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Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields

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Abstract

This study represents part of a project by the Global Change and Terrestrial Ecosystem Soil Erosion Network to validate wind erosion models. Soil loss measurements from 46 storm events from eroding fields in six states were compared to predictions from the Wind Erosion Prediction System (WEPS) erosion submodel. The field data were collected from small (2.5 ha), circular, cropland fields with nonerodible boundaries. Samplers were arranged in vertical clusters to sample horizontal soil discharge passing a point. Weather data, including wind speed, wind direction, solar radiation, relative humidity, air temperature, and rainfall, were collected on-site. Temporal field site characteristics were measured periodically and included surface roughness, plant/residue cover, and dry aggregate size distribution. The WEPS erosion submodel was used to calculate the threshold erosion friction velocity based on surface conditions and then simulate soil loss during daily periods when the speed exceeded that threshold. Measured and simulated erosion values were in reasonable agreement ($R^2 = 0.71$). On average, the erosion model underpredicted soil loss, and the probable reasons are discussed.

Keywords: Wind erosion; Soil; Aggregate stability; Aggregate size distribution; Soil crust

1. Introduction

Wind erosion models are used for a variety of purposes including estimating the on-site and off-site consequences of wind erosion, as well as for designing erosion control measures. Because of their widespread use, it is imperative to validate the performance of erosion prediction models. Recently, the Global Change and Terrestrial Ecosystems Soil Erosion Network (GCTE-SEN) initiated a project to validate wind erosion models. Data on selected storm events collected during the last decade by ARS scientists and other cooperators (Fryrear et al., 1991) were distributed to participating scientists for model validation tests (Zobeck et al., 2001). In this study we compared observed soil loss with simulated soil loss predictions for daily erosion events using the Wind Erosion Prediction System (WEPS) erosion submodel.

The WEPS model is a process-based, daily time-step model that simulates weather, field conditions, and wind erosion on croplands (Hagen et al., 1995; Wagner, 1996). The WEPS model has a modular structure that includes a daily weather simulator along with an hourly wind speed simulator. There are five additional submodels in WEPS, and these simulate crop growth, residue decomposition, hydrology, soil status, and management operations. The erosion submodel determines when friction velocity exceeds the threshold and then simulates soil loss and deposition over the simulation region on a subhourly basis (Hagen et al., 1999). During erosion, the submodel separately simulates the saltation/creep and suspension components of wind-eroded soil. This approach was used because the saltation/creep component has a defined transport capacity, whereas the suspension component generally continues to increase over the entire length of eroding fields. Based on conservation of mass, the saltation/creep discharge is simulated with two sources (entrainment of loose, mobile soil and entrainment of soil abraded from clods and crust) and three sinks (breakage of saltation/creep to suspension-size, trapping of saltation/creep by surface roughness,

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Table 1
Test sites, symbols, and surface soil characteristics

Location	Location symbol	Soil texture	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Calcium carbonate (%)	No. of Storms
Eads, CO	ECO	Clay loam	29.3	38.6	32.1	1.6	1.0	2
Elkhart, KS	EKS	Sandy loam	68.1	21.5	10.4	0.7	0.0	1
Kennet, MO	KMO	Sand	90.0	7.1	2.9	0.7	0.2	8
Sidney, NB	SNB	Loam	39.8	42.9	17.4	2.3	0.0	4
Big Spring, TX	BSTX	Loamy sand	83.6	8.4	8.0	0.3	0.0	24
Mabton, WA	MWA	Loamy sand	82.3	12.8	4.9	0.8	0.0	5
Prosser, WA	PWA	Silt loam	44.2	50.2	5.7	1.1	0.0	2

and interception by plant stalks). Similarly, the suspension component is simulated with three sources (entrainment of loose soil, entrainment of material abraded from clods and crust, and breakage from saltation/creep to suspension-size). Simulating the saltation/creep and suspension components separately greatly facilitates estimating off-site erosion impacts (Wagner and Hagen, 2001).

2. Field site characteristics and instrumentation

This study included data from 46 storms occurring at seven locations in six different states of the US (Table 1). The sites included a wide range of soils with sand fractions ranging from 29% to 90%. However, all the soils had relatively low calcium carbonate content. The individual experimental sites were a 2.5-ha circular areas that were tilled and located within larger fields that remained in relatively nonerodible condition. The circular site pattern permitted collection of erosion data regardless of wind direction (Fryrear et al., 1991).

