional tillage. This reduction in soil loss may be attributed in part to consistently greater stem area index and surface cover for undercutter tillage as compared with conventional tillage during 2005 and 2006. Data of Feng and Sharratt (2009) suggest that stem area index and biomass surface cover were 0·015 $m^2 m^{-2}$ and 20% for conventional tillage and 0·04 $m^2 m^{-2}$ and 30% for undercutter tillage averaged across the two sampling periods in 2005. In 2006, stem area index and biomass surface cover were 0·005 $m^2 m^{-2}$ and 15% for conventional tillage and 0·015 $m^2 m^{-2}$ and 35% for undercutter tillage averaged across the four sampling periods. The importance of stem area index and surface cover in controlling wind erosion is substantiated by Siddoway *et al.* (1965) and Hagen (1996) who found that soil loss decreases non-linearly with an increase in amount of prostrate or standing residue on the soil surface. Furthermore, from 82% to 96% of the variation in wind-driven soil loss can be accounted for by the respective variation in stem area index (van de Ven *et al.*, 1989) and amount of standing stubble on the soil surface (Siddoway *et al.*, 1965). Based upon the earlier biomass surface cover of tillage treatments averaged across sampling periods each year, we estimated the reduction in soil loss that could be achieved using undercutter tillage from the algorithm of Horning *et al.* (1998). Horning *et al.* (1998), working in the Columbia Plateau, expressed soil loss as a function of both surface cover and random roughness. Although Feng and Sharratt (2009) did not find consistent or large differences in random roughness between tillage treatments across sampling periods each year (random roughness was 10·4 mm for conventional tillage and 8·8 mm for undercutter tillage in 2005 and 10·3 mm for conventional tillage and 9·8 mm for undercutter tillage in 2006), we estimated a 40% to 65% reduction in soil loss from undercutter tillage compared with conventional tillage in successive years. Other soil characteristics may influence erosion and dust emissions, but differences in these characteristics were not consistent or large between tillage treatments (Feng and Sharratt, 2009). For example, averaged across the four sampling periods in which erosion occurred by wind, the geometric mean diameter of soil surface dry aggregates was 0·60 mm for conventional tillage and 0·57 mm for undercutter tillage.

Tillage can have a profound effect on soil and vegetation characteristics that influence wind erosion. Tillage, for example, can affect dry aggregate structure and wind erosion potential (Siddoway, 1963; Hevia *et al.*, 2007). We are aware of only one study that has examined the effect of undercutter tillage on wind erosion (Merrill *et al.*, 1999). Although Merrill *et al.* (1999) did not assess PM10 flux or loss, they did assess windblown soil loss from conventional and undercutter tillage in the northern Great Plains of the US. While soil loss was simulated and not measured during the fallow phase of a spring wheat–fallow rotation, their results are applicable to the tillage methods used in our study. Soil loss was simulated by measuring soil

Table III. Soil and PM10 loss from field plots managed using conventional (conv.) and undercutter (under.) tillage during high wind events in 2005 and 2006

		Soil loss[a]		PM10 loss[b]	
Year	Sampling period	Conv. (g m^{-2})	Under. (g m^{-2})	Conv. (g m^{-2})	Under. (g m^{-2})
2005	23 June–8 July	0	0	0	0
	31 August–14 September	12·0	8·5	0·7	0·5
2006	14–19 July	2·9	0·9	0·2	0·1
	19–25 July	0	0	0	0
	29–30 August	40·1	27·0	5·0	3·3
	30 August–6 September	25·8	21·5	1·7	1·2

[a] Soil loss as determined by integrating creep and BSNE sediment catch from the soil surface to the height of the dust plume and by accounting for inefficiency of BSNE collector.

