2018

Crop residue harvest impacts wind erodibility and simulated soil loss in the Central Great Plains

Yuxin He
Sichuan University

Deann R. Presley
Kansas State University

John Tatarko
USDA, Agricultural Research Service

Humberto Blanco-Canqui
University of Nebraska - Lincoln, hblanco2@unl.edu

GLOBAL CHANGE BIOLOGY
BIOENERGY

GCB Bioenergy (2018) **10**, 213–226, doi: 10.1111/gcbb.12483

Crop residue harvest impacts wind erodibility and simulated soil loss in the Central Great Plains

YUXIN HE[1,2], DEANN R. PRESLEY[3], JOHN TATARKO[4] and HUMBERTO BLANCO-CANQUI[5]

[1]*State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, China,* [2]*Department of Drainage and Irrigation Engineering, Sichuan University, Chengdu, China,* [3]*Department of Agronomy, Kansas State University, Manhattan, KS, USA,* [4]*USDA-ARS Rangeland Resources and Systems Research Unit, Fort Collins, CO, USA,* [5]*Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE, USA*

Abstract

Crop residue removal can affect the susceptibility to soil wind erosion in climates such as those of the Central Great Plains, United States. Six on-farm trials were conducted in Kansas from 2011 to 2013 to determine the effects of winter wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), and grain sorghum (*Sorghum bicolor* (L.) Moench), residue removal at 0, 25, 50, 75, and 100% of initial height on soil wind erosion parameters. Those parameters include soil surface random roughness (RR), and wind erodible fraction (EF; aggregates <0.84 mm), geometric mean diameter (GMD) and geometric standard deviation (GSD), stability of dry aggregates (DAS). Complete (100%) residue removal decreased the surface RR, increased EF, and decreased GMD. Overwinter EF values increased for five of six sites from fall 2011 to spring of 2012, particularly for the uppermost removal height (≥75%). Measured EF, GMD, GSD, DAS, and RR were also input into the Single-event Wind Erosion Evaluation Program (SWEEP) to determine the effect of these parameters on simulated soil loss. The SWEEP simulated the wind velocity needed to initiate wind erosion as well as soil loss under each residue removal height at a wind velocity of 13 m s^{-1} for three hours. Threshold wind velocity required to initiate wind erosion generally decreased with increasing crop residue removal height, particularly for >75% removal. Total estimated soil loss over the three-hour event ranged from ≈2 to 25 Mg ha^{-1}, depending on EF, GMD, GSD, RR, and percent crop residue cover. Removing 75% residue increased simulated wind erosion at three of six sites while removing 50% appears sustainable at all six study sites. Findings reinforce the need for site-by-site consideration of the potential amount of crop residue that may be harvested while mitigating wind erosion. Study results indicate the value of maintaining residue at >75% of original height.

Keywords: bioenergy, crop residue removal, erodible fraction, soil wind erosion, threshold velocity, winter wheat

Received 28 July 2017; revised version received 25 September 2017 and accepted 27 September 2017

Introduction

Large-scale crop residue removal for bioenergy production is predicted in the near future due to the concerns of rising energy costs, dwindling crude oil supplies, increasing energy demand from developing economies, and increasing levels of greenhouse gas emissions from fossil fuel combustion (Blanco-Canqui & Lal, 2009a; Lal, 2009). Corn, sorghum, and wheat residues are the primary feedstocks for first-generation bioenergy production in the United States because of their perceived abundance (Perlack *et al*., 2005; Sarath *et al*., 2008; Blanco-Canqui & Lal, 2009b). However, the amount of residue available for removal and resulting impacts on soil and environmental quality, especially on soil wind erodibility, have not been widely documented in the Central Great Plains, where wind erosion is of major concern (Evers *et al*., 2013). In this region, weather fluctuations in spring can result in strong wind events while the soil weathering processes (wet and dry, freeze and thaw, freeze and dry) can reduce soil aggregate stability and thus aggregate size during early winter to spring (Tatarko, 2001), exacerbating wind erosion. Some of the worst dust storms in US history occurred in the Great Plains in the 1930s (Colacicco *et al*., 1989). Thus, judicious management of crop residues is critical to control wind erosion.

Crop residues, particularly standing residues, can reduce near surface wind speed. Residues can also reduce soil erodibility by adding soil organic matter and increasing soil aggregate size and stability (Lyles &

[Affiliation of the author Yuxin He is corrected on 18th December 2017, after first online publication].

Correspondence: John Tatarko, tel. 970 492 7320, fax 970 492 7310, e-mail: john.tatarko@ars.suda.gov

Allison, 1981; Rhoton *et al.*, 2002; Lal, 2004; Wilhelm *et al.*, 2007; Blanco-Canqui, 2010). Residue serves to absorb wind energy and therefore buffers against wind forces. Thus, removal of residue can lead to increased wind erosion potential (Lyles & Allison, 1981; Lal, 2009). The effectiveness of crop residue cover on wind erosion control depends on the amount and duration of soil surface vegetative cover.

The role of crop residues in protecting soil from erosion has long been recognized (Lal, 1982; Mengel *et al.*, 1982; Arshad *et al.*, 1999; Wuest *et al.*, 2005), but the quantity of residue that is required to control wind erosion and maintain soil productivity for different ecoregions is not well documented (Wilhelm *et al.*, 2007; Blanco-Canqui & Lal, 2009a). Some previous studies suggested that 50 to 75% of the total residue production in the Corn Belt might be available for removal (Kim & Dale, 2004; Nelson *et al.*, 2004; Graham *et al.*, 2007). To establish definitive permissible levels of crop residue removal while maintaining wind erosion control, more experimental data are needed for different soil types, cropping systems, and climatic conditions. Experimental data are also needed as inputs to wind erosion models to accurately predict potential erosion loss or control under various levels of removal.

The Single-event Wind Erosion Evaluation Program (SWEEP), which is the erosion submodel of the Wind Erosion Prediction System (WEPS) model, can be used for modeling wind erosion potential. The WEPS model is a process-based model designed to simulate wind erosion soil loss on cultivated agricultural lands (Wagner, 2013). The SWEEP model was developed for single-day storm events under user-supplied surface conditions. It can estimate total soil loss and the threshold wind velocity required to initiate erosion for different crop residue removal rates, and thus, it could be used to estimate the permissible residue removal levels for different soil conditions. Measured field surface parameters (e.g., aggregate size distribution and stability, RR, and vegetation) are user inputs and wind speeds (15 min to 1 h average) are applied to SWEEP to simulate results (Hagen *et al.*, 1999). The SWEEP model has been used to estimate soil loss and the threshold friction velocity from cultivated fields (Feng & Sharratt, 2009; Jia *et al.*, 2014) as well as under residue removal by grazing and baling (Blanco-Canqui *et al.*, 2016). The SWEEP model as well as a User Manual that provides more information is available as part of the WEPS model download at https://www.ars.usda.gov/research/software/download/?softwareid=415).

The WEPS and SWEEP models have undergone extensive field and wind tunnel testing and validation. A number of studies reported a satisfactory agreement (i.e., R^2 = 0.87–0.98) between measured and WEPS simulated erosion (Funk *et al.*, 2004; Buschiazzo & Zobeck, 2008; Liu *et al.*, 2014). Hagen (2004) found 'reasonable agreement' (R^2 = 0.71) between measured and WEPS simulated erosion values for 46 wind storm events in six states. Similarly, Pi *et al.* (2016) validated SWEEP in a desert–oasis ecotone in China and reported that SWEEP provided adequate estimates of wind erosion.

Land use models paired with alternative future climate scenarios predict that portions of the US Great Plains would shift from grain production to a land use for dedicated bioenergy using perennials that markedly increase soil cover and reduce soil erosion (Khanal *et al.*, 2013); however, this shift will occur over several decades, and therefore, crop residues will likely be used in until larger areas of land are planted to perennials. Research that pairs experimental field measurements and computer modeling data on soil wind erosion after crop residue removal are limited, particularly for on-farm conditions. An assessment of soil wind erosion is essential to establish the threshold of residue removal levels in the Central Great Plains. Therefore, the main objectives of this research were to use six, on-farm study sites representative of soils and cropping systems in the US Great Plains to (1) measure the effects of corn, wheat, and sorghum residue removal from typical no-till (NT) crop rotations on soil wind erodibility parameters under dryland conditions in western Kansas; (2) simulate wind erosion under different residue treatments and resulting surface conditions using the SWEEP model; and from these data, (3) determine the threshold levels of residue removal based on soil wind erodibility.

