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Evaluation of the SWEEP model during high winds on the Columbia Plateau†

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ABSTRACT: A standalone version of the Wind Erosion Prediction System (WEPS) erosion submodel, the Single-event Wind Erosion Evaluation Program (SWEEP), was released in 2007. A limited number of studies exist that have evaluated SWEEP in simulating soil loss subject to different tillage systems under high winds. The objective of this study was to test SWEEP under contrasting tillage systems employed during the summer fallow phase of a winter wheat–summer fallow rotation within eastern Washington. Soil and PM10 (particulate matter ≤10 μm in diameter) loss and soil and crop residue characteristics were measured in adjacent fields managed using conventional and undercutter tillage during summer fallow in 2005 and 2006. While differences in soil surface conditions resulted in measured differences in soil and PM10 loss between the tillage treatments, SWEEP failed to simulate any difference in soil or PM10 loss between conventional and undercutter tillage. In fact, the model simulated zero erosion for all high wind events observed over the two years. The reason for the lack of simulated erosion is complex owing to the number of parameters and interaction of these parameters on erosion processes. A possible reason might be overestimation of the threshold friction velocity in SWEEP since friction velocity must exceed the threshold to initiate erosion. Although many input parameters are involved in the estimation of threshold velocity, internal empirical coefficients and equations may affect the simulation. Calibration methods might be useful in adjusting the internal coefficients and empirical equations. Additionally, the lack of uncertainty analysis is an important gap in providing reliable output from this model. Published in 2009 by John Wiley & Sons, Ltd.

KEYWORDS: SWEEP model; WEPS; soil wind erosion; PM10; wheat–summer fallow rotation; undercutter tillage; Columbia Plateau; air quality

Introduction

Wind erosion is a severe problem and a threat to sustainable agriculture and environmental quality in arid and semi-arid regions of the world. Development of soil conservation management practices and cropping systems are important and necessary for controlling soil loss and suppressing dust emission from agricultural lands. A soil wind erosion model can be a useful tool in development of control measures for windblown soil loss and dust emission. Such a model can predict soil erosion risk under various land management practices and evaluate the effect of alternative cropping systems and management scenarios on soil erosion. As a result, best management practices can be selected and tested for future adoption in preventing wind erosion.

The United States Department of Agriculture – Agricultural Research Service (USDA-ARS) has developed a process-based Wind Erosion Prediction System (WEPS) for soil conservation and environmental planning (Hagen, 1991; Hagen *et al.*, 1995; Wagner, 2001). The USDA-ARS first released a beta 1·0 version of WEPS in 1995 and has since continued to update and improve the model. The current version is WEPS 1·0 beta release 20, which replaces the empirical Wind Erosion Equation (WEQ) that has been used historically by the USDA Natural Resource Conservation Service (NRCS) as a tool in conservation planning. WEPS will be used by the USDA-NRCS to determine the eligibility of agricultural lands for enrollment in conservation programs and evaluate the effect of alternative field operations and tillage management and cropping systems for conserving soil and environmental resources.

The Columbia Plateau region of the Pacific Northwest US is highly susceptible to wind erosion. Nearly one-half of the 75 000 km^2 region located in north-central Oregon and south-central Washington, USA is cropland of which 1·5 million hectares is in a wheat–fallow rotation (Papendick, 2004). The conventional dryland wheat–fallow system necessitates multiple passes with tillage implements during the summer fallow phase of the rotation to create a 10–15 cm layer of dust mulch to minimize soil moisture losses and to manage weed populations (Schillinger and Young, 2004). The tillage-intensive fallow practice, coupled with dry and windy conditions in autumn and spring, contributes to wind erosion. Land in summer fallow is the primary source of fugitive dust that adversely impacts air quality in downwind areas. Sharratt *et al.* (2007) measured a loss of topsoil of 2320 kg ha^{-1} from a field maintained in summer fallow during a single dust storm on the Columbia Plateau in 2003. Feng and Sharratt (2007a) used WEPS to estimate an annual soil loss of 14 250 kg ha^{-1} from fields in summer fallow within the Plateau. Therefore, best management practices are needed for controlling wind erosion from the land in summer fallow.

