SENSITIVITY ANALYSIS OF SOIL AND PM_{10} LOSS IN WEPS USING THE LHS-OAT METHOD

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ABSTRACT. *The Wind Erosion Prediction System (WEPS) was developed for the specific application of simulating erosion processes from agricultural lands. WEPS is a physically based model, with a moderate to large number of input parameters. Knowledge about model sensitivity is essential to both model developers and users in ascertaining those parameters most influential to modeled object functions. A combined method of Latin hypercube sampling (LHS) and one-factor-at-a-time (OAT) parameter examination was used to assess the sensitivity of parameters in the WEPS erosion submodel in simulating total soil loss, creep/saltation, suspension, and PM_{10} emission. The ranges of the parameters considered in this analysis were obtained from the WEPS User's Manual and determined for the Columbia Plateau region of the U.S. Overall, the analysis indicated that the model was most sensitive to changes in biomass flat cover, near-surface soil water content, ridge height, wind speed, rock volume, soil wilting-point water content, field length and width, crust cover, aggregate and crust stability, and random roughness. The model was least sensitive to changes in bulk density, silt content, and aggregate and crust density. For the Columbia Plateau, erosion processes were more sensitive to surface soil water content and random roughness in spring than in autumn and more sensitive to residue cover and aggregate mean diameter in autumn than in spring. This sensitivity analysis suggests that residue management, surface soil moisture conservation, aggregation, and field size can effectively influence soil loss and PM_{10} emission.*

Keywords. *Air quality, Columbia Plateau, Creep, PM_{10}, Saltation, Sensitivity analysis, Soil wind erosion, Suspension, WEPS.*

Wind erosion threatens soil productivity and air quality throughout the world. On-site and off-site impacts of wind erosion can only be minimized by developing a thorough understanding of erosion processes. Models are useful in assimilating our knowledge about physical systems; indeed, models capable of simulating wind erosion can aid in ascertaining which lands are susceptible to erosion and in designing soil conservation systems for susceptible lands. The Wind Erosion Prediction System (WEPS) is a process-based model that simulates the modes of soil transport including creep-size aggregates (0.84 to 2.0 mm diameter) rolling along the surface, saltation-size aggregates (0.10 to 0.84 mm diameter) hopping over the surface, suspension-size aggregates (<0.10 mm diameter) moving above the surface in the turbulent flow, and PM_{10} (particulates $\leq$10 μm in aerodynamic diameter) emissions from agricultural lands (Hagen et al., 1999). Few studies, however, have been undertaken to examine the performance of WEPS (Van Donk and Skidmore, 2003).

WEPS consists of seven submodels: weather, erosion, hydrology, management, soil, crop, and residue decomposition. The erosion submodel is key to predicting loss of soil in WEPS (Van Donk and Skidmore, 2003). The other six submodels of WEPS were developed to dynamically update parameters for the erosion submodel. The erosion submodel performs the following functions:

- Calculates friction velocities based on the aerodynamic roughness of the surface.
- Calculates static threshold friction velocities based on the current soil surface random and oriented roughness, flat and standing biomass, aggregate size distribution and density of a non-crusted surface, crust and rock cover, loose erodible material on a crust, surface soil wetness, and wilting point water content (at 1.5 MPa).
- Computes soil loss/deposition within each grid cell over the entire simulation region once friction velocity exceeds static threshold friction velocity.
- Updates soil surface variables to reflect changes in soil surface "state" caused by erosion.

The erosion submodel requires knowledge about soil and crop parameters, many of which can only be measured with great difficulty in the field, to predict soil loss. Thus, the need arises to identify those parameters that are most influential to soil loss and should be measured with the greatest accuracy in the field. Hagen et al. (1999) performed a sensitivity analysis of the WEPS erosion submodel and determined the ranking of important parameters solely based on soil loss. They found that wind speed, soil water content, and aggregate or crust stability were the most important factors influencing soil loss. No analyses, however, were performed to ascertain those parameters most influential in causing creep, saltation, suspension, and emission of PM_{10}. A linear sensitivity model was used in their analysis even though the responses of soil loss to changes in many parameters in the erosion submodel are nonlinear. The dynamic interactions

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among parameters were not considered in their study and illustrate the need for further studies concerning possible interactions among parameters that influence erosion.

Wind erosion has long been a problem in the western U.S. Today, growers are confronted with regulations that are aimed at reducing wind erosion and improving air quality. For example, wind erosion within the Columbia Plateau has led to noncompliance with air quality standards for PM_{10} (Saxton et al., 2000). Wind erosion that contributes to poor air quality is particularly acute in the low-precipitation zone (annual precipitation <260 mm) of the Columbia Plateau, where wheat-fallow is the predominate crop rotation (Schillinger and Young, 2004). WEPS may be a potentially useful tool to help growers choose conservation practices that are environmentally friendly as well as economically viable, but little is known concerning the performance of WEPS in the region. Such an evaluation, which may include determining the ranking of parameters in the erosion submodel and characterizing the range in these parameter values across soil types, could provide great assistance to potential users of WEPS in the region.

There is a paucity of information regarding the performance of WEPS and more particularly the WEPS erosion submodel parameters that are most influential in causing creep, saltation, suspension, and emission of PM_{10}. The overall objective of this study was therefore to identify the most important soil properties and surface characteristics in the WEPS erosion submodel that influence creep, saltation, suspension, and PM_{10} emission. Of particular interest was characterizing the sensitivity of the erosion submodel parameters in simulating erosion processes within the low-precipitation zone of the Columbia Plateau.

METHODS

Model evaluation can include sensitivity analysis, uncertainty analysis, calibration, and validation. Sensitivity analysis is of primary importance in evaluating any model (Nearing et al., 1990) and is potentially useful in all phases of model development: model formulation, model calibration, and model verification (McCuen, 1973). Sensitivity analysis can be used to determine the relative response of the model to changes in values of model parameters. As such, sensitivity analysis can aid in identifying parameters that greatly influence processes of the physical system. Sensitivity analysis can also be used to ascertain the impact of parameter variability on the modeled variance (Nearing et al., 1990).

Sensitivity analyses can be classified according to (1) graphical methods, such as “visual” sensitivity analysis, (2) mathematical methods, and (3) statistical methods. Graphical methods are typically used for screening and providing a visual indication of the modeled response to changes in parameter values. Mathematical methods determine the modeled response to only a few changes in parameter values and do not address the variance in the modeled response due to variances in the parameters. Statistical methods involve simulating a response using a given distribution in parameter values and therefore determine the effect of parameter variance on the simulated response (Andersson et al., 2000).