Materials and methods

Description of study sites and treatments

This study was conducted for three years on six producers' fields established in summer 2011 in western Kansas, United States. The six on-farm experimental sites were at La Crosse, Rush Center, Colby, Norcatur, Garden City, and Scott City, KS. Geographic coordinates, elevation, and soil properties for each site are reported in Table 1.

Annual precipitation amounts for each study year (i.e., 2011, 2012, and 2013) as well as the average normal precipitation for 1981–2010 are provided in Table 2. Note that all study years were drier that the annual average except for 2011 at Norcatur which was 42 mm greater than average and 2013 at Scott City which was only 1 mm greater than average. Precipitation for 2012 was noticeably lower for the other study years at all locations and was 25% lower than average at Rush Center to 45% lower than average at La Crosse and Scott City.

Cropping systems, cropping intensity (the number of crops planted per year in a given field), and length of time the field had been under no-till management were defined by the producers and thus differed from site to site (Table 3).

Table 1 Baseline site and soil information for the 0–5 cm soil depth at each site

Experimental site	Coordinates	Elevation (m)	Soil series	Soil organic carbon (%)	Sand (%)	Silt (%)	Clay (%)
La Crosse	38°33′N, 99°23′W	627	Harney silt loam	3.21	24	62	14
Rush Center	38°29′N, 99°10′W	599	Bridgeport silt loam	3.26	22	60	18
Colby	39°15′N, 101°12′W	963	Richfield silt loam	3.96	28	56	16
Norcatur	39°47′N, 100°10W	806	Ulysses silt loam	3.76	28	56	16
Garden City	38°04′N, 100°45′W	865	Ulysses silt loam	2.07	28	52	20
Scott City	38°27′N, 101°00′W	908	Richfield silt loam	1.35	24	58	18

All sites slopes are <1%, surface soil textures are silt loam according to USDA classification, and the sand fraction is dominated by very fine (0.05–0.1 mm) and fine (0.25–0.1 mm) sand.

Table 2 Annual total precipitation (mm) values recorded at the nearest Kansas Mesonet weather station

	Annual precipitation			Average
	2011	2012	2013	1981–2010
Site	(mm)			
La Crosse	609	395	509	657
Rush Center	500	468	542	623
Colby	516	294	377	525
Norcatur	578	349	384	536
Garden City	308	308	442	486
Scott City	443	281	513	512

Data source: Kansas Mesonet (2017). Available at: http://mesonet.k-state.edu/.

The experimental design was a randomized complete block with five treatments and four replications. The treatments consisted of removing crop residue at five heights after harvest (0, 25, 50, 75, and 100% of the initial height). At the start of the experiment in summer 2011, the six farmer's fields were under wheat stubble following wheat harvest in 2011. A forage harvester was used to cut wheat stubble at the 25, 50, 75, and 100% removal heights. The 100% removal plots were established by cutting stubble to the soil surface to portray complete removal. According to the distance between the soil and the forage cutter blade for each treatment, 0.0, 0.075, 0.15, 0.225, and 0.3 m height was removed during cutting with wheat straw residue average heights corresponding to 100, 75, 50, 25, and 0% residue removal heights at each site. In the second year and third year, corn and sorghum were grown at some of the sites (Table 3); therefore, 0.0, 0.15, 0.3, 0.45, and 0.6 m were used as sorghum stalk residue heights; and 0.0, 0.125, 0.25, 0.375, and 0.5 m were for corn stalk heights. The dimension of the individual plots was 9.1 × 9.1 m, and a 9.1-m-wide alleyway was also established between blocks at each site.

Soil sampling

Soils were sampled during fall 2011, spring 2012, fall 2012, and spring 2013 at each site. At the start of the experiment, soils

Table 3 Sampling time and cropping history for each site

Experimental site	Fall 2011	Spring 2012	Fall 2012	Spring 2013	Cropping system (spring 2011–spring 2013)	Cropping intensity	Years no-till
La Crosse	2011 Wheat stubble	Growing wheat	2012 Sorghum	2012 Sorghum	W-W-S	1.5	11
Rush Center	2011 Wheat stubble	Growing wheat	2012 Wheat stubble	2012 Wheat stubble	W-W	1	8
Colby	2011 Wheat stubble	2011 Wheat stubble	2012 Corn stubble	2012 Corn stubble	W-C	1	15
Norcatur	2011 Wheat stubble	2011 Wheat stubble	2012 Corn stubble	2012 Corn stubble	W-C	1	20
Garden City	2011 Wheat stubble	2011 Wheat stubble	2011 Wheat stubble	Growing wheat	W-F	0.5	5
Scott City	2011 Wheat stubble	2011 Wheat stubble	2012 Sorghum stubble	2012 Sorghum stubble	W-S	1	17

The residue or crop present at each sampling time is noted. Fall 2011 collected in October; spring 2012 collected in March; fall 2012 collected in October; spring 2013 for Colby, Norcatur, Garden City, and Scott City were sampled in March, while La Crosse and Rush Center were collected in May. Cropping intensity refers to the number of crops harvested between June 2011 and May 2013, divided by three, to equal the number of crops harvested in the three-year study period. W, wheat; C, corn; S, sorghum; F, fallow.

were sampled from the 0 to 5 cm depth from each plot to determine soil texture by the pipette method (Gee & Bauder, 1986) and soil organic carbon (C) by the LECO TruSpecCN analyzer (LECO Corp., St. Joseph, MI, USA), and the samples were pretreated with acid to remove inorganic C.

To measure the effect of crop residue removal on wind erosion potential, soil properties affecting soil wind erodibility including aggregate size distribution parameters, DAS, and soil surface RR were evaluated in fall and spring during the experiment along with the type of crop residue present in the field at the time of sampling (Table 3).

Soil aggregate size distribution

Soil samples for aggregate size distribution were collected in October 2011, March 2012, and October 2012 from all six sites. In spring 2013, soil was sampled in March at the Colby, Norcatur, Garden City, and Scott City sites; and in early May at La Crosse and Rush Center. Approximately 3 kg of soil from the 0 to 5 cm depth was sampled from each plot using a flat-bottom shovel according to Lyles *et al.* (1970). Samples were oven-dried at 60 °C for three days prior to sieving. A rotary sieve apparatus (Chepil, 1962; Lyles *et al.*, 1970) was used to separate aggregates into size classes and associated mass fractions determined for size classes of: <0.42, 0.42–0.84, 0.84–2.0, 2.0–6.35, 6.35–14.05, 14.05–44.45, and >44.45 mm in diameter. Wind erodible fraction (EF), geometric mean diameter (GMD), and geometric standard deviation (GSD) were calculated. The EF is the percentage of aggregates <0.84 mm in diameter (Chepil & Woodruff, 1963) and is calculated as

$$\mathrm{EF} = \frac{M_a}{M_t} \times 100$$

where M_a is the weight (g) of aggregates with diameter <0.84 mm, and M_t is the total weight (g) of all size fractions.

The GMD is a measure of the aggregate size diameter at which 50% of soil sample mass is larger than and 50% of it is smaller and GSD describes the distribution of soil aggregate size about the mean. The GMD and GSD were calculated as (Wagner & Ding, 1994)

$$\mathrm{GMD} = \exp\left[\sum_{i=1}^{n} m_i \ln d_i\right]$$

$$\mathrm{GSD} = \exp\left[\sum_{i=1}^{n} m_i (\ln d_i)^2 - (\ln \mathrm{GMD})^2\right]^{0.5}$$

where m_i represents the mass of soil aggregates (g) retained on a given sieve size, and d_i represents the mean diameter (mm) of each of the seven size fractions. The GMD and GSD are inputs into the SWEEP model and are used to recreate the aggregate size distribution and EF.

Dry aggregate stability (DAS)

When aggregate size distribution samples were collected, samples were also collected from the 0–5 cm depth for DAS. Aggregate samples were prescreened in the field to exceed a 12.7 mm minimum diameter then air-dried in a greenhouse ~25 °C for seven days. A soil aggregate crushing energy meter (SACEM) was used to measure the energy required to crush 30 individual aggregates, ~5 g each (i.e., 1200 aggregates with mean weight of 4.92 ± 1.39 g) according to Boyd *et al.* (1983). The SACEM is comprised of two parallel plates supported by a load cell, which is connected to a computer to measure force and energy as the plates crush each aggregate. DAS is reported as the natural logarithm of the crushing energy per unit mass ($\ln(\mathrm{J\ kg^{-1}})$) (Hagen *et al.*, 1992).

