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Crop Residue In North Dakota: Measured And Simulated By The Wind Erosion Prediction System

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Abstract. *Residue cover is very important for controlling soil erosion by water and wind. Thus, the Wind Erosion Prediction System (WEPS) includes a model for the decomposition of crop residue. It simulates the fall rate of standing residue and the decomposition of standing and flat residue as a function of temperature and moisture. It also calculates residue cover from flat residue mass. Most of the data used to develop and parameterize this model have been collected in the southern U.S. We compared WEPS-simulated residue cover with that measured in south-central North Dakota for 50 two-year cropping sequences from nine crops species that were grown using no-till management. Measured data included residue mass at the time of harvest and residue cover just after seeding the next spring. Simulated residue cover significantly ($P < 0.05$) underestimated measured cover for 33 out of the 50 simulated cropping sequences and overestimated measured cover for five cropping sequences. Some of the differences may be explained by the fact that, for many WEPS crops, residue decomposition parameters are not based on measured field data, but on expert judgment. In addition, WEPS did not predict any stem fall for most of the crops during winter, which contradicts observations that storms flatten many residue stalks of crops such as sunflower. In addition to stem fall and residue decay by biological means, which are driven by temperature and moisture, the model needs to explicitly simulate stem fall by mechanical forces, such as wind- and snowstorms, which are important in northern climates. Furthermore, WEPS does not model the migration of unanchored residue caused by rain- or windstorms, although this does affect residue mass-to-cover ratios and susceptibility to erosion. This study will help improve the WEPS decomposition model and its parameterization, but more data on residue decay and stem fall are needed for different climates and crops to ensure the applicability of the model over a wide range of conditions.*

Keywords. *Residue cover, Residue decomposition, WEPS, Wind erosion.*

Wind erosion is a serious problem in many parts of the world, especially in arid and semi-arid regions. To better deal with the damage done by wind erosion, an effort has been in progress by the USDA Agricultural Research Service (USDA-ARS) to better understand the processes involved and to develop a process-based computer model, the Wind Erosion Prediction System (WEPS; Hagen, 1991; USDA, 1995; Wagner, 2001). WEPS is a daily-time-step model for the simulation of wind-blown sediment loss from a field. It is intended primarily for soil conservation and environmental planning. The model can be used to evaluate the effect of alternative cropping systems and management scenarios on wind erosion. It tracks eroded sediment amounts in three particle size classes: creep/saltation, suspension, and particulate matter with an aerodynamic diameter less than 10 μm (PM_{10}). WEPS has been designated to replace the more empirical Wind Erosion Equation (WEQ) for use by the USDA Natural Resources Conservation Service (USDA-NRCS) in the U.S.

The core of WEPS is the erosion submodel. There are a number of supporting submodels in WEPS, including submodels for weather, soil processes, management, hydrology, crop growth, and crop residue decomposition (USDA, 1995). Accurate prediction of wind erosion depends greatly on reliable simulations by all submodels. The weather submodel stochastically generates weather variables, with a special focus on wind speed and direction (Skidmore and Tatarko, 1990; van Donk et al., 2005). The soil submodel simulates changes in soil aggregate size and stability, crusting, and roughness. The hydrology submodel simulates soil wetness at the soil surface. It also supports the crop growth submodel, which determines how much live crop biomass is available for protection against wind erosion. The management submodel simulates the effect of different kinds of agricultural equipment on soil properties and crop residue, and determines the extent of flattening of standing residue and burial of flat residue, caused by equipment passage.

Crop residue is very important for controlling wind erosion (Englehorn et al., 1952; Skidmore et al., 1979; Skidmore, 1983; Hagen, 1996), especially during periods when a crop is not present or has not yet formed a canopy. Crop residue reduces momentum transfer to the soil (Hagen, 1996) and

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increases the threshold friction velocity above which erosion starts (Hagen, 1995).

The WEPS submodel for the decomposition of crop residue simulates the fall rate of standing residue and the decomposition of standing and flat residue as a function of temperature and moisture. It also calculates the fraction of soil covered by residue from flat residue mass. Most of the data used to develop this submodel have been measured in the southern U.S. (Steiner et al., 1994; Schomberg and Steiner, 1997; Steiner et al., 1999).

Steiner et al. (1994) monitored standing stem persistence of four small grain crops (winter wheat, spring wheat, winter barley, and spring oat) for 14 months at Bushland in northwest Texas. They developed an equation to predict standing stem number over time, based on precipitation and temperature. They indicated that additional testing is needed over a broader range of climates and for crops other than small grains. Steiner et al. (1999) monitored crop residue biomass for the same four small grain crops at the same location in order to quantify crop residue decomposition as affected by irrigation, initial residue biomass, and initial N concentration in standing biomass. Schomberg and Steiner (1997) estimated crop residue decomposition coefficients for five crops (alfalfa, corn, grain sorghum, winter wheat, and spring wheat) using substrate-induced respiration. This approach has the potential to greatly reduce labor and time needed to determine these coefficients.

A complete description of the WEPS decomposition submodel can be found in Steiner et al. (1995). The next section provides an abbreviated description of those aspects of the residue decomposition submodel that are the most relevant to this study.

Dryland agriculture in the northern Great Plains is characterized by an increasing diversity of species in cropping systems formerly dominated by wheat and the practice of summer-fallow. This diversity means that a number of crops that provide less residue (e.g., sunflower, pea, bean) are becoming more prevalent (Merrill et al., 2006). No-till is considered the best management practice, but there are erosion risks when lower-residue crops interact with tillage disturbance and/or summer-fallowing. The most vulnerable time for wind erosion in the semi-arid dryland cropping areas of the northern Great Plains is in the spring after seeding, before a crop canopy has established itself.

A crop sequence experiment by the USDA-ARS Northern Great Plains Research Laboratory provided residue biomass data at the time of harvest and residue cover data the next spring (Krupinsky et al., 2006). The objective of this study was to compare the WEPS-simulated residue cover with that measured in south-central North Dakota for nine different crops: barley, canola, dry bean, dry pea, flax, safflower, soybean, spring wheat, and sunflower.