The Columbia Plateau PM10 (particulate matter ≤10 μm in diameter) Project (CP3) was initiated in 1992. The intent of the Project was to develop new and improved methods, technologies, and strategies for predicting and controlling wind-induced soil erosion and PM10 emissions from the region's farmlands (Papendick, 2004; Sharratt and Schillinger, 2005). Since then, alternative conservation tillage practices and technologies (i.e. chemical fallow, minimum tillage, and undercut tillage) have been developed for adoption. Undercutter tillage, which minimizes soil inversion and retains large clods and crop residue on the soil surface, has been promoted as a promising conservation tillage implement for reducing wind erosion. The USDA-NRCS has recently initiated a program to encourage farmers to adopt the use of the undercutter tillage implement. We conducted a two-year field study on farmlands to quantitatively compare wind erosion and PM10 emissions from summer fallow fields managed using conventional tillage and undercutter tillage (Sharratt and Feng, 2009). Since WEPS has not been tested in predicting erosion simultaneously from different tillage practices, this study was designed to test WEPS under two different tillage practices. This evaluation is vital for using WEPS in developing future alternative conservation field management practices.

A standalone version of the WEPS erosion submodel, named the Single-event Wind Erosion Evaluation Program (SWEEP), was released in 2007. The objective of this study was to test SWEEP under contrasting surface conditions resulting from conventional and undercutter tillage during the summer fallow phase of a winter wheat–summer fallow rotation within the Columbia Plateau.

Materials and Methods

SWEEP was validated at two field sites, each individually operated by wheat growers, in Adams County, Washington. 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.

Two tillage treatments, conventional tillage and undercutter tillage, were initiated after harvest of wheat in July of 2004 and 2005 during the fallow phase of a winter wheat– summer fallow rotation. Each treatment plot was 200 m × 100 m in 2004 and 200 m × 200 m in 2005. The tillage plots were adjacent to one another each year. Soil and PM10 losses were continuously monitored at the two field sites during the two-year study. A detailed description of tillage practices and field instrumentation used to monitor horizontal soil flux and PM10 concentration at the field sites each year can be found in the accompanied paper (Sharratt and Feng, 2009).

SWEEP requires information on 38 crop and soil parameters (Table I). All parameters required to test the model were periodically measured on-site at three random locations within each tillage plot before or after each high wind event or after each tillage or precipitation event.

Crop parameters

Crop residue flat cover was measured using a pin-type profile meter with 40 pins spaced 2·5 cm apart that protruded and moved vertically through holes in a steel frame mounted on the soil surface (Allmaras *et al.*, 1966). The profile meter was positioned randomly and parallel to tillage tool marks in the field. Residue flat cover was determined as the fraction of pins that lay upon prostrate residue elements. Standing wheat stubble was assessed by counting the number of standing stubble elements and measuring the height of the elements from 0·25 m^2 areas within tillage plots. Stem area index was determined as the ratio of the product of stubble density, height, and diameter to sampling area. Leaf area index was estimated as the ratio of the product of leaf density, length, and width to sampling area.

Soil parameters

Soil bulk density was determined by extracting soil core samples (0·07 m diameter and 0·03 m long) and placing the samples in an oven at 105 °C prior to measuring the soil dry weight (bulk density). Soil particle size and aggregate size distribution in the upper 30 mm of the profile were respectively determined using a Malvern Mastersizer and rotary sieve (Chepil, 1962; Lyles *et al.*, 1970) equipped with 0·42, 0·84, 2·0, 6·4, and 19·0 mm sieves. Minimum and maximum aggregate size was assumed to be 0·001 and 43 mm. Soil aggregate geometric mean diameter (GMD) and aggregate geometric standard deviation (GSD) were determined by fitting the measured percentage of different aggregate sizes to a log-normal function. Aggregate dry stability and density and wilting point water content previously measured for a Ritzville silt loam by Feng and Sharratt (2007b) were assumed to be representative of our field sites. Soil surface crust fraction was measured using the profile meter and determined as the fraction of pins that lay upon a surface crust. Random roughness was calculated as the standard deviation of pin height, measured by the profile meter, after correcting for slope (Currence and Lovely, 1970). Soil water content was assessed gravimetrically in the upper 5 and 30 mm of the profile. Hourly surface water content required by the model was assumed to be constant and unchanged during an event.