Surface random roughness (RR)

Surface RR was also measured at the time of soil sampling and is defined as the micro-elevation differences in the soil surface as a result of aggregates or other soil disturbances that are not oriented as the result of tillage (i.e., ridges). A microrelief pin meter as described by Wagner & Yu (1991) was used to measure RR of each plot along the ridge tops for all site years except for La Crosse and Rush Center in spring, 2012 due to the presence of a wheat crop growing in those fields. The pin meter used consists of 101 pins (1 cm apart, 50 cm in length, and 6 mm in diameter), and the pins are lowered to the soil surface so that the pin tops replicate the soil surface elevations. Any residues present were carefully removed to not disturb the soil surface so that the pins only touched the actual soil surface. A digital image of the tops of the pins was captured in each plot by digital camera which was analyzed using SIGMA SCAN PRO 5 (SPSS Science, 1998) image analysis software to obtain soil elevation of each pin. Roughness was calculated as the standard deviation of the pin heights after correction for slope trend (Allmaras *et al.*, 1966; Wagner & Yu, 1991; van Donk & Skidmore, 2003).

SWEEP modeling

The SWEEP model (version 1.3.9) simulated wind erosion from an 805 × 805 m square field with no wind barriers for the five residue removal heights at each of the six sites using the field-measured soil parameters that affect wind erosion. An 805× 805 m field is equivalent to a one-fourth section of land area, a fairly common size for the region. Measured data, including biomass, GMD, GSD, DAS, RR, residue height, and residue characteristics, were used as input parameters for the model. The soil surface conditions simulated represent those conditions at the time of soil sampling. The other parameters were calculated according to the estimation equations in the SWEEP model (see SWEEP User Manual available as part of the WEPS model download at https://www.ars.usda.gov/research/software/download/?softwareid=415). Residue stem area index was calculated by SWEEP from stem diameter, stem height, and stem population. In this study, we used 3, 30, and 60 mm as wheat, sorghum, and corn residue diameters. We also used the WEPS default database stem populations for wheat straw, sorghum stubble, and corn stalks which were 500.0, 24.71, and 7.41 plants $\mathrm{m^{-2}}$, respectively. Residue leaf area index was assumed to be zero under all treatments at all sites because the leaf parts of plant were removed during harvest. Residue flat cover parameters were estimated by comparing field plots with photographs of known cover. Cover values of 0.0, 0.3, 0.5, 0.6, and 0.7 $m^2\ m^{-2}$ corresponded to 100, 75, 50, 25, and 0% residue removal heights. Growing crop parameters were all assumed to be zero in SWEEP simulations to represent scenarios without growing crops at all sites. We imported soil information (e.g., sand, silt, clay, organic matter) from the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) Soil Data Mart (http://sdmdataaccess.nrcs.usda.gov) for the soil series at each site. Then, field-measured parameters of GMD, GSD, and RR replaced the database-generated values. To estimate air density at sampling time, elevation and daily average temperature for the sampling month were applied. All simulations of soil loss were conducted to determine mass of soil loss (Mg $ha^{-1}\ h^{-1}$) for a single windstorm event with a wind velocity of 13 m s^{-1} for a duration of 3 h. The relatively high wind velocity of 13 m s^{-1} was chosen so that relative differences in wind erosion could be observed. Using a lower wind speed at some sites would have shown little or no erosion loss and thus no observable differences in erosion. In addition, threshold wind velocity (i.e., the wind velocity at which soil erosion initiates) and percent of days that greater than threshold wind velocities can be expected in the sampling month were simulated by the SWEEP model using the model database historical wind parameters at each site.

Statistical analysis

All data were statistically analyzed using Mixed Procedure in SAS version 9.3 (SAS Institute, 2011, Cary, NC, USA). Crop residue removal height was the fixed effect and replication the random effect. Least square mean separation for each treatment during the sampling period was at the $P = 0.05$ significance level (SAS Institute, 2011). Treatments were compared by site each year, and were not compared across sites because soil, precipitation input, crop rotation, and length of time under no-till management varied among the six sites.

Results

All sites have a silt loam soil texture at the surface with sand values ranging from 22 to 28% and clay contents 14 to 20% (Table 1). The sand fraction was dominated by fine and very fine sand (data not shown). Soil organic content (SOC) values ranged from 1.35 to 3.96% and with no clear relationship between the SOC and the length of time in no-till. Each field has been managed by different landowners, and no information is available regarding the SOC prior to when the fields were converted from tillage to no-till. In addition, the objective of this experiment was not to measure such changes in SOC, but rather, the SOC values are given here to characterize the sites.

Wind erodible fraction (EF)

The EF generally increased with increasing height of residue removal (Fig. 1); however, the main difference was between the 100 and 0% removal heights. On average, EF increased by 20 to 40% with complete residue removed compared to zero removal at five of the six sites (except La Crosse). The Colby and Garden City sites had the largest EF values of all the study sites, suggesting that these sites and soils are more sensitive to wind erosion. This may be partially explained by management and environmental factors, in that Garden City had the lowest cropping intensity (Table 3), the least number of years in NT, and the second lowest SOC and highest sand content, and lowest average annual precipitation in both 2011 and 2012. Colby is among the sites that have been no-tilled the longest and has the highest surface SOC and sand content of all sites. This site had a very large EF in spring 2012 at a time when the drought of 2011–2012 was beginning to deepen (NOAA, 2013). For the other four sites (La Crosse, Rush Center, Norcatur, and Scott City), the largest difference was between the 100% removal and the 0% removal. Norcatur had the lowest overall EF in the study, which was the site that had been under NT management the longest, had the second highest SOC, and among the sites with a cropping intensity of one crop per year.

Geometric mean diameter (GMD)

Crop residue removal negatively affected soil GMD in at least half of the sampling periods per site (Fig. 2). Generally, GMD decreased with increasing residue removal height, and when comparing 100% removal with 0% removal, 23 of 24 sampling periods across all sites showed a decrease in GMD. To display the data in detail, there are two different *y*-axis scales in Fig. 2. The y-axes of the La Crosse, Rush Center, and Norcatur sites range from 0 to 20 mm, which was chosen because the La Crosse site generally had larger GMD values, and the Rush Center and Norcatur sites each had one sampling period with generally larger GMD values. The Colby, Garden City, and Scott City sites had relatively smaller GMD values, ranging from 0 to 4 mm. Thus, a 0- to 5-mm *y*-axis was used. In November 2011 (only four months after the study was initiated), statistical differences were measured at four of six sites. By spring (March) 2012, significant impacts on GMD due to treatment were observed at all six sites. No removal and 100% removal differed at La Crosse, Rush Center, and Norcatur in fall 2012 unlike at other sites. In spring 2013, treatment differences for GMD at La Crosse, Rush Center, and Scott City were significant.

Geometric standard deviation (GSD)

The GSD is a measure of the distribution around the GMD value with higher values indicating a wider