Sensitivity analysis was performed on the WEPS erosion submodel (eros18.exe, built October 2004). Only those parameters that characterize wind, field width and length, surface residue, soil properties, and ridge topographic features (table 1) were considered in this analysis. The statistical approach employed in this study included examining the model response to changes in parameter values. Parameters values were obtained using a Latin hypercube sampling strategy, and parameters were examined using a one-factor-at-a-time procedure. This approach provides an efficient sensitivity analysis, particularly when analyzing a large number of parameters (Francos et al., 2003; Van Griensven et al., 2002).

LATIN HYPERCUBE SAMPLING (LHS)

Monte Carlo techniques provide approximate solutions to a variety of mathematical problems by performing statistical sampling experiments on a computer (Fishman, 1996). These techniques are robust and have been widely used in modeling (Krajewski et al., 1991), but they generally require lengthy computation times. The concept of LHS (McKay et al., 1979; McKay, 1988) is based on Monte Carlo techniques and has been successively applied in water quality modeling (Weijers and Vanrolleghem, 1997; Manache, 2001; van Griensven et al., 2002). LHS uses a stratified sampling approach that allows efficient estimation of output statistics. LHS subdivides the parameter range into N segments, each with a probability of occurrence equal to $1/N$. Each segment is sampled only once, thus generating N random values for each parameter.

ONE-FACTOR-AT-A-TIME (OAT) PARAMETER EXAMINATION

Parameter values obtained by LHS were examined using the one-factor-at-a-time (OAT) procedure, as proposed by Morris (1991), which takes into account both local and global sensitivities. Local sensitivity is achieved because the modeled response can be unambiguously attributed to the change in only one parameter. Global sensitivity is achieved by sampling over the entire parameter range using LHS. The OAT procedure randomly chooses a value for each parameter from the LHS sample pool (fig. 1). The assembled parameter set, containing one value for every parameter, is then screened to avoid unreasonable combinations of correlated parameters. For the purpose of this analysis, correlated parameters must have values that satisfy the following criteria:

- The total fraction of sand, silt, and clay must equal 1, and very fine sand must be less than the total sand fraction.
- Ridge spacing must be at least twice the height of the ridge, or equal to 0 mm when the ridge height is 0 mm.
- Aggregate geometric diameter must be less than the maximum aggregate size.
- Leaf and stem areas must be 0 $m^2\ m^{-2}$ when plant height is 0 m.
- The fraction of soil surface covered with biomass and crust must be $\leq$1.
- Soil crust thickness is 0 mm, crust stability is 0 J kg^{-1}, fraction of the crusted surface covered by loose material is 0 $m^2\ m^{-2}$, and mass of loose material on the crusted surface is 0 kg m^{-2} when the fraction of soil surface crusted is 0 $m^2\ m^{-2}$.

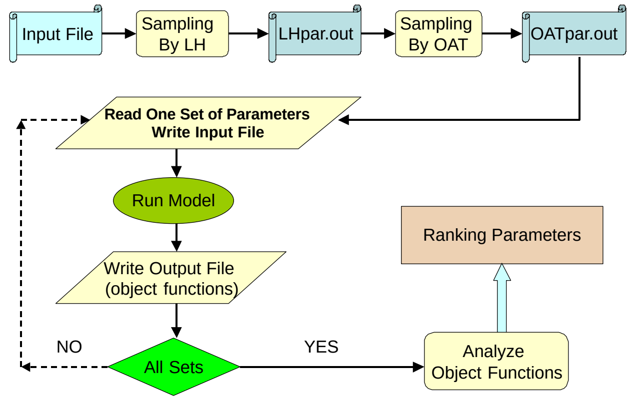

Figure 1. Flowchart of the LHS-OAT sensitivity analysis procedure for the WEPS erosion submodel.

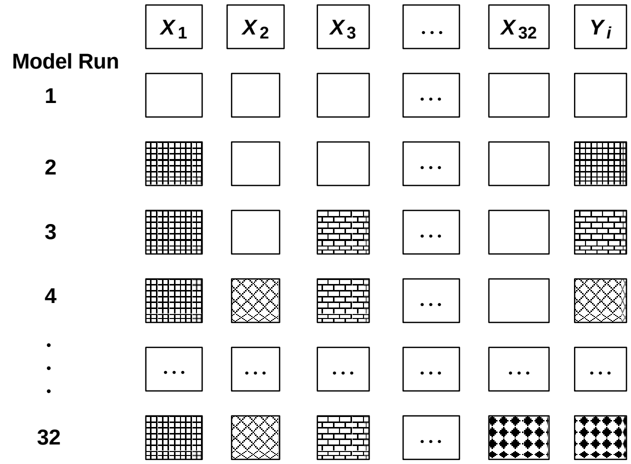

Figure 2. One-factor-at-a-time procedure used to assess the sensitivity of parameters in the WEPS erosion submodel (X_i represents the tested parameters, and Y_i represents the model outputs).

If any correlated parameters fail to meet one of the preceding criteria, then those unreasonable parameter values are replaced with new values obtained from the LHS sample pool. The model is run using each of the *N* parameter sets. The model response can be attributed to the change in one parameter by means of an elementary partial effect (Y_{ij}), defined by :

$$Y_{ij} = \left[\sum_{k=1}^{N} \left| f(X_1,..., X_i * (1+\Delta),..., X_n) - f(X_1,..., X_{ij},..., X_n) \right| \right] \div N \quad (1)$$

where Y_{ij} is a partial effect for parameter X_i around an LHS value *j*, *f* is the model output, Δ is the fraction by which the parameter X_i is randomly increased or decreased (a predefined constant), *k* is a sample from the *N* number of segments in LHS, and *n* is the number of parameters.

The partial effect is quantitative, but the measure of sensitivity is only relative because the influence of X_i may depend on the values chosen for the remaining parameters. Therefore, the analysis is repeated for all sets of parameters. The sensitivity of the modeled response (ranking of parameters) is then calculated as the average of the partial effects (eq. 1). The parameter with the largest average partial effect is the first ranked parameter. The variance of the partial effects can also provide information about the presence or absence of nonlinearities or interactions with other parameters. Ideally, the computational procedure should account for all parameters $\{x_i\}$. Considering *n* parameters (i.e., $i = 1, ..., n$), the analysis involves performing $n + 1$ model runs to obtain one partial effect for each parameter. The OAT procedure for our analysis is illustrated in figure 2. In our study, either 28 or 32 parameters were examined with a set of initial values (unfilled squares). For each model run, only one parameter was randomly changed (filled squares). The partial effect was determined after each pair of model runs (i.e., the partial effect for parameter X_1 was evaluated using model runs 1 and 2, and X_2 was evaluated using model runs 2 and 3).