Weather

An automated meteorological station was established at the leeward position in each tillage plot to continuously measure wind speed and direction, precipitation, solar radiation, and atmospheric temperature and relative humidity. Anemometers were placed at heights of 0·1, 0·5, 1, 2, 3 and 6 m above the soil surface and wind direction was monitored at a height of 3 m. Micrometeorological sensors were monitored every 10 seconds and data recorded every 15 minutes by a datalogger [Model 23X, Campbell Scientific Inc., Logan, Utah (mention of trade names does not constitute an endorsement)] except during high wind events when data were recorded at 1 minute intervals.

Single-event Wind Erosion Evaluation Program (SWEEP)

SWEEP consists of the erosion submodel of WEPS coupled with a graphical user interface and simulates wind erosion for a single high wind event. Input parameters required by SWEEP

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Table I. Input parameters required by the SWEEP model for the validation. Parameters were measured prior to or after each high wind event in 2005 and 2006 within field plots subject to conventional and undercutter tillage

Parameters	2005				2006							
	23 June–8 July (183, 187[a])		31 August–14 September (252)		14–19 July (198)		19–25 July (205)		29–30 August (241)		30 August–6 September (242)	
	C	U	C	U	C	U	C	U	C	U	C	U
Crop												
Residue average height (m)	0·032 ± 0·027	0·112 ± 0·023	0·103 ± 0·025	0·037 ± 0·032	0·04 ± 0·01	0·06 ± 0·006	0·03 ± 0·006	0·05 ± 0·01	0·03 ± 0·008	0·04 ± 0·005	0·03 ± 0·008	0·04 ± 0·005
Residue stem area index ($m^2 m^{-2}$)	0·005 ± 0·002	0·060 ± 0·016	0·023 ± 0·008	0·024 ± 0·034	0·004 ± 0·002	0·022 ± 0·004	0·005 ± 0·008	0·020 ± 0·009	0·003 ± 0·002	0·006 ± 0·003	0·003 ± 0·002	0·006 ± 0·003
Residue leaf area index ($m^2 m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0
Residue flat cover ($m^2 m^{-2}$)	0·3 ± 0·02	0·48 ± 0·07	0·09 ± 0·04	0·11 ± 0·01	0·18 ± 0·01	0·34 ± 0·11	0·25 ± 0·03	0·45 ± 0·06	0·12 ± 0·01	0·29 ± 0·08	0·12 ± 0·01	0·29 ± 0·08
Growing crop average height (m)	0	0	0·15 ± 0·01	0·2 ± 0·01	0	0	0	0	0	0	0·09 ± 0·01	0·10 ± 0·02
Growing crop stem area index ($m^2 m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0
Growing crop leaf area index ($m^2 m^{-2}$)	0	0	0·046 ± 0·002	0·059 ± 0·001	0	0	0	0	0	0	0·0013 ± 0·0003	0·0018 ± 0·0016
Row spacing (m)	0	0	0·45	0·45	0	0	0	0	0·45	0·45	0·45	0·45
Seed placement	None	None	Furrow	Furrow	None	None	None	None	Furrow	Furrow	Furrow	Furrow
Soil												
Number of soil layers	1	1	1	1	1	1	1	1	1	1	1	1
Layer thickness (mm)	50	50	50	50	50	50	50	50	50	50	50	50
Bulk density ($Mg m^{-3}$)	0·99 ± 0·06	1·03 ± 0·03	1·02 ± 0·02	1·10 ± 0·05	0·99 ± 0·02	0·94 ± 0·03	0·97 ± 0·04	0·97 ± 0·13	1·06 ± 0·02	0·98 ± 0·06	1·06 ± 0·02	0·98 ± 0·06
Sand fraction (0·05–2·0 mm, $Mg mg^{-1} \times 100$)	38·46 ± 2·30	38·46 ± 2·30	38·46 ± 2·30	38·46 ± 2·30	25·84 ± 2·22	25·84 ± 2·22	25·84 ± 2·22	25·84 ± 2·22	25·84 ± 2·22	25·84 ± 2·22	25·84 ± 2·22	25·84 ± 2·22
Very fine sand fraction (0·05–0·1 mm, $Mg Mg^{-1} \times 100$)	24·54 ± 1·27	24·54 ± 1·27	24·54 ± 1·27	24·54 ± 1·27	17·87 ± 1·10	17·87 ± 1·10	17·87 ± 1·10	17·87 ± 1·10	17·87 ± 1·10	17·87 ± 1·10	17·87 ± 1·10	17·87 ± 1·10
Silt fraction (0·002–0·05 mm, $Mg Mg^{-1} \times 100$)	51·79 ± 1·34	51·79 ± 1·34	51·79 ± 1·34	51·79 ± 1·34	61·38 ± 1·40	61·38 ± 1·40	61·38 ± 1·40	61·38 ± 1·40	61·38 ± 1·40	61·38 ± 1·40	61·38 ± 1·40	61·38 ± 1·40
Clay fraction (<0·002 mm, $Mg Mg^{-1} \times 100$)	9·76 ± 1·17	9·76 ± 1·17	9·76 ± 1·17	9·76 ± 1·17	12·78 ± 0·93	12·78 ± 0·93	12·78 ± 0·93	12·78 ± 0·93	12·78 ± 0·93	12·78 ± 0·93	12·78 ± 0·93	12·78 ± 0·93
Rock volume fraction ($m^3 m^{-3}$)	0	0	0	0	0	0	0	0	0	0	0	0
Average aggregate density ($Mg m^{-3}$)	1·50	1·50	1·50	1·50	1·50	1·50	1·50	1·50	1·50	1·50	1·50	1·50
Average dry aggregate stability [ln(J kg^{-1})]	1·60	1·60	1·60	1·60	1·60	1·60	1·60	1·60	1·60	1·60	1·60	1·60
GMD of aggregate size (mm)	0·082 ± 0·024	0·023 ± 0·013	0·094 ± 1·30	0·035 ± 0·025	0·938 ± 0·596	1·227 ± 0·779	1·671 ± 2·194	0·343 ± 0·293	0·678 ± 1·429	0·499 ± 1·069	0·678 ± 1·429	0·499 ± 1·069
GSD of aggregate size ($mm mm^{-1}$)	248 ± 91	312 ± 35	1063 ± 869	214 ± 252	124 ± 86	105 ± 47	341 ± 431	303 ± 431	55 ± 76	55 ± 81	55 ± 76	55 ± 81
Minimum aggregate size (mm)	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001	0·001
Maximum aggregate size (mm)	43	43	43	43	43	43	43	43	43	43	43	43
Soil wilting point water content ($Mg Mg^{-1}$)	0·055	0·055	0·055	0·055	0·070	0·070	0·070	0·070	0·070	0·070	0·070	0·070
Surface crust fraction ($m^2 m^{-2} \times 100$)	100	100	0	0	50 ± 5·3	50 ± 6·7	32 ± 4·5	44 ± 8·7	0	0	0	0
Surface crust thickness (mm)	9 ± 1	7 ± 2	0	0	1	1	1	1	0	0	0	0
Loose material on crust ($m^2 m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0
Loose mass on crust ($kg m^{-2}$)	0	0	0	0	0	0	0	0	0	0	0	0