[b] PM10 loss as determined by integrating PM10 catch of BSNE collectors and PM10 samplers between 0·025 m and height of dust plume.

and crop residue characteristics of tillage treatments and using those characteristics as input to the Revised Wind Erosion Equation. Their results indicated that undercutter tillage reduced soil loss during fallow by 40% to 75% as compared with conventional tillage. Soil loss from undercutter tillage, however, exceeded that from conventional tillage during one fallow period. Simulated soil loss was lower from undercutter tillage primarily due to more standing or prostrate residue for undercutter tillage than conventional tillage. The percent reduction in soil loss associated with undercutter tillage versus conventional tillage simulated by Merrill *et al.* (1999) is very similar to field measurements reported in this study.

PM10 flux and loss

Vertical PM10 flux is a function of friction velocity and PM10 concentration gradient (Equation 5). Estimates of friction velocity and aerodynamic roughness were obtained from the wind profile characteristic (Equation 6) of tillage treatments. Friction velocity ranged from 0·27 to 0·51 m s^{-1} for conventional tillage and from 0·29 to 0·60 m s^{-1} for undercutter tillage while aerodynamic roughness ranged from 0·001 to 0·012 m for conventional tillage and from 0·002 to 0·021 m for undercutter tillage across the six sampling periods in this study. The wide range in friction velocity and aerodynamic roughness is likely due to variations in both wind velocity as well as surface characteristics occurring across the sampling periods. Friction velocity and aerodynamic roughness were typically greater for undercutter tillage as a result of greater surface roughness and stem area indices for undercutter tillage than conventional tillage (Feng and Sharratt, 2009). Friction velocities in this paper are comparable to those (0·2 to 0·8 m s^{-1}) previously reported for conventional tillage practices on silt loams within the Columbia Plateau (Kjelgaard *et al.*, 2004b; Stetler and Saxton, 1996).

For those periods in which erosion occurred by wind, vertical PM10 flux respectively ranged from 2 and 9 μg m^{-2} s^{-1} for undercutter and conventional tillage during the 14–19 July 2006 sampling period to 64 and 81 μg m^{-2} s^{-1} for undercutter and conventional tillage during the 29–30 August 2006 sampling period. The range in vertical flux observed in this study is comparable to fluxes previously reported by Sharratt *et al.* (2007), Kjelgaard *et al.* (2004b), and Stetler and Saxton (1996) for agricultural soils in summer fallow within the Columbia Plateau. We are not aware of any previous work that investigated vertical PM10 flux from agricultural fields managed using contrasting tillage systems. Despite a lack of information on vertical PM10 flux, Lopez *et al.* (1998) examined vertical flux of suspended sediment during high wind events as affected by tillage of a loam soil in Spain. They found the range in vertical sediment flux was twice as high from moldboard plow as from chisel plow. The higher vertical flux of sediment from moldboard plow was attributed to smaller aggregates and less crop residue on the soil surface after moldboard plow than after chisel plow.

Vertical PM10 flux was compared to total near-surface horizontal sediment flux to assess the production rate of PM10 generated from the horizontal movement of sediment near the soil surface. Total near-surface horizontal sediment flux, or total sediment flux over a height of 0 to 1·5 m, was determined from sediment trapped by creep collectors and BSNE collectors (corrected for catch efficiency). For those periods in which erosion occurred by wind, total near-surface horizontal sediment flux respectively ranged from 3 and 5 mg m^{-2} s^{-1} for undercutter and conventional tillage during the 14–19 July 2006 sampling period to 30 and 35 mg m^{-2} s^{-1} for undercutter and conventional tillage during the 30 August–6 September 2006 sampling period. The ratio of vertical PM10 flux to near-surface horizontal sediment flux ranged from 1×10^{-3} to 3×10^{-3} across all tillage treatments and sampling periods in this study. Our results are comparable to the ratio of vertical flux (diameter smaller than 20 μm) to horizontal sediment flux as found by Gillette (1977) above an eroding field in Texas. He found the ratio to vary from 5×10^{-1} to nearly 1×10^{-5} across a range of soil types and friction velocities.