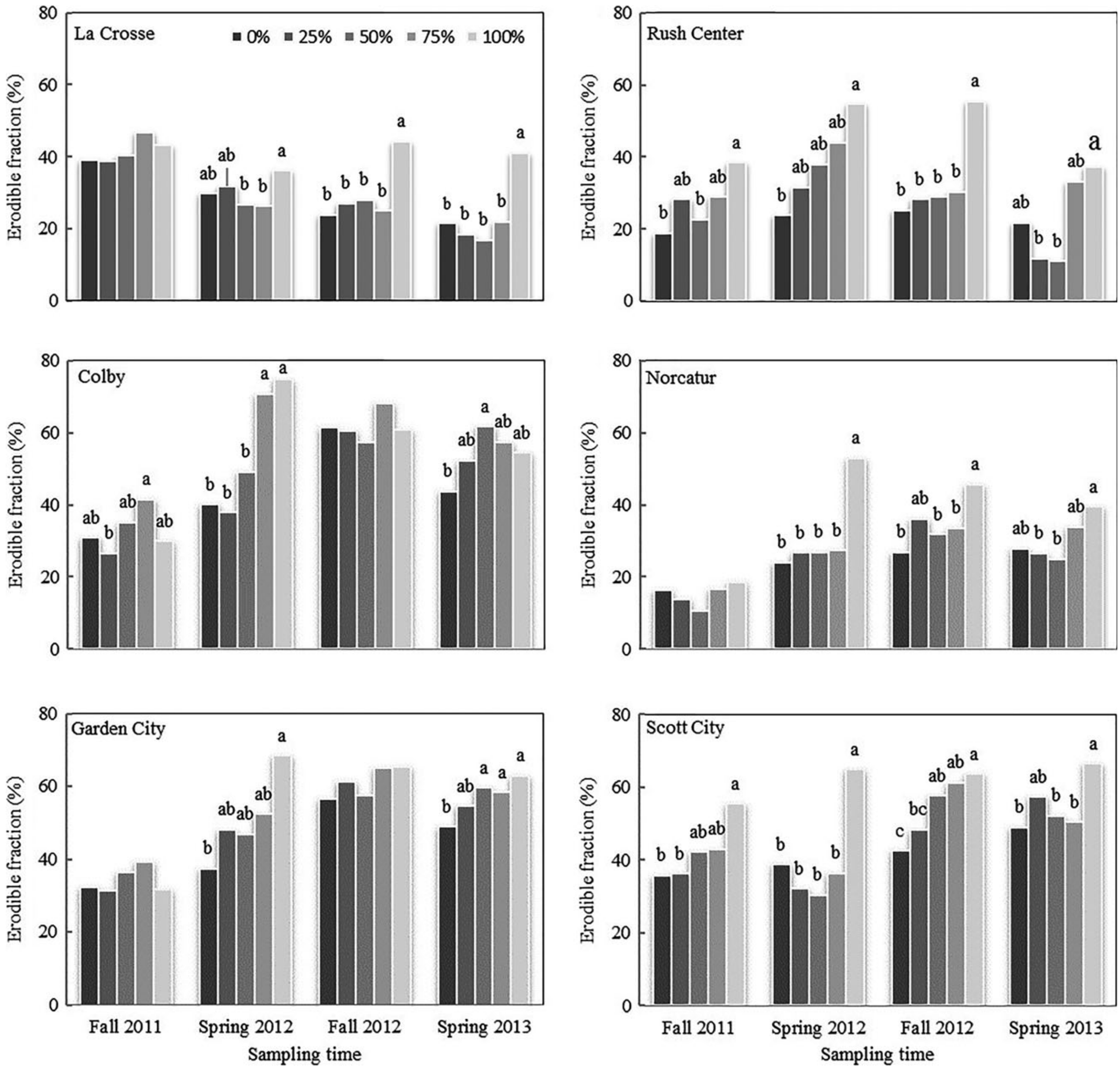

Fig. 1 Wind erodible fraction (EF) (% <0.84 mm dry aggregates) at all six sites. Treatments with different letters indicate significant differences at the $P = 0.05$ level within the same sampling time. The absence of letters indicates no significant differences among treatments for that sampling time.

distribution. Values for GSD ranged from 8 to 17 mm for this study and were similar to ranges reported in other studies (van Donk & Skidmore, 2003; Blanco-Canqui *et al.*, 2016). A majority of the results for GSD were not significant and therefore not presented here. However, GSD was used in SWEEP to calculate EF and soil loss.

Dry aggregate stability (DAS)

Similar to GSD, this study found that a majority of the results for DAS were not significant and therefore not presented. These results were similar to Evers *et al.* (2013) who found inconsistent treatment effects on DAS. DAS was also used in SWEEP simulations in the current study.

Surface random roughness (RR)

RR generally decreased with increasing residue removal (Fig. 3). Treatment affected RR for all four sampling periods at the Scott City site, where 100% removal reduced RR compared to the other treatments.

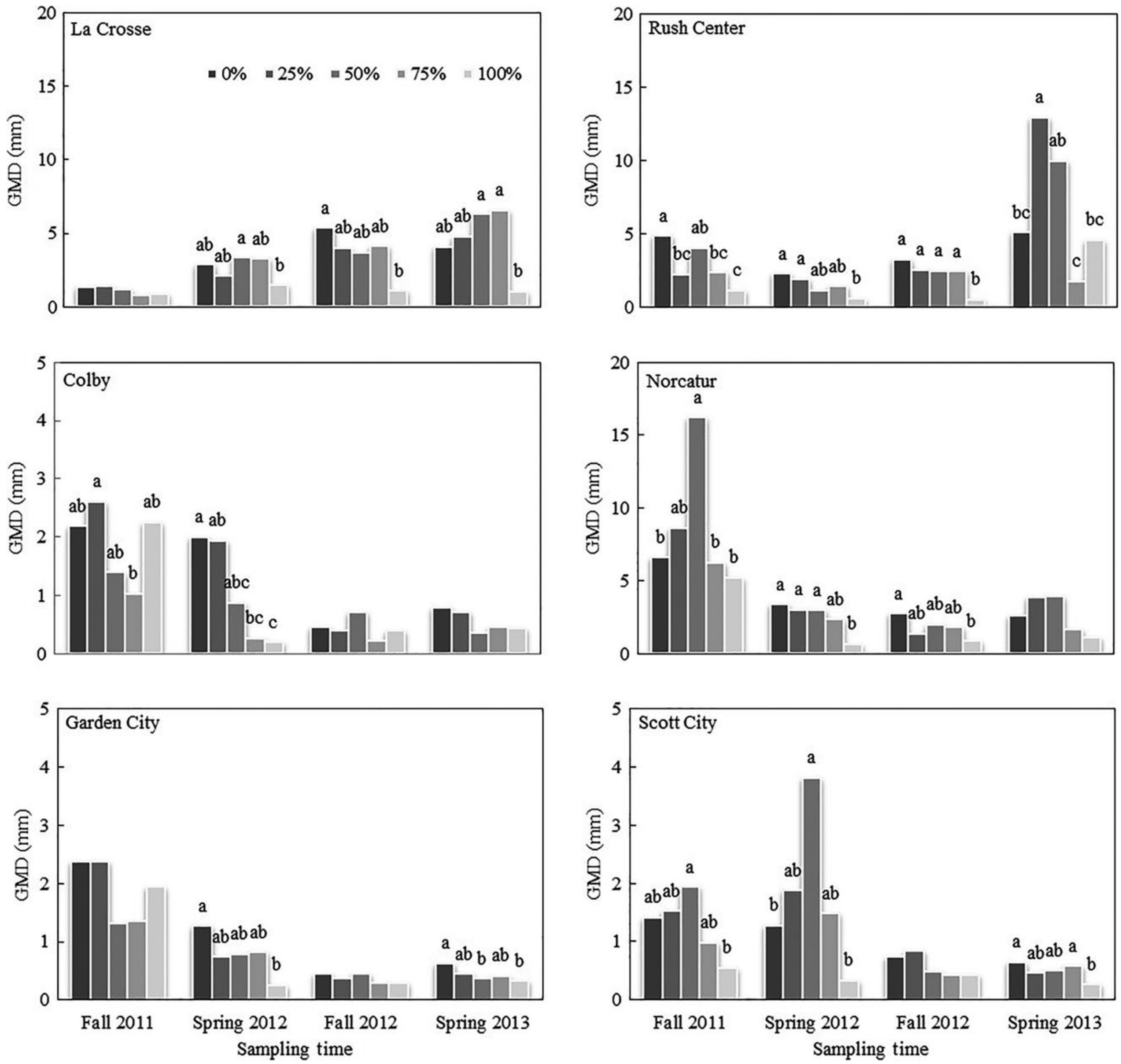

Fig. 2 Geometric mean diameter (GMD) of dry aggregates at all six sites. Treatments with different letters indicate significant differences at the $P = 0.05$ level within the same sampling time. The absence of letters indicates no significant differences.