Table I. (*Continued*)

Parameters	2005				2006							
	23 June–8 July (183, 187[a])		31 August–14 September (252)		14–19 July (198)		19–25 July (205)		29–30 August (241)		30 August–6 September (242)	
	C	U	C	U	C	U	C	U	C	U	C	U
Crust density (Mg m^{-3})	0·9	0·9	0	0	0·9	0·9	0·9	0·9	0	0	0	0
Crust stability [ln(J kg^{-1})]	0·6	0·6	0	0	0·6	0·6	0·6	0·6	0	0	0	0
Allmaras random roughness (mm)	11·9 ± 4·1	14·5 ± 5·1	10·4 ± 1·8	8·8 ± 0·5	8·9 ± 2·8	12·7 ± 1·8	8·4 ± 0·8	10·7 ± 5·3	11·0 ± 2·0	8·3 ± 0·8	11·0 ± 2·0	8·3 ± 0·8
Ridge height (mm)	0	0	100	100	0	0	0	0	100	100	100	100
Ridge spacing (mm)	0	0	450	450	0	0	0	0	450	450	450	450
Ridge width (mm)	0	0	100	100	0	0	0	0	100	100	100	100
Ridge orientation (deg)	0	0	0	0	0	0	0	0	0	0	0	0
Dike spacing (mm)	0	0	0	0	0	0	0	0	0	0	0	0
Snow depth (mm)	0	0	0	0	0	0	0	0	0	0	0	0
Hourly surface water content (Mg mg^{-1} × 100)	0·84 ± 0·09	0·66 ± 0·16	0·42 ± 0·19	0·20 ± 0·002	1·8 ± 0·13	2·0 ± 0·58	2·2 ± 0·35	1·8 ± 3·0	2·3 ± 0·39	1·7 ± 0·25	2·3 ± 0·39	1·7 ± 0·25
Weather												
Wind direction (deg)	244	244	228	228	234	234	262	262	233	233	231	231
Number of interval/days to run SWEEP	96	96	96	96	96	96	96	96	96	96	96	96
Anemometer height (m)	2	2	2	2	2	2	2	2	2	2	2	2
Wind speed (m s^{-1})	See Figure 1											