Preliminary tests indicated that sensitivity analysis was affected by the number of segments examined within the parameter range. The sensitivity of each parameter remained constant (rankings did not change) when the number of segments was at least 1,000. In this study, each parameter range was divided into 2,500 equal segments in order to reduce the probability of unreasonable combinations of correlated parameters. The WEPS erosion submodel was continuously run by updating parameter values using the random parameter sets (2,500 sets) until all parameters sets were tested (fig. 1). Every model run (72,500 runs based on examining 28 parameters for the Columbia Plateau, and 82,500 runs based on examining 32 parameters in the WEPS User's Manual) was evaluated for total soil loss, saltation/creep, suspension, and PM_{10} emission.

Parameter Selection and Values

Parameters that influence creep, saltation, suspension, and PM_{10} emission in the WEPS erosion submodel considered in this study are listed in table 1. Initial tests revealed that the sensitivity of the model was greatly affected by the ranges in value of the parameters. Therefore, we chose to specify the ranges of parameter values according to those listed in the WEPS User's Manual (USDA-ARS, 2004) and those that typify soils subject to conventional summer fallow in the low-precipitation zone of the Columbia Plateau.

Wind, field, biomass, soil, and hydrology parameters listed in the WEPS User's Manual were examined in this study (table 1). Parameters associated with barriers, dikes, and bed or ridge width were excluded from this analysis. The typical ranges listed in the WEPS User's Manual were used for the soil and hydrology parameter values (parameters 7 to 30). However, the listed range for random roughness (2 to 10 mm) was modified to 2 to 50 mm (Zobeck and Onstad, 1987). The typical range is representative of most agricultural soils and would characterize the overall performance of the erosion submodel. The value ranges for the wind, field, and biomass parameters are not specified in the WEPS User's Manual; thus, these values were approximated as follows: wind speed of about 8 m s^{-1} is required to initiate wind erosion (Kjelgaard et al., 2004), and winds in excess of 20 m s^{-1} typically occur across much of the U.S. (U.S. Department of Commerce, 2005). Field lengths of 50 to 1600 m and field widths of 20 to 600 m were assumed to be representative of agricultural fields. Plant height, leaf area, and stem area were approximated for three major agricultural crops (cotton, corn, and wheat) grown in the Great Plains, Atlantic coastal plain, and Pacific Northwest, where wind erosion is particu−

Table 1. The range in values of selected WEPS erosion submodel parameters. Parameter values are those listed in the WEPS User's Manual and those that typify a summer fallow field in the spring and autumn on the Columbia Plateau.

		WEPS User's Manual		Fallow Field on the Columbia Plateau			
				Spring		Autumn	
No.	Parameter	Low	High	Low	High	Low	High
1	Field length (m)	50	1600	50	1600	50	1600
2	Field width (m)	20	600	20	600	20	600
3	Biomass height (m)	0	3	0	0.3	0	0.3
4	Stem area index (m^2 m^{-2})	0	3	0	0.2	0	0.2
5	Leaf area index (m^2 m^{-2})	0	8	0	0	0	0
6	Biomass flat cover (m^2 m^{-2})	0	1	0.15	0.6	0.15	0.55
7	Bulk density (Mg m^{-3})	0.8	1.6	0.9	1.6	0.9	1.6
8	Sand content (kg kg^{-1})	0	1	0.14	0.99	0.14	0.99
9	Very fine sand (kg kg^{-1})	0	1	0.08	0.54	0.08	0.54
10	Silt content (kg kg^{-1})	0	1	0.006	0.73	0.006	0.73
11	Clay content (kg kg^{-1})	0	1	0.035	0.14	0.035	0.14
12	Rock volume fraction (m^3 m^{-3})	0	0.5	0	0.11	0	0.11
13	Aggregate density (Mg m^{-3})	0.8	2	1.7	2.0	1.7	2.0
14	Aggregate stability (ln[J kg^{-1}])	0.5	5	1.35	2.56	1.35	2.56
15	Aggregate geometric diameter (mm)	0.1	15	0.98	26.6	0.98	26.6
16	Minimum aggregate size (mm)	0.006	0.02	0.006	0.01	0.006	0.01
17	Maximum aggregate size (mm)	2	100	34.88	62.53	34.88	62.53
18	Aggregate geometric standard deviation (mm mm^{-1})	4	15	10.32	16.14	10.32	16.14
19	Fraction of soil surface crusted (m^2 m^{-2})	0	1	0	1	0	1
20	Soil crust thickness (mm)	0	10	0	10	0	10
21	Fraction of crusted surface covered by loose material (m^2 m^{-2})	0	0.5	0	0.5	0	0.5
22	Mass of loose material on crusted surface (kg m^{-2})	0	1	0	1	0	1
23	Soil crust density (Mg m^{-3})	0.8	1.6	1.69	2.0	1.69	2.0
24	Soil crust stability (ln[J kg^{-1}])	0.3	5	1.35	2.56	1.35	2.56
25	Random roughness (mm)	2	50	0	25	0	6
26	Soil wilting point water content (kg kg^{-1})	0.005	0.242	0.033	0.097	0.033	0.097
27	Surface water content (kg kg^{-1})	0.005	0.44	0.01	0.15	0.01	0.05
28	Ridge height (mm)	0	300	0	0	0	0
29	Ridge space (mm)	60	1000	0	0	0	0
30	Ridge orientation (°)	0	179	0	0	0	0
31	Wind speed (m s^{-1})	8	20	8	20	8	20
32	Wind direction (°)	0	179	0	179	0	179

larly acute (Hagen, 1991). Cotton and wheat are typically 1 m in height, but corn can exceed 3 m in height (Karlen et al., 1987). Leaf area indices of cotton, corn, and wheat can approach 8 (Amir and Sinclair, 1991; Hattendorf et al., 1988; Reddy et al., 2004), but little information is available concerning stem area index for agricultural crops. Therefore, stem area index was estimated for cotton, corn, and wheat using stem diameter and stem density or total stem length. Stem diameter of cotton was assumed to equal that of wheat (3 mm; McMaster et al., 2000), and stem diameter of corn was assumed to be 20 mm or more (Karlen et al., 1987). Stem density can vary considerably, but it was assumed to vary from 7.5 stems m^{-2} for corn (Hicks and Thomison, 2004) to about 1000 stems m^{-2} for wheat (Schillinger and Young, 2004). Lei (2002) indicated that total stem length of cotton can exceed 20 m m^{-2}. Thus, stem area index is likely to vary from about 0.1 m^2 m^{-2} for cotton, to 0.5 m^2 m^{-2} for corn, to nearly 3 m^2 m^{-2} for wheat. Fraction biomass flat cover was assumed to approach 1.