Description of the WEPS Residue Decomposition Submodel

The general decomposition equation is a simple first-order rate-loss equation (Steiner et al., 1999):

$$M_t = M_0 \exp^{-kCDD} \tag{1}$$

where M_t is present biomass (kg m^{-2}) in one of four pools (standing, flat, buried, or root), M_0 is initial biomass (kg m^{-2}), k is a crop-specific rate (kg kg^{-1} day^{-1}), and CDD is cumulative decomposition days (day), a weighted-time variable calculated from functions of temperature and moisture (fig. 1). WEPS uses the same k value for the standing, flat, buried, and root residue pools. An example of slowly decomposing residue is wheat residue (k = 0.0133 kg kg^{-1} day^{-1}). Soybean residue decomposes much faster (k = 0.03 kg kg^{-1} day^{-1}). Decomposition rate k depends on biochemical constituents of the plant, such as lignin, cellulose, hemicellulose, and simple sugars (Paul and Clark, 1989).

Optimum moisture and temperature conditions result in the accumulation of one decomposition day for each day of the simulation. When moisture or temperature limit the rate of decomposition, the minimum of the moisture and temperature functions is used to accumulate a fraction of a

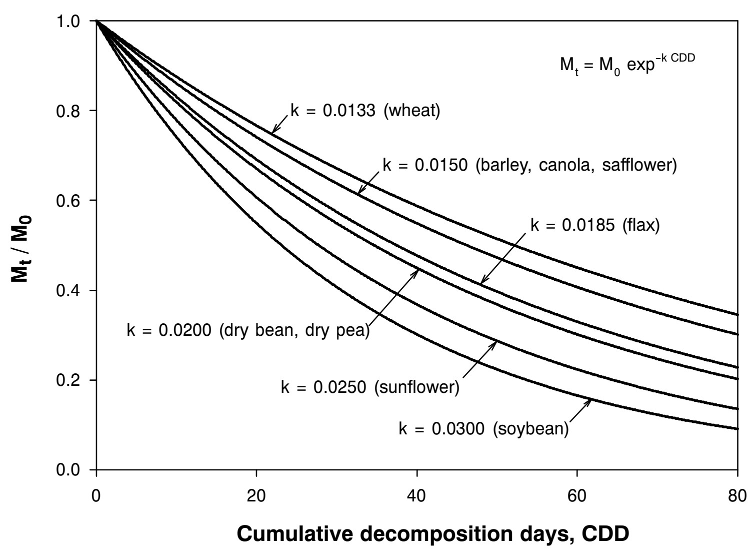

Figure 1. WEPS residue decomposition rates, k (kg kg^{-1} day^{-1}), for the nine crops in this study. If moisture and temperature are both optimum for decomposition, then residue mass decreases by a crop-specific rate k. If conditions are sub-optimum, then residue mass decreases by a fraction of this rate. After 60 decomposition days (days when both moisture and temperature are optimum for decomposition), soybean residue mass, M_t, is less than 20% of initial mass, M_0, but wheat residue mass is still more than 40% of initial mass.

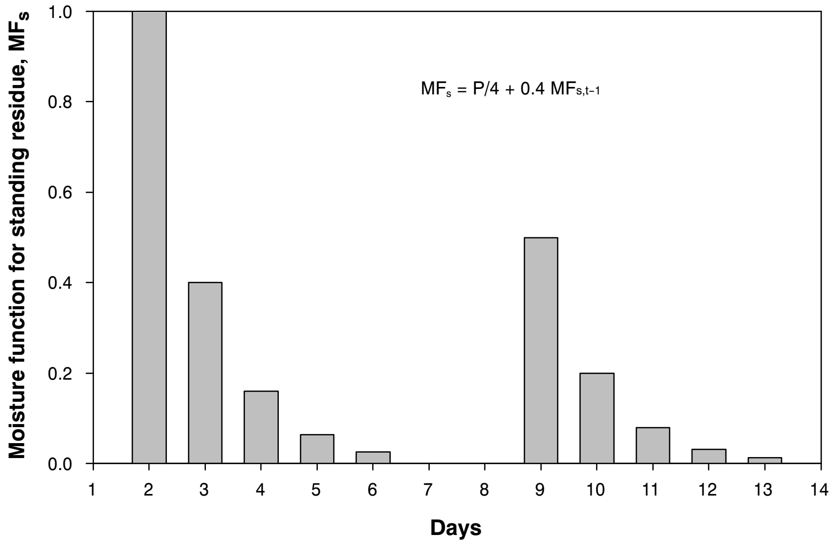

Figure 2. Behavior of the moisture function for standing residue (MF_s) if precipitation were equal to or greater than 4 mm on day 2, equal to 2 mm on day 9, and all other days were dry. In this example, moisture is optimum for decomposition on day 2, 40% of optimum on day 3, etc. No decomposition occurs on days 1, 7, 8, and 14 because of a lack of moisture. For flat residue, not only precipitation, but also surface soil water content affects decomposition.

decomposition day. Biomass loss is calculated by using the numeric form of equation 1:

$$M_t = M_{t-1}(1 - kDD) \tag{2}$$

where M_{t-1} is biomass (kg m^{-2}) on the previous day, and DD is decomposition day:

$$DD = MIN(TF, MF) \tag{3}$$

where TF is a temperature function, and MF is a moisture function. Thus, if moisture and temperature are optimum for decomposition on a given day, a k value of 0.01 kg kg^{-1} day^{-1} results in a 1% reduction of residue mass on this day. TF and MF range between 0 and 1, and depend on residue placement (standing, flat, or buried).

For standing residue, the moisture function is (Steiner et al., 1994):

$$MF_s = \frac{P}{4} + 0.4MF_{s,\,t-1} \tag{4}$$

where MF_s is the moisture function for standing residue on the current day, and $MF_{s,t-1}$ is the same but for the previous day. The function is based on precipitation P (mm), with 4 mm of precipitation considered to saturate the standing residue. MF_s decreases by 60% each day after a wetting event. After more than 4 dry days in a row, $MF_s = 0$ (fig. 2).

The decomposition of flat residue is influenced by both precipitation and soil water content at the soil surface. The maximum of MF_s and function MF_f are used. Calculation of MF_f assumes that moisture in flat residue is in equilibrium with that at the soil surface, and MF_f is calculated from the soil water content at the soil surface at noon, Θ_{surf}, and the optimum water content for decomposition. Water content at field capacity of the upper soil layer, $\Theta_{fc,1}$, is used for the optimum water content:

$$MF_f = \frac{\Theta_{surf}}{\Theta_{fc,1}} \tag{5}$$

For both standing and flat residue, the temperature function is calculated similarly to a function describing the influence of temperature on photosynthesis (Taylor and Sexton, 1972) and used by Stroo et al. (1989) and Steiner et al. (1999) for residue decomposition:

$$TF = \frac{2(T - T_b)^2 (T_0 - T_b)^2 \; - \; (T - T_b)^4}{(T_0 - T_b)^4} \tag{6}$$

where T is temperature (°C), T_0 is the optimum temperature for decomposition (32°C), and T_b is a base temperature (0°C) below which no decomposition occurs (fig. 3). TF is calculated as the average of two TF values: one calculated using daily maximum air temperature, and a second using daily minimum air temperature.