Note: C denotes conventional tillage and U undercutter tillage.
[a] Signifies day of year of a recorded high wind event when wind speed at 3-m height exceeded 6·4 m s^{-1} for 10 consecutive minutes.

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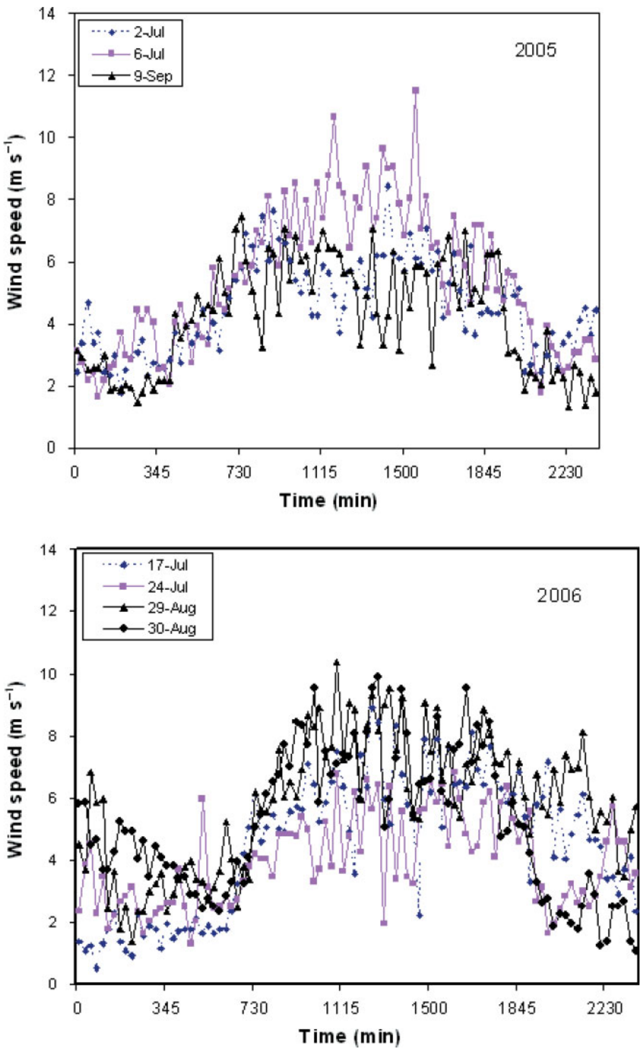

Figure 1. Wind speed at a height of 2 m averaged every 15 minutes on days with high winds in 2005 and 2006. This figure is available in colour online at www.interscience.wiley.com/journal/espl

are classified according to field, crop, soil, and weather parameters (Table I). Wind speed data are input separately using 15 minute averages (Figure 1).

Friction velocity and threshold friction velocity are important physical parameters that govern wind erosion and estimated by SWEEP. Friction velocity is determined based upon the aerodynamic roughness of the log-law wind speed profile. Aerodynamic roughness is calculated as a function of oriented roughness, random roughness, and leaf and stem area index. Oriented roughness is characterized by ridge height, ridge spacing, ridge width, and ridge orientation. Threshold friction velocity is defined as the velocity at which numerous aggregates begin to saltate and is calculated using soil aggregate geometric mean diameter and geometric standard deviation, minimum and maximum aggregate size, aggregate density, clod/crust cover, loose material on crust, surface roughness, flat biomass cover, surface soil water content, and soil wilting point water content. If friction velocity exceeds threshold friction velocity, the model initiates the simulation of soil movement.