Compared to the 100% removal, the 0% removal was nearly twice as rough for all sampling periods. Norcatur and Garden City had treatment differences for three of four sampling periods, and the roughness was reduced as the height removed increased. The Colby site had treatment differences for the first two sampling periods, and the 75 and 100% removal height RR values were nearly one half of those for 0, 25, and 50% removal. For the Colby spring 2012 sampling, the 75 and 100% removal treatments averaged 3 mm in roughness, as compared to about 8 mm for the 0, 25, and 50% removal heights, which corresponds with the occurrence of greatest EF for the 75 and 100% removal treatments (Fig. 1). This seems to indicate that the Colby site had instances where 75 and 100% removal heights were significantly more sensitive to erosion than the 0, 25, and 50% removal heights. The roughness was measured three times at La Crosse and Rush Center, as winter wheat was growing there in spring 2012 and the roughness was not measured for that time period. There were no significant treatment differences for La Crosse, but there was one instance of a treatment difference at Rush Center, where the 100% removal height was smoother than the 0, 25, and 50% removal heights. Treatment

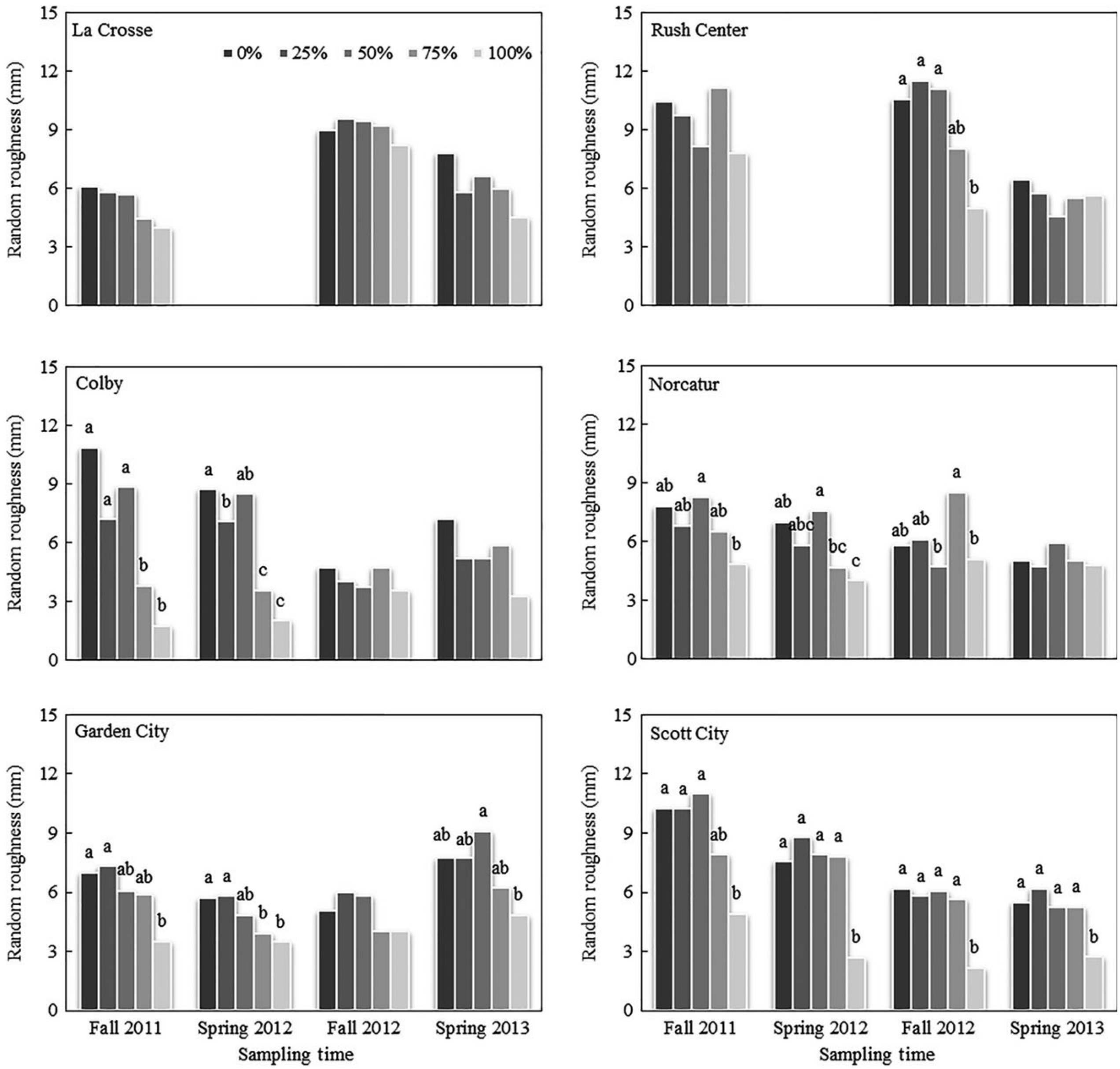

Fig. 3 Surface random roughness at all six sites. Treatments with different letters indicate significant differences at the $P = 0.05$ level within the same sampling time. The absence of letters indicates no significant differences among treatments for that sampling time.

differences for spring 2013 were only observed at Garden City and Scott City, where 50 and 100% removal were significant at Garden City and 100% was significantly different from all treatments at Scott City.

SWEEP: threshold velocity and probability of wind speed ≥ threshold velocity

The measured physical parameters were input to the SWEEP model. The simulated threshold velocity (V_t) required to initiate wind erosion decreased as more residue was removed from each site (Fig. 4); that is, slower wind speeds could initiate wind erosion when more residue is removed. For example, wind speeds of 17 to 21 m s^{-1} were required to initiate wind erosion for any of the 0% removal treatments, while only 6 to 10 m s^{-1} wind speeds are needed to initiate wind erosion on the 100% removal plots. Threshold velocities under 100% removal at each site were significantly less than the 75% removal treatments during every sampling period for all sites.

The probabilities of wind speed exceeding the wind erosion V_t (Fig. 4) are reported in Table 4 which can be used to determine the likelihood of a wind erosion event occurring. For example, SWEEP calculated a V_t of

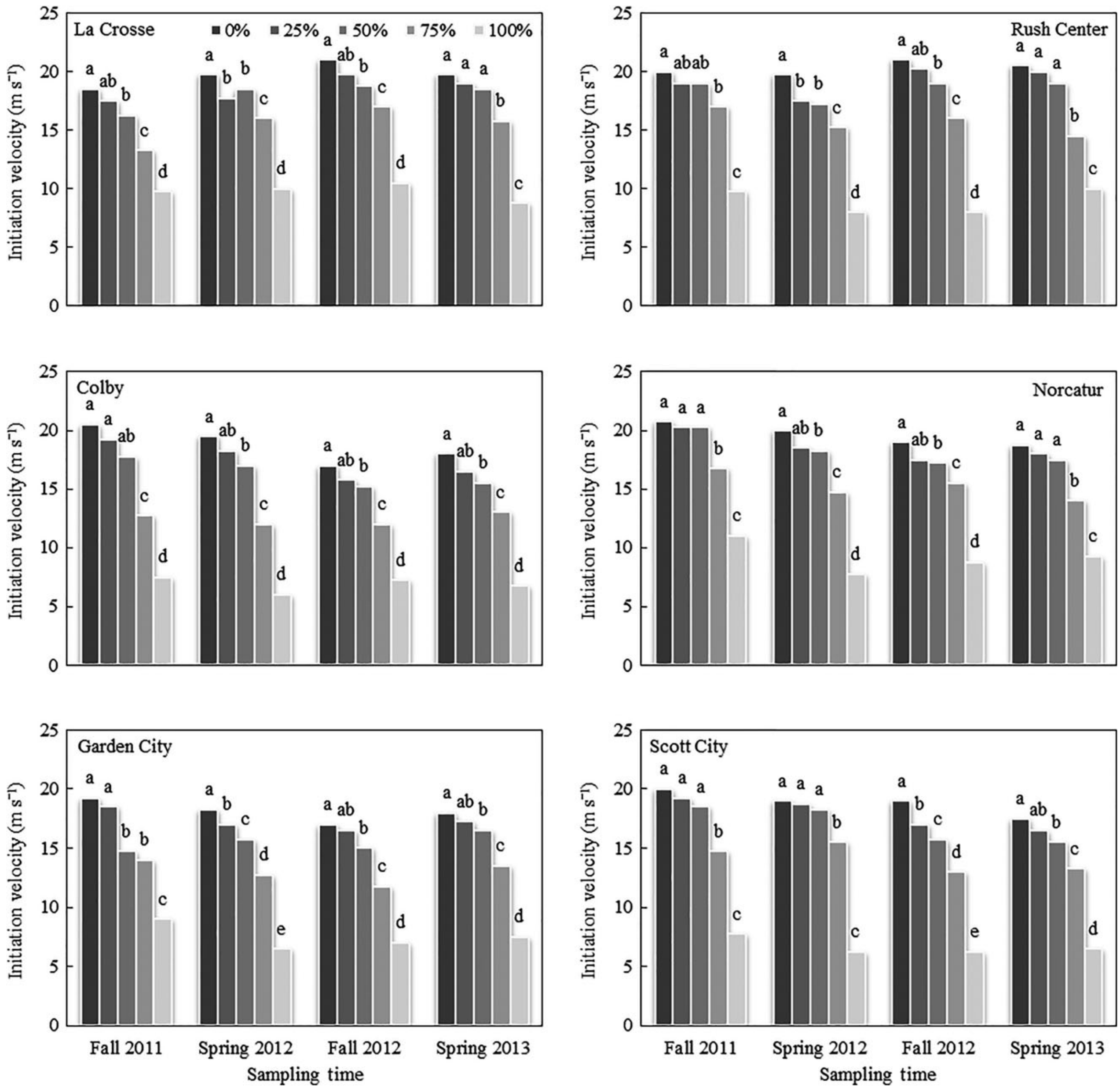

Fig. 4 Wind erosion threshold velocity simulated by the Single-event Wind Erosion Evaluation Program (SWEEP) at all six sites. Treatments with different letters indicate significant differences at the $P = 0.05$ level within the same sampling time. The absence of letters indicates no significant differences among treatments for that sampling time.