The ranges in parameter values for the Columbia Plateau (table 1) are representative of those that occur during the summer fallow period when soils are most susceptible to erosion. These values are different from those in the WEPS User's Manual due to our specific application to summer fallow and the range of soil types across the Columbia Plateau. High wind events (>8 m s^{-1}) occur in spring and autumn, but soil surface conditions are quite different during these seasons due to weather and as a result of a sequence of tillage operations that occur during the summer fallow period (Schillinger, 2001). Thus, the ranges in parameter values will differ between spring and autumn.

The ArcGIS 8.1 software aided in generating ranges in parameter values for soils within the low-precipitation zone of the Columbia Plateau (fig. 3). Boundaries of the Columbia Plateau were drawn and overlain by 40-year average annual precipitation data obtained from the Oregon Climate Service at Oregon State University. The low-precipitation zone was identified where annual precipitation was ≤260 mm. The USDA-NRCS STATSGO soil database was used to create a layer with soil properties. This procedure generated lower and upper ranges for bulk density, sand content, very fine sand, silt content, clay content, rock volume, and wilting point water content (parameters 7-12 and 26 in table 1) across soil types in the low-precipitation zone of the Columbia Plateau. Soil aggregate and soil crust properties (parameters 13-18, 23, and 24 in table 1) were generated by WEPS using the USDA-NRCS SSURGO database. Soil crust fraction and thickness and loose material on the crusted surface could not be derived using WEPS, nor have they been reported for the Columbia Plateau, but field observations by the authors suggest that the ranges of values of these properties (parameters 19-22 in table 1) are similar to those reported in the WEPS User's Manual.

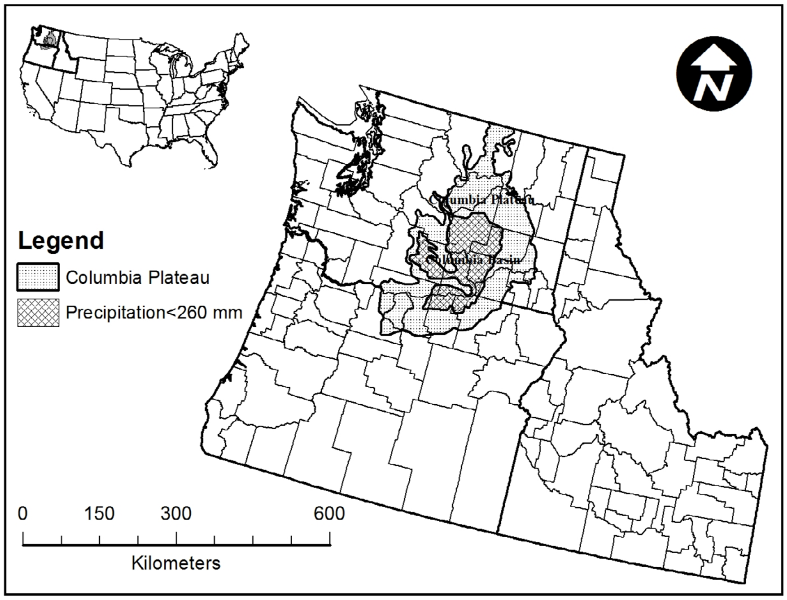

Figure 3. Location of the Columbia Plateau and the low-precipitation zone (<260 mm).

Other erosion submodel parameters were derived based on conventional tillage and cropping practices in the low-precipitation zone of the Columbia Plateau. The soil surface is devoid of viable vegetation during the summer fallow period; thus, leaf area is zero. Stem or biomass height after harvest of winter wheat is typically 0.3 m, which corresponds to the maximum height at which there is no grain loss during the combine process (McMaster et al., 2000). Stem height, however, diminishes during the fallow cycle due to tillage and weathering; in fact, little standing stubble may remain on the soil surface at the end of the fallow cycle. Stem silhouette area was determined from stem diameter, stem height, and stem population. Winter wheat typically has a stem diameter of 3 mm (McMaster et al., 2000) and stem, or equivalent spike, populations range from 100 to 650 stems m^{-2} in the low-precipitation zone (Schillinger and Young, 2004). These populations diminish with time due to burial and breakage of stems by tillage implements and degradation and breakage of stems over winter. Conventional tillage in the low-precipitation zone consists of sweeping and chiseling in autumn, disking and fertilizing in spring, and rodweeding during summer (Schillinger et al., 2004). Autumn and spring tillage and fertilizer operations, in addition to over-winter processes, reduce stem populations by at least 65% (Papendick and Moldenhauer, 1995). The expected range in stem population after fertilizer is applied in spring is therefore 35 to 240 stems m^{-2}. Further reduction in stem population occur as a result of rodweeding during summer, resulting in an estimated standing stem population of 30 to 205 stems m^{-2} at the end of the summer fallow period. These stem populations result in a silhouette area of 0.03 to 0.2 m^2 m^{-2} in both spring and at the end of the summer fallow period.

Biomass flat cover was estimated from prostrate residue biomass. Schillinger and Young (2004) reported a range in straw production from about 1100 to 6400 kg ha^{-1} over six years in the low-precipitation zone, but these observations included standing stubble and prostrate residue. This range in straw production corresponded to stem populations that varied from 100 to 650 stems m^{-2}. Straw has a specific density of about 170 kg m^{-3} (Unger and Parker, 1976); thus, the biomass of 0.3 m tall stubble was estimated to vary from 360 to 2340 kg ha^{-1}. Prostrate residue biomass is the difference between straw production and standing stubble biomass; thus, prostrate residue was estimated to vary from 740 to 4060 kg ha^{-1}. Prostrate residue biomass diminishes with time due to tillage and weathering (Papendick and Moldhauer, 1995). Thus, taking into account tillage and weathering effects, the amount of prostrate residue remaining on the soil surface in a conventional tillage system ranges from 270 to 1490 kg ha^{-1} after fertilizer is applied in spring, and from 230 to 1280 kg ha^{-1} at the end of the summer fallow period. These estimates of residue biomass remaining at the end of the fallow period are similar to those of Schillinger (2001), who measured 250 to 1700 kg ha^{-1} of residue at the end of conventional summer fallow over five years in the low-precipitation zone. Our estimates, which do not reflect the addition of residue to the soil surface as a result of breakage and weathering of standing stubble, correspond to 15% and 60% flat cover in spring and to 15% and 55% flat cover at the end of the summer fallow period (Papendick and Moldhauer, 1995).