Results and Discussion

High wind events (defined as sustained wind speeds in excess of 6·4 m s^{-1} at a height of 3 m for at least 10 consecutive minutes) that had prevailing winds between 180°–245° were observed over two sampling periods in 2005 and between 225°–270° were observed over four sampling periods in 2006. The most severe of these events occurred during 23 June–8 July 2005 and 29–30 October 2006 when winds in excess of 6·4 m s^{-1} were sustained for 24 and 16 consecutive hours, respectively (Sharratt and Feng, 2009). No erosion was observed during two of the six sampling periods (23 June–8 July 2005 and 19–25 July 2006) although winds greater than 6·4 m s^{-1} were respectively sustained for 24 and 6 hours. Winds attained a maximum velocity of 13·0 and 9·3 m s^{-1} during the respective 23 June–8 July 2005 and 19–25 July 2006 sampling periods. Details concerning measured soil and PM10 loss during the six sampling periods over the two year observation period used for validation of SWEEP are reported by Sharratt and Feng (2009).

Field surface characteristics and soil properties required by SWEEP and measured prior to or after each high wind event in 2005 and 2006 are listed in Table I. The Shano silt loam that characterized the field site in 2005 contained more sand and less silt and clay than the Ritzville silt loam that characterized the field site in 2006. Differences in soil surface and biomass characteristics between tillage treatments resulted from disking versus undercutting in the spring of both years. Prior to sowing, undercutter tillage retained more residue on the soil surface and had a greater random roughness compared with conventional tillage. Stem area index was greater for undercutter tillage as a result of taller stubble and greater stubble density in undercutter tillage than in conventional tillage. Contrary to our expectations, there was a tendency for GMD of aggregates to be larger in conventional tillage than undercutter tillage except on the first sample date in 2006. Any differences in other crop and soil parameters between tillage treatments likely had little impact on erosion. For example, although near surface water content appeared higher for conventional tillage, any difference in water content likely had little effect on soil erosion due to water contents (<2%) well below the wilting point (6%). In fact, McKenna-Neuman and Nickling (1989) found little variation in threshold friction velocity below the permanent wilting point. Wheat seedlings had little impact on wind erosion in this study as seedlings emerged on 7 September 2005, two days prior to the occurrence of high winds during the last sampling period in 2005, and on 3 September 2006, four days after the occurrence of high winds during the last sampling period in 2006. A soil surface crust was observed in both tillage treatments during the 23 June–8 July 2005, 14–19 July 2006, and 19–25 July 2006 events.

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 (Sharratt and Feng, 2009). The reduction in soil and PM10 loss resulted from altering field surface conditions by undercutter tillage as shown in Table I.

Simulating soil loss using SWEEP

Differences in soil and PM10 loss between conventional and undercutter tillage were not simulated by SWEEP. In fact, SWEEP simulated zero erosion for both treatments during all six high wind events in this study. Feng and Sharratt (2007b) found that the WEPS erosion submodel underestimated the relative importance of suspension in the erosion process and predicted zero erosion for conventional tillage systems during three of six high wind events observed in the Columbia Plateau

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in 2003 and 2004. These three events, for which the WEPS erosion submodel predicted zero erosion, where characterized by winds that attained velocities no greater than 12·5 m s^{-1} at a height of 3 m and soil loss of 0·004 to 0·16 kg m^{-2}. A maximum wind speed of 12·5 m s^{-1} does not constitute the threshold for erosion in the region since the WEPS erosion submodel did simulate 0·07 kg m^{-2} of soil loss for a high wind event characterized by a maximum wind speed of 11·9 m s^{-1} in 2003 (Feng and Sharratt, 2007b). In this study, the maximum 3-m wind speed observed for each high wind event was ≤12·0 m s^{-1} except for the 23 June–8 July event when the maximum wind speed was 13·0 m s^{-1}.

Hagen (2004) validated the WEPS erosion submodel using data from 46 storms at seven locations across the US. The submodel simulated no erosion for 30% of the storms when measured soil loss ranged from 0·01 to 0·11 kg m^{-2}. In addition, the model underestimated soil loss for 67% of the storms. Van Donk and Skidmore (2003) examined the performance of the WEPS erosion submodel on a silt loam sown to winter wheat in Colorado. The model predicted no erosion despite winds attaining a velocity of 15 m s^{-1} and a measured soil loss of 0·06 kg m^{-2} during a singular event. However, sediment transport was highly variable across their field site. The results of Hagen (2004), Van Donk and Skidmore (2003), and Feng and Sharratt (2007b) suggest collectively that the WEPS erosion submodel may underestimate erosion during events with less than gale force winds (<15 m s^{-1}), minimal or highly variable sediment transport across the landscape, or suspension dominating the erosion process.