9.8 m s^{-1} at La Crosse for the measured conditions under 100% residue removal in November (e.g., fall 2011). From historical wind data within SWEEP, the probability of a 9.8 m s^{-1} wind in November at Lacrosse is 9.7%. This probability means that on average ~72 h (9.7% of 744 h in November) at this location historically have wind speeds of 9.8 m s^{-1} or greater. These 72 h of wind may all occur in one event or they may be spread out over multiple different times in the month of November (i.e., multiple wind storm events). This indicates that 9.7 m s^{-1} (34.9 km h^{-1}) winds in November are not uncommon at the study site.

Overall, the probability data fall into three statistical groups. First, the 100% removal treatments all have the highest probability of exceeding the threshold velocity. Second, the 75% removal treatments are always different from other heights. Finally, the 0, 25, and 50% removal heights depend on the site. As the SWEEP model uses the measured data as input for each given sampling time, the probability values reflect this in terms of the

Table 4 Probability* (%) that winds on a given day will exceed the wind erosion threshold velocity as simulated by the Single-event Wind Erosion Evaluation Program (SWEEP) for each of the six sites and four sampling periods

Site	Removal (%)	Fall 2011	Spring 2012	Fall 2012	Spring 2013
La Crosse	100	9.70[a]	11.28[a]	9.63[a]	17.65[a]
	75	1.66[b]	0.58[b]	0.34[b]	0.76[b]
	50	0.29[c]	0.15[c]	0.14[c]	0.18[c]
	25	0.13[c]	0.23[c]	0.07[c]	0.12[c]
	0	0.05[c]	0.07[c]	0.02[c]	0.08[c]
Rush Center	100	10.50[a]	21.98[a]	15.81[a]	14.03[a]
	75	0.16[b]	1.06[b]	0.11[b]	1.21[b]
	50	0.03[c]	0.28[c]	0.01[c]	0.12[c]
	25	0.05[c]	0.25[c]	0.00[c]	0.06[c]
	0	0.02[c]	0.07[c]	0.00[c]	0.05[c]
Colby	100	21.74[a]	49.98[a]	25.52[a]	41.52[a]
	75	1.77[b]	6.49[b]	6.49[b]	5.45[b]
	50	0.15[c]	1.06[c]	1.91[c]	1.76[c]
	25	0.06[c]	0.57[c]	1.63[c]	1.27[c]
	0	0.02[d]	0.33[d]	1.05[d]	0.68[d]
Norcatur	100	5.22[a]	26.38[a]	11.77[a]	16.16[a]
	75	0.25[b]	1.11[b]	0.81[b]	2.06[b]
	50	0.04[c]	0.22[c]	0.30[c]	0.26[c]
	25	0.04[c]	0.16[c]	0.22[c]	0.22[c]
	0	0.02[c]	0.05[d]	0.04[d]	0.13[c]
Garden City	100	14.38[a]	47.88[a]	31.56[a]	36.38[a]
	75	1.05[b]	5.37[b]	4.40[b]	4.12[b]
	50	0.59[c]	1.51[c]	1.25[c]	1.14[c]
	25	0.10[d]	0.87[d]	0.56[d]	0.82[c]
	0	0.07[d]	0.49[d]	0.47[d]	0.57[d]
Scott City	100	25.92[a]	50.88[a]	39.42[a]	47.88[a]
	75	0.68[b]	1.67[b]	2.41[b]	4.43[b]
	50	0.11[c]	0.58[c]	0.74[c]	1.65[c]
	25	0.09[c]	0.41[c]	0.46[c]	1.12[c]
	0	0.05[c]	0.36[c]	0.24[c]	0.74[d]

Treatments with different letters indicate significant differences at the $P = 0.05$ level. Results were separately compared among treatments at every site at each sampling period.
*Probability is based on historical wind records contained in SWEEP for weather stations nearest to each study site.

range in values. For example, the Garden City site 100% removal had a probability of 14.38% of reaching the threshold wind speed in fall 2011. In the spring 2012, this same treatment had a 47.88% probability. This is due to the large change in EF and GMD at this site between fall and spring for the two sampling dates. The 75% probabilities for removal, for these same time periods, are 1.05 and 5.37%, respectively, which had smaller magnitudes in difference in the EF and GMD.

For the 75% residue removal treatment, the greatest probability of wind speed greater than V_t was significantly less relative to 100% removal for all sites and all sampling periods. The largest probabilities of exceeding the threshold velocity at 75% removal were measured at Colby and Garden City, ranging from 1.77 to 6.49% for Colby, and 1.05 to 5.37% at Garden City. For the Colby, Garden City, and Scott City sites, the probability of exceeding the threshold velocity declined to <2% for all sampling periods when more than 50% residue was left on the surface. At 50% removal, the La Cross, Rush Center, and Norcatur sites had <1% probability for all sampling periods.

SWEEP: soil loss

According to the SWEEP model output, no soil erosion was predicted for any of the sites for any sampling period for the 0, 25, and 50% removal heights during a simulated three-hour event with a wind velocity of 13 m s^{-1}. Data are presented for the 75 and 100% removal heights only (Table 5). There were several instances where the mass of predicted soil loss increased between the fall 2011 and spring 2012 sampling periods. At La Crosse, total soil loss increased from 9.7 Mg ha^{-1} in fall 2011 to 16.9 Mg ha^{-1} in spring 2012. A similar increase from fall 2011 to spring 2012 was found at all sites (Table 5). From fall 2012 to spring 2013, four sites (i.e., La Crosse, Norcatur, Garden City, and Scott City) had simulated increase in soil loss while the other two sites (Rush Center and Colby) decreased. Values >11.2 Mg ha^{-1} exceed the annual tolerable soil loss limit. At 100% removal, each site had one or more sampling periods that lost more than the tolerable annual amount in the three-hour SWEEP wind event. The Colby spring 2012

Table 5 Soil loss (Mg ha^{-1}) for three hours at 13 m s^{-1} wind speed simulated by the Single-event Wind Erosion Evaluation Program (SWEEP) under 75 and 100% removal heights at each site

Site	Removal (%)	Fall 2011	Spring 2012	Fall 2012	Spring 2013
La Crosse	100	9.7	16.9*	12.6*	13.6*
	75	0.6	0.0	0.0	0.0
Rush Center	100	4.0	11.4*	11.9*	5.3
	75	0.0	0.0	0.0	0.0
Colby	100	6.7	27.0*	11.0	10.0
	75	0.5	2.9	2.3	1.3
Norcatur	100	4.8	9.1	9.5	15.5*
	75	0.0	0.0	0.0	0.3
Garden City	100	6.6	20.6*	9.5	23.2*
	75	0.1	1.6	1.7	1.3
Scott City	100	13.7*	23.8*	13.6*	14.1*
	75	0.0	0.0	0.8	0.8

*Soil losses during the three-hour SWEEP simulation are above the U.S. Department of Agriculture Natural Resources Conservation Service (USDA-NRCS) tolerable soil loss limit of 11.2 Mg ha^{-1} yr^{-1}.

SWEEP modeled soil loss was 27.0, which was 2.4 times the tolerable annual loss. Garden City and Scott City also had large losses at 100% removal. At the 75% removal height, Colby and Garden City had soil losses predicted at the 75% removal height for all four sampling periods, ranging from 0.5 to 1.7 Mg ha^{-1}. The other four sites had <0.8 Mg ha^{-1} soil loss predicted by SWEEP for the 75% removal height for any sampling period, with several instances of zero soil loss at the 75% removal height.