Stems are allowed to fall over only after a threshold of cumulative decomposition days since harvest has been reached (Steiner et al., 1994). For example, a threshold of 20 decomposition days means that standing stalks would begin to fall 20 days after harvest if moisture and temperature conditions were optimum during these 20 days. If conditions are not optimum, then the number of days that stalks remain standing increases. After reaching the threshold, the change in stem number is calculated similarly to the loss in biomass (eq. 2):

$$N_t = N_{t-1}[1 - k_{stem} MIN(TF, MF_s)] \tag{7}$$

where N_t is the number of stems standing on day t (# m^{-2}, where # indicates number), N_{t-1} is the number of stems standing on the previous day (# m^{-2}), and k_{stem} is a crop-specific stemfall rate (# #$^{-1}$ day^{-1}) (Steiner et al., 1994).

On a day of tillage, the distribution of residue will change between standing, flat, and buried components depending on the tillage implement being used. The WEPS management submodel updates current biomass for each pool (standing, flat, buried, and root).

Soil cover from flat residue mass is predicted by an equation developed by Gregory (1982) and used by Steiner et al. (2000):

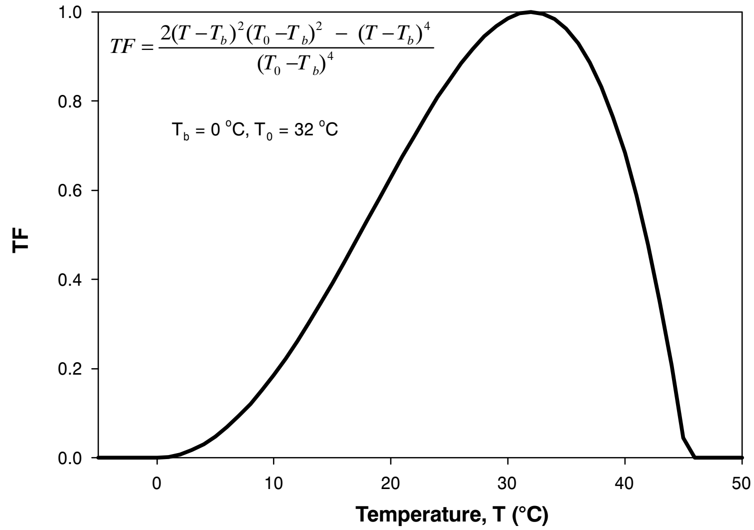

Figure 3. Plot of the temperature function (*TF*). Temperature is optimum for decomposition at 32°C. Below 0°C and above 46°C, no decomposition occurs.

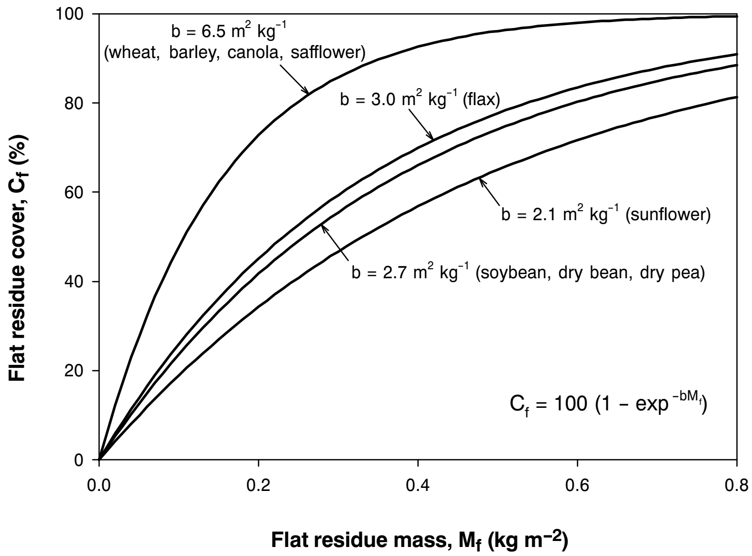

Figure 4. Relationship in WEPS to calculate flat residue cover from flat residue mass for the nine crops in this study. A flat residue mass of 0.2 kg m^{-2} provides about 35% cover for soybean, dry bean, and dry pea. The same mass provides about 70% cover for wheat, barley, canola, and safflower.

$$C_f = 100(1 - \exp^{-b M_f}) \qquad (8)$$

where C_f is flat residue cover (%); b is the mass-to-cover factor, which is a crop-specific coefficient (m^2 kg^{-1}); and M_f is flat residue mass (kg m^{-2}) (fig. 4). Residue from a crop such as sunflower (b = 2.1 m^2 kg^{-1}) does not provide much cover per unit mass, whereas wheat residue (b = 6.5 m^2 kg^{-1}) provides much more cover.

Methods

Measurements

Residue mass and cover were measured at the Area IV Soil Conservation Districts USDA-ARS Cooperative Research Farm located approximately 7 km southwest of Mandan, North Dakota (46° 46′ N, 100° 57′ W). The crops were grown under no-till conditions on a Wilton silt loam soil (fine-silty, mixed, superactive frigid Pachic Haplustoll) receiving on average about 400 mm of precipitation per year (Krupinsky et al., 2006). Mean annual temperature is 4°C, and daily averages range from 21°C in the summer to −11°C in the winter. Measured data include residue mass at the time of harvest (Tanaka et al., 2001) and residue cover (fraction of soil covered by residue) just after wheat seeding the next spring (Merrill et al., 2006).

A crop-sequence project was carried out by formation of a ten-by-ten crop matrix over a two-year period (Krupinsky et al., 2006). The ten crops were barley (*Hordeum vulgare* L.), dry bean (*Phaseolus vulgaris* L.), dry pea (*Pisum sativum* L.), canola (*Brassica napus* L.), crambe (*Crambe abyssinica* Hochst. ex R. E. Fr.), flax (*Linum usitatissimum* L.), safflower (*Carthamus tinctorius* L.), soybean (*Glycine max* (L.) Merr.), spring wheat (*Triticum aestivum* L.), and sunflower (*Helianthus annuus* L.). In the first year, the ten crops were seeded in randomized 9 m wide strips. In the second year, the same ten crops were seeded in re-randomized strips perpendicular to the first set. In this manner, 100 two-year sequences of the crops could be evaluated. The crop matrix, which had 4-fold replication, was repeated at a second site immediately adjacent to the first. Cropping sequences with crambe were excluded from this study because crambe is not included in WEPS.