Perspectives on simulating no erosion using SWEEP

SWEEP simulates erosion only when the friction velocity exceeds the threshold friction velocity. Therefore, failure to simulate erosion could result from underestimating friction velocity or overestimating threshold friction velocity. Friction velocity is influenced by drag exerted by surface roughness elements upon the wind. Surface roughness parameters that influence friction velocity include random roughness, ridge height and spacing, and silhouette area index. The model determines threshold friction velocity based upon the fraction of soil covered with rock, crust, or non-erodible aggregates, surface roughness, amount of prostrate biomass lying on the soil surface, and the soil water content above the wilting point. Failure to simulate erosion in our study could be due in part to improperly specifying soil and biomass parameters important in determining friction velocity and threshold friction velocity. A comprehensive sensitivity study on the WEPS erosion submodel (Feng and Sharratt, 2005) indicated that the most sensitive parameters in simulating erosion were biomass flat cover, near-surface soil water content, soil wilting point water content, aggregate and crust stability, clay content, and aggregate geometric diameter. Visser *et al.* (2005) found that the model is extremely sensitive to soil surface wetness. Soil crust and crop cover have a large influence on the erodibility of the soil and the transport capacity (Hagen, 1996; Molion and Moore, 1983; Rice *et al.*, 1997; Visser *et al.*, 2005). Van Donk and Skidmore (2003) concluded that the WEPS erosion submodel overestimates the protective role of small wheat plants in simulating erosion.

Parameter variation to improve SWEEP simulations

The greatest soil loss reported in this study occurred during the 29–30 August and 30 August–6 September 2006 events. We analyzed these events to explore possible causes for SWEEP simulating zero erosion. Field surface conditions were measured on 24 August and 6 September 2006. Since wheat was sown on 27 August, field conditions measured on 6 September were assumed to better represent field surface conditions during the high wind events and therefore used in the simulation (Table I). Wheat did not emerge until 3 September and thus growing crop parameters were excluded from the simulations. The field site was not trafficked nor did rainfall occur between 29 August and 6 September. Simulation of the two events with SWEEP yielded no erosion. Hagen (2004) indicated that small inclusions of soil that do not typify average field conditions may influence the simulation. Since spatial variation of measured input parameters could affect the simulation, we simulated erosion based upon the error in measuring soil and biomass parameters from each treatment plot. Mean values of soil and biomass parameters along their standard deviations are reported in Table I. Despite using mean values plus or minus one standard deviation, no erosion was simulated by SWEEP for either tillage treatment.

Estimating threshold friction velocity in SWEEP

Since surface roughness, standing biomass, aggregate size and density, clod/crust cover, surface roughness, residue flat cover and surface soil wetness influence friction velocity and threshold friction velocity, we adjusted these parameters to determine whether underestimation of friction velocity or overestimation of threshold friction velocity resulted in zero erosion. For the 29–30 August 2006 and 30 August–6 September 2006 high wind events, eliminating random roughness and standing biomass resulted in zero erosion. Therefore, it appears that underestimation of friction velocity for these two high wind events did not influence the simulated results of this study. This is in accordance with Visser *et al.* (2005) who showed that the WEPS erosion submodel gave a good estimation of the friction velocity on a non-cultivated field without vegetation cover. We furthermore reduced the measured aggregate GMD to 0·01 mm, aggregate GSD to 1 mm mm^{-1}, and soil water content to 0 Mg Mg^{-1} without any resultant erosion. However, after modifying the above soil and crop parameters and then reducing residue flat cover to 9% did we achieve some soil loss (0·07 kg m^{-2}). In the absence of standing biomass, soil loss (0·3 kg m^{-2}) was also generated by reducing residue flat cover to 0%, random roughness to 0 mm, aggregate GMD to 0·01 mm, aggregate GSD to 1 mm, and soil water content to 0·01 Mg mg^{-1}. Soil loss could also be generated by other combinations of values for these parameters. Thus, parameters that govern threshold friction velocity can greatly affect simulated soil loss. The relationship between residue flat cover and threshold friction velocity in SWEEP was derived from wind tunnel experiments using sandy soils (Hagen, 1996). Results obtained from sandy soils may not be applicable to the silt loam in our study. Van Donk and Skidmore (2003) concluded the model overestimated the protective role of standing biomass in wind erosion and both Van Donk and Skidmore (2003) and Visser *et al.* (2005) indicated that the model is very sensitive to surface soil wetness. Therefore, complex interactions among all parameters exist in the model and a comprehensive sensitivity analysis that accounts for these interactions could provide consistent results (Feng and Sharratt, 2005).