Ridge or seed row spacing typically varies from 400 to 450 mm in the low-precipitation zone (Papendick and Moldenhauer, 1995). At the time of harvest in the autumn, ridge height varies greatly due to erosion processes during the crop cycle; ridges 200 mm in height have been commonly observed by the authors. In spring, ridges are indiscernible due to erosion caused by post-harvest tillage operations and over-winter processes.

Few measurements of random roughness have been made in the field during the summer fallow period in the low-precipitation zone. For example, Thorne et al. (2003) observed random roughness of 10 to 15 mm during the summer fallow period over two years, but Papendick (2004) indicated that random roughness can vary from 6 mm near the end of the fallow cycle to 25 mm in early fallow or spring. Similarly, few observations have been made of soil surface water content during the summer fallow period. Soils are

Table 2. Ranked order for the sensitivity of the parameters to the objective functions of the output variables in cropland soil.

Rank Order	Total Soil Loss ($kg\ m^{-2}$)	Saltation/Creep ($kg\ m^{-2}$)	Suspension ($kg\ m^{-2}$)	PM_{10} Emission ($kg\ m^{-2}$)
1	Biomass flat cover	Biomass flat cover	Biomass flat cover	Biomass flat cover
2	Soil water content	Ridge height	Soil water content	Soil water content
3	Ridge height	Soil water content	Ridge height	Rock volume fraction
4	Wind speed	Wind speed	Wind speed	Sand content
5	Rock volume fraction	Wind direction	Rock volume fraction	Ridge height
6	Soil wilting point water content	Rock volume fraction	Sand content	Wind speed
7	Ridge orientation	Sand content	Very fine sand	Very fine sand
8	Aggregate stability	Ridge orientation	Aggregate stability	Aggregate stability
9	Crust stability	Soil wilting point water content	Aggregate geometric diameter	Crust stability
10	Aggregate geometric diameter	Very fine sand	Soil wilting point watercontent	Soil wilting point water content
11	Wind direction	Crust stability	Crust stability	Field width
12	Sand content	Aggregate stability	Wind direction	Aggregate geometric diameter
13	Mass of loose material on crusted surface	Field width	Field width	Crust cover
14	Crust cover	Mass of loose material on crusted surface	Ridge orientation	Random roughness
15	Field width	Biomass height	Field length	Ridge orientation
16	Very fine sand	Aggregate geometric diameter	Crust cover	Wind direction
17	Crust thickness	Stem area index	Mass of loose material on crusted surface	Field length
18	Biomass height	Crust cover	Crust thickness	Crust thickness
19	Stem area index	Random roughness	Random roughness	Mass of loose material on crusted surface
20	Field length	Crust thickness	Stem area index	Stem area index
21	Random roughness	Ridge space	Biomass height	Maximum aggregate size
22	Ridge space	Clay content	Maximum aggregate size	Clay content
23	Maximum aggregate size	Field length	Ridge space	Biomass height
24	Clay content	Fraction of crusted surface covered by loose material	Clay content	Ridge space
25	Fraction of crusted surface covered by loose material	Aggregate geometric standard deviation	Fraction of crusted surface covered by loose material	Minimum aggregate size
26	Aggregate geometric standard deviation	Maximum aggregate size	Aggregate geometric standard deviation	Fraction of crusted surface covered by loose material
27	Minimum aggregate size	Minimum aggregate size	Minimum aggregate size	Aggregate geometric standard deviation
28	Leaf area index	Leaf area index	Leaf area index	Leaf area index
29	Bulk density	Bulk density	Bulk density	Bulk density
30	Silt content	Silt content	Silt content	Silt content
31	Aggregate density	Aggregate density	Aggregate density	Aggregate density
32	Crust density	Crust density	Crust density	Crust density

typically wet in the spring and very dry in late summer due to the Mediterranean-type climate of the region. Field observations made over several years and at different locations in the low-precipitation zone suggest that near-surface (0 to 20 mm depth) water content can vary from 0.01 to 0.05 $m^3\ m^{-3}$ at the end of the summer fallow period or at the time of sowing winter wheat (Schillinger et al., 1998; Schillinger and Bolton, 1996). Near-surface water content of soil subject to conventional tillage has not been observed during the spring in the low-precipitation zone. Observations made in the upper 0.3 m of a soil profile sown to spring wheat suggest that water content can approach 0.15 $m^3\ m^{-3}$ (Schillinger and Young, 2000), which far exceeds that required to control soil movement by wind (Dong et al., 2002).

Soil erosion is initiated at wind speeds of about 8 $m\ s^{-1}$ in the low-precipitation zone (Kjelgaard et al., 2004). Wind speeds are generally highest during spring (March-May), with average monthly wind speeds of about 4 $m\ s^{-1}$ (Elliott and Barchet, 1980). Peak wind gusts can exceed 20 $m\ s^{-1}$ every two years and 30 $m\ s^{-1}$ every ten years within the region (Wantz and Sinclair, 1981).

Results and Discussion

The sensitivity analysis of the WEPS erosion submodel examined a wide range of parameter values listed in the WEPS User's Manual; these ranges characterize most soils and cropping systems found in areas prone to wind erosion throughout the world. The parameters that affect erosion processes are ranked in tables 2 and 3. The rankings in table 2 are representative of cropland soils, whereas the rankings in table 3 are representative of fallow soils in the WEPS erosion submodel. These rankings are based on the same ranges in parameter values, except that biomass flat cover and height, leaf area, and stem area were assumed nonexistent for fallow soils.

Table 3. Ranked order for the sensitivity of the parameters to the objective functions of the output variables in fallow soil.

