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MEASUREMENT AND SIMULATION OF WIND EROSION, ROUGHNESS DEGRADATION AND RESIDUE DECOMPOSITION ON AN AGRICULTURAL FIELD

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ABSTRACT

The Wind Erosion Prediction System (WEPS) includes submodels to simulate soil erosion by wind, roughness degradation and residue decomposition. These WEPS submodels were tested using data measured on a 600 m by 415 m farmer's field, planted with winter wheat, near Burlington, Colorado, USA. Big Spring Number Eight (BSNE) samplers were used to measure wind blown sediment flux and automated devices (Sensits) detected saltating sediment. A weather station recorded relevant meteorological data. Detailed measurements of field surface conditions were taken on three dates. One significant dust storm occurred during the experimental period (November 2000 to April 2001). Spatial variability of sediment discharge was high. This could partially be explained by spatial differences in residue cover and mass, leaf area index, sand fraction and wetness of the surface soil.

WEPS overestimated the ability of small wheat plants to protect the soil against wind erosion. A simulation without any wheat plants produced a large field sediment loss of 4·43 kg m^{-2}, whereas a simulation with very small wheat plants (height = 10 mm, leaf area index = 0·1, stem area index = 0·01) produced no erosion. This component of WEPS is based on laboratory wind tunnel experiments with simulated standing biomass uniformly spaced on a flat surface. Wheat biomass in the field is not uniformly spaced. WEPS should be modified to account for these non-uniform realities.

Mean ridge height was reduced from 42 mm on 19 December to 34 mm (36 mm simulated using WEPS) on 12 April. Mean random roughness was reduced from 5·8 mm on 19 December to 5·2 mm (5·3 mm simulated) on 8 March. Mean corn residue biomass was reduced only slightly from 1204 kg ha^{-1} on 19 December to 1174 kg ha^{-1} (1075–1175 kg ha^{-1} simulated) on 12 April. These differences between measured data and simulations were not significant ($P > 0·05$), enhancing confidence in the ability of WEPS to simulate roughness degradation and residue decomposition. Published in 2003 by John Wiley & Sons, Ltd.

KEY WORDS: wind erosion; roughness degradation; residue decomposition; field experiment; winter wheat

INTRODUCTION

Agricultural producers in the central High Plains of the USA are interested in locally developed strategies for conservation of natural resources. This interest resulted in the High Plains Pilot Project (HPPP), covering extreme northwestern Kansas (Cheyenne, Rawlins, Sherman, Thomas and Wallace counties) and adjacent counties (Sedgwick, Phillips, Yuma and Kit Carson) in eastern Colorado. The most common cropping system in the HPPP region is a wheat–fallow system with a 14-month fallow period, and winter wheat in the remaining 10 months of the 2-year cycle. This system is vulnerable to wind erosion, especially in early spring with high wind speeds, small wheat plants, and a soil structure weakened by freeze–thaw cycles of the previous winter. There are also concerns about wind erosion during the summer fallow period following sunflower harvest (Nielsen and Aiken, 1998).

Agricultural producers and the USDA-Natural Resources Conservation Service (NRCS) need to understand the impact of different management practices on wind erosion. The USDA-ARS Wind Erosion Research Unit

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(WERU) in Manhattan, Kansas, is developing a process-based Wind Erosion Prediction System (WEPS; Hagen, 1991; Wagner, 2001) for the simulation of wind erosion and dust emission for various management scenarios, such as different cropping and tillage systems, which thus has the potential to meet this need. There are a number of submodels in WEPS, including models for soil roughness degradation (Hagen *et al.*, 1995), crop residue decomposition (Steiner *et al.*, 1995), and crop growth (Retta and Armbrust, 1995a). The core of WEPS is the erosion submodel (Hagen, 1995). Accurate prediction of wind erosion depends greatly on reliable simulations by all submodels.

WEPS needs to be tested in the field (Hagen, 1991). Until recently, actual measurements of wind erosion under field conditions were virtually non-existent (Fryrear, 1995). Fryrear (1986) developed a field dust sampler and named it the Big Spring Number Eight (BSNE). Fryrear *et al.* (1991) describe a set-up for wind erosion measurements on a circular field with a radius of 91 m. Using this set-up, wind erosion was measured at sites in five different states for the verification of WEPS (Fryrear, 1995). Sterk (1997) measured wind erosion on a rectangular field of 60 m by 40 m in Niger, West Africa. His measurements showed that spatial soil loss and deposition can be highly variable.

Gillette and Stockton (1986) developed the Sensit, which is a piezoelectric device that produces a signal upon impact of saltating soil particles. It has been used both in the open field and in wind tunnels. The instrument has proven useful for the determination of the threshold friction velocity at which erosion by wind starts. Use of the Sensit to measure horizontal sediment mass flux has not been very successful, but would be useful since it provides much better time resolution of mass flux during a single storm than one can obtain from sediment samplers, such as the BSNE.

More data need to be collected to verify wind erosion models under a broad range of climatic, soil, and management conditions (Fryrear, 1995). The Wind Erosion Customer Focus Meeting organized by WERU in December 1998 listed the completion of an extensively field-tested WEPS as the number one priority for WERU. The main objective of this study was to test the WEPS erosion submodel using data measured on a farmer's winter wheat field in eastern Colorado, USA. Measured data from this field were also used to compare roughness degradation and residue decomposition with those simulated by WEPS.

METHODS

Field measurements

A farmer's field of 1720 m by 810 m was selected 17 km south of Burlington, Colorado, USA (39·13 N, 102·30 W, elevation = 1292 m). The surface soil was a silt loam with 31 per cent sand, 53 per cent silt, and 16 per cent clay. A sunflower crop was grown on the field in the summer of 1998 and a corn crop in the summer of 1999. The field was tandem-disked once in the spring of 2000, then bladed twice and rod-weeded three times. Wheat was planted in an east–west direction with a row spacing of 305 mm on 29 August 2000. Only the NW corner (600 m by 415 m, Figure 1) of the field was instrumented. When we started field measurements in December 2000, the crop residue on the field was mainly corn.

To the north of the study site was a field with standing corn residue. The western border was a dirt road flanked on both sides by ditches and a wheat field to the west. The southern and eastern borders were extensions of the same field with wheat. BSNE sampler stations were placed according to field topography: stations 4, 9 and 17 were placed on a ridge (Figure 1); stations 2 and 5 on another ridge; 10–13 and 18 on a flat part of the field; 3, 6, 14, and 19 on yet another ridge; and stations 7, 15, and 20 on a slope. Stations 1, 2, 3, 8 and 16 were positioned on the field boundaries for measurement of 'background' movement of sediment originating from adjacent fields. The difference between the highest and the lowest point on the instrumented field was about 7 m. Each BSNE station consisted of six BSNE samplers with their openings at 0·05, 0·10, 0·35, 0·60, 1·00, and 1·50 m above the soil surface. The two lowest samplers had openings 20 mm wide and 10 mm high; the other four samplers had openings 20 mm wide and 50 mm high. The field instrumentation set-up was similar to that of Fryrear *et al.* (1991). A major difference was the field size: 600 m by 415 m instead of a circle of 91 m radius. This was done in order to obtain a longer distance from a non-erodible boundary so the field would be large enough to reach transport capacity.