PM10 loss was estimated from the product of vertical PM10 flux and duration of high wind event. For those periods in which erosion occurred by wind, PM10 loss respectively ranged from 0·1 and 0·3 g m^{-2} for undercutter and conventional tillage during the 14–19 July 2006 sampling period to 2·4 and 3·1 g m^{-2} for undercutter and conventional tillage during the 29–30 August 2006 sampling period. These estimates of PM10 loss agreed well with those determined from the leeward and windward PM10 concentration profiles (Table III). Loss of PM10, as determined from the leeward and windward PM10 concentration profiles, was smaller from undercutter tillage as compared with conventional tillage (Table III). With the exception of the 23 June–8 July 2005 and 19–25 July 2006 sampling periods, loss of PM10 ranged from 0·2 to 5·0 g m^{-2} for conventional tillage and from 0·1 to 3·3 g m^{-2} for undercutter tillage. Thus, for those sampling periods in which erosion occurred by wind, PM10 loss was 30% to 70% less for undercutter tillage as compared with conventional tillage. PM10 losses measured in this study are comparatively small compared with losses previously measured in the Columbia Plateau (Sharratt *et al.*, 2007). Nevertheless, these small losses can impact air quality within the Columbia Plateau. For example, Sharratt *et al.* (2007) illustrated that the National Ambient Air Quality Standard for PM10 could be exceeded during a typical high wind event when nearly all land in summer fallow throughout the Columbia Plateau is emitting 0·5 g PM10 m^{-2}.

Loss of PM10 from tillage treatments constituted from 5% to 12% of total soil loss. The higher percentage occurred during the 29–30 August 2006 high wind event. For all other high wind events in which we measured PM10 loss, PM10 loss generally constituted 5% to 6% of total soil loss. For all four high wind events in which we measured PM10 loss, PM10 appeared to comprise a lower percentage of total soil loss for undercutter tillage than for conventional tillage. PM10 loss, for example, comprised 5·3% and 5·5% of soil loss for the respective undercutter and conventional tillage treatments during the 14–19 July 2006 sampling period while PM10 loss constituted 12·2% and 12·5% of soil loss for the respective undercutter and conventional tillage treatments during the 29–30 August 2006 sampling period. PM10 may have constituted a high fraction of total soil loss during the 29–30 August 2006 high wind event because this event occurred two days after sowing winter wheat. In the absence of winds and precipitation to alter the composition and structure of the soil surface by winnowing or aggregation, the likelihood for an abundant supply of perched fine soil particles on the soil surface may have enriched the eroded sediment with fine particles. Kjelgaard *et al.* (2004b) also noted that soils in the Columbia Plateau are most susceptible to PM10 emissions from the positioning of perched particles caused by mechanical disturbances.

Conclusions

While wind erosion from agricultural lands contributes to the degradation of the soil resource base, dust emissions from agricultural lands also contribute to poor air quality within the Columbia Plateau region of the Pacific Northwest US. A winter wheat–summer fallow rotation is practiced on 1·5 million ha in the region, the purpose of which is to fallow the land every other year to store sufficient water in the soil profile for the establishment of the successive crop. Summer fallow, however, has traditionally resulted in a highly disaggregated soil with little crop residue cover. The USDA-Natural Resource Conservation Service has therefore established a cost-sharing program with growers for acquiring an undercutter tillage implement to reduce soil disturbance and wind erosion during summer fallow. Observations during periods of high winds over two years on a Ritzville silt loam in summer fallow indicated that vertical PM10 flux was lower from undercutter than conventional tillage. Undercutter tillage also resulted in a 15% to 65% reduction in soil loss and 30% to 70% reduction in PM10 loss as compared with conventional tillage. This reduction in sediment loss was partly attributed to nearly twice the stem area index and crop residue cover on the soil surface using the undercutter versus disk implement. Although the undercutter implement is one tool that growers can use to reduce erosion of soils during summer fallow, other tillage or cropping practices are sought for reducing wind erosion and dust emissions from conventional winter wheat–summer fallow land within the Columbia Plateau.

References

Burnham TJ. 2007. Study finds savings in using undercutter. *Western Farmer – Stockman* May: 6.