SWEEP also predicted no erosion for the 23 June–8 July 2005 high wind event. The field was rodweeded on 10 May and the soil surface was completely crusted on 23 June due to seven rainfall events (total precipitation equaled 17·8 mm) occurring between 10 May and 23 June 2005. At the time of the high wind event, the soil surface of the conventional tillage treatment had 30% residue flat cover, 0·1-m tall stubble, 9-mm thick crust, and no ridges. Apparently the thick crust was solely responsible for a measured soil loss of 0 kg m^{-2}. However, in the absence of any crust and using measured biomass and soil properties, SWEEP yielded no erosion. Furthermore, excluding standing stubble, no erosion was still simulated by SWEEP and suggests that SWEEP may overestimate the threshold friction velocity (erosion did not occur because friction velocity did not exceed the threshold). Van Donk and Skidmore (2003) were able to simulate some erosion when a small amount (0·01 kg m^{-2}) of loose material, covering a crusted soil surface, was included in the simulation. In the Pacific Northwest, little if any loose material has been observed to cover a crusted soil. Nevertheless, the model produced no erosion when a large amount (0·1 kg m^{-2}) of loose material, covering the crusted soil, was introduced into the simulation. This finding suggests that the simulated zero erosion was not entirely caused by the crust. In addition, when surface crust cover equaled zero, residue flat cover reduced from 30% to 10%, and all other measured parameters remained unchanged, SWEEP predicted a soil loss of 0·1146 kg m^{-2}. In the absence of residue flat cover, the model yielded a soil loss of 0 kg m^{-2} when the soil surface was entirely crusted and a soil loss of 0·1299 kg m^{-2} when the surface had a 40% crust cover. No erosion was predicted when the crust cover was greater than 40%. This indicates that both residue flat cover and crust cover play a significant role in controlling erosion in the model.

Role of wind gusts in simulating erosion

SWEEP requires input of wind speed with a temporal resolution of 15, 30 or 60 minutes. These time-averaged wind speeds largely exclude the importance of much smaller temporal perturbations in wind speed (i.e. wind gusts) to altering friction velocity and thus soil erosion. Although friction velocity may be below the threshold friction velocity based upon time-averaged wind speeds, wind gusts could result in much larger friction velocities that exceed the threshold many times during an averaging period. Wind gusts may, therefore, induce soil movement. In regions where wind gusts are prevalent, the use of time-averaged wind speed in wind erosion models may result in a failure to simulate erosion due to friction velocities not exceeding threshold friction velocities. Simulation of erosion by SWEEP may possibly be improved for the conditions of our study by considering the effect of wind gusts on friction velocity or by using wind speeds averaged over a shorter period of time. This may be particularly important in regions characterized by light or gusty winds. Gregory *et al.* (2004) noted the importance of wind gusts in eroding soils and therefore included a gust factor to adjust the threshold friction velocity.

Conclusions

SWEEP failed to simulate any difference in soil loss between conventional and undercutter tillage employed in the Pacific Northwest. In fact, the model simulated zero erosion for all high wind events observed in 2005 and 2006. The reason for the lack of simulated erosion is complex owing to the number of parameters and interaction of these parameters on erosion processes. A possible cause might be overestimation of the threshold friction velocity in SWEEP since friction velocity must exceed the threshold to initiate erosion. Although many parameters are involved in the estimation of threshold velocity, internal empirical coefficients and equations may affect the simulation. While the model appears sensitive to various parameters, modification of this model is not straightforward. Automatic calibration methods might be useful in adjusting the internal coefficients and empirical equations. Additionally, the lack of uncertainty analysis is an important gap in providing reliable output from this model.

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