The experiment was carried out with no-till management practices employing regular farming equipment. Crops were seeded with a John Deere 750 no-till drill, a coulter type with relatively little soil disturbance. This drill has little residue burial, tending to move residue aside and then back during passage. Row spacing was 19 cm with 40% to 50% surface soil disturbance and narrow vertical disturbance 5 to 8 cm deep. Weeds were controlled with herbicide applications, both in pre-seeding and post-seeding periods. The only disturbances to the soil and residue were (1) by the drill at seeding; (2) by two (or possibly three) trips for most crops per year by tractor-mounted herbicide sprayer; and (3) by passage of the harvesting combine.

Residue mass at the time of harvest was determined by hand sampling all aboveground biomass (excluding any residue mass from a previous crop) in a 0.34 m^2 area and subtracting the seed yield, which was determined by harvesting 11.4 m^2 with a plot combine (Tanaka et al., 2001). Residue cover measurements were taken in selected plots in spring 2000 and spring 2001, after seeding but before crop emergence. In this interdisciplinary research project, selection criteria were mainly driven by plant pathology research needs.

Residue cover was measured with two different techniques: a transect technique and a photographic technique. With the transect technique, residue presence was determined at 25 points equally spaced along a 7.6 m cable, which was stretched across each plot four times to count the number of residue contacts, for a total of 100 points. All residue was counted that was visible to the operator at semicircular, 2 mm diameter areas defined by small metal pieces affixed to the cable. At each plot, two V patterns were formed by successive layings of the cable, which pointed in the direction of seeding. With the photographic technique, a 35 mm camera, held by a light frame, was used to produce nadir-view film slides from a height of 2 m, covering a land area of about 1 m^2. One slide was made for each plot, and the slides were evaluated for residue presence at 50 points on a projector screen (Merrill et al., 2006).

Simulations

Each two-year cropping sequence simulation started with the measured total aboveground residue mass remaining in the field after harvest of the first crop (Tanaka et al., 2001). Any residue from previous crops was ignored under the assumption that it would be totally decomposed by the time of residue cover measurement. USDA-ARS scientists at Mandan, North Dakota, assert that this is a realistic assumption. It is their experience that little, if any, residue is left two and a half years after harvest.

For each simulation, the WEPS crop submodel was manually (iteratively) calibrated, by adjusting the biomass conversion efficiency (radiation use efficiency) parameter, to match the measured total aboveground residue mass remaining in the field after harvest. Estimates were made of crop height at the time of harvest and cutting height (table 1). WEPS uses these proportionally to divide total residue mass into standing and flat residue mass. For example, if the crop height is 1.0 m and the cutting height is 0.25 m, then 75% of the total mass goes to the flat pool and 25% to the standing pool. The flattening of standing stems by harvest equipment further reduces the standing pool.

The WEPS crop submodel was set up so that the estimated crop height at harvest was achieved in the simulation. To accomplish this, the maximum crop height parameter in WEPS was set equal to the estimated crop height at harvest, and crop growth was simulated without any water stress so that crops would actually reach their maximum height.

Estimates were also made of the effects of operations on residue. These effects include flattening of standing residue (from seeding, spraying, and harvesting operations) and burying of flat residue (from seeding only). The estimates for flattening of standing residue were based on (1) percentage of tire tracking (and packer wheel tracking in the case of seeding) and (2) estimates of the percentage of stalks that spring back after flattening by tires and/or packer wheels. The estimates for burying of flat residue by the John Deere 750 drill were 10% for the legume crops (dry bean, dry pea, and soybean), 7% for spring wheat, 6% for barley, 4% for canola and safflower, 3% for sunflower, and 2% for flax.

Local weather data, needed to drive the WEPS decomposition submodel, were available: precipitation, maximum and minimum air temperature, solar irradiance, and relative humidity. Only precipitation and temperature (fig. 5) influence residue decomposition directly in this

Table 1. Decomposition and stemfall rates, stemfall threshold, mass-to-cover factor (all from WEPS databases), estimated crop height at harvest, and estimated cutting height for the nine crops in this study.

Crop	Decomposition Rate[a] ($kg\ kg^{-1}\ day^{-1}$)	Stemfall Rate[b] ($\#\ \#^{-1}\ day^{-1}$)	Stemfall Threshold (ddays[c])	Mass-to-Cover Factor[d] ($m^2\ kg^{-1}$)	Estimated Crop Height (m)	Estimated Cutting Height (m)
Barley	0.0150	0.18	17.1	6.5	0.85	0.25
Canola	0.0150	0.18	17.1	6.5	1.15	0.20
Bean	0.0200	0.20	20.0	2.7	0.45	0.05
Pea	0.0200	0.20	20.0	2.7	0.60	0.05
Flax	0.0185	0.28	17.1	3.0	0.60	0.18
Safflower	0.0150	0.18	17.1	6.5	0.65	0.30
Soybean	0.0300	0.20	20.0	2.7	0.60	0.05
Sunflower	0.0250	0.15	20.0	2.1	1.20	0.70
Wheat	0.0133	0.12	17.1	6.5	1.00	0.25

[a] k in equations 1 and 2.
[b] k_{stem} in equation 7.
[c] ddays = decomposition days.
[d] b in equation 8.

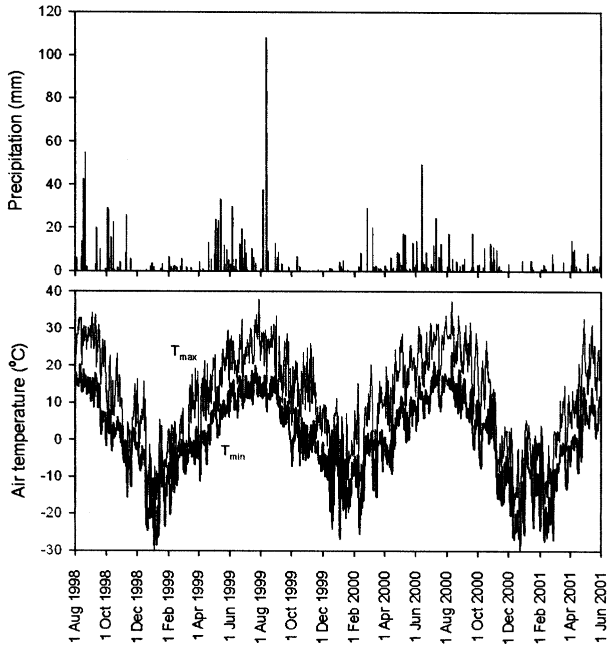

Figure 5. Daily precipitation, maximum air temperature (T_{max}), and minimum air temperature (T_{min}), measured at the Area IV Soil Conservation Districts USDA-ARS Research Farm near Mandan, North Dakota, used to drive the WEPS decomposition model.