Buser MD, Parnell Jr CB, Shaw BW, Lacey RE. 2007. Particulate matter sampler errors due to the interaction of particle size and sampler performance characteristics: ambient PM10 samplers. *Transactions of the American Society of Agricultural and Biological Engineers* **50**: 229–240.

Chepil WS. 1944. Utilization of crop residue for wind erosion control. *Scientific Agriculture* **24**: 307–319.

Chepil WS, Milne RA. 1941. Wind erosion of soil in relation to roughness of surface. *Soil Science* **52**: 417–430.

Claiborn C, Lamb B, Miller A, Beseda J, Clode B, Vaughan J, Kang L, Newvine C. 1998. Regional measurements and modeling of windblown agricultural dust: the Columbia Plateau PM10 program. *Journal of Geophysical Research* **103**: 19753–19767.

Feng G, Sharratt B. 2007. Validation of WEPS for soil and PM10 loss from agricultural fields within the Columbia Plateau of the United States. *Earth Surface Processes and Landforms* **32**: 743–753.

Feng G, Sharratt B. 2009. Validation of WEPS for undercutter and conventional tillage within the Columbia Plateau. *Earth Surface Processes and Landforms* submitted for publication.

Fryrear DW. 1984. Soil ridges-clods and wind erosion. *Transactions of the American Society of Agricultural Engineers* **27**: 445–448.

Fryrear DW. 1985. Soil cover and wind erosion. *Transactions of the American Society of Agricultural Engineers* **28**: 781–784.

Fryrear DW. 1986a. Wind erosion and its effect on plant growth. *Annals of Arid Zone* **25**: 245–254.

Fryrear DW. 1986b. A field dust sampler. *Journal of Soil and Water Conservation* **41**: 117–120.

Fryrear DW, Saleh A. 1993. Field wind erosion: vertical distribution. *Soil Science* **155**: 294–300.

Fryrear DW, Stout JE, Hagen LJ, Vories ED. 1991. Wind erosion: field measurement and analysis. *Transactions of the American Society of Agricultural Engineers* **34**: 155–160.

Gillette DA. 1977. Fine particulate emissions due to wind erosion. *Transactions of the American Society of Agricultural Engineers* **20**: 155–160.

Gillette DA. 1988. Threshold friction velocities for dust production for agricultural soils. *Journal of Geophysical Research* **93**: 12645–12662.

Goossens D, Offer Z, London G. 2000. Wind tunnel and field calibration of six Aeolian dust samplers. *Atmospheric Environment* **34**: 1043–1057.

Hagen LJ. 1996. Crop residue effects on aerodynamic processes and wind erosion. *Theoretical and Applied Climatology* **54**: 39–46.

Hagen LJ. 2004. Evaluation of the wind erosion prediction system (WEPS) erosion submodel on cropland fields. *Environmental Modelling and Software* **19**: 171–176.

Hagen LJ, van Pelt S, Zobeck TM, Retta A. 2007. Dust deposition near and eroding source field. *Earth Surface Processes and Landforms* **32**: 281–289.

Hevia GG, Mendez M, Buschiazzo DE. 2007. Tillage affects soil aggregation parameters linked with wind erosion. *Geoderma* **140**: 90–96.

Horning LB, Stetler LD, Saxton KE. 1998. Surface residue and soil roughness for wind erosion protection. *Transactions of the American Society of Agricultural Engineers* **41**: 1061–1065.

Hudson T, Cary A. 1999. Dust storm causes deadly pileup on I-84. *Tri-City Herald* September **26**: A1.

Kjelgaard JF, Chandler DG, Saxton KE. 2004a. Evidence for direct suspension of loessial soils on the Columbia Plateau. *Earth Surface Processes and Landforms* **29**: 221–236.

Kjelgaard J, Sharratt B, Sundram I, Lamb B, Claiborn C, Saxton K. 2004b. PM10 emission from agricultural soils on the Columbia Plateau: comparison of dynamic and time-integrated field-scale measurements and entrainment mechanisms. *Agricultural and Forest Meteorology* **125**: 259–277.