On the field sites, soil sediment samplers (Fryrear, 1986) were arranged in vertical clusters to sample the horizontal soil discharge passing a point. A typical cluster consisted of five samplers located at 0.05, 0.10, 0.20, 0.5, and 1.0 m above the soil surface. Thirteen clusters were placed within each circular field site (Fig. 1). Six clusters were located at 60° intervals on each of two concentric circles with radii of 55 and 87 m, and the remaining cluster was located at the center of the site. A meteorological tower also was located near the center of each site and instrumented to record wind speed, wind direction, air temperature, solar radiation, rainfall, and relative humidity. For most events, the duration of erosion was recorded with a SENSIT[1] transducer that is based on using a piezoelectric quartz crystal to sense saltation impacts.

[1] Identification of experimental apparatus is for informational purposes only and does not imply endorsement by ARS, USDA.

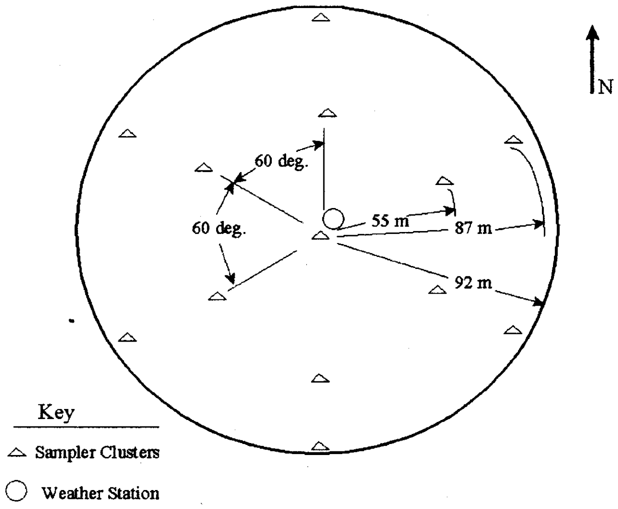

Fig. 1. Schematic layout of field site instrumentation.

3. Data analyses procedures

The horizontal soil flux trapped by the catchers in each cluster was fitted to a four-parameter equation as suggested by Vories and Fryrear (1991)

$$f(z) = az^b + c\exp(dz) \quad (1)$$

where $f(z)$ is horizontal flux (kg m^{-2}) per storm at height z (m), and a, b, c, d's are fitting coefficients. The vertical profile of the horizontal flux (Eq. (1)) was then integrated to a height of 2 m to determine the soil discharge (kg m^{-1}) passing each cluster location. Wind direction and upwind distance to the edge of the field also were calculated for each cluster.

Next, we fitted the measured point-discharge cluster data to empirical equations to estimate soil discharge at 180 m downwind from the nonerodible boundary. The discharge for each storm then was divided by 180 to provide an estimate of soil loss per unit area for a 180-m long, 1-m wide, strip of field. The empirical equation providing the best fit to most of the cluster discharge data was of the form

$$q = f + gX^h \quad (2)$$

where q is downwind horizontal discharge (kg m^{-1}), X is downwind distance from nonerodible boundary, and f, g, h are empirical fitting coefficients.

A relatively good fit ($R^2 = 0.74$) of Eq. (2) was observed with data from a 1997 storm at Big Spring (Fig. 2). The shape of the downwind discharge curves varied between convex, as in Fig. 2, and concave depending upon field surface conditions.

The wind statistics provided for each daily storm included the maximum speed, average speed, and a wind factor related to erosive wind energy that assumed a threshold wind speed of 5 m s^{-1} at a 2-m height (Fryrear et al., 1998). However, WEPS uses subhourly wind speeds and varying threshold wind speeds. To estimate wind speeds during each storm day, we calculated three parameters for a Weibull cumulative wind speed distribution of the form

$$F(u) = (1-F_0)\left(1-\exp\left[-\left(\frac{u}{c}\right)^k\right] + F_0\right) \quad (3)$$

where $F(u)$ is cumulative fraction of day with wind speed less than u (m s^{-1}), c is a scale factor (m s^{-1}), k is a dimensionless shape factor, and F_0 is the $F(u)$-axis intercept. The intercept is positive when there are calm periods and negative when there are no calm periods. The distribution parameters were calculated by converging iteration until the distribution matched the maximum and average wind speeds, as well as the wind factor for the day using Mathcad software (MathSoft, 1999). From the daily Weibull distribution, a synthetic distribution of subhourly wind speeds was generated that was symmetric about the maximum daily wind speed. These subhourly wind speeds then were used to drive the erosion submodel. The symmetric form was selected, because the wind generator used in the WEPS model generates a similar form for the daily wind distribution.