model. The inputs of precipitation duration and intensity, required by WEPS, were not available. These influence runoff and infiltration, which may affect surface wetness, which, in turn, affects the decomposition of flat residue. This has a very indirect, minor effect on simulation results. It was verified that large differences in duration and intensity resulted in only very small differences in simulated decomposition. A duration of 3.25 h (average storm duration of neighboring Bismarck, N.D.) was assumed for every storm. Reliable and complete wind speed data were not available either, so the WEPS stochastic wind generator was used with the station of neighboring Bismarck. Wind speed affects evaporation, which affects soil surface wetness, which, in turn, affects decomposition of flat residue. However, not using actual wind speed data has only a minor effect on simulation results. The t-test was used to determine whether measured and simulated residue cover were significantly different at the 5% level ($P < 0.05$).

Results and Discussion

Most precipitation fell during late spring and early summer (fig. 5), consistent with climatology. This, along with warm temperatures, is favorable for residue decomposition. The cold, dry winters essentially stop decomposition.

As examples, simulation results are discussed for a soybean-soybean (fig. 6) and spring wheat - spring wheat (fig. 7) cropping sequence. The soybean simulation started just after harvest of the first crop, late September 1999 (fig. 6). The starting point was the measured total mass of 0.3622 kg m^{-2} (table 2), achieved by iterative, manual calibration of the WEPS crop model. At harvest, WEPS divided the total mass into standing and flat mass. Because of the short cutting height of 0.05 m (table 1) and some flattening of standing stems by harvest equipment, the standing mass was only a small fraction of the total mass (fig. 6).

Simulated residue mass did not decline much over winter (fig. 6), mainly because of cold temperatures (fig. 5). Simulated residue decomposition picked up the following spring with warmer temperatures. The second soybean crop was seeded in May 2000. This operation buried a small fraction of the residue, which explains the abrupt, but slight, decrease in residue mass and cover at this time. The same happened again with the seeding of wheat in April 2001 (fig. 6). At the time of the second soybean harvest in September 2000, there was still some flat residue left from the previous harvest, but no standing residue. The measured residue mass of 0.2245 kg m^{-2} (table 2) was added to the total residue mass. Again, WEPS divided this added mass into standing and flat mass.

Simulated flat residue cover (fig. 6) followed the same pattern as simulated flat residue mass because, every day, cover is calculated from mass using the relationship shown in figure 4. The mean flat residue cover, measured in the beginning of May 2001, was 65% (table 2). The simulated cover on this date was 30% (fig. 6 and table 2), which is a significant ($P < 0.05$) underestimation of the measured cover.

The spring wheat simulation started just after harvest of the first crop, late August 1998 (fig. 7). The starting point was the measured total mass of 0.4778 kg m^{-2} (table 2). Because of the greater cutting height of 0.25 m (table 1), the standing mass for wheat was a larger fraction of the total mass, compared with that for soybean.

Simulated standing stems did not fall until May 1999 when the decomposition day threshold was reached. After this, standing stems fell quickly (fig. 7). This standing mass was transferred to the pool of flat mass, which explains the period of about a month in May and June 1999, in which flat residue mass and cover did not decline much. At the time of the second spring wheat harvest, in late August 1999, there was about 0.1 kg m^{-2} flat residue left from the previous harvest. This amount still provided more than 40% of residue cover (fig. 7).

The mean flat residue cover, measured in April 2000, was 97% (table 2). The simulated cover on this date was 90% (fig. 7 and table 2), which is a significant ($P < 0.05$) underestimation of the measured cover. The simulated cover for the spring wheat - spring wheat cropping sequence was much greater than that for the soybean-soybean cropping sequence, because of (1) greater residue mass to start with, (2) more cover for the same amount of mass (fig. 4), and (3) a lower decomposition rate (fig. 1).

For 33 out of the 50 simulated cropping sequences, the simulated residue cover significantly ($P < 0.05$) underestimated the measured cover (table 2). There were only five cropping sequences (barley-safflower, flax-safflower, pea-sunflower, safflower-safflower, and spring wheat-safflower) for which the simulated cover significantly overestimated the measured cover. They all occurred in 2001, and four of the five involved safflower.

The results in table 2 were summarized by second-year crop, which is the dominant crop determining residue cover the spring after harvest of the second crop (table 3). Sequences with sunflower as the second crop had the lowest measured residue cover (58% on average) and pea the second-lowest cover (60%). Sequences with flax as the

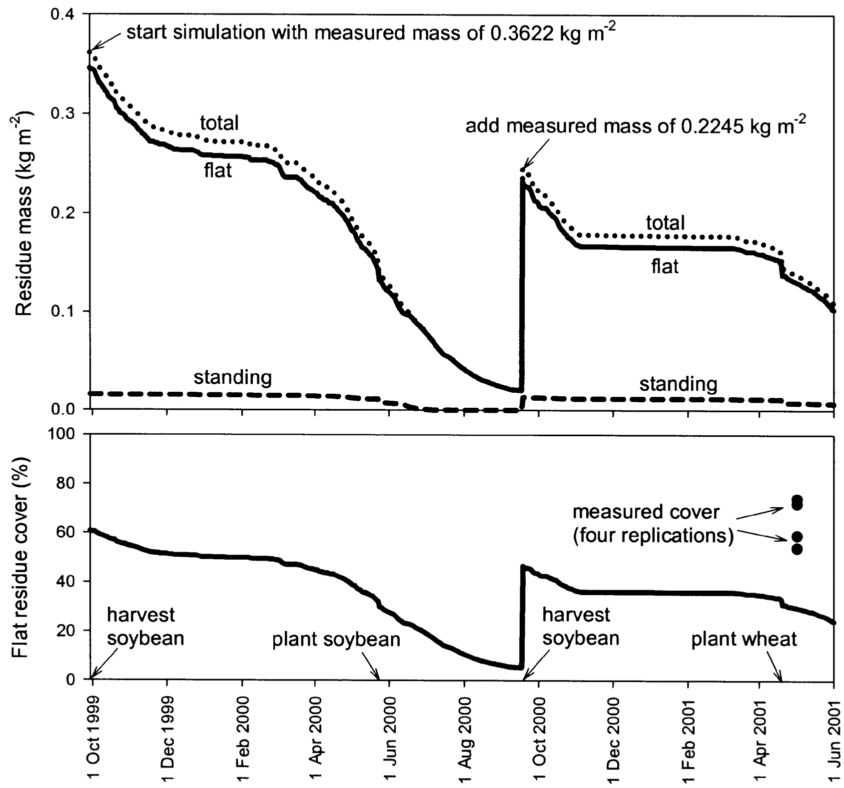

Figure 6. Simulated residue mass and cover for a cropping sequence of two soybean crops. The simulation was started after the first soybean harvest with a measured residue mass of 0.3622 kg m^{-2}. After the second soybean harvest, a measured residue mass of 0.2245 kg m^{-2} was added to the existing residue pool. Measured residue mass is the mean of four replications.