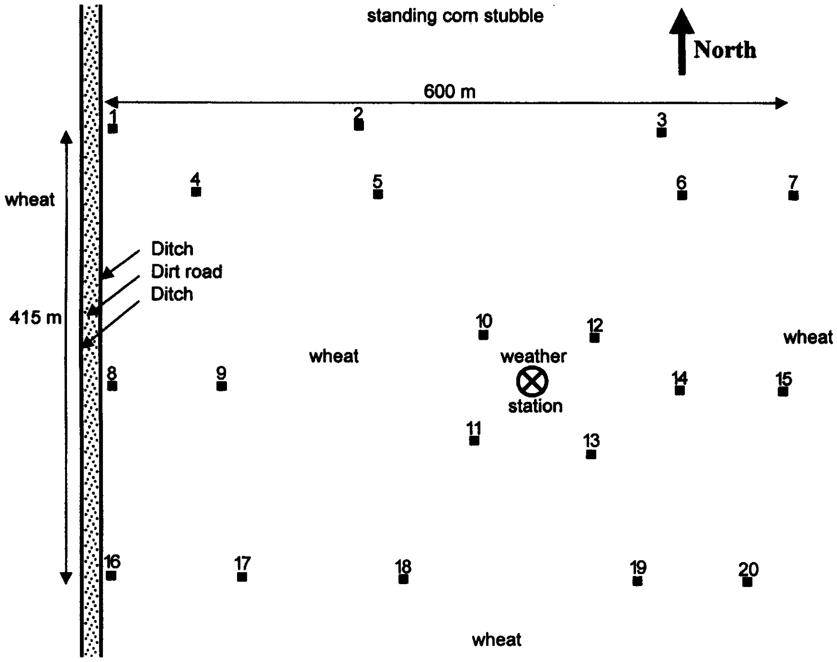

Figure 1. Placement of BSNE stations on the experimental field. Numbers are station identifiers. Each station consists of six BSNE samplers with openings at heights of 0·5, 0·10, 0·35, 0·60, 1·00, and 1·50 m above the soil surface

At the weather station (Figure 1) measurements included wind speed at 2·0 m, using a cup anemometer (1005DC, Sierra Misco, Berkeley, CA), wind direction at 3·5 m using a wind vane (WSD330, RM Young, Traverse City, MI), air temperature and relative humidity at 0·2 m and at 2·0 m (CS500, Campbell Scientific, Logan, UT), incoming and reflected shortwave radiation at 1·5 m using a double-sided pyranometer or albedometer (3023, Qualimetrics, Sacramento, CA), net radiation at 1·5 m using a net radiometer (Q7·1, Radiation and Energy Balance Systems, Seattle, WA), soil temperature at −0·03 m (107, Campbell Scientific), and rainfall with a tipping bucket rain gauge (6010, Qualimetrics).

At each of the BSNE stations 10–13 (Figure 1) the occurrence of saltating soil particles was measured with a Sensit (Sensit Company, Portland, ND) at 0·05 m, and wind speed was measured at 2·0 m, using a cup anemometer (1005DC, Sierra Misco). Figure 2 shows the set-up at one of the four stations that were configured this way. All sensors were calibrated before being deployed in the field.

Data were measured and recorded with equipment from Campbell Scientific: a data logger (CR10X), a solid state multiplexer (25AMT), and an eight-channel interval timer (SDM-INT8). Sensors were sampled every 10 s and data recorded for 15 min periods. Recorded data were transmitted twice a day from the data logger to a PC at WERU in Manhattan, KS, using a mobile phone system: a cellular transceiver with RJ11 interface (Alltel, Manhattan, KS) and a telephone modem (COM200, Campbell Scientific). The system was powered using two solar panels (MSX20R, Campbell Scientific) and a sealed, lead-acid battery with a capacity of 115 Amphours. The site was operational from 25 November 2000 to 12 April 2001.

On 19 December, one day after the only significant wind erosion event during the experimental period, BSNE samplers were emptied in plastic bags and weighed in the laboratory. For each BSNE station, measured mass from the samplers was fitted to:

$$q = a(z + 1)^b \tag{1}$$

where q is sampler mass (kg m^{-2}), z is height of the BSNE sampler opening above the soil surface (m), and a and b are fitting parameters. Sediment discharge was determined by integrating Equation 1 from 0 to 2 m. Net

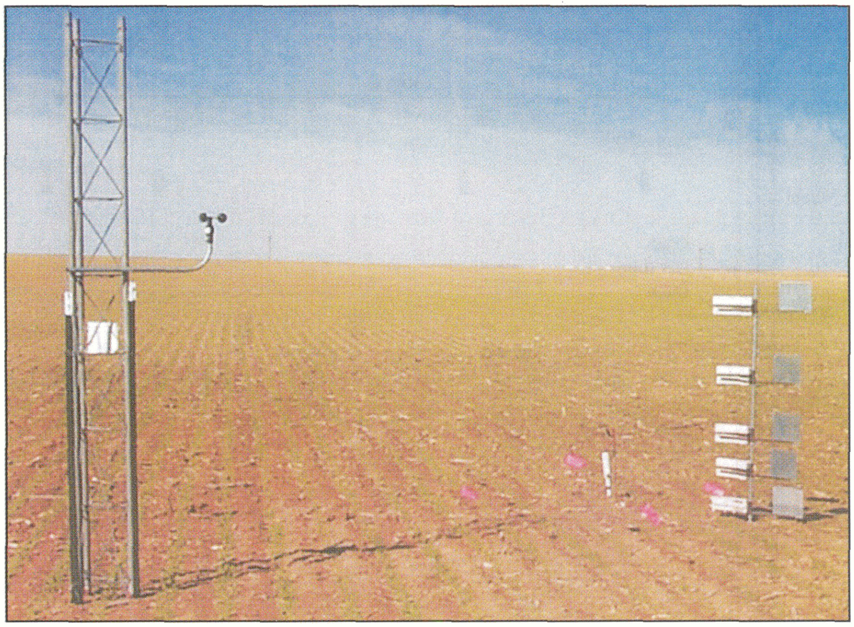

Figure 2. Station 11 was one of four stations (10–13, see Figure 1) instrumented with BSNE samplers, a Sensit and an anemometer

soil loss from the field was calculated from sediment crossing the field boundaries. Sample aggregate size distribution was determined using a sonic sifter (ATM Corporation, Milwaukee, WI) with 5, 10, 20, 53, 106, 250 μm sieves.

Field conditions were recorded on three dates – 19 December, 8 March, and 12 April – near every BSNE station not located on a field boundary. Data included status of wheat, residue, topsoil, soil roughness, soil surface moisture, and crust condition. Wheat plants occupying 0·10 m within a row were dug up and placed in a plastic bag with a wet paper towel to keep the plants from drying out. In the laboratory the number of plants was counted and their heights (as standing in the field; not stretched out) measured. Leaves and stems were separated. Leaf area and stem silhouette area were measured using a leaf area meter (LI-3000, LI-COR, Lincoln, NE). Leaf area index (LAI) and stem area index (SAI) were calculated from these measurements. In addition, leaf and stem dry mass (in oven for 24 hours at 70 °C) was determined.

Above-ground flat corn residue was collected within a rectangular frame of 305 mm by 584 mm. Dirt was removed from the residue using various hand tools. The residue was air dried and weighed in the laboratory. Flat residue cover was measured using a 15·2 m (50 feet) long measuring tape, counting, at 0·3 m (1 foot) intervals, the foot marks that covered pieces of residue. No standing residue was present on the field.

Soil was collected from the top 0·05 m using a flat shovel. In the laboratory this soil was used to determine soil texture using the pipette method (Gee and Bauder, 1986). The aggregate size distribution was determined using a rotary sieve (Chepil, 1962; Lyles *et al*., 1970) for sizes down to 0·42 mm (0·42, 0·84, 2·0, 6·4, 19·0, 45·0, and 76·0 mm sieves) and using a sonic sifter (ATM Corporation, Milwaukee, WI) with 5, 10, 20, 53, 106, 250 μm sieves for the finer material. The aggregate size distribution was described mathematically according to Wagner and Ding (1994). Dry aggregate stability (Boyd *et al*., 1983) and wet aggregate stability (Kemper and Rosenau, 1986) were also determined.

Ridge height for each field location was calculated as the average of the depths of four adjacent furrows, measured using a straight edge and a measuring tape. Soil random roughness was measured using a pinmeter having 101 pins, separated 1 cm from each other (Wagner and Yu, 1991; Skidmore *et al*., 1994). One measurement was taken parallel with a ridge at each field location. Pinmeter photographs were taken using a digital camera and analysed using SigmaScan Pro software (SPSS Inc., Chicago, IL). Random roughness was calculated as the standard deviation of pin positions (Allmaras *et al*., 1966), which was corrected for trends, i.e. downward

Table I. Precipitation (mm) measured at three nearby stations and a hypothetical scenario. Burlington airport and Burlington 4S are both 10 km north of the field. Precipitation from Burlington 4S and the hypothetical 'scenario 2' were used in the simulations of roughness degradation and residue decomposition

Station	19 Dec. to 8 Mar. (mm)	9 Mar. to 12 Apr. (mm)
Field	8	21
Burlington airport	21	22
Burlington 4S	43	24
Scenario 2	63	24

or upward trends of pin positions from one side of the pinmeter to the other. Such trends increase the standard deviation without contributing to soil roughness.

Surface (top 8 mm) soil moisture was measured gravimetrically using the sampling method described by Reginato (1975) and practised by Durar *et al.* (1995). Note that for a rough surface the top 8 mm is not well defined, making sampling quite challenging. Pieces of crust were placed in plastic bags for later analysis. Crust (consolidated zone) thickness was measured using a caliper in the laboratory. Loose material covering the crust was collected from an area of 305 mm by 305 mm, using a soft brush and dustpan.

Simulation of roughness degradation and residue decomposition

The amount of precipitation is critical for the simulation of the degradation of ridge height and random roughness. During the snowy period from 19 December 2000 to 8 March 2001, precipitation measured on our field differed greatly from that measured at nearby stations (Table I). For the period from 9 March to 12 April 2001, when precipitation came mostly in the form of rain, the three stations agreed well with each other. The windswept Great Plains is a very difficult area to accurately measure the water content of snow. Using ASOS type rain gauges (the type used at Burlington airport), the office of the Colorado State Climatologist conducted a study that showed substantial undermeasurement of snow, down to as little as 10 per cent of actual precipitation. Errors are not linear and are not easily corrected (N. Doesken, Assistant State Climatologist, personal communication).

Thus, it is very likely that Burlington airport underestimated precipitation during the winter. On our field we measured even less (Table I). Therefore, simulations were conducted using precipitation from Burlington 4S, the station that reported the most precipitation during the winter (Table I). Because of the uncertainty in precipitation, additional simulations were conducted using precipitation 'scenario 2' (Table I), that was constructed by tripling the winter precipitation of Burlington airport ($3 \times 21 = 63$ mm). This scenario seems reasonable, considering that the ASOS type rain gauge used at Burlington airport underestimates snow up to ten-fold.

The model for ridge height degradation is based on research by Lyles and Tatarko (1987) and the model for random roughness degradation is based on work described by Zobeck and Onstad (1987) and Potter (1990). Both models, as implemented in WEPS, have been presented by Hagen *et al.* (1995). In WEPS, the simulation of roughness degradation starts immediately after roughness has been created by an operation such as tillage or planting. Thus, we started simulations on the day of wheat planting (29 August 2000). Simulated ridge height and random roughness were forced to match the mean of the measured values on the first day of measurement (19 December 2000). No wind erosion occurred between 19 December and 12 April, so all roughness degradation was due to precipitation during this period.

Total biomass (dead crop residue plus live wheat plants) cover was estimated to be between 0 and 30 per cent throughout the period of simulation. Within this range, simulated ridge height and random roughness did not change much, so a more accurate estimate of biomass cover was not critical for this study. A constant biomass cover of 15 per cent was used for all roughness simulations.

Research underlying the WEPS residue decomposition model has been reported by Schomberg *et al.* (1994, 1996) and by Schomberg and Steiner (1997). The model, as implemented in WEPS, has been presented by Steiner *et al.* (1995). Decomposition greatly depends on temperature and moisture, as well as on the type of crop.

For flat residue, WEPS considers both precipitation and soil water content. Since we did not have continuous soil water content data, we only used precipitation (from Burlington 4S) for the simulation, which would underestimate decomposition. We therefore also simulated with moisture being at its optimum for decomposition, which would overestimate decomposition. T-tests were used for statistical comparisons of measured versus simulated ridge height, random roughness, and residue mass.

RESULTS AND DISCUSSION

Field measurements

The Sensits recorded high particle counts on many days, although the storm of 17/18 December was the only significant wind erosion event (Figure 3). High Sensit particle count on most other days can be traced back to snowfall or blowing snow, to which the Sensits are very sensitive. The highest winds during the period were on 11 April, but there was no significant soil movement because it was raining at the same time. The wet soil surface, together with growing wheat, prevented soil movement despite the very strong winds.

Wheat cover in December (Figure 4b) had decreased compared to that in November (Figure 4a) because of the onset of dormancy. On 8 March (Figure 4c), wheat cover was very similar to that of December, indicating that dormancy had not yet been broken. On 12 April (Figure 4d), the wheat had been growing, providing much more protection from wind erosion than before. WEPS calculates LAI from leaf mass. Thus, it is important to have experimental data defining this relationship. The ratio of LAI and leaf mass is specific leaf area (m^2 kg^{-1}). It is represented by the slope of the regression equations in Figure 5. Specific leaf area calculated from our measurements ranged between 11 and 17 m^2 kg^{-1} (Figure 5). This compares reasonably well with that found by other researchers. Retta and Armbrust (1995b) obtained 13 m^2 kg^{-1} and van Keulen (1986) 20 m^2 kg^{-1}. The soil was crusted most of the time (Figure 4). Table II shows field conditions on the three measurement dates. Wilting point (−1·5 MPa) water content, calculated from texture (Saxton *et al.*, 1986), was 0·077 kg kg^{-1}.

Only one significant wind erosion event occurred, on 17/18 December, during the period of the experiment. Soil movement on the field had high spatial variability (Figure 6). This was confirmed by visual observation on the afternoon of 18 December. At this time sediment was moving heavily only in two narrow 'corridors' (Figure 6). High spatial variability is probably typical for many agricultural fields. Even experimental fields created to be uniform, frequently showed large spatial variations in erosion (Hagen, 2001).

For the erosion event of 17/18 December, the northern field boundary was non-erodible, but the western boundary (dirt road) did not prevent sediment from moving in from an adjacent field, as evidenced by the large soil discharges of the BSNE stations located on this boundary (Figure 6). More soil movement in the western part of the field may be explained by field conditions less favourable than average. These conditions included lower residue cover (8, 10, and 8 per cent cover at BSNE stations 4, 9, and 17, respectively, and 530 and 827 kg ha^{-1} at stations 4 and 9, respectively), lower LAI at stations 9 and 11, higher sand fraction (50 per cent at station 4) and drier surface soil (0·027 kg kg^{-1} at station 4). Net sediment loss for the 600 m by 415 m experimental site was about 0·06 kg m^{-2}. This was calculated as the sediment leaving the field across the eastern and southern boundaries minus that entering the field across the western boundary (Figure 6).

Winds picked up very rapidly around 5 pm on 17 December (Figure 7), then died down during the night and picked up again on 18 December. Wind direction was rather constant throughout the event, coming from the NNW (328 degrees from north). Sensit response, indicating soil movement, closely followed wind speed. Threshold wind speeds, as indicated by Sensit, were around 12 m s^{-1} (Figure 8a). At wind speeds higher than this, soil movement became significant. Wind power density was calculated as:

$$WPD = \rho(u_i^2 - u_t^2)^{3/2} \tag{2}$$

where *WPD* is wind power density above threshold wind speed (W m^{-2}), ρ is air density (kg m^{-3}), u_t is threshold wind speed (m s^{-1}) and u_i is measured wind speed (m s^{-1}). The relationship between particle count and wind power density (Figure 8b) illustrates the near-linear dependence of saltation impacts on wind speed cubed after the threshold wind speed is reached.

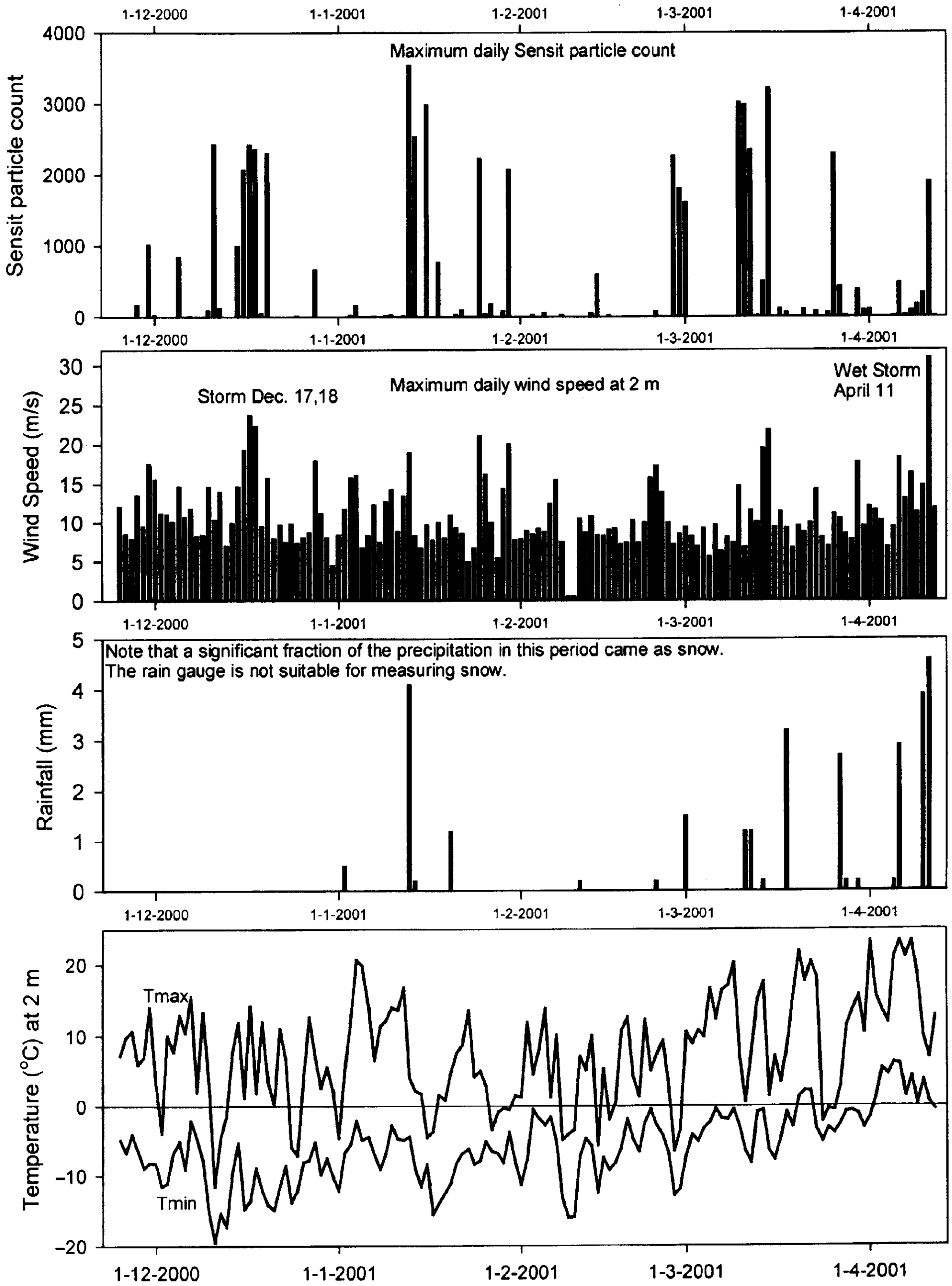

Figure 3. Overview of daily weather and Sensit (at station 13) data for the experimental period, November 2000–April 2001

Albedo (short-wave reflection coefficient) indicated the presence of a snow cover (Figure 9). February started with a snow cover as indicated by an albedo of more than 0·6 on 1 February. During the first week of February albedo gradually decreased from 0·6 to less than 0·2 on 7 February, indicating a gradual snow melt. On 7 February, the soil surface was no longer covered with snow and it was wet (a dry surface typically had an albedo of about 0·26 in this field). Then on 9 February, fresh snow fell as shown by the albedo jumping back up to almost 0·6. Fresh snow also fell on 14 and 27 February. This kind of information is important in wind erosion field research, especially with remote sites, since a snow cover may make the difference between soil

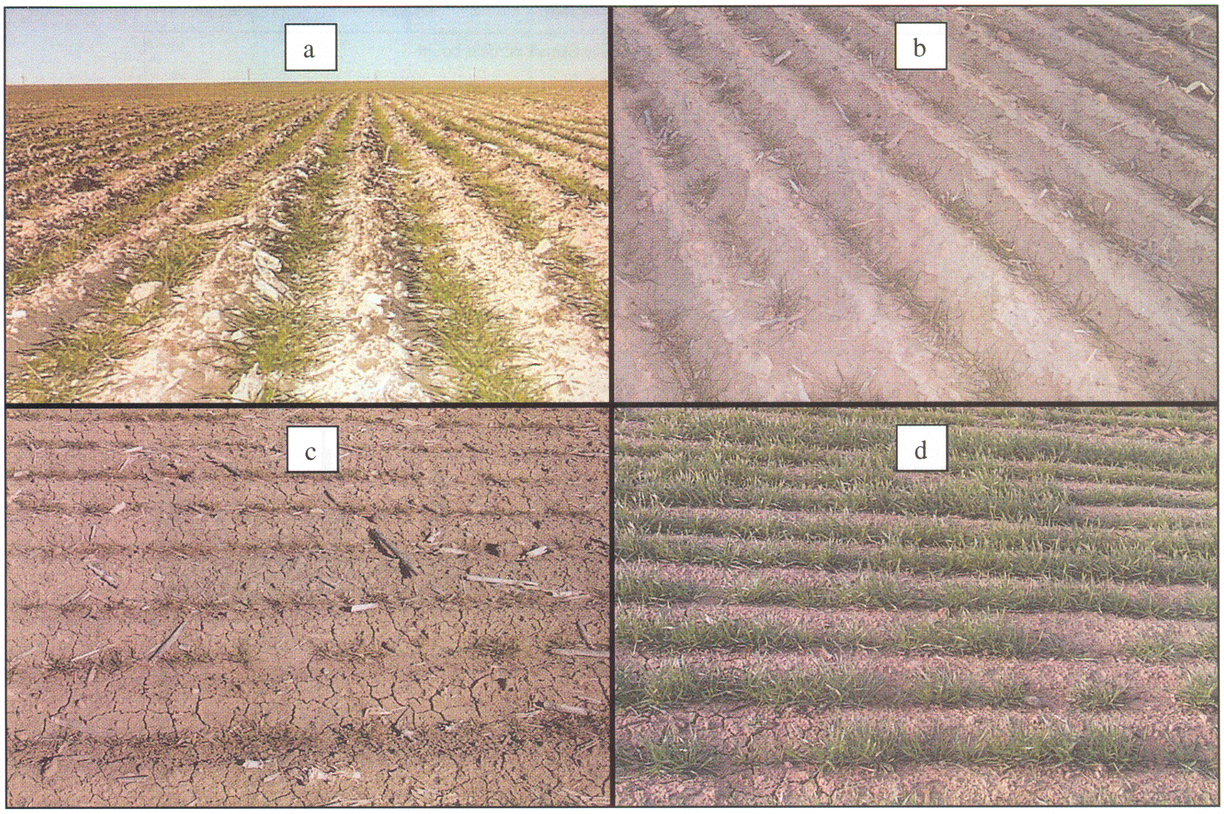

Figure 4. Condition of the field surface on (a) 9 November 2000, (b) 19 December 2000, (c) 8 March 2001, and (d) 12 April 2001

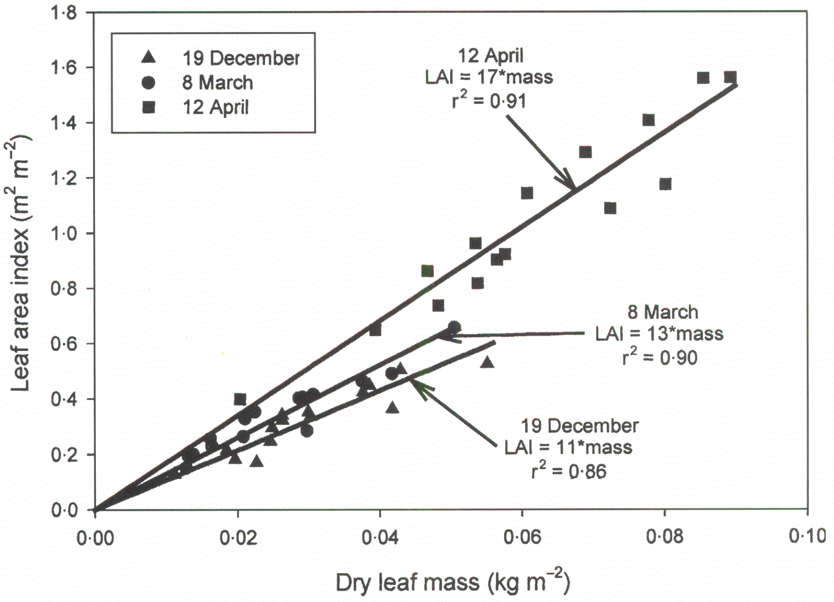

Figure 5. Measured wheat leaf mass versus leaf area index. Wheat samples were taken near 15 BSNE stations on the field (Figure 1) on 19 December 2000, 8 March 2001, and 12 April 2001. The intercept of the regression equations was forced to zero. The slope of the regression equations represents specific leaf area (m^2 kg^{-1})

Table II. Measured field conditions on three dates. Average and standard deviation are for 15 samples (except as indicated in the footnotes), one near each of the 15 BSNE stations that were not located on a field boundary. The last column indicates whether a variable is used in the WEPS erosion submodel (X = variable used in WEPS)

Variable	19 December		8 March		12 April		WEPS
	avg.	st dev.	avg.	st dev.	avg.	st dev.	
Surface soil moisture (kg kg^{-1})	0·036	0·007	0·061	0·039	0·120	0·020	
Plant height h (mm)	43	11	57	6	149	22	X
LAI ($\text{m}^2\ \text{m}^{-2}$)	0·32	0·12	0·34	0·14	1·03	0·33	X
SAI ($\text{m}^2\ \text{m}^{-2}$)	0·05	0·02	0·04	0·02	0·11	0·04	X
Population (plants m^{-2})	203	88	173	77	157	62	
Leaf dry mass (g m^{-2})	30·0	11·4	25·6	11·3	60·8	18·7	
Stem dry mass (g m^{-2})	9·5	4·5	2·4	2·0	15·1	7·3	
Residue cover (%)	14·0	7·9	9·7	3·5	9·8†		X
Air dry corn residue mass (kg ha^{-1})	1204	660	1368	626	1174	566	
Sand (%)	31	7					X
Silt (%)	53	6					X
Clay (%)	16	5					X
Aggregates <84 μm (%)	59	6	48	12	56[a]	15[a]	
Minimum aggregate size* (mm)	0·019		0·044		0·020[a]		X
Maximum Aggregate size* (mm)	79·5		77·9		44·4[a]		X
GMD* (mm)	0·62		1·32		0·75[a]		X
GSD* (mm mm^{-1})	12·0		18·7		14·7[a]		X
Crust thickness (mm)	11[c]	3[c]	21[d]	6[d]	21‡		X
Loose material on crust (kg m^{-2})	0·65‡		0·65[b]	0·61[b]	0	0	X
Dry aggregate stability ($\ln[\text{J kg}^{-1}]$)	3·11[e]	1·00[e]	2·54[e]	0·90[e]	2·51[f]	1·22[f]	X
Wet aggregate stability (%)	23	6					
Ridge height (mm)	42	7	36	7	34	6	X
Ridge roughness (mm)	12·5	2·2	12·1	1·8			
Random roughness (mm)	5·8	1·9	5·2	1·1			X

GMD, geometric mean diameter; GSD, geometric standard deviation.

* Obtained by fitting the cumulative distribution function (Wagner and Ding, 1994) to the average of the measured cumulative aggregate size distribution using Tablecurve (SPSS Inc. Chicago, IL) software.

† Not measured; estimated from residue mass.

‡ Not measured; used March measurement for simulation.

[a] $n = 3$ (one sample near each of three BSNE stations: station identifiers 5, 12, 17; see Figure 1).

[b] $n = 30$ (two samples near each of 15 BSNE stations).

[c] $n = 92$ (several samples near each of 15 BSNE stations).

[d] $n = 86$ (several samples near each of 15 BSNE stations).

[e] $n = 300$ (20 samples near each of 15 BSNE stations).

[f] $n = 60$ (20 samples near each of three BSNE stations: station identifiers 5, 12, 17; see Figure 1).

moving or not. Snow and snow cover are difficult to measure directly in an automated fashion. A regular tipping bucket rain gauge does not capture snow very well.

Albedo is also a good indicator of soil surface wetness (Figure 10). The soil surface was dry on 8, 9 and 10 April, with albedo around 0·25. It was wetted by rain on the evening of 10 April and on 11 April. The albedo on 11 April had decreased from 0·25 to about 0·17. On 12 April the soil surface dried and the albedo went back up to about 0·25. Soil surface wetness is very important in wind erosion. If the surface is wet, much greater friction velocities are needed to move the soil. For this reason, wind erosion was insignificant on 11 April, although wind speeds were much greater than during the dust storm of 17/18 December. Measurement of soil moisture at the surface is difficult, making the albedo information quite valuable. This has also been recognized by other researchers, such as Idso *et al.* (1975).

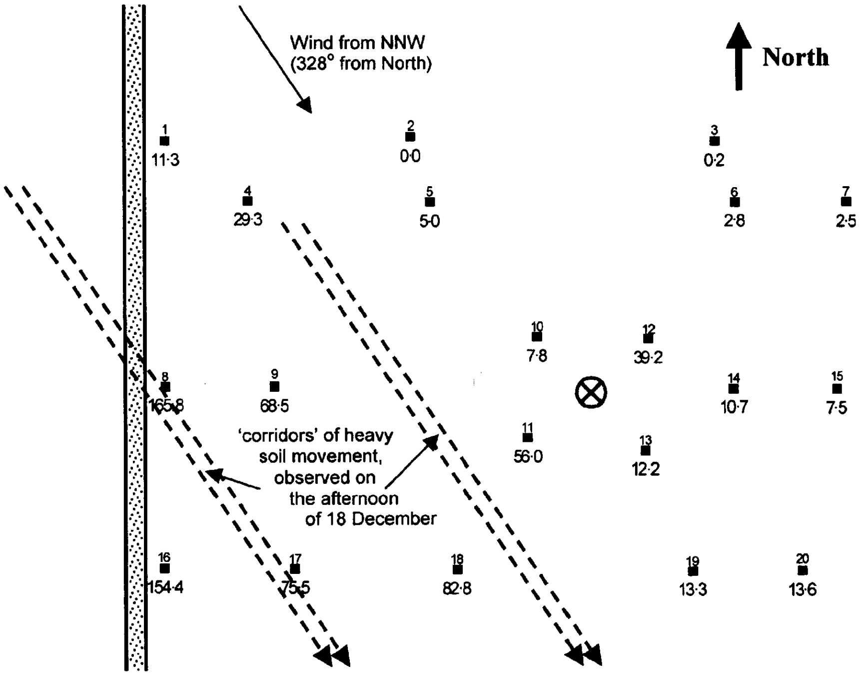

Figure 6. Soil discharge (kg m^{-1}) associated with the storm on 17/18 December 2000. Numbers in small print, located above the square location markers, are station identifiers

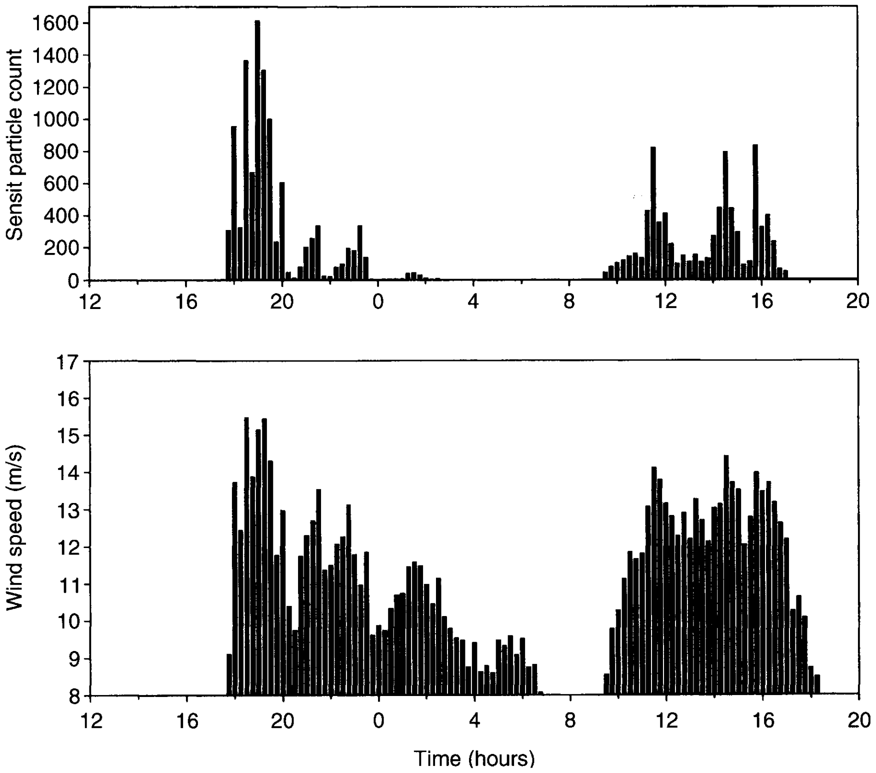

Figure 7. Detail of wind erosion event on 17/18 December 2000. Data are 15 min averages, measured at station 12

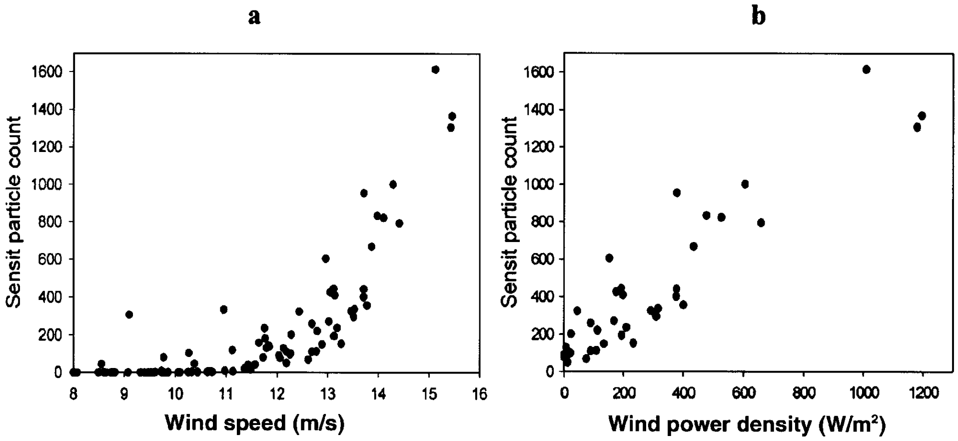

Figure 8. Determination of threshold wind speed from Sensit and wind speed data (a) and Sensit particle count as influenced by wind power density (Equation 2) using a threshold wind speed of 12 m^{-1} measured at a height of 2 m (b). Data are 15 min averages, measured at station 12 on 17/18 December 2000

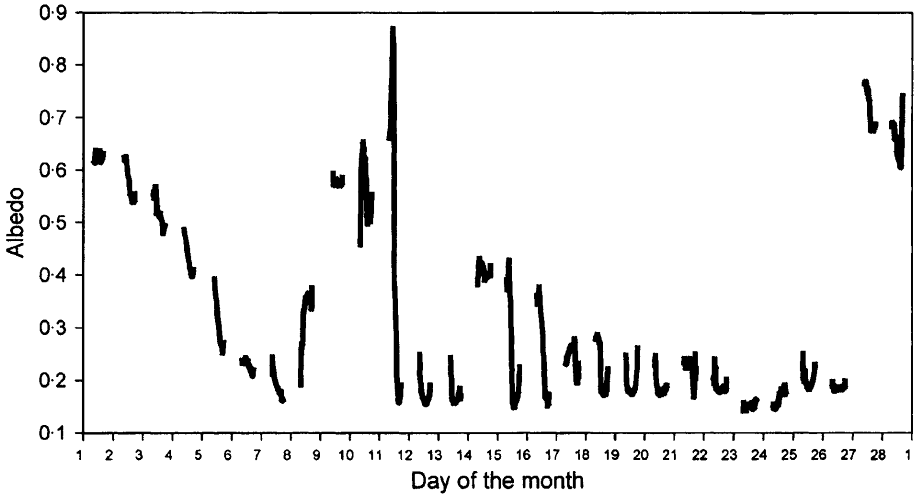

Figure 9. Albedo (short-wave reflection coefficient) for February 2001. High albedo indicates the presence of a snow cover

Simulations

Simulation of the 17/18 December storm with the WEPS erosion submodel, using the 19 December field conditions shown in Table II, yielded no erosion (Table III). Assuming a totally dry soil surface, WEPS still produced no erosion. Reducing the wheat to very small plants (Table III) of about one-fourth the size of the real wheat cover (Figure 4b) produced no erosion. A simulation entirely without wheat produced a field loss of 1·07 kg m^{-2}, which is much larger than the measured loss. Apparently, WEPS is very sensitive to small changes in standing biomass. This component of WEPS is based on laboratory wind tunnel experiments with simulated standing biomass uniformly spaced on a flat surface. In our experimental field the wheat biomass was not uniformly spaced, because wheat plants were standing in rows, with much more space between plants in adjacent rows than between plants within a row. This makes them much less effective in preventing wind erosion than biomass that is uniformly spaced. Furthermore, our field was not flat, but ridged with the small wheat plants 'hiding' in the furrows, being barely taller than the ridges (Figure 4b, Table II).

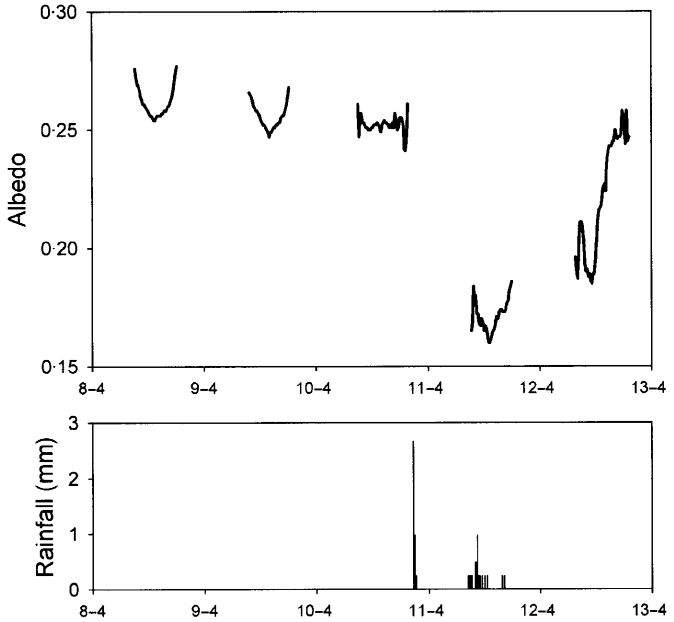

Figure 10. Albedo and rainfall for 8 April to 12 April 2001. Albedo decreases after rain has wetted the soil surface. It increases again on 12 April, as the soil surface is drying

Table III. Simulated and measured field soil loss for the 17/18 December and the 11 April storms

Simulation input	Field soil loss (kg m^{-2})
Simulation of 17/18 December event using	
19 December conditions (Table II)	0·00
Dry soil surface	0·00
Dry and very small wheat plants*	0·00
Dry and no wheat plants	1·07
Soil surface moisture as in Table II and no wheat plants	0·03
Measured	0·06
Simulation of 11 April event using	
12 April conditions (Table II)	0·00
Dry and no wheat plants	0·00
Dry and no wheat plants, loose material on crust = 0·00 kg m^{-2}	4·43
Dry and very small wheat plants*, loose material on crust = 0·01 kg m^{-2}	0·00
Dry and no wheat plants, loose material on crust = 0·65 kg m^{-2}	10·36
Measured	0·00

* Very small wheat plants: height = 10 mm, leaf area index = 0·1, stem area index = 0·01.

Simulation of the 17/18 December storm, without wheat and a surface soil moisture content of 0·036 kg kg^{-1} (Table II), yielded a field loss of 0·03 kg m^{-2}, down from 1·07 kg m^{-2} for a dry soil surface. This shows that WEPS is very sensitive to surface soil moisture and raises the question of accurate and timely measurement of surface soil moisture in field experiments like this. Automated sensors (TDR, dual probe, etc.) are timely (continuous), but do not function well near the surface. Soil moisture at the surface would have to be estimated using soil moisture measured deeper in the soil, in conjunction with other data, such as evaporation. Albedo is timely and gives an indication of soil moisture at the surface, but does not quantify soil moisture, so it cannot be used directly in simulation models. Gravimetric measurements are not timely and sampling at the surface is a challenge. The surface soil moisture of 0·036 kg kg^{-1} in Table II came from gravimetric measurements on samples taken from the top 8 mm of the soil, one day after the erosion event. Therefore, it is questionable that this represents soil moisture at the surface during the event.

The 11 April wind event was simulated using the measured field condition data of 12 April as inputs (Table II), yielding no erosion (Table III). A simulation without wheat and with a dry soil surface still produced no erosion, because no loose material was present on the surface crust to initiate erosion through abrasion. When a very small amount (0·01 kg m^{-2}) of loose material was introduced in the simulation, field loss was 4·43 kg m^{-2}, which is a large loss. By comparison, the largest measured field loss in the study by Zobeck *et al.* (2001) was 5·62 kg m^{-2}, out of 41 storm events, and the largest field loss measured by Larney *et al.* (1995) was 3·0 kg m^{-2}, out of 16 storm events. This shows that abrasion is a very important wind erosion mechanism. It also implies that large differences in sediment transport may occur on the same field caused by very small differences in available loose material upwind. In one location on the field there may be a small amount of loose material available to create an abrasive 'avalanche' effect downwind, and in another location there may be no loose material, resulting in no erosion at all.

No erosion was predicted for the 11 April event when introducing very small wheat plants ($h = 10$ mm, LAI = 0·1, SAI = 0·01). Again, it appears that the model overestimated the ability of small wheat plants to protect the soil against wind erosion. It is not likely that a wheat cover that is much lower than that of 19 December (Figure 4b) would have reduced field loss this much. WEPS needs to be modified to account for standing biomass that is not uniformly spaced. The necessary information may be obtained using a portable wind tunnel on surfaces with different configurations of standing biomass. An extension of WEPS along similar lines is also needed for simulating wind erosion on rangelands, where standing elements, such as bushes and shrubs, are not spaced uniformly.

When a larger amount (0·65 kg m^{-2}, which is the value measured on 8 March) of loose material was introduced in the simulation in a scenario without any wheat plants, a field loss of 10·36 kg m^{-2} was predicted. This seems a reasonable estimate, given the fact that this storm had much more wind energy than the storm with a measured field loss of 5·62 kg m^{-2} in the study by Zobeck *et al.* (2001).

Using precipitation from Burlington 4S, ridge height seemed overestimated (Figure 11), but the difference between simulation and measurement was not significant ($P > 0·05$). Random roughness seemed slightly overestimated, but this was not significant either. Furthermore, when simulating using precipitation scenario 2 (Table I), measured and simulated ridge height matched almost exactly and random roughness was underestimated, but not significantly (Figure 11). WEPS treats rain and snow the same. In reality, it is expected that rain reduces roughness more than snow, due to its higher impact energy. Refinement of the model in this respect may be warranted.

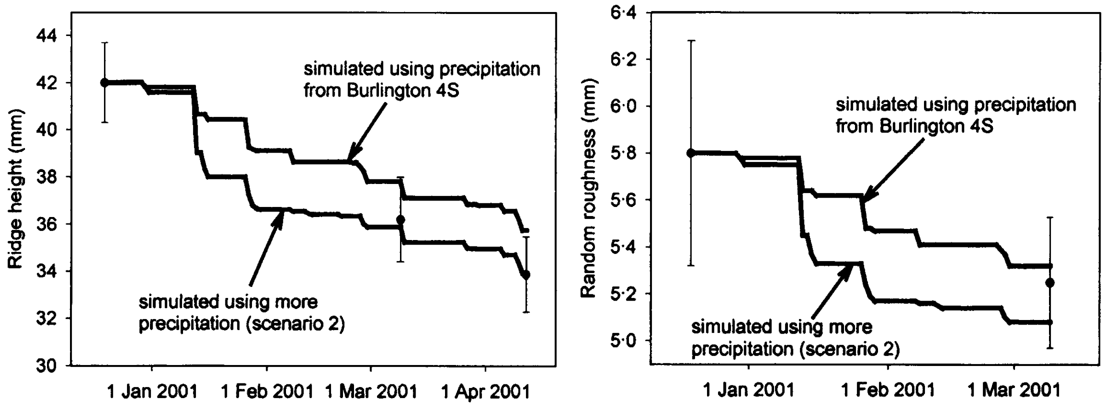

Figure 11. Simulated (lines) and measured (dots and vertical error bars) ridge height and random roughness. Simulations were done with two different precipitation scenarios (Table I). They were forced to coincide with the mean of the measured values on 19 December 2000. Measurements were taken near 15 BSNE stations on a 600 m by 415 m field (Figure 1). Vertical bars are ±1 SE of the mean ($n = 15$)

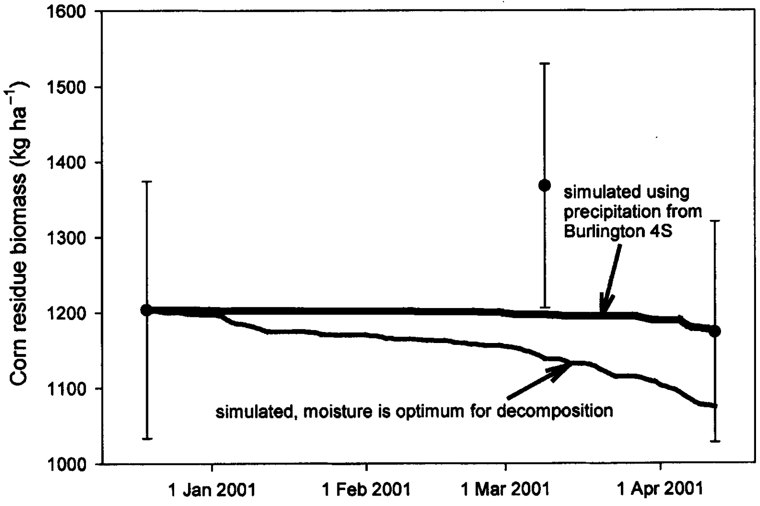

Figure 12. Simulated (lines) and measured (dots and vertical error bars) corn residue biomass. Simulations were initialized at the mean of the measured values on 19 December 2000 (1204 kg ha^{-1}). Corn residue biomass samples were taken near 15 BSNE stations on a 600 m by 415 m field (Figure 1). Vertical bars are ±1 SE of the mean ($n = 15$)

Simulated residue decomposition was slight when moisture was assumed to be limited to precipitation only (Figure 12). It increased when moisture was assumed to be optimum for decomposition. Temperature was the most limiting factor. Decomposition increased with warming in the spring (Figures 3 and 12). On 8 March measured residue biomass seemed greater than on 19 December, but the difference was not significant ($P > 0{\cdot}05$). Simulated and measured corn residue biomass did not differ significantly from each other either.

NRCS personnel have measured 7–39 per cent loss of residue biomass during the period October – March in the northern Great Plains of the USA (Montana, Wyoming, North Dakota). Measurements included stems, leaves, chaff, etc. (G. Tibke, personal communication). WEPS predicted, and measurements showed, less decomposition at Burlington, Colorado (Figure 12), where temperatures were at least as warm as those during the NRCS measurements. At least two reasons may explain this discrepancy. (1) At harvest, WEPS disregards everything but stems. Thus, subsequent decomposition only includes stems, which decompose more slowly than leaves and chaff. If the NRCS had measured only the loss of stem mass, losses would probably have been much smaller. (2) Some of the decrease in residue mass, measured by the NRCS, may be due to removal by wind rather than decomposition.

CONCLUSION

One significant dust storm occurred during the experimental period (November 2000 to April 2001), with a net field sediment loss of 0·06 kg m^{-2}. Spatial variability of sediment discharge was high. This could be partially explained by spatial differences in residue cover and mass, leaf area index, sand fraction and wetness of the surface soil. Albedo is a good indicator of soil wetness at the soil surface. Additional research is needed to study the use of albedo for quantifying soil surface water content.

WEPS overestimated the ability of small wheat plants to protect the soil against wind erosion. A simulation without any wheat plants produced a large field sediment loss of 4·43 kg m^{-2}, whereas a simulation with very small wheat plants produced no erosion. This sensitivity to such a small change in standing biomass seems unrealistic. Simulation by WEPS of the effect of standing biomass on wind erosion is based on laboratory wind tunnel experiments with simulated standing biomass uniformly spaced on a flat surface. In our experimental field the wheat biomass was not uniformly spaced and our field was not flat, but ridged with the small wheat plants 'hiding' in the furrows. WEPS needs to be modified to account for these non-uniformities, since they are very common in the field.

Measured specific leaf area ranged between 11 and 17 $m^2\,kg^{-1}$, comparing reasonably well with values of 13 and 20 $m^2\,kg^{-1}$ found by other researchers. The mean ridge height of 42 mm on 19 December 2000 was reduced to 34 mm (36 mm simulated) on 12 April 2001. The mean random roughness of 5·8 mm on 19 December was reduced to 5·2 mm (5·3 mm simulated) on 8 March. The simulation of roughness degradation is driven by precipitation, which is very difficult to measure in windy climates, especially when it comes in the form of snow. The mean corn residue biomass of 1204 $kg\,ha^{-1}$ on 19 December was reduced only slightly to 1174 $kg\,ha^{-1}$ (1075–1175 $kg\,ha^{-1}$ simulated) on 12 April. None of the differences between measured data and simulations were significant ($P > 0{\cdot}05$), enhancing confidence in the ability of WEPS to simulate roughness degradation and residue decomposition.

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