Lopez MV, Sabre M, Gracia R, Arrue JL, Gomes L. 1998. Tillage effects on soil surface conditions and dust emissions by wind erosion in semiarid Aragon (NE Spain). *Soil and Tillage Research* **45**: 91–105.

Merrill SD, Black AL, Fryrear DW, Saleh A, Zobeck TM, Halvorson AD, Tanaka DL. 1999. Soil wind erosion hazard of spring wheat–fallow as affected by long-term climate and tillage. *Soil Science Society of America Journal* **63**: 1768–1777.

Romkens MJM, Wang JY. 1986. Effect of tillage on surface roughness. *Transactions of the American Society of Agricultural Engineers* **29**: 429–433.

Saxton K. 1995. Wind erosion and its impact on off-site air quality in the Columbia Plateau – an integrated research plan. *Transactions of the American Society of Agricultural Engineers* **38**: 1031–1038.

Saxton K, Chandler D, Stetler L, Lamb B, Claiborn C, Lee BH. 2000. Wind erosion and fugitive dust fluxes on agricultural lands in the Pacific Northwest. *Transactions of the American Society of Agricultural Engineers* **43**: 623–630.

Schillinger WF. 2001. Minimum and delayed conservation tillage for wheat-fallow farming. *Soil Science Society of America Journal* **65**: 1203–1209.

Sharratt B, Lauer D. 2006. Particulate matter concentration and air quality affected by windblown dust in the Columbia Plateau. *Journal of Environmental Quality* **35**: 2011–2016.

Sharratt B, Schillinger W. 2005. The Columbia Plateau Wind Erosion/Air Quality Project: predicting and controlling windblown dust. Atmospheric Sciences and Air Quality Conference, American Meteorological Society. http://ams.confex.com/ams/pdfpapers/89381.pdf [Accessed 30 March 2009].

Sharratt BS, Feng G, Wendling L. 2007. Loss of soil and PM10 from agricultural fields associated with high winds on the Columbia Plateau. *Earth Surface Processes Landforms* **32**: 621–630.

Siddoway FH. 1963. Effects of cropping and tillage methods on dry aggregate soil structure. *Proceedings of the Soil Science Society of America* **27**: 452–454.

Siddoway FH, Chepil WS, Armbrust DV. 1965. Effect of kind, amount, and placement of residue on wind erosion control. *Transactions of the American Society of Agricultural Engineers* **8**: 327–331.

Stetler LD, Saxton KE. 1996. Wind erosion and PM10 emissions from agricultural fields on the Columbia Plateau. *Earth Surface Processes and Landforms* **21**: 673–685.

Van de Ven TAM, Fryrear DW, Spaan WP. 1989. Vegetation characteristics and soil loss by wind. *Journal of Soil and Water Conservation* **44**: 347–349.

Vories ED, Fryrear DW. 1991. Vertical distribution of wind eroded soil over a smooth bare field. *Transactions of the American Society of Agricultural Engineers* **34**: 1763–1768.

Wagner LE, Nelson RG. 1995. Mass reduction of standing and flat crop residues by selected tillage implements. *Transactions of the American Society of Agricultural Engineers* **38**: 419–427.

Woodruff NP, Siddoway FH. 1965. A wind erosion equation. *Proceedings of the Soil Science Society of America* **29**: 602–608.

Zobeck TM, Onstad CA. 1987. Tillage and rainfall effects on random roughness: a review. *Soil & Tillage Research* **9**: 1–20.

Zobeck TM, Fryrear DW, Pettit RD. 1989. Management effects on wind-eroded sediment and plant nutrients. *Journal of Soil and Water Conservation* **44**: 160–163.

Zobeck TM, Sterk G, Funk R, Rajot JL, Stout JE, van Pelt RS. 2003. Measurement and data analysis methods for field-scale wind erosion studies and model validation. *Earth Surface Processes and Landforms* **28**: 1163–1188.

DOI: 10.1002/esp