Discussion

Physical measurements

Many of the reasons for the inconsistencies among sites can be attributed to management differences. One potential explanation for some of the results may be due to the cropping intensity, thus residue production of each site. All sites were established on fields in the fall of 2011 where wheat had been harvested the prior summer. The La Crosse site then grew three more crops during the remainder of the experiment, one of which was a failure from a grain-production standpoint but still produced plants that covered the soil surface. Four sites (Rush Center, Colby, Norcatur, and Scott City) each produced two crops after the initiation of the experiment. The least intensive cropping rotation was at the Garden City site with only one crop after the initiation of the experiment. The ranking of selected management and physical measured values are summarized below where CO, Colby; GC, Garden City; La Crosse, LC; NC, Norcatur; RC, Rush Center; and SC, Scott City:

Cropping intensity:GC<CO<SC=NC=RC<LC
Years in NT:GC<RC<LC<CO<SC<NC
SOC:SC<GC<LC=RC<NC<CO
EF: CO>GC>SC=RC=LC>NC
GMD: CO=GC=SC<NC=RC=LC
Single-event soil loss @ 75% removal:CO=GC>SC> LC=NC=LC>RC

Data showed that, in general, total (100%) crop residue removal could cause significant (in excess of tolerable values) wind erosion risks in the study region. However, the magnitude and frequency of residue removal height on soil erodibility varied, likely due to the differences in soil types, cropping systems, management history, and the seasonal variation and drought-related effects of weather (Table 2). For example, the length under no-till prior to experiment establishment varied among sites. Finding fields with the same length of no-till management for this experiment was difficult. The main finding from this study is that, at most sites and sampling times, complete residue removal significantly increased EF and reduced GMD, and to a lesser extent RR relative to the 0% height. Wind erosion risks are high in late winter and early spring in the US Great Plains due to the effect of weathering on soil aggregates (Layton *et al.*, 1993; Kenney *et al.*, 2015) in addition to low vegetation cover and higher wind velocities. During the winter, soil pore water turns to ice, which occupies more volume than liquid water, expanding the pore size between soil aggregates. This ultimately ruptures aggregates, weakens stability, and leads to increases in EF and decreases in GMD as soil wind erosion rates increase (Bullock *et al.*, 2001; Li *et al.*, 2004; Wang *et al.*, 2014). However, thawing under high water contents (i.e., close to saturation) can cause particles to reconsolidate into stronger aggregates. Kenney *et al.* (2015) observed more F-T events with greater residue removal (>50%) due to increased soil temperature fluctuations compared to 0% removal in a recent study in Kansas.

Results suggest that excessive residue removal has exposed soils to physical weathering forces of WD, FT and FD changing soil aggregate size. This is particularly true when considering EF values across the six research sites. Without the weather-moderating effects of crop residue, a bare soil with a higher EF can be subject to erosion when V_t is reached.

The EF values increased at five sites from the fall of 2011 to the spring of 2012 (Fig. 1), particularly for plots with the highest removal rate (i.e., 75 and 100% removal). Some inconsistencies in response of EF and other parameters to residue removal could be due to the following reasons. In 2012, the Central Great Plains experienced above average temperatures and the lowest precipitation ever recorded for the region (NOAA, 2013). The drought of 2011–2012 was the worst drought since the 1930s in the Great Plains, receiving a designation of 'Exceptional', meaning widespread water shortages and crop losses occurred (Grigg, 2014). Due to the 2012 drought (Table 2), crop yields were generally lower than normal in the Great Plains and producers at the La Crosse, Colby, Norcatur, and Scott City sites did not harvest their grain crops. Therefore, the residue height remaining in the field at these sites for that year was greater than in the previous and subsequent harvested years. The presence of greater residue amounts following the drought vs. the previous sampling periods likely accounts for the lack of increase in EF and decrease in GMD in winter of 2012–2013.

Rough surfaces reduce wind velocity near the soil surface (Bielders *et al.*, 2000) by absorbing wind energy and can also trap eroding soil particles (Hagen & Armbrust, 1992), reducing wind erosion. For five of six sites, soil surface roughness decreased with increases in residue removal height. Precipitation can flatten the soil surface and reduce aggregation, as observed by Lyles and Tatarko (1987). This was likely the reason for reduced RR under the complete removal treatment where surface soil was exposed to temperature fluctuations and precipitation at Colby, Norcatur, Garden City, and Scott City. Growing wheat will help protect the soil from raindrop impact which allowed the Lacrosse and Rush Center sites to have relatively high RR in the following fall of 2012.

SWEEP modeled risk and loss

The SWEEP model was used to simulate the V_t (Fig. 4), the probability of wind speed reaching V_t (Table 3), and total soil loss (Table 4) for a three-hour wind event at 13 m s^{-1} under all treatments at each site. Reduced V_t with 100% residue removal indicates the importance of the protective value of crop residue on reducing soil wind erodibility. The effect that 100% removal has on these no-tilled fields is consistent, suggesting other factors (i.e., management history, cropping system, local weather condition, and resulting soil properties) do not affect soil wind erodibility as much as the absence or abundance of crop residues, particularly in the short term (2–3 years) of this study. However, as this study shows, removal of residues can also affect soil erodibility in addition to the effects on reducing wind energy at the surface.

Complete residue removal increased the probability of exceeding V_t (Table 4) to 10–50% for the months sampled for all sites, and lowered probability to <2% for all sites at ≤50% removal. No general acceptable probability level is proposed at this time based on the limited data in this study. However, our data show that ≤50% removal significantly reduces the likelihood of a wind erosion event, whereas 100% removal has a great risk for wind erosion at all sites. If we arbitrarily assume that a < 2% risk of reaching the threshold velocity is an acceptable limit, then 75% removal is the height at which the sites segregate as follows: Rush Center, Norcatur, and La Crosse, on average, have probabilities <1% at 75% removal; whereas Colby, Garden City, and Scott City have probabilities ~2–4% at 75% removal.

The probability of wind speeds ≥13 m s^{-1} in April is ~2–5% for all sites (Table 6). This is equivalent to 17–33 h with winds >13 m s^{-1} for the month between all sites. Therefore, this is not an uncommon wind speed and higher wind speeds can cause extreme erosion events. In addition, more than half of the erosion losses for a 3-h wind event at 13 m s^{-1} for 100% removal were more than the USDA-NRCS annual tolerable soil loss limit of 11.2 Mg ha^{-1} for these soils (Table 5), and all but one (Rush Center, fall 2011) were equal to or >4.8 Mg ha^{-1}. At the Colby and Garden City sites, results show that wind erosion could occur for the soil conditions measured at 75% residue removal, which are significantly different compared to 0, 25, and 50% removal treatments. No-till systems often have better soil aggregation at the soil surface than other tillage systems (Devine *et al.*, 2014). Therefore, greater soil wind erosion at Garden City may potentially be attributed to the short NT management history (5 years). However, this cannot explain the results for the Colby site as it has a 15-year NT history. Overall, across six sites, the SWEEP model indicates ≤75% crop residue removal is a minimum threshold height for maintaining crop residue to prevent soil loss by wind erosion. However, in years of extreme drought or high winds, wind erosion soil losses could still result on 0–75% removal heights if sufficient residues were not produced.

This study in western Kansas of the US Great Plains was conducted at six on-farm sites in a precipitation zone ranging from 495 to 595 mm yr^{-1} indicated that excessive (>75%) crop residue removal can increase risks of wind erosion. Excessive residue removal increased EF and decreased GMD and surface RR compared to the other treatments (<75%), likely due to the exposure of the soil surface to weather forces due to residue removal. At some sites, 75% of residue removal increased wind erosion potential, which suggests that

Table 6 Probability* (%) that the wind speed wind on a given day will be ≥13 m s^{-1} at the nearest weather station from each study site in each month

Research site	Nearest wind station used	County	Month†											
			1	2	3	4	5	6	7	8	9	10	11	12
La Crosse and Rush Center	Hays Municipal (AWAS)	Ellis	1.1	1.3	2.8	2.4	0.7	1.0	0.6	0.2	0.7	1.7	1.0	0.6
Colby	Goodland/Renner (AW)	Thomas	1.8	2.2	4.5	4.1	2.5	1.2	0.4	0.3	0.7	1.5	2.0	1.5
Norcatur	US NE McCook	Decatur	1.3	1.7	2.9	3.7	1.7	0.8	0.3	0.2	0.5	1.4	1.6	1.0
Garden City and Scott City	Garden City Municipal	Finney	1.8	2.6	4.9	4.6	2.6	1.9	1.0	0.6	1.2	1.8	2.4	1.9

*Probability is based on historical wind records contained in SWEEP for weather stations nearest to each study site.
†Numbers correspond with months of the year accordingly: (1) January, (2) February, (3) March, (4) April, (5) May, (6) June, (7) July, (8) August, (9) September, (10) October, (11) November, and (12) December.

removal at >50% can increase soil erodibility. Although <75% residue removal appear to be appropriate to prevent wind erosion in this region, removal of 75% of height in low residue-producing years is not recommended. The effects of removing high levels of crop residue are unpredictable for the climate in this region. Droughts, intense or localized rainstorms, and high winds are highly variable and can occur at any site and year across the US Great Plains. However, more long-term experiments of residue removal are needed to better establish and recommend permissible amounts of residue removal in this region. The SWEEP model, using field-measured parameters also supported field measurements, suggesting that complete removal can increase wind erosion when exposed to a 3-h wind event with speeds of 13 m s^{-1}, but predicted very little wind erosion at ≤50% removal for all sites. For this study, 75% removal had small or no effect on soil loss for three of the six sites, while the other three sites, 75% removal showed some risk. Therefore, decisions about residue removal must be made on a field-by-field and season-by-season basis. In semi-arid regions, the amount of crop residue produced each year is highly dependent upon precipitation, particularly for dryland farming conditions. Future studies are recommended to comprehensively consider the relationship among soil properties, amount of biomass retained in field, local weather conditions and variability, cropping system, and crop productivity.