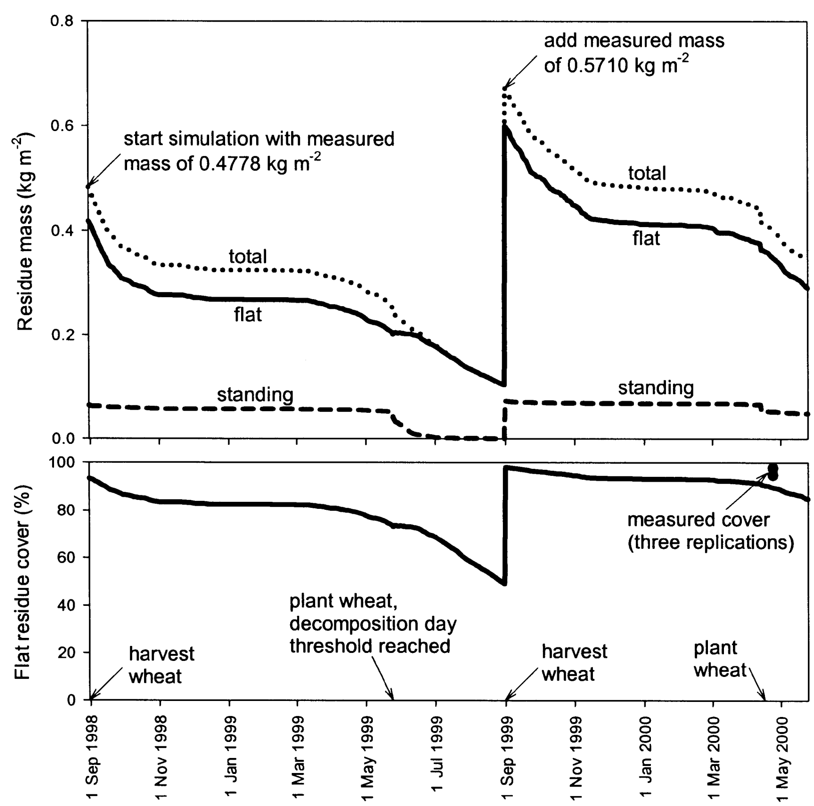

Figure 7. Simulated residue mass and cover for a cropping sequence of two spring wheat crops. The simulation was started after the first wheat harvest with a measured residue mass of 0.4778 kg m^{-2}. After the second wheat harvest, a measured residue mass of 0.5710 kg m^{-2} was added to the existing residue pool. Measured residue mass is the mean of four replications.

Table 2. Residue mass remaining in the field, measured immediately after harvest; and measured and simulated residue cover in the spring after the second harvest. Residue mass at the time of harvest was determined by hand sampling all aboveground biomass (excluding any residue mass from a previous crop) and subtracting the seed yield (four replications; Tanaka et al., 2001). Residue cover measurements were taken in the spring of 2000 (three replications) and 2001 (four replications), after seeding but before crop emergence (Merrill et al., 2006).

		Harvest 1 Mass (kg m^{-2})	Harvest 2 Mass (kg m^{-2})	Measured Cover (%)	Simulated Cover (%)	Diff. (%)	LSD[a] (%)	
Residue cover measured in Spring 2000	Barley-barley	0.3518	0.4204	97	74	-23	1	*
	Barley-bean	0.3518	0.1852	72	38	-34	19	*
	Barley-safflower	0.3518	0.5252	92	86	-6	6	
	Bean-bean	0.1705	0.1340	56	20	-36	45	
	Canola-canola	0.3366	0.3296	86	72	-14	10	*
	Flax-canola	0.3254	0.4062	93	75	-18	9	*
	Flax-flax	0.3254	0.2605	80	36	-44	22	*
	Flax-pea	0.3254	0.2582	69	27	-42	24	*
	Flax-sunflower	0.3254	0.5142	82	49	-33	23	*
	Pea-pea	0.3729	0.3288	43	28	-15	56	
	Pea-sunflower	0.3729	0.5869	48	51	3	5	
	Safflower-safflower	0.5112	0.3975	81	85	4	30	
	Soybean-flax	0.1773	0.5851	93	56	-37	7	*
	Soybean-soybean	0.1773	0.2757	81	31	-50	22	*
	Sunflower-sunflower	0.8486	0.3551	43	43	-0	33	
	Wheat-barley	0.4778	0.3338	97	74	-23	1	*
	Wheat-bean	0.4778	0.1235	92	45	-47	12	*
	Wheat-canola	0.4778	0.3673	95	79	-16	9	*
	Wheat-flax	0.4778	0.4089	97	64	-33	3	*
	Wheat-pea	0.4778	0.3636	62	53	-9	60	
	Wheat-safflower	0.4778	0.4499	97	85	-12	1	*
	Wheat-soybean	0.4778	0.2133	85	51	-34	32	*
	Wheat-sunflower	0.4778	0.4286	87	60	-27	12	*
	Wheat-wheat[b]	**0.4778**	**0.5710**	**97**	**90**	**-7**	4	*
Residue cover measured in Spring 2001	Barley-barley	0.3811	0.3292	85	62	-23	14	*
	Barley-bean	0.3811	0.1975	74	42	-32	18	*
	Barley-safflower	0.3811	0.6294	66	91	25	22	*
	Bean-bean	0.4188	0.2208	46	29	-17	12	*
	Canola-canola	0.4352	0.3469	83	73	-10	4	*
	Flax-bean	0.4031	0.1880	74	29	-45	38	*
	Flax-canola	0.4031	0.4026	87	74	-13	7	*
	Flax-flax	0.4031	0.2904	86	33	-53	7	*
	Flax-pea	0.4031	0.4756	67	42	-25	18	*
	Flax-safflower	0.4031	0.4463	72	81	9	0	*
	Flax-sunflower	0.4031	0.5755	60	57	-3	13	
	Pea-pea	0.6175	0.4750	52	39	-13	15	
	Pea-sunflower	0.6175	0.5449	40	54	14	14	*
	Safflower-safflower	0.5910	0.4460	44	88	44	23	*
	Soybean-flax	0.3622	0.3762	80	35	-45	10	*
	Soybean-soybean[b]	**0.3622**	**0.2245**	**65**	**30**	**-35**	16	*
	Sunflower-sunflower	0.5820	0.4222	35	49	14	14	
	Wheat-barley	0.6321	0.4005	89	76	-13	8	*
	Wheat-bean	0.6321	0.2056	78	57	-21	7	*
	Wheat-canola	0.6321	0.3608	89	77	-12	2	*
	Wheat-flax	0.6321	0.3107	87	57	-30	4	*
	Wheat-pea	0.6321	0.4628	68	62	-6	12	
	Wheat-safflower	0.6321	0.5356	76	90	14	12	*
	Wheat-soybean	0.6321	0.3038	80	61	-19	10	*
	Wheat-sunflower	0.6321	0.5696	66	73	7	20	
	Wheat-wheat	0.6321	0.6039	94	84	-10	3	*