The field surface conditions used in the storm simulations are listed in Tables 2 and 3. Unfortunately, some of the field surface parameters needed for WEPS were not measured and had to be estimated. Crust cover fraction was estimated from cumulative rainfall since last tillage operation, except at Big Spring, TX in 1996, when the field was assumed to be crusted as a result of unreported factors. Aggregate and crust dry stabilities were assigned average values based on soil texture. The surface soil was assumed to be air dry during the erosion events, but may have affected erosion for one event at Prosser, WA (Table 3).

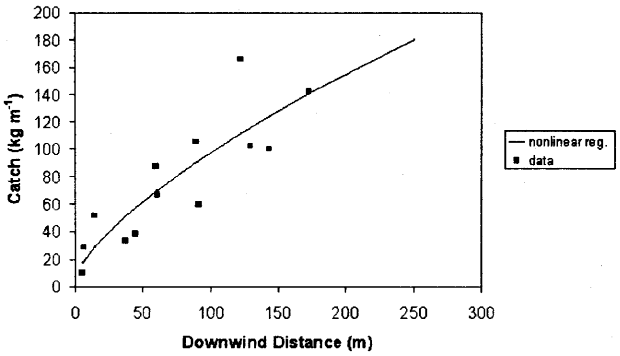

Fig. 2. Example of measured and estimated soil catch (Eq. (2), $R^2 = 0.74$) variation with downwind distance for a single storm.

4. Results and discussion

The average storm loss from the cluster measurements extrapolated using Eq. 2 to 180 m downwind was 0.82 kg m^{-2}, while the average predicted soil loss was 0.67 kg m^{-2}. The maximum differences between observed and predicted loss occurred during large erosion events where the predicted values were frequently less than those observed (Fig. 3). Validation of another model reported a similar response with this data set (Zobeck et al., 2001). Reasons for the differences include the scatter in the cluster data along the wind direction, which suggested the initial field surfaces were not always uniform as assumed in the model. There were also uncertainties about some of the input field surface conditions when they were not measured close to the storm dates. Weathering processes and prior erosion events may have increased surface soil erodibility prior to some of the large erosion events.

Analysis of the storm data using linear regression showed reasonable agreement between predicted and observed erosion ($R^2 = 0.71$) with a slope less than one and an intercept greater than zero ($p = 0.05$) (Fig. 3). However, inspection of the data suggests the differences between measured and observed values are not linear over the entire range.

Hence, nonlinear regression of the storm data using a power equation with the form of Eq. (2) was calculated (Fig. 4). These results showed that for storm losses less than 2 kg m^{-2} the predictions were close to the 1:1 line, and the intercept was slightly less than zero.

Another measure of model performance is the Nash Sutcliffe model efficiency criterion (Nash and Sutcliffe, 1970). Using the daily storm measured and predicted values, the Nash Sutcliffe model efficiency was calculated as

$$S^2 = 1 - \frac{\sum_{i=1}^{n} (q_{mi} - q_{pi})^2}{\sum_{i=1}^{n} (q_{mi} - q_m)^2} \quad (4)$$

where S^2 is the efficiency of the model, q_{mi} represents

Table 2
Field surface conditions for selected erosion events and observed and predicted soil losses for these events at Big Spring, TX