Rank Order	Total Soil Loss ($kg\ m^{-2}$)	Saltation/Creep ($kg\ m^{-2}$)	Suspension ($kg\ m^{-2}$)	PM_{10} Emission ($kg\ m^{-2}$)
1	Soil water content	Soil water content	Soil water content	Soil water content
2	Wind speed	Wind speed	Wind speed	Wind speed
3	Rock volume fraction	Rock volume fraction	Rock volume fraction	Clay content
4	Soil wilting point water content	Soil wilting point water content	Soil wilting point water content	Soil wilting point water content
5	Aggregate stability	Clay content	Aggregate stability	Rock volume fraction
6	Field length	Field length	Wind direction	Aggregate stability
7	Wind direction	Aggregate geometric diameter	Field length	Wind direction
8	Clay content	Wind direction	Crust stability	Aggregate geometric diameter
9	Crust stability	Crust stability	Clay content	Crust stability
10	Aggregate geometric diameter	Ridge height	Ridge height	Field length
11	Ridge height	Crust cover	Aggregate geometric diameter	Ridge height
12	Crust cover	Aggregate stability	Crust cover	Random roughness
13	Random roughness	Very fine sand	Field width	Crust cover
14	Field width	Sand content	Random roughness	Field width
15	Ridge orientation	Field width	Ridge orientation	Very fine sand
16	Very fine sand	Random roughness	Very fine sand	Sand content
17	Sand content	Ridge orientation	Sand content	Ridge orientation
18	Mass of loose material on crusted surface	Mass of loose material on crusted surface	Mass of loose material on crusted surface	Ridge space
19	Ridge space	Ridge space	Ridge space	Mass of loose material on crusted surface
20	Fraction of crusted surface covered by loose material	Fraction of crusted surface covered by loose material	Fraction of crusted surface covered by loose material	Fraction of crusted surface covered by loose material
21	Crust thickness	Crust thickness	Crust thickness	Crust thickness
22	Aggregate geometric standard deviation	Aggregate geometric standard deviation	Aggregate geometric standard deviation	Aggregate geometric standard deviation
23	Maximum aggregate size	Maximum aggregate size	Maximum aggregate size	Minimum aggregate size
24	Minimum aggregate size	Minimum aggregate size	Minimum aggregate size	Maximum aggregate size
25	Bulk density	Bulk density	Bulk density	Bulk density
26	Silt content	Silt content	Silt content	Silt content
27	Aggregate density	Aggregate density	Aggregate density	Aggregate density
28	Crust density	Crust density	Crust density	Crust density

As shown in table 2, biomass flat cover, near-surface soil water content, ridge height, wind speed, and rock volume are the five most influential parameters affecting creep, saltation, suspension, and emission of PM_{10} from cropland soils. Biomass flat cover was the single most important parameter influencing erosion processes in cropland soils and is one of the practical ways for minimizing soil loss by wind erosion. Soil water content influences the static threshold friction velocity, while biomass flat cover and wind speed are important in defining the friction velocity at the soil surface. Although soil wetness influenced erosion processes in cropland soils, soil water content was the single most important parameter influencing creep, saltation, suspension, and PM_{10} emission from fallow soils (table 3). The importance of soil wetness in erosion processes was also noted by Van Donk and Skidmore (2003) and suggests the need for accurate and timely monitoring of soil water content to adequately simulate erosion processes. Few techniques exist, however, to continuously measure near-surface (within millimeters of the soil surface) water content. The high sensitivity of the erosion submodel to soil water content also indicates the need to accurately predict near-surface soil water content. The WEPS hydrology submodel was developed for this purpose, but few if any studies have been undertaken to examine the performance of the submodel.

As one of many factors, the ratio of surface soil water content to water content at 1.5 MPa (wilting point water content) was used in WEPS to calculate static threshold velocity. Therefore, processes in the erosion submodel may be sensitive to not only soil water content, but also to wilting point water content. The high sensitivity of erosion processes to wilting point water content, particularly in fallow soils, may suggest the importance of capillary forces in binding soil particles. Indeed, McKenna-Neuman and Nickling (1989) found sands to be extremely susceptible to erosion at water potentials below −10 MPa, suggesting that changes in cohesive forces near the wilting point greatly affect erosion.

Ridge height ranked among the top five and eleven most important parameters influencing erosion processes in cropland and fallow soils, respectively. Ridge height can influence erosion processes by altering surface roughness and friction velocities, but other ridge characteristics, such as ridge orientation and spacing, appear to be of lesser importance in simulating erosion from cropland and fallow soils (tables 2 and 3). Ridge orientation can be very effective in reducing soil wind erosion when ridges are perpendicular to the wind direction. Our analysis indicates that ridge orientation has a greater effect on erosion process in cropland soils than in fallow soils, with creep and saltation being the erosion processes most affected in cropland soils. Rocks play a very important role in not only creating roughness and surface resistant to erosion, but also in causing breakage of bombarding saltation/creep size aggregates.

The WEPS erosion submodel appeared to be more sensitive to field dimensions in fallow soils than in cropland soils. Indeed, field length ranked among the ten most important parameters affecting erosion processes in fallow soils (table 3). In addition, field length appears to be more important in creep/saltation processes than in suspension processes and emission of PM_{10} in fallow soils. Transport capacity for creep and saltation processes is typically reached at some distance downwind in a fallow field, but it is rarely attained for suspension processes (Hagen et al., 1999). Thus, suspension and emission of PM_{10} will be less sensitive to field length, as compared with creep and saltation.

Soil aggregate and crust parameters, namely aggregate stability, aggregate geometric diameter, crust stability, and crust cover, were ranked in the upper 50% of important parameters affecting erosion processes in cropland and fallow soils (tables 2 and 3). These soil properties can impact soil loss as a result of abrasion of clods/crust by saltation impact, breakage of saltation/creep size aggregates to suspension-size particles, and trapping of creep/saltation-size aggregates. Random roughness seldom ranked in the upper 50% of important parameters affecting erosion process in either cropland or fallow soil (tables 2 and 3). This finding is particularly disconcerting since roughness typically affects friction velocity and is one of the more practical means of controlling erosion (Papendick, 2004). Hagen et al. (1999) also reported that random roughness was one of the least-sensitive parameters in the WEPS erosion submodel. Random roughness, however, does appear to influence PM_{10} emission more than other erosion processes.

Biomass height typically ranked among the lower 50% of tested parameters affecting erosion processes (table 2). Hagen et al. (1999) also reported that biomass height was one of the least-sensitive parameters affecting erosion in the WEPS erosion submodel. In fact, results from both this study and Hagen et al. (1999) suggest that erosion processes are much more sensitive to biomass flat cover than to biomass height. This finding appears to contradict previous studies, which have demonstrated that standing biomass is more effective in reducing soil loss than biomass flat cover (Bilbro and Fryrear, 1994; Hagen, 1996). Data presented by Hagen (1996) suggest, however, that soil loss is responsive only to a very narrow range in biomass height (e.g., 0 to 0.1 m for wheat stubble at a population of 200 stems m^{-2}), as compared to a wide range in biomass flat cover (e.g., 0 to 0.5). Thus, inclusion of a wider range in biomass height (0 to 3 m) in our analysis beyond the effective narrow range likely influenced the simulated results. Mass of loose material on a crusted soil surface also typically ranked among the lower 50% of tested parameters affecting erosion processes (table 3). Although Van Donk and Skidmore (2003) reported that erosion was significantly influenced by the mass of loose material on a crusted surface, lack of any sensitivity analysis on other parameters precluded determining the relative importance of loose material in simulating erosion processes in their study.