[a] LSD = least significant difference ($P < 0.05$). An asterisk (*) signifies that measured and simulated cover are significantly ($P < 0.05$) different.
[b] Detailed simulation results of the **bolded** cropping sequences (2000 wheat-wheat and 2001 soybean-soybean) are shown in figures 6 and 7.

second crop had the greatest differences (40% on average) between measured and simulated cover, soybean was next (34%), and dry bean was third (33%).

It is difficult to say whether it was the decomposition rate (fig. 1), the conversion from mass to cover (fig. 4), or both, that caused the discrepancies between measured and simulated residue cover. There are a few cropping sequences, however, for which it is clear that the mass-to-cover conversion must have contributed to the differences: for two cropping sequences (soybean-flax and soybean-soybean,

Table 3. Measured and simulated residue cover the spring after the second harvest, summarized by second-year crop.

Second-Year Crop	First-Year Crops	Measured Cover (%) Avg.	Measured Cover (%) Range	Simulated Cover (%) Avg.	Simulated Cover (%) Range	Difference (%) Avg.	Difference (%) Range	Sig.[a]	Total[b]
Barley (BR)	BR, WT	92	85 - 97	72	62 - 76	-21	-23 to -13	4	4
Bean (BN)	BR, BN, FX, WT	70	46 - 92	37	20 - 57	-33	-47 to -17	6	7
Canola (CN)	CN, FX, WT	89	83 - 95	75	72 - 79	-14	-18 to -10	6	6
Flax (FX)	FX, SB, WT	87	80 - 97	47	33 - 64	-40	-53 to -30	6	6
Pea (PE)	FX, PE, WT	60	43 - 69	42	27 - 62	-18	-42 to -6	2	6
Safflower (SF)	BR, FX, SF, WT	75	44 - 97	87	81 - 91	11	-12 to 44	5	7
Soybean (SB)	SB, WT	78	65 - 85	43	30 - 61	-34	-50 to -19	4	4
Sunflower (SN)	PE, FX, SN, WT	58	35 - 87	55	43 - 73	-3	-33 to 14	3	8
Wheat (WT)	WT	96	94 - 97	87	84 - 90	-9	-10 to -7	2	2

[a] Sig. = number of cropping sequences for which measured and simulated cover are significantly ($P < 0.05$) different.
[b] Total = total number of cropping sequences.

cover measured in the spring of 2000), simulated cover was still less than measured cover, even when it was assumed that (1) there was no decomposition at all and (2) all mass was flat mass (data not shown).

Factors other than decomposition rate and conversion from mass to cover may have contributed to the discrepancies between measured and simulated residue cover. These factors include uncertainties in the division at harvest into the standing and flat residue pools, the effect of operations on residue flattening and burying, and the falling rate of standing residue. For example, if the residue does not fall as quickly as WEPS simulates, then it will stay standing longer, and eventually take longer to decompose completely. However, it is our experience that the decomposition rate and the mass-to-cover factor are the two most important factors causing the differences between measured and simulated residue cover.

The WEPS crop and residue decomposition parameters are based on measured field data for only a handful of crops. For the many other crops in WEPS, these parameters have been derived based on similarity arguments. One such crop is flax, which has been added recently to WEPS. Flax experts were consulted in an effort to obtain the best estimates of flax parameter values. One expert indicated that, with respect to residue mass-to-cover ratios, flax is similar to proso millet. The WEPS mass-to-cover factor for proso millet is 3.0 m^2 kg^{-1}. The results of the cropping sequences involving flax in tables 2 and 3 are based on this estimate. Another expert asserted that flax mass-to-cover ratios are similar to those of spring wheat (mass-to-cover factor = 6.5 m^2 kg^{-1}). If we use 6.5 m^2 kg^{-1}, the average simulated cover for sequences with flax as the second crop was 68%, versus 47% with a mass-to-cover factor of 3.0 m^2 kg^{-1}, and the average difference between measured and simulated cover was −19%, versus −40% with a mass-to-cover factor of 3.0 m^2 kg^{-1} (table 3). We cannot simply adjust WEPS parameters so that simulated matches measured residue cover better. Doing so may improve simulations for the north-central U.S., but not necessarily for the rest of the U.S. and beyond. Measured field data on mass-to-cover ratios, residue decay, and stem fall are needed for different climates and for a variety of crops.

Another possible explanation for the differences between measured and simulated cover may be that the WEPS residue decomposition model and parameter values were developed using data from more southern locations, perhaps under lower residue cover levels, associated with higher temperatures. Lower residue levels would result in more contact of flat residue with soil, accelerating decomposition.

WEPS does not model the process of residue migration caused by rain or windstorms. Migration of residue at sub-meter to 1 to 2 m scales is often evident after rainstorms in North Dakota. Residue photos clearly showed evidence of residue patchiness. Pea-pea and pea-sunflower sequences were especially affected by this. The extent of residue migration depends on the number and nature of rainstorms. Residue migration and the resulting patchiness are very difficult to model, but they do affect mass-to-cover ratios and susceptibility to erosion.

WEPS did not predict any stem fall during the winter months for most of the crops (data not shown) because the decomposition day threshold since harvest had not yet been reached. This contradicts observations that storms flatten many residue stalks of crops such as sunflower in North Dakota. Physical forces, such as wind and snow, cause stems to fall over (Steiner et al., 1994).There is a need to enhance the decomposition model with an explicit mechanism that flattens residue stalks in response to the mechanical forces associated with wind- and snowstorms.