Storm date	Flat cover (fraction)	Aggregate <0.84 mm (fraction)	Crust cover (fraction)	Crust and aggregate stability Ln (J kg^{-1})	Random roughness (mm)	Ridge height (mm)	Observed soil loss (kg m^{-2})	Predicted soil loss (kg m^{-2})
4-22-89	0.00	0.55	0.60	1.93	8.0	0.0	0.41	0.33
4-23-89	0.00	0.55	0.60	1.93	7.0	0.0	0.51	0.31
1-22-90	0.04	0.65	0.50	1.93	1.7	20.0	0.09	0.04
1-24-90	0.04	0.64	0.50	1.93	1.7	20.0	1.77	1.85
1-26-90	0.04	0.65	0.50	1.93	1.7	0.0	0.61	1.17
1-29-90	0.04	0.64	0.50	1.93	1.7	20.0	0.78	1.03
2-12-90	0.04	0.65	0.50	1.93	1.7	20.0	0.40	1.28
3-12-90	0.04	0.65	0.85	1.93	1.7	20.0	0.08	0.47
3-14-90	0.04	0.65	0.30	1.93	1.7	20.0	4.57[a]	3.98
4-02-93	0.01	0.74	0.05	1.93	4.5	0.0	3.47[b]	2.36[b]
3-17-94	0.03	0.60	0.40	1.93	2.0	0.0	0.14	0.20
3-18-94	0.03	0.60	0.40	1.93	2.0	0.0	0.14	0.04
3-22-94	0.03	0.60	0.40	1.93	2.0	0.0	0.38	0.11
3-24-94	0.03	0.60	0.40	1.93	2.0	0.0	0.18	0.30
4-07-94	0.03	0.60	0.40	1.93	2.0	0.0	0.52	0.89
4-15-94	0.03	0.60	0.40	1.93	2.0	0.0	2.02	1.52
4-25-94	0.03	0.60	0.40	1.93	2.0	0.0	4.85	2.27
2-10-95	0.05	0.72	0.40	1.93	2.0	0.0	1.08	1.51
3-22-95	0.03	0.72	0.57	1.93	1.7	0.0	0.20	0.36
1-23-96	0.02	0.60	1.00	1.93	5.1	0.0	0.01	0.00
2-14-96	0.03	0.58	1.00	1.93	5.0	0.0	0.01	0.00
3-05-96	0.03	0.57	1.00	1.93	5.0	0.0	0.00	0.00
4-29-97	0.06	0.50	1.00	1.93	1.8	0.0	0.80	0.27
5-02-97	0.06	0.50	1.00	1.93	1.8	0.0	1.24	1.38

[a] Observed soil loss with two low-catch clusters deleted; including these two clusters observed soil loss = 1.44 kg m^{-2}.
[b] Observed and predicted soil loss includes all 4-02-93 and first 8 h of 4-03-93.

the measured value of an event i, q_{pi} is the predicted value for event i, and q_m is the mean of the measured values. In this criterion, a value of one indicates a perfect model, and a value of zero indicates model results are not better than the mean measured value. A value of S^2 less than zero indicates model predictions would be worse than using the mean. For the current data calculated over all storms, S^2 was 0.72.

Overall, the model was significantly better than using the mean value. However, at some individual locations, using the measured mean value was superior to the model result. But for general applications, one generally does not have the mean measured soil loss.

5. Conclusions

The WEPS erosion submodel predictions were compared to measured data for 46 individual erosion events in six states as part of the international GCTE-SEN wind erosion model validation project. Overall, the model provided reasonable estimates ($R^2 = 0.71$) of soil loss. But on average, the model underpredicted soil loss, particularly for some of the largest erosion events. Nevertheless, for soil losses less than 2 kg m^{-2} the model tended to follow the 1:1 line between predicted and measured values. Thus, the submodel should perform well when used for design of systems whose objective is erosion control.

There are two probable causes for the underprediction of soil loss. First, some of the needed model inputs were not measured, so average parameter values for the specific soils were substituted for these inputs. Second, weathering and prior erosion may have increased soil erodibility after the time of the reported surface measurements. Hence, when erosion occurred it is likely that some of the soil conditions were more erodible than reflected in the input surface conditions. To partially account for these problems, the changes in surface conditions will be simulated on a daily basis in the completed WEPS model.

In several other cases, the model estimated zero erosion when small amounts of erosion occurred. This occurs when test site conditions are not uniform and have small inclusions with higher erodibility than the average conditions that are assumed in the model inputs. However, for practical model applications, this should be of little consequence.