Aggregates size distribution of the parent soil material influences the modes of soil transport. During wind events, aggregates ranging from 0.84 to 2.0 mm in diameter tend to roll along the surface, aggregates ranging from 0.10 to 0.84 mm in diameter are likely to saltate or hop over the surface, and aggregates less than 0.10 mm in diameter move above the surface in the turbulent flow (Hagen et al., 1999). Thus, in addition to aggregate size, soil particle size may also influence erosion processes (tables 2 and 3), particularly with regard to sand (0.05 to 2.0 mm), very fine sand (0.05 to 0.1 mm), and clay (<0.002 mm). Very fine sand is susceptible to suspension and has been found to comprise half of the mass of the suspension discharge (Zobeck and Fryrear, 1986). Sand and very fine sand ranked much higher in order of importance than clay content in cropland soil, whereas clay content ranked much higher in importance than sand and very fine sand in fallow soil. The reason for this apparent change in importance of soil particle sizes between cropland and fallow soil is unclear, as only the plant parameters were excluded from the sensitivity analysis on fallow soil. Perhaps larger particles become increasingly important in determining soil loss when saltation-driven processes are affected by plant parameters.

Overall, the erosion submodel was least sensitive to bulk density, silt content, and aggregate and crust density (tables 2 and 3). Note that the ranking of these parameters remained the same across all erosion processes (total soil loss, creep/saltation, suspension, and PM_{10} emission) for both cropland and fallow soil. The ranking of all other parameters, however, changed with respect to either erosion processes or land management. For example, the ranking of the ten most-sensitive parameters differed among the total soil loss, creep/saltation, suspension, and PM_{10} emission processes or between the cropland and fallow soil. Although the parameter ranges examined in this study remained the same for cropland and fallow soil (except leaf area, stem area, biomass height, and biomass flat cover), the change in ranking of all other parameters implies a nonlinear effect of the parameters on the submodel performance.

Hagen et al. (1999) noted that total soil loss simulated using the WEPS erosion submodel was very sensitive to wind speed, near-surface soil water content, aggregate/crust stability, and ridge height. Our results for the cropland soil are consistent with their findings, although the ranking of parameters were not exactly the same between studies. Such disparity may be partially associated with differences in parameter ranges or with the number of parameters examined. In addition, differences in ranking of parameters between the two studies may also be associated with methods of analysis. Hagen et al. (1999) varied one parameter at a time, keeping all other parameters at a base value. While they determined sensitivity based on extremes in parameter values, we believe the LHS-OAT method provides a more realistic response to changes in parameter values.

Application to the Columbia Plateau

Wind erosion occurs in response to high winds in spring and autumn, even though soil surface conditions are different during these two seasons on the Columbia Plateau. The rankings of important parameters in erosion processes during spring and during autumn in the low-precipitation zone of the Columbia Plateau are listed in tables 4 and 5, respectively. Among all parameters that could be regulated by management practices, near-surface soil water content was the dominant parameter affecting erosion processes and PM_{10} emission in spring. Biomass flat cover was the key management parameter influencing soil loss and PM_{10} emission in autumn. These results emphasize the importance of conserving soil water in spring and residue management in autumn for controlling soil erosion in the region. In the low-precipitation zone of the Columbia Plateau, organic matter content in

Table 4. Ranked order for the sensitivity of the parameters to the objective functions of the output variables for a dryland fallow field in spring on the Columbia Plateau.

Rank Order	Total Soil Loss (kg m^{-2})	Saltation/Creep (kg m^{-2})	Suspension (kg m^{-2})	PM_{10} Emission (kg m^{-2})
1	Soil water content	Soil water content	Soil water content	Soil water content
2	Wind speed	Wind speed	Biomass flat cover	Wind speed
3	Biomass flat cover	Biomass flat cover	Wind speed	Biomass flat cover
4	Soil wilting point water content	Soil wilting point water content	Wind direction	Wind direction
5	Wind direction	Field width	Soil wilting point water content	Random roughness
6	Random roughness	Random roughness	Random roughness	Field length
7	Field width	Wind direction	Field width	Field width
8	Field length	Field length	Field length	Soil wilting point water content
9	Aggregate geometric diameter	Crust cover	Aggregate geometric diameter	Aggregate geometric diameter
10	Mass of loose material on crusted surface	Aggregate geometric diameter	Mass of loose material on crusted surface	Mass of loose material on crusted surface
11	Crust cover	Mass of loose material on crusted surface	Stem area index	Crust cover
12	Stem area index	Stem area index	Crust cover	Stem area index
13	Rock volume fraction	Sand content	Aggregate stability	Rock volume fraction
14	Biomass height	Rock volume fraction	Rock volume fraction	Clay content
15	Aggregate stability	Biomass height	Biomass height	Aggregate stability
16	Sand content	Very fine sand	Sand content	Very fine sand
17	Very fine sand	Fraction of crusted surface covered by loose material	Crust stability	Biomass height
18	Fraction of crusted surface covered by loose material	Aggregate stability	Fraction of crusted surface covered by loose material	Crust stability
19	Crust stability	Crust thickness	Crust thickness	Sand content
20	Crust thickness	Clay content	Very fine sand	Crust thickness
21	Clay content	Crust stability	Clay content	Fraction of crusted surface covered by loose material
22	Aggregate geometric standard deviation	Aggregate geometric standard deviation	Aggregate geometric standard deviation	Minimum aggregate size
23	Maximum aggregate size	Maximum aggregate size	Maximum aggregate size	Maximum aggregate size
24	Minimum aggregate size	Minimum aggregate size	Minimum aggregate size	Maximum aggregate size
25	Bulk density	Bulk density	Bulk density	Bulk density
26	Silt content	Silt content	Silt content	Silt content
27	Aggregate density	Aggregate density	Aggregate density	Aggregate density
28	Crust density	Crust density	Crust density	Crust density

cultivated dryland soil is less than 1% (Schillinger et al., 2004). Soils containing little organic matter are susceptible to erosion due to poor water retention and lack of soil cohesion. Erosion processes in spring and autumn are also highly sensitive to field width and length; thus, consideration should be given to field layout in controlling erosion.

Random roughness during the summer fallow period is four times greater in spring than in autumn, owing to a decline in roughness associated with multiple tillage operations during summer. The sensitivity of the erosion submodel to random roughness was therefore much greater in spring than in autumn. The sensitivity of all erosion processes to biomass flat cover was greater in autumn than in spring despite the greater range in biomass flat cover in spring than in autumn. The greater importance of biomass flat cover in autumn may be associated with a reduction in roughness from spring to autumn. A reduction in roughness in autumn may be compensated for by biomass flat cover.

Aggregate geometric diameter is an important parameter influencing erosion processes on the Columbia Plateau. Creep, saltation, suspension, and PM_{10} emission were more sensitive to this parameter in autumn than in spring. The emission of PM_{10} was particularly sensitive to aggregate geometric diameter in autumn. The higher ranking of aggregate geometric diameter in the autumn suggests that emission of fine soil particulates (PM_{10}) is influenced more by aggregate size distribution during autumn than during spring in the Columbia Plateau. The importance of aggregate size distribution to erosion processes in autumn may compensate for the low roughness and biomass cover on the soil surface during autumn as compared to the spring. Larger aggregates may be maintained on the soil surface to control erosion by using conservation tillage, such as delayed tillage or minimum tillage.

Rock volume in the Columbia Plateau is far less important as compared with results obtained using ranges provided by WEPS User's Manual. The lower sensitivity of this parameter may be due to the small range in rock volume of soils across the Columbia Plateau. Soils in the region are typically derived from extensive loess deposits. As found in our analysis using parameter ranges specified in the WEPS User's Manual, the erosion submodel was relatively insensitive to crust density, aggregate density, silt content, and bulk density during spring and autumn in the low-precipitation zone of the Columbia Plateau.

Saxton et al. (2000) developed an empirical model for simulating horizontal soil flux and PM_{10} emission from soils on the Columbia Plateau. Their model assumes that soil flux

Table 5. Ranked order for the sensitivity of the parameters to the objective functions of the output variables for a dryland fallow field in autumn on the Columbia Plateau.

Rank Order	Total Soil Loss (kg m^{-2})	Saltation/Creep (kg m^{-2})	Suspension (kg m^{-2})	PM_{10} Emission (kg m^{-2})
1	Wind speed	Wind speed	Biomass flat cover	Wind speed
2	Biomass flat cover	Biomass flat cover	Wind speed	Biomass flat cover
3	Soil water content	Soil water content	Soil water content	Aggregate geometric diameter
4	Wind direction	Soil wilting point water content	Wind direction	Soil water content
5	Soil wilting point water content	Field width	Soil wilting point water content	Wind direction
6	Field width	Wind direction	Field width	Soil wilting point water content
7	Field length	Field length	Field length	Field width
8	Aggregate geometric diameter	Sand content	Aggregate geometric diameter	Field length
9	Stem area index	Aggregate geometric diameter	Stem area index	Crust cover
10	Crust cover	Stem area index	Crust cover	Mass of loose material on crusted surface
11	Mass of loose material on crusted surface	Crust cover	Aggregate stability	Stem area index
12	Rock volume fraction	Mass of loose material on crusted surface	Mass of loose material on crusted surface	Rock volume fraction
13	Biomass height	Rock volume fraction	Rock volume fraction	Minimum aggregate size
14	Aggregate stability	Biomass height	Biomass height	Aggregate stability
15	Sand content	Very fine sand	Sand content	Clay content
16	Fraction of crusted surface covered by loose material	Fraction of crusted surface covered by loose material	Crust thickness	Aggregate geometric standard deviation
17	Crust thickness	Aggregate stability	Crust stability	Crust thickness
18	Very fine sand	Clay content	Fraction of crusted surface covered by loose material	Biomass height
19	Crust stability	Crust thickness	Very fine sand	Sand content
20	Clay content	Crust stability	Random roughness	Crust stability
21	Random roughness	Random roughness	Clay content	Very fine sand
22	Aggregate geometric standard deviation	Aggregate geometric standard deviation	Aggregate geometric standard deviation	Random roughness
23	Minimum aggregate size	Minimum aggregate size	Maximum aggregate size	Fraction of crusted surface covered by loose material
24	Maximum aggregate size	Maximum aggregate size	Minimum aggregate size	Maximum aggregate size
25	Bulk density	Bulk density	Bulk density	Bulk density
26	Silt content	Silt content	Silt content	Silt content
27	Aggregate density	Aggregate density	Aggregate density	Aggregate density
28	Crust density	Crust density	Crust density	Crust density

and PM_{10} emission are related to wind speed, soil erodibility, surface roughness, and biomass cover. They indicated that erosion is also influenced by soil water content and crusting, but neither was parameterized in the model. Soil erodibility was assumed to be intrinsically related to soil physical properties; although not mentioned, these properties may include aggregate size, aggregate stability, sand content, clay content, and bulk density. Failure to parameterize soil water content and crusting in their empirical model appears to be a detriment to simulating soil loss and PM_{10} emission based on the results of this study, where soil water content ranked as one of the top four most-important parameters and soil crusting consistently ranked in the top 50% of important parameters influencing erosion processes. In addition, sensitivity analysis of the WEPS erosion submodel suggests that field width and length, soil wilting point water content, and stem area index are extremely important parameters affecting creep, saltation, suspension, and PM_{10} emission. These parameters, however, were not considered by Saxton et al. (2000) and illustrate the differences between modeling approaches.

CONCLUSIONS

A sensitivity analysis of the WEPS erosion submodel was carried out for all model output objective functions (i.e., total soil loss, saltation and creep, suspension, and PM_{10} emission) using the ranges in parameter values specified by the WEPS User's Manual and as determined for the Columbia Plateau region of the U.S. The study showed that biomass flat cover, near-surface soil water content, ridge height, wind speed, rock volume, soil wilting-point water content, field length and width, crust cover, aggregate and crust stability, and random roughness are the most influential parameters affecting total soil loss, creep, saltation, suspension, and emission of PM_{10}. Sand and very fine sand content in cropland soils and clay content in fallow soils play a very important role in erosion processes. Clay content has more of an effect on PM_{10} emission than other erosion processes. The results consistently indicate the insensitivity of the model to changes in leaf area index, bulk density, silt content, and aggregate and crust density.

The sensitivity analysis, as applied to the Columbia Plateau, suggested the importance of soil water in spring and residue cover in autumn for controlling soil erosion. Reduction in field size as well as improvement in soil water retention through amendments such as fly ash and organic matter could also reduce soil loss and PM_{10} emission. Erosion processes were more sensitive to random roughness but less sensitive to crust cover in spring than autumn. The PM_{10} objective function revealed greater parameter sensitivity to aggregate geometric diameter in autumn than in spring. The results of this study suggest that tillage practices that conserve soil water, maintain more residue or large aggregates on the surface, and promote soil crusting will minimize wind erosion and PM_{10} emission on the Columbia Plateau.

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