Acknowledgements

We express our thanks to the Sustainable Agriculture Research and Education (SARE) program (NCR-SARE Project LNC10-318) and the regional research project NC-1178, Impacts of Crop Residue Removal for Biofuel on Soils, for funding this on-farm project. We also appreciate the six farmer cooperators in western Kansas (Dale Yonker and Gail Schwindt near Hays, Mike Brown and Stan Miller near Colby, and Boyd Funk and Jack Schmitt near Garden City) for letting us access their farms to conduct the on-farm experiments. We also thank Mr. Tom Prosser, agricultural technician, for assisting with the experiment establishment, annual imposition of crop residue removal treatments, and field data collection from all sites. This is contribution no. 17-398-J from the Kansas Agricultural Experiment Station.

References

Allmaras RR, Burwell RE, Larson WE, Holt RF (1966) Total porosity and random roughness of the interrow zone as influenced by tillage. *USDA Conservation Research Report 7*.

Arshad MA, Franzluebbers AJ, Azooz RH (1999) Components of surface soil structure under conventional and no-tillage in northwest Canada. *Soil and Tillage Research*, **53**, 41–47.

Bielders CL, Michels K, Rajot JL (2000) On-farm evaluation of ridging and residue management practices to reduce wind erosion in Niger. *Soil Science Society of America Journal*, **64**, 1776–1785.

Blanco-Canqui H (2010) Energy crops and their implications on soil and environment. *Agronomy Journal*, **102**, 403–419.

Blanco-Canqui H, Lal R (2009a) Crop residue removal effects on soil productivity and environmental quality. *Critical Reviews in Plant Sciences*, **28**, 139–163.

Blanco-Canqui H, Lal R (2009b) Corn stover removal for expanded uses reduces soil fertility and structural stability. *Soil Science Society of America Journal*, **73**, 943–946.

Blanco-Canqui H, Tatarko J, Stalker AL, Shaver TM, van Donk SJ (2016) Impacts of corn residue grazing and baling on wind erosion potential in a semiarid environment. *Soil Science Society of America Journal*, **80**, 1027–1037.

Boyd DW, Skidmore EL, Thompson JG (1983) A soil-aggregate crushing-energy meter. *Soil Science Society of America Journal*, **47**, 313–316.

Bullock MS, Larney FJ, Izaurralde RC, Feng Y (2001) Overwinter changes in wind erodibility of clay loam soils in southern Alberta. *Soil Science Society of America Journal*, **65**, 423–430.

Buschiazzo DE, Zobeck TM (2008) Validation of WEP, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinean Pampas. *Earth Surface Processes and Landforms*, **33**, 1839–1850.

Chepil WS (1962) A compact rotary sieve and the importance of dry sieving in physical soil analysis. *Soil Science Society of America Journal*, **26**, 4–6.

Chepil WS, Woodruff NP (1963) The physics of wind erosion and its control. *Advances in Agronomy*, **15**, 211–302.

Colacicco D, Osborn T, Alt K (1989) Economic damage from soil erosion. *Journal of Soil Water Conservation*, **44**, 35–39.

Devine S, Markewitz D, Hendrix P, Coleman D (2014) Soil aggregates and associated organic matter under conventional tillage, no-tillage, and forest succession after three decades. *PLoS ONE*, **9**, e84988.

van Donk SJ, Skidmore EL (2003) Measurement and simulation of wind erosion, roughness degradation and residue decomposition on an agricultural field. *Earth Surface Processes and Landforms*, **28**, 1243–1258.

Evers BJ, Blanco-Canqui H, Staggenborg SA, Tatarko J (2013) Dedicated bioenergy crop impacts on soil wind erodibility and organic carbon in Kansas. *Agronomy Journal*, **105**, 1271–1276.

Feng G, Sharratt B (2009) Evaluation of the SWEEP model during high winds on the Columbia Plateau. *Earth Surface Processes and Landforms*, **34**, 1461–1468.

Funk R, Skidmore EL, Hagen LJ (2004) Comparison of wind erosion measurements in Germany with simulated soil losses by WEPS. *Environmental Modelling and Software*, **19**, 177–183.

Gee GW, Bauder JW (1986) Particle-size analysis. In: *Methods of Soil Analysis, Part 1, Agronomy* (ed. Klute A), pp. 399–404. Academic Press, Cambridge, MA, USA.

Graham RL, Nelson R, Sheehan J, Perlack RD, Wright LL (2007) Current and potential US corn stover supplies. *Agronomy Journal*, **99**, 1–11.

Grigg NS (2014) The 2011–2012 drought in the United States: new lessons from a record event. *International Journal of Water Resources Development*, **30**, 183–199.

Hagen LJ (2004) Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. *Environmental Modelling and Software*, **19**, 171–176.

Hagen LJ, Armbrust DV (1992) Aerodynamic roughness and saltation trapping efficiency of tillage ridges. *Transactions of the American Society of Agricultural Engineers*, **35**, 1179–1184.

Hagen LJ, Skidmore EL, Saleh A (1992) Wind Erosion: prediction of aggregate abrasion coefficients. *Transactions of the American Society of Agricultural Engineers*, **35**, 1847–1850.

Hagen LJ, Wagner LE, Skidmore EL (1999) Analytical solutions and sensitivity analyses for sediment transport in WEPS. *Transactions of the American Society of Agricultural Engineers*, **42**, 1715–1721.

Jia Q, Al-Ansari N, Knutsson S (2014) Modeling of wind erosion of the Aitik Tailings Dam using SWEEP model. *Engineering*, **6**, 355–364.

Kenney I, Blanco-Canqui H, Presley DR, Rice CW, Janssen K, Olson B (2015) Soil and crop response to stover removal from rainfed and irrigated corn. *Global Change Biology Bioenergy*, **7**, 219–230.

Khanal S, Anex RP, Anderson CJ, Herzmann DE, Jha MK (2013) Implications of biofuel policy-driven land cover change for rainfall erosivity and soil erosion in the United States. *Global Change Biology Bioenergy*, **5**, 713–722.

Kim S, Dale BE (2004) Global potential bioethanol production from wasted crops and crop residues. *Biomass Bioenergy*, **26**, 361–375.

Lal R (1982) No-till farming: soil and water conservation and management in the humid and subhumid tropics. IITA Monograph No.2, IITA, Ibadan, Nigeria, 64 pp.

Lal R (2004) Soil carbon sequestration impacts on global climate change and food security. *Science*, **304**, 1623–1627.

Lal R (2009) Soil quality impacts of crop residue removal for bioethanol production. *Soil and Tillage Research*, **102**, 233–241.

Layton JB, Skidmore EL, Thompson CA (1993) Winter-associated changes in dry-soil aggregation as influenced by management. *Soil Science Society of America Journal*, **57**, 1568–1572.

Li F, Zhao L, Zhang H, Zhang T, Shirato Y (2004) Wind erosion and airborne dust deposition in farmland during spring in the Horqin Sandy Land of eastern Inner Mongolia, China. *Soil and Tillage Research*, **75**, 121–130.

Liu B, Qu J, Niu Q, Han Q (2014) Comparison of measured wind tunnel and SWEEP simulated soil losses. *Geomorphology*, **207**, 23–29.

Lyles L, Allison BE (1981) Equivalent wind-erosion protection from selected crop residues. *Transactions of the American Society of Agricultural Engineers*, **2**, 405–407.

Lyles L, Tatarko J (1987) Precipitation effects on ridges created by grain drills. *Journal of Soil and Water Conservation*, **42**, 269–271.

Lyles L, Dickerson JD, