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Validation of WEPS for soil and PM10 loss from agricultural fields within the Columbia Plateau of the United States

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Abstract

Wind erosion from agricultural fields contributes to poor air quality within the Columbia Plateau of the United States. Erosion from fields managed in a conventional winter wheat–summer fallow rotation was monitored during the fallow period near Washtucna, WA, in 2003 and 2004. Loss of soil and PM10 (particulates ≤10 μm in diameter) was measured during six high wind events (sustained wind speed at 3 m height >6·4 m s^{-1}). Soil loss associated with suspension, saltation and creep as well as PM10 emission was used to validate the Wind Erosion Prediction System (WEPS) erosion submodel. Input parameters for WEPS simulations were measured before each high wind event. The erosion submodel produced no erosion for half of the observed events and over-predicted total soil loss by 200–700 kg ha^{-1} for the remaining events. The model appears to over-predict total soil loss as a result of overestimating creep, saltation and suspension. The model both over-predicted and under-predicted PM10 loss. High values for the index of agreement ($d > 0{\cdot}5$) suggest that the performance of the model is acceptable for the conditions of this study. While the performance of the model is acceptable, improvements can be made in modeling efficiency by better specifying the static threshold friction velocity or coefficients that govern emissions, abrasion and breakage of silt loams on the Columbia Plateau. Copyright © 2006 John Wiley & Sons, Ltd.

Keywords: WEPS; standalone erosion model; PM10; suspension; saltation; creep; wind erosion; Columbia Plateau; validation; air quality

Introduction

Wind erosion threatens soil productivity, air quality and visibility in many arid and semiarid regions throughout the world. Loss of topsoil associated with high winds can deplete the soil resource most valuable for crop production as well as impairing water and air resources as a result of deposition and suspension of particulates in the atmosphere. Therefore, wind erosion must be suppressed through the use of conservation practices wherever economically viable.

Conservation planning often requires the use of computer simulation for predicting erosion. Prediction strategies may require information about numerous spatial and temporal variables and complex interactions that affect erosion. The Wind Erosion Prediction System (WEPS) simulates soil erosion and dust emissions from agricultural lands that may be subject to varying climatic conditions and management practices (Hagen, 1995; Wagner, 2001). WEPS can be used to assist farmers, ranchers, conservation workers, policy makers and scientists in developing and assessing erosion control methods. However, WEPS needs to be verified under a broad range of climatic, soil and management conditions (Fryrear, 1995). To our knowledge, few studies have attempted to validate WEPS.

The WEPS erosion submodel can be used to simulate or predict loss of soil and PM10 (particulates ≤10 μm in aerodynamic equivalent diameter) for single events and is the key of the seven submodels (Weather, Hydrology, Management, Crop, Residue Decomposition, Soil, and Erosion) that comprise WEPS (Hagen, 1995). The WEPS erosion submodel has been tested within six states of the United States including Washington. In Washington, Hagen

(2004) examined seven dust storms where sediment loss ranged from 100 to 5200 kg ha^{-1}. Many parameters required by WEPS, such as crust cover fraction, aggregate and crust stability and surface soil water content, were either estimated or measured at times distant from the high wind events. Nevertheless, Hagen (2004) found that the erosion submodel under-estimated soil loss. Parameter values can significantly affect WEPS simulation (Feng and Sharratt, 2005; Hagen, 1999; Van Donk and Skidmore, 2003) and Hagen (2004) concluded that uncertainties in field surface conditions may affect model validation.

Van Donk and Skidmore (2003) tested the WEPS erosion submodel on a 25 ha field in eastern Colorado and found that the submodel under-estimated total soil loss. Funk *et al*. (2002) observed soil loss from a 2·25 ha field over two years in Germany. Although parameters that describe surface characteristics such as roughness and crust cover were estimated, they found good agreement between measured and simulated soil loss. These studies examined the capability of the WEPS erosion submodel to simulate total soil loss and did not consider PM10 emissions.

WEPS was developed in regions where saltation, and not direct suspension, dominates the entrainment process. The WEPS erosion submodel has not been adequately evaluated in the Columbia Plateau of eastern Washington where direct suspension is believed to be the dominant process by which particulates are eroded from the soil surface (Kjelgaard *et al*., 2004a). In addition, the soils, cropping systems and climate of the region contribute to windblown dust and poor air quality associated with elevated PM10 concentrations (Saxton *et al*., 2000). Wind erosion prediction and assessment tools such as WEPS are needed for developing best management practices to control soil loss and PM10 emissions. The primary objective of this study was to examine the performance of WEPS in simulating loss of soil and PM10 from agricultural fields within the Columbia Plateau of eastern Washington.

Materials and Methods

The Columbia Plateau is a 75 000 km^2 region located in north-central Oregon and south-central Washington, USA (Figure 1) and receives from 150 to 600 mm of annual precipitation. Soils in the region were formed from loess deposits that range in depth up to 76 m (Busacca, 1989). Winds are predominantly from the south and west and are typically the strongest in spring or autumn, when peak gusts exceed 20 m s^{-1} every 2 years or 30 m s^{-1} every 10 years (Wantz and Sinclair, 1981). Winter wheat–summer fallow is the conventional crop rotation employed on >1·5 million ha within the Columbia Plateau. The 14-month fallow period of the rotation extends from August to September of the next year.

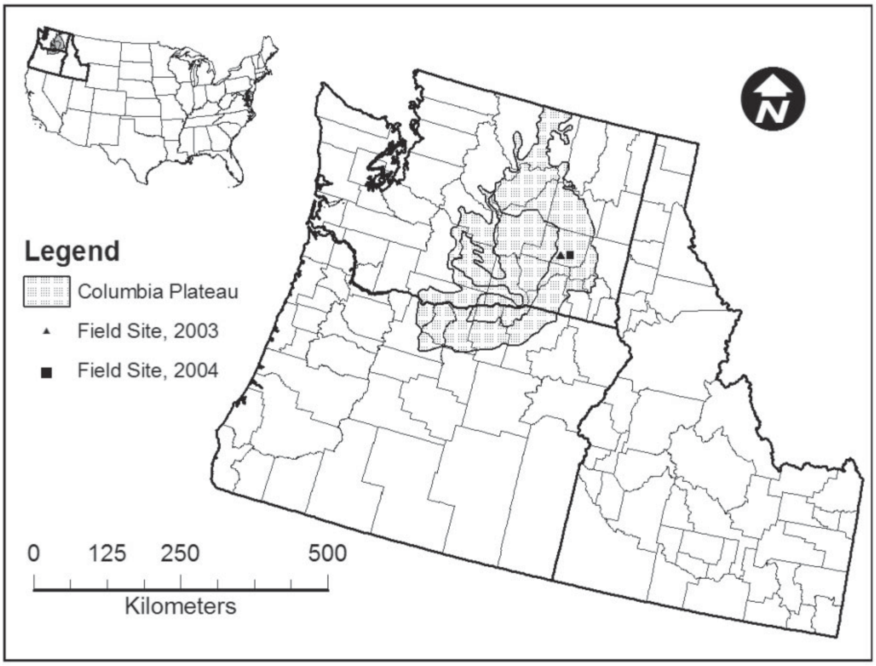

Figure 1. The location of the validation field sites on the Columbia Plateau of the Pacific Northwest, USA.

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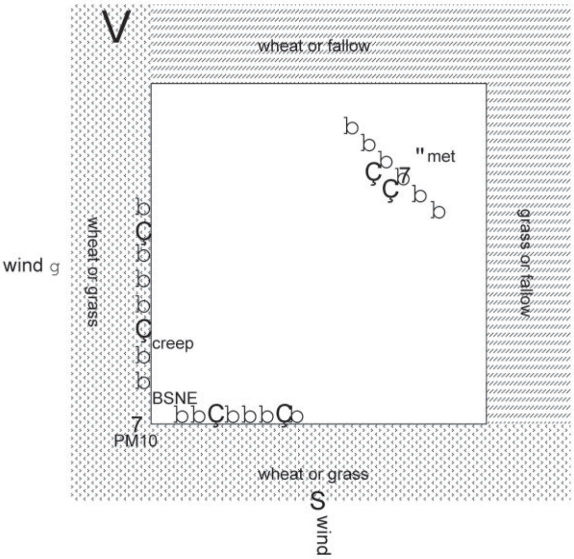

Figure 2. Instrumentation at the field site with symbols representing placement of PM10 samplers, BSNE and creep collectors and meteorological (met) station.

Table I. Physical and hydrologic properties (0–30 mm) of a silt loam during the 2003 and 2004 field campaign

Year	Sand content	Fine sand content	Silt content	Clay content	Rock volume	Organic matter ($kg\ kg^{-1}$)	$CaCO_3$ (%)	pH	CEC (meq/100 g)	Bulk density ($Mg\ m^{-3}$)	θ_s ($kg\ kg^{-1}$)	θ_{fc} ($kg\ kg^{-1}$)	θ_r ($kg\ kg^{-1}$)	K_s ($10^{-5}\ m\ s^{-1}$)
2003	0·3	0·2	0·63	0·07	0	0·016	<2	5·4	12	1·05	0·33	0·19	0·074	0·755
2004	0·4	0·15	0·53	0·07	0	0·015	0	6·5	13	1·10	0·42	0·18	0·065	1·218

CEC, cation exchange capacity; θ_s, water content at saturation; θ_{fc}, water content at field capacity; θ_r, water content at wilting; K_s, saturated hydraulic conductivity.

Field campaign

Soil and PM10 losses were monitored at two field sites (Figure 1) located near Washtucna, Adams County, WA, USA (46°50′N, 118°30′W, elevation 510 m). The sites were in fallow in 2003 and 2004. A nonerodible surface was maintained along the south and west boundaries of the field sites; the nonerodible surface consisted of winter wheat or wheat stubble in 2003 and permanent grass in 2004 (Figure 2). Sharratt *et al.* (2006) indicated that the boundaries were very effective in minimizing soil transport into the field. The height of vegetation along the boundaries was less than 50 cm during this study. The soil type at both field sites was predominately Ritzville silt loam (Andic Aridic Haplustoll) on a 2 per cent slope. The measured chemical, physical and hydrologic properties of the Ritzville silt loam required by WEPS are reported in Table I. The field sites encompassed an area of 9 ha in 2003 and 16 ha in 2004. In 2003, the site was cultivated with a double disk on 10 April and rod-weeded on 6 May, 18 June, 4 September, 18 September and 21 October 2003. In 2004, the site was cultivated with a sweep implement on 20 October 2003 and double disk on 20 April 2004 and rod-weeded on 10 May and 23 June prior to sowing winter wheat on 27 August 2004. Ridges created by the sowing operation were oriented at 140 degrees.

Creep and BSNE airborne soil collectors[1] (Custom Products and Consulting, Big Spring, TX) and high-volume PM10 samplers (model PM 10, Graseby Andersen Division, Smyrna, GA) were located along the south and west boundaries and near the northeast corner of the field site to assess the influx and efflux of soil and PM10 (Figure 2). Placement of the instruments ensured a minimum fetch of 225 m in 2003 and 300 m in 2004. Creep samplers collected sediment to a height of 0·025 m while BSNE (Fryear, 1986) airborne collectors were positioned 0·1, 0·2, 0·5, 1 and 1·5 m above the soil surface. The high volume samplers were mounted at heights of 3 and 5 m in 2003 and at heights

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[1] *Mention of trade names does not constitute an endorsement.*

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of 1·5, 3 and 6 m in 2004. The high volume samplers were activated when wind speeds exceeded 6·4 m s^{-1} at a height of 3 m for 10 consecutive minutes and then deactivated when wind speed was less than 5·8 m s^{-1} for 15 minutes (high wind event). Data collection was periodic due to the episodic nature of storms in the region and remoteness of the field sites. Soil and PM10 loss were calculated and simulated only for those high wind events that were characterized by winds from 160 to 290 degrees (nonerodible boundary maintained upwind of the field site).

Sediment catch in the BSNE for the most erosive event observed in this study (27–29 October 2003) was separated into 10, 30, 45, 53, 100 and 150 μm diameter size fractions using a sonic sieve (Gilson, Worthington, OH) to determine fractions of saltation/creep (840–100 μm), suspension (≤100 μm) and PM10 (≤10 μm). Since the BSNE is inefficient in collecting all suspended sediment (Goossens and Offer, 2000), the catch efficiency of the BSNE was determined for suspended Ritzville silt loam sediment and PM10 (Sharratt *et al*., 2006). The catch efficiency of the BSNE collector for suspended sediment was 60 per cent and that for PM10 was 10–25 per cent.

Total horizontal soil flux at the upwind and downwind field positions was determined as the sum of creep and BSNE sediment catch. The vertical distribution of sediment captured by BSNE collectors was described using the equation of Zobeck and Fryrear (1986) and integrating from 0·025 to 5 m (Sharratt *et al*., 2006). Net soil loss from the field was calculated as the difference between total horizontal soil flux at the upwind and downwind field positions.

PM10 concentration profiles were constructed using both BSNE sediment catch and high volume sampler concentrations. BSNE sediment catch was used to determine PM10 concentration below a height of 1·5 m according to the equation

$$C_z = \frac{M_z}{u_z f S t} \tag{1}$$

where C_z is PM10 concentration at height z, M_z is the PM10 mass in the BSNE collector at height z, u_z is wind velocity at height z, S is the area of the BSNE opening, t is the duration of an event and f is the PM10 catch efficiency of BSNE collectors. Loss of PM10 from the field site was ascertained for each high wind event by subtracting horizontal PM10 flux at the downwind position from that at the upwind position in the field. Horizontal PM10 flux at each field position was determined by

$$PM10\ flux = \int [C_z u_z t] dz \tag{2}$$

where PM10 flux is in μg m^{-1}. The integral was evaluated from 0·025 m to the height of the PM10 plume, where plume height was obtained by extrapolating the PM10 concentration profiles to the height where the upwind and downwind profiles intersected.

Soil surface and crop residue characteristics were assessed at three locations within each field immediately before (within 3 days) each high wind event or after each tillage or precipitation event. Precipitation only occurred during the 27–29 October 2003 event. We assumed that soil properties or surface characteristics changed little between dates of data collection since little change would occur to the soil in the absence of precipitation and tillage in this semiarid region. Soil water content was assessed gravimetrically in the upper 5 and 30 mm of the profile. Random roughness and crop residue cover were measured using a pin-type profile meter with 40 pins spaced 2·5 cm apart (Allmaras *et al*., 1966). The profile meter was positioned randomly, or parallel to tillage tool marks, in the field. Random roughness was calculated as the standard deviation of pin height measurements while residue cover was determined as the fraction of pins overlying a residue element. Oriented roughness (ridge height and spacing) was measured using a ruler. Soil samples were collected from the upper 30 mm of soil profile to determine bulk density, aggregate size distribution, aggregate stability and aggregate density. Soil bulk density was determined by extracting soil core samples using stainless steel tubing (0·07 m diameter and 0·03 m long). The tubing was inserted into the soil until the upper edge of the tube was level with the soil surface. The tubing was then extracted by hand and the soil was trimmed level with the upper and lower edges of the tube. The core samples were then placed in an oven and allowed to dry at 105 °C prior to measuring the soil dry weight (bulk density). Aggregate size distribution was determined by sieving 1 kg samples. A rotary sieve (Chepil, 1962; Lyles *et al*., 1970) was used to determine the size fraction of aggregates 0·42, 0·84, 2·0, 6·4, 19·0, 45·0 and 76·0 mm in diameter while a sonic sieve (Gilson, Worthington, OH) was used to determine the size fraction of aggregates <0·42 mm in diameter (Wagner and Ding, 1994). About 1 g of the 0·42 mm size fraction was sieved through an oscillating column of air at 60 Hz while tapping the sieve horizontally and vertically at 1 Hz. Aggregate size distribution was described mathematically according to Wagner and Ding (1994). Six 6·4 mm aggregates were used to assess dry stability and density. Dry aggregate stability was measured using a soil-aggregate crushing-energy meter (Boyd *et al*., 1983) and aggregate density was determined by volume displacement using saran-coated aggregates (USDA, 1996). Soil water retention of repacked soil columns was characterized using a hanging water column for potentials from 10^{-8} to 0·006 MPa, pressure plate apparatus for potentials from 0·01 to 1·0 MPa and a psychrometer for potentials of 1·5 MPa. Saturated hydraulic conductivity of soil columns was measured by the constant-head method (Klute and Dirksen, 1986). Above-ground prostrate and standing residue was collected from 0·25 m^2 areas and dried to constant weight.

An automated meteorological station was established at the northeast corner of the field site to continuously measure wind speed and direction, precipitation, solar radiation, atmospheric temperature and relative humidity. Three-cup anemometers (model 14A, Met One, Grants Pass, OR) were placed at heights of 0·1, 0·5, 1, 2, 3 and 5 m and wind direction (model 024A, Met One, Grants Pass, OR) was monitored at 3 m. Micrometeorological sensors were monitored every 10 s and data recorded every 30 minutes by a data-logger (model 23X, Campbell Scientific, Logan, UT) except during high wind events, when data were recorded at 10 minute intervals.

Wind Erosion Prediction System (WEPS)

The Wind Erosion Prediction System (WEPS) is a process-based daily time step model. The WEPS includes seven submodels: Soil, Crop, Hydrology, Residue Decomposition, Management, Weather, and Erosion. Erosion is the key submodel, which has the capability to simulate creep, saltation, suspension and PM10 emission in response to wind speed, wind direction, field orientation and surface conditions on a subhourly basis during single events. A complete description of the erosion submodel is given by Hagen (1991, 2004) and Hagen *et al.* (1995, 1999). All other submodels serve to dynamically provide and update parameters for the erosion submodel. The erosion submodel considers the simulation region to be rectangular and grids the region into numerous cells. A series of equations is used in the model to calculate dynamic friction velocity and static threshold friction velocity. When the dynamic friction velocities exceed the static threshold friction velocity, the submodel calculates soil and PM10 loss over a series of individual grid cells representing the field. Dynamic friction velocities are determined in terms of the log-law wind profile. The static threshold friction velocity is defined as the velocity at which numerous aggregates begin to saltate. This threshold is calculated based on a combination of surface conditions: random and oriented roughness, aggregate size and density, clod/crust cover, flat biomass cover and surface wetness. The WEPS erosion submodel was run between sampling dates and only when winds were between 160 and 290 degrees. The submodel used parameter values measured in the field and 30 min climate data.

Statistical performance criteria

Correlation and correlation-based statistics (e.g. correlation coefficient and coefficient of determination) have been widely used to evaluate the 'goodness-of-fit' of wind erosion models (Funk *et al.*, 2002; Zobeck *et al.*, 2001). Legates (1999) and Morgen and Quinton (2001) indicated that these statistics are oversensitive to extreme values (outliers) and are insensitive to additive and proportional differences between model predictions and observations. They further suggested that both the correlation coefficient (r) and coefficient of determination (R^2) should be used with caution in assessing model performance. Considering these limitations, the following statistical indices including R^2 are used to evaluate the performance of WEPS.

Willmott (1981) sought to overcome the insensitivity of correlation-based statistics to differences in the observed and model simulated means and variances by developing the index of agreement d, given by

$$d = 1{\cdot}0 - \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \right] \tag{3}$$

where P is the predicted value, O is the observed or measured value, n is the number of comparisons and d varies from 0 to 1·0. Higher values indicate better agreement between the model results and observations. As with R^2, d is sensitive to extreme values.

Loague and Green (1991) used modeling efficiency (EF) to evaluate the performance of solute transport models. The mathematical expression of the statistic is

$$EF = \left(\sum_{i=1}^{n} (O_i - \bar{O})^2 - \sum_{i=1}^{n} (P_i - O_i)^2 \right) \Big/ \sum_{i=1}^{n} (O_i - \bar{O})^2 \tag{4}$$

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where $\bar{O}$ is the mean observed value. EF can be negative and have a maximum value of 1·0. A negative EF value indicates that the averaged measured values give a better estimate than the simulated values. Higher EF values indicate better agreement between simulated and measured values.

A complete assessment of model performance should include root mean square error (RMSE) with additional supporting information (e.g. means, maximum errors (ME) and standard deviations) as these indices can provide an evaluation of the error in the units of the variables (Legates, 1999). RMSE is defined as

$$RMSE = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{1/2} \tag{5}$$

whereas ME is defined as

$$ME = Max|P_i - O_i|_{i=1}^{n} \tag{6}$$

Legates (1999) highly recommended that the all above statistical measures be reported to assess model performance.

Results and Discussion

High wind events (e.g. sustained wind speeds in excess of 6·4 m s^{-1} at a height of 3 m) were observed over four sampling dates in 2003 and two sampling dates in 2004. The most severe of these events occurred from 27 to 29 October 2003 when winds in excess of 6·4 m s^{-1} were sustained for 14 consecutive hours. Details concerning measured soil and PM10 loss during these high wind events are reported by Sharratt *et al*. (2006).

Field surface characteristics and soil properties required by WEPS and measured prior to each high wind event in 2003 and 2004 are listed in Table II. In general, biomass flat cover was smaller in 2003 (1–3 m^2 m^{-2}) than in 2004 (4–17 m^2 m^{-2}). The small biomass cover in 2003 was due to the field site being in summer fallow for two consecutive years (2002–2003), during which time the soil was subject to nine tillage or rod-weeding operations prior to the 12–22 September 2003 event. In contrast, the field site in 2004 had been subject to four tillage or rod-weeding operations prior to the 6–23 August 2004 event. Vegetative growth, and thus leaf area index, was negligible during summer fallow due to lack of moisture and periodic cultivations. No crust was present on the soil surface prior to high wind events in 2003, but a crust was apparent prior to the 6–23 August 2004 event. Loose soil material was not observed on the crusted surface prior to the 6–23 August 2004 event. Hourly surface soil water content is required by the model, but soil water content was measured only periodically and prior to each high wind event. Soils are typically very dry from late spring to early autumn (dust storm season) and little change in water content is expected to occur over the course of a day or days due to lack of capillary continuity caused by the dust mulch that characterizes the uppermost part of the profile near the soil surface (Schillinger and Bolton, 1996; Schillinger *et al*., 1998) and dry atmospheric conditions. Soil water content varied little across events and did not exceed 0·05 m^3 m^{-3}. Schillinger and Bolton (1996) also found that soil water content did not exceed 0·05 m^3 m^{-3} throughout the summer in the region. However, high wind events may be accompanied by precipitation. This is exemplified by the 27–29 October 2003 event, when 3 mm of precipitation was received and caused a crust to form on the soil surface, which stabilized the soil from eroding toward the end of the event. Random roughness was typically <10 mm, indicating a smooth surface. Thorne *et al*. (2003) also visually observed random roughness of about 10 mm during the fallow cycle of a long term winter wheat–summer fallow rotation within the region.

Total soil loss observed over the course of this study ranged from 43 to 2317 kg ha^{-1}, while loss of PM10 ranged from 5 to 212 kg ha^{-1} (Table III). Although soil and PM10 loss represented that accumulated over a period of several days (PM10 and BSNE samplers were serviced after each significant high wind event), loss between dates was due to a singular event or series of episodes varying in magnitude that lasted several hours.

Simulated and measured loss of soil and PM10 for each high wind event in 2003 and 2004 are presented in Table III. The erosion submodel simulated no erosion during one event in 2003 (12–22 September) and both events in 2004 (6–23 August and 23 August–9 September); these events were characterized by soil loss that ranged from 43 to 1604 kg ha^{-1} and PM10 loss that ranged from 5 to 163 kg ha^{-1}. The erosion submodel simulates erosion only when the friction velocity exceeds the static threshold friction velocity. Thus, erosion did not occur because the surface friction velocity did not exceed the surface threshold friction velocity even though wind speeds in excess of

Table II. Input parameters for the validation of WEPS erosion submodel. Parameters were measured prior to each of the high wind events

	Sampling interval					
	2003				2004	
Parameters	**12–22 Sep**	**3–15 Oct**	**15–27 Oct**	**27–29 Oct**	**6–23 Aug**	**23 Aug–9 Sep**
	0	0	0	0		
Stem area index (m^{2} m^{-2})	0	0	0	0	0	0
Leaf area index (m^{2} m^{-2})	0	0	0	0	0	0·05
Biomass flat cover (m^{2} m^{-2})	0·012	0·031	0·025	0·022	0·17	0·04
Aggregate density (Mg m^{-3})	1·24	1·27	1·30	1·28	2·07	1·82
Aggregate stability (ln[J kg^{-1}])	1·92	1·73	1·61	1·73	1·90	1·75
Aggregate geometric diameter (mm)	0·72	1·32	1·43	1·5	2·14	1·80
Minimum aggregate size (mm)	0·003	0·001	0·007	0·008	0·006	0·009
Maximum aggregate size (mm)	47·4	94	102	114	47	45
Aggregate geometric standard deviation (mm mm^{-1})	18·7	24	39	35	12·9	12·7
Fraction of soil surface crusted (m^{2} m^{-2})	0	0	0	0	0·80	0
Soil crust thickness (mm)	0	0	0	0	3	0
Fraction of crusted surface covered by loose material (m^{2} m^{-2})	0	0	0	0	0	0
Mass of loose material on crusted surface (kg m^{-2})	0	0	0	0	0	0
Soil crust density (Mg m^{-3})	0	0	0	0	0	0
Soil crust stability (ln[J kg^{-1}])	0	0	0	0	0	0
Random roughness (mm)	7·7	9·6	10·5	10·8	11·1	10·0
Ridge height (cm)	0	0	0	0	0	10
Ridge space (cm)	0	0	0	0	0	40
Surface water content (kg kg^{-1})	0·041	0·019	0·015	0·019	0·011	0·014

Table III. Characteristics of high wind events and measured and simulated loss of soil and PM10 from a silt loam during the events at two field sites near Washtucna, WA, in 2003 and 2004

Year	**Sampling period**[1]	**Number of events**[2]	**Total hours**[3]	**Mean wind direction**[4]	**Wind**[5]		**Total soil loss**		**PM10 loss**	
					Mean	**Maximum**	**Measured**	**Simulated**	**Measured**	**Simulated**
				Degrees	**m s^{-1}**		**kg ha^{-1}**		**kg ha^{-1}**	
2003	12–22 Sep	4	26	276	6·7	12·5	43	0	5	0
	3–15 Oct	8	47	225	7·6	14·4	118	300	10	27
	15–27 Oct	7	41	217	7·2	11·9	44	700	5	18
	27–29 Oct	1	14	240	10·3	17·6	2317	3000	212	100
2004	6–23 Aug	4	20	230	6·9	10·3	138	0	16	0
	23 Aug–9 Sep	7	43	243	7·1	10·7	1604	0	163	0

[1] Dates over which eroded sediment was collected.

[2] Number of high wind events observed during the sampling period.

[3] Number of hours during the sampling period for which wind speed exceeded 6·4 m s^{-1} at a height of 3 m.

[4] Mean wind direction at 3 m height during the high wind events.

[5] Mean and maximum wind speed at 3 m height during high wind events.

10 m s^{-1} at 3 m height occurred during the 12–22 September 2003, 6–23 August and 23 August–9 September 2004 high wind events. WEPS appeared to overestimate the threshold friction velocity for the soil and surface conditions encountered in this study. Indeed, the WEPS erosion submodel specifies that the static threshold friction velocity must be $\geq$0·35 m s^{-1}. Previous work by Kjelgaard *et al*. (2004b) and Sharratt *et al*. (2006) found that the threshold friction velocity may be <0·3 m s^{-1}, particularly when particles are perched on the soil surface after tillage (Kjelgaard

et al., 2004b). A wind tunnel study indicated that the threshold friction velocity of a dry and smooth silt loam was 0·34 m s^{-1} (Goossens, 2001).

Van Donk *et al*. (2003) examined the performance of WEPS on a silt loam sown to winter wheat in Colorado. The WEPS erosion submodel predicted no erosion despite a measured soil loss of 600 kg ha^{-1} during a singular event. They concluded that the erosion submodel overestimated the protective role of small wheat plants in simulating erosion. This may be a possible reason that WEPS failed to predict erosion for the 23 August–9 September 2004 event as the field site was sown on 27 August 2004 and winter wheat emerged on 3 September. In addition, the erosion submodel may have overestimated the protective role of ridges in simulating erosion in our study as ridges (height of 0·1 m and spacing of 0·4 m) were apparent after sowing in 2004. While changes in biomass and ridge parameters were accounted for in the WEPS simulation during the 23 August–9 September 2004 event, the simulation also indicated no erosion in the absence of biomass and ridges. Therefore, the erosion submodel appears to overestimate the threshold friction velocity for the silt loam in this study.

Hagen (2004) validated the WEPS erosion submodel using data from 46 storms at seven locations across the United States. The submodel simulated no erosion for 30 per cent of the storms when soil loss ranged from 100 to 1100 kg ha^{-1}. In addition, the model underestimated soil loss for 67 per cent of the storms, apparently due to lack of uniformity within the test sites (e.g. small inclusions of highly erodible soils). Hagen's (2004) results suggest that the WEPS erosion submodel underestimates erosion during events with little soil loss. In contrast, we found that the erosion submodel lacked consistency in underestimating soil loss for the four smallest events (loss < 150 kg ha^{-1}) observed in this study.

Zobeck *et al*. (2001) reported soil loss as high as 56 Mg ha^{-1} across 41 high wind events in Texas and Larney *et al*. (1995) measured soil loss approaching 30 Mg ha^{-1} across 16 events in Alberta, Canada. Although we observed a maximum soil loss of 2·3 Mg ha^{-1} across six events in the Columbia Plateau (Table III), the differences in maximum soil loss among studies may be related to soil type. Indeed, soil loss was reported from sandy soils in Texas and a clayey soil in Alberta, whereas loss in this study was from a silt loam. Similarly, Van Donk and Skidmore (2003) observed a maximum soil loss of 0·6 Mg ha^{-1} for a silt loam in Colorado.

A previous study reported that direct suspension is the major process by which loessial soils erode on the Columbia Plateau (Kjelgaard *et al*., 2004a). Both measured and simulated results from this study support their conclusion. For example, >80 per cent of the soil eroded was by suspension and ≤20 per cent of the eroded mass was by saltation and creep (Table IV). WEPS over-predicted suspension by about 23 per cent, and saltation and creep by about 160 per cent. The WEPS erosion submodel simulates all major wind erosion processes, including direct entrainment of fine particulates by wind and/or saltation impacts, abrasion of clods/crust by saltation impacts and breakage of saltation/creep-size aggregates. Although equations that describe these processes are physically based and thus are likely applicable to a wide range of conditions, the coefficients in these equations are empirically based and likely to depend on soil type or physical state. The erosion submodel specifies coefficients for emission, abrasion, breakage, trapping and interception of soil particles. For example, an emission coefficient of 0·06 m^{-1} is specified in the model. This coefficient was derived for a Kansas soil and is assumed to be representative of a loose and bare soil (Hagen *et al*., 1999; Hagen, 2001). The sensitivity and uncertainty of these coefficients has not been analyzed and perhaps may be a source of disparity between measured and simulated results in this study. Therefore, these coefficients should be examined for a wide range of soil types on the Columbia Plateau.

The erosion submodel is designed with the capability to simulate creep, saltation, suspension and emission of PM10. We are not aware of any previous study that has tested this capability in the field. For this purpose, we validated the WEPS wind erosion submodel using data collected from agricultural fields over two years. For the 27–29 October 2003 high wind event, the erosion submodel over-predicted creep and saltation as well as suspension by about 370 kg ha^{-1}. Furthermore, the model under-predicted PM10 emission by 53 per cent. The model also predicted

Table IV. Measured and predicted soil loss and percentage of each soil discharge component to total soil loss for the 27–29 October 2003 high wind event

	Total	Creep/saltation		Suspension[1]		PM10	
	(kg ha^{-1})	(kg ha^{-1})	(%)	(kg ha^{-1})	(%)	(kg ha^{-1})	(%)
Measured	2317	232	10	1873	81	212	9
Simulated	3000	600	20	2300	77	100	3

[1] Suspension includes all particulates <100 μm in diameter, except PM10.

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Table V. Statistical parameters in evaluating model performance of simulating soil loss and PM10 emission from a silt loam during 2003 and 2004 on the Columbia Plateau

	Total soil loss		**PM10 emission**	
Statistic	**Observed**	**Simulated**	**Observed**	**Simulated**
Mean (kg ha^{-1})	710	670	69	21
Standard deviation (kg ha^{-1})	995	1176	94	31
Maximum error (ME) (kg ha^{-1})		1604		163
Root mean square error (RMSE) (kg ha^{-1})		766		82
Index of agreement (*d*)		0·86		0·68
Modeling efficiency (EF)		0·38		0·21
Correlation coefficient (R^2)		0·55		0·46

no loss of PM10 for the 12–22 September 2003, 6–23 August 2004 and 23 August–9 September 2004 events. For the two remaining events in 2003 (3–15 October and 15–27 October) the model overestimated PM10 loss (Table III). Over- or under-estimation of PM10 emission by the erosion submodel over the two years may be in part due to parameter specification. Parameters are used in the submodel for estimating PM10 emissions associated with direct ejection from the soil surface, abrasion of clods and crust and breakage of creeping and saltating particles. These parameters, such as the abrasion coefficient and coefficient of emission, have been largely obtained for coarse soils or soils from other regions, or in the laboratory (Hagen *et al*., 1999; Hagen, 2001). Further testing or calibration of these coefficients should be conducted for soils across the Columbia Plateau.

Performance of the erosion submodel was based upon the following seven statistical indices: mean, standard deviation, maximum error (ME), root mean square error (RMSE), coefficient of determination (R^2), index of agreement (*d*) and modeling efficiency (EF). Values of the seven statistical indices for total soil loss and PM10 emissions for the six high wind events observed in this study are reported in Table V. The standard deviation of simulated total soil loss was 18 per cent higher than for the observed soil loss whereas the standard deviation of simulated PM10 emissions was 67 per cent lower than for the observed PM10 emissions. The differences between the simulated and observed means and standard deviations for total soil loss were 40 and 181 kg ha^{-1} and those between the simulated and observed means and standard deviations for PM10 emission were 48 and 63 kg ha^{-1}, respectively. High values of index of agreement (*d*) indicate good agreement between observed and simulated soil loss. Thus, *d* values > 0·5 for simulating both total soil loss and PM10 emission are encouraging. Since the coefficient of determination (R^2) is oversensitive to the extreme values, the values of R^2 were relatively low (≈0·5) for both total soil and PM10 prediction compared with *d*. In contrast, root mean square error (RMSE) values were close to the observed mean values, maximum errors (MEs) exceeded the measured mean values and EF values were less than 0·5 for both total soil loss and PM10 emissions. These three statistical indices indicate poor agreement between observed and simulated emissions. Quinton (1997) suggested that a value of EF > 0·5 represents a satisfactory model performance. Although high values of index of agreement indicate good agreement, low values of EF suggest that the model lacks precision and needs improvement for application to the Columbia Plateau.

Conclusions

The WEPS erosion submodel was validated with measured input parameters at field sites maintained in summer fallow in eastern Washington in 2003 and 2004. The validation results indicated that the WEPS erosion submodel both under- and over-estimated loss of soil and PM10. No erosion was simulated by the model for three of the six high wind events observed in this study, possibly due to overestimation of the threshold friction velocity.

Suspension is the predominant process by which soils eroded on the Columbia Plateau. Although the model over-predicted suspension, the model also under-predicted the relative importance of suspension and PM10 emissions to total soil loss for the majority of high wind events. Due to the impact of wind erosion on air quality, better simulation of PM10 emission may be warranted for silt loams in the region.

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