Table 3
Field surface conditions for selected erosion events and observed and predicted soil losses for these events

Location and storm dates	Flat cover (fraction)	Aggregate <0.84 mm (fraction)	Crust cover (fraction)	Crust and aggregate stability Ln (J kg^{-1})	Random roughness (mm)	Ridge height (mm)	Observed soil loss (kg m^{-2})	Predicted soil loss (kg m^{-2})
ECO								
4-28-91	0.10[a]	0.36	0.0	3.42	8.0	62.0	0.21	0.05
5-08-91[b]	0.10[a]	0.36	0.0	3.42	7.9	62.0	0.12	0.19
EKS								
3-9-92	0.10	0.70	0.46	2.47	3.0	0.0	7.47[c]	4.83[c]
KMO								
3-7-93	0.03	0.87	1.00	1.28	2.0	0.0	0.01	0.04
3-13-93	0.03	0.87	1.00	1.28	3.0	0.0	2.14[f]	5.20
4-04-93	0.15	0.87	1.00	1.28	2.0	0.0	0.11	0.00
4-23-93	0.17	0.87	1.00	1.28	2.0	0.0	1.53[d]	1.50[d]
5-08-93	0.22	0.91	1.00	1.28	2.0	0.0	0.07	0.00
12-13-93	0.15	0.91	1.00	1.28	10.0	0.0	0.01	0.00
3-23-94	0.15	0.91	1.00	1.28	3.0	0.0	0.02	0.00
4-02-94	0.15	0.91	1.00	1.28	3.0	0.0	0.02	0.00
SNB								
11-07-89	0.20	0.35	0.00	2.88	7.0	90.0	0.01	0.00
11-26-89	0.20	0.35	0.00	2.88	7.0	80.0	0.01	0.00
1-08-90	0.21	0.40	0.00	2.88	7.0	75.0	0.33	0.12
3-15-90	0.21	0.46	0.4	2.88	7.5	70.0	0.01	0.00
MWA								
2-19-91	0.25	0.79	0.0	1.56	10.0	68.0	0.09	0.00
4-02-91	0.15[e]	0.79	0.0	1.56	10.0	68.0	0.52	0.11
4-05-91	0.15[e]	0.79	0.0	1.56	10.0	68.0	0.37	0.12
4-09-91	0.15[e]	0.79	0.0	1.56	10.0	68.0	0.49	0.22
4-24-91	0.40	0.79	0.0	1.56	10.0	68.0	0.01	0.00
PWA								
9-24-92	0.15	0.73	0.00	1.69	5.0	76.0	0.06[f]	0.19
10-01-92	0.15	0.74	0.00	1.69	5.0	76.0	0.01	0.00

[a] Data record gives both 0.15 and 0.05 as flat cover estimates for these storms, so used average.
[b] Used wind data for storm on 5-02-91, soil collected on 5-08-91.
[c] Observed and predicted soil loss includes storms on 3-08,09-92.
[d] Observed and predicted soil loss includes storms on 4-23,24,25-93.
[e] Flat cover estimated after subsoiler and disk/roller tillage.
[f] Rain may have restricted erosion.

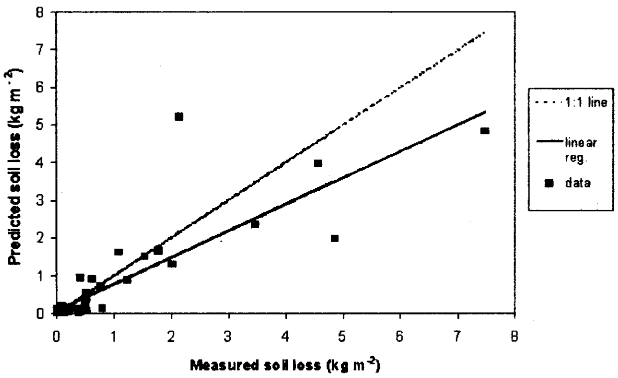

Fig. 3. Measured and WEPS predicted soil loss values for individual storms with linear regression analysis.

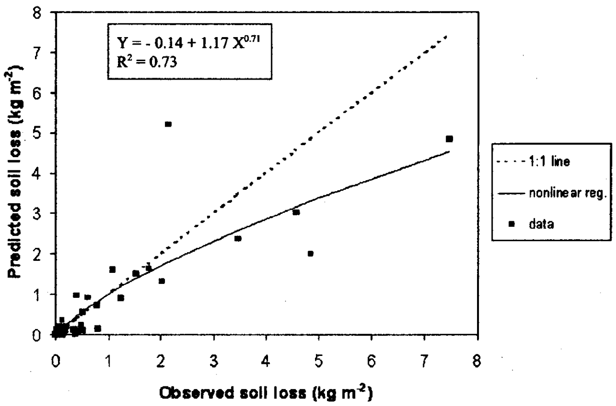

Fig. 4. Measured and WEPS predicted soil loss values for individual storms with nonlinear regression analysis.

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