The processes described above play out differently among different climates, such as those of the northern and southern U.S., and they are currently not modeled in the WEPS residue decomposition submodel. To account for not modeling these and other processes, a solution would be to develop different, regionalized coefficients for different regions of the U.S. and the world. Another, more permanent, solution would be to expand the model to include these processes, but this is not a trivial task. For either solution, more research data are required.

Summary and Conclusion

WEPS-simulated residue cover significantly under-estimated measured cover for most cropping sequences. Some of the differences may have been because, for many WEPS crops, the residue decomposition parameters are based on similarity arguments, not on measured field data. In addition, the WEPS residue decomposition model and parameter values were developed using data from more southern climates, and that may have contributed to the differences between measured and simulated cover. The underestimation of residue cover may lead to substantial overestimation of wind erosion.

Measured field data are needed for more crops and climates, and more detailed data are needed. For example, simultaneous measurements of residue mass (flat and standing) and residue cover need to be taken at several points in time, so that deviations from model results can be traced back to the decomposition rate, the mass-to-cover conversion, or both. In addition, with such data, it would be possible to determine if differences between measured and simulated decomposition occur primarily in the decomposition of residue of the most recent crop or in the decomposition of residue of the previous crop.

WEPS did not predict any stem fall for most of the crops during winter, which contradicts observations that storms flatten many residue stalks of crops such as sunflower. In addition to stem fall and residue decay by biological means, driven by temperature and moisture, the model needs to explicitly simulate stem fall by mechanical forces, such as wind- and snowstorms, that are important in northern climates. In addition, WEPS does not model the process of residue migration caused by rain or windstorms, although it affects mass-to-cover ratios and susceptibility to erosion.

Other models, such as the Water Erosion Prediction Project (WEPP) and the Revised Universal Soil Loss Equation (RUSLE), include similar submodels for the simulation of residue decomposition and residue cover. Developers and users of these models might be interested in comparing their simulations with the measured data presented here.

References

Englehorn, C. L., A. W. Zingg, and N. P. Woodruff. 1952. The effects of plant residue cover and clod structure on soil losses by wind. *SSSA Proc.* 16(1): 29-33.

Gregory, J. M. 1982. Soil cover prediction with various amounts and types of residue. *Trans. ASAE* 25(5): 1333-1337.

Hagen, L. J. 1991. A wind erosion prediction system to meet user needs. *J. Soil and Water Cons.* 46(2): 106-111.

Hagen, L. J. 1995. WEPS technical documentation: Erosion submodel. In *Proc. WEPP/WEPS Symposium.* Ankeny, Iowa: Soil and Water Conservation Society.

Hagen, L. J. 1996. Crop residue effects on aerodynamic processes and wind erosion. *Theoretical and Applied Climatology* 54(1-2): 39-46.

Krupinsky, J. M., D. L. Tanaka, S. D. Merrill, M. A. Liebig, and J. D. Hanson. 2006. Crop sequence effects of 10 crops in the northern Great Plains. *Agric. Systems* 88(2-3): 227-254.

Merrill, S. D., J. M. Krupinsky, D. L. Tanaka, and R. L. Anderson. 2006. Soil coverage by residue as affected by ten crop species under no-till in the northern Great Plains. *J. Soil and Water Cons.* 61(1): 7-13.

Paul, E. A. and F. E. Clark. 1989. *Soil Microbiology and Biochemistry.* New York, N.Y.: Academic Press.

Schomberg, H. H., and J. L. Steiner. 1997. Estimating crop residue decomposition coefficients using substrate-induced respiration. *Soil Biol. and Biochem.* 29(7): 1089-1097.

Skidmore, E. L. 1983. Wind erosion calculator: Revision of residue table. *J. Soil and Water Cons.* 28(2): 110-112.

Skidmore, E. L., and J. Tatarko. 1990. Stochastic wind simulation for erosion modeling. *Trans. ASAE* 33(6): 1893-1899.

Skidmore, E. L., M. Kumar, and W. E. Larson. 1979. Crop residue management for wind erosion control in the Great Plains. *J. Soil and Water Cons.* 34(2): 90-96.

Steiner, J. L., H. H. Schomberg, C. L. Douglas, Jr., and A. L. Black. 1994. Standing stem persistence in no-tillage small-grain fields. *Agronomy J.* 86(1): 76-81.

Steiner, J. L., H. H. Schomberg, and P. W. Unger. 1995. WEPS technical documentation: Residue decomposition submodel. In *Proc. WEPP/WEPS Symposium.* Ankeny, Iowa: Soil and Water Conservation Society.

Steiner, J. L., H. H. Schomberg, P. W. Unger, and J. Cresap. 1999. Crop residue decomposition in no-tillage small-grain fields. *SSSA J.* 63(6): 1817-1824.

Steiner, J. L., H. H. Schomberg, P. W. Unger, and J. Cresap. 2000. Biomass and residue cover relationships of fresh and decomposing small grain residue. *SSSA J.* 64(6): 2109-2114.

Stroo, H. F., K. L. Bristow, L. F. Elliott, R. I. Papendick, and G. S. Campbell. 1989. Predicting rates of wheat residue decomposition. *SSSA J.* 53(1): 91-99.

Tanaka, D. L., J. M. Krupinsky, S. D. Merrill, R. E. Ries, M. A. Liebig, and J. R. Hendrickson. 2001. Dynamic cropping systems: Crop production and crop sequence. In *Annual Meeting Abstracts*, CD-ROM. Madison, Wisc.: SSSA, CSSA, ASA.

Taylor, S. E., and O. J. Sexton. 1972. Some implications of leaf tearing in musacea. *Ecology* 53(1): 143-149.

USDA. 1995. WEPS technical documentation. In *Proc. WEPP/WEPS Symposium.* Ankeny, Iowa: Soil and Water Conservation Society.

van Donk, S. J., L. E. Wagner, E. L. Skidmore, and J. Tatarko. 2005. Comparison of the Weibull model with measured wind speed distributions for stochastic wind generation. *Trans. ASAE* 48(2): 503-510.

Wagner, L. E. 2001. WEPS 1.0: What it is and what it isn't. In *Proc. Intl. Symp. and Exhibition: Soil Erosion Research for the 21st Century*, 372-375. J. C. Ascough II and D. C. Flanagan, eds. St. Joseph, Mich.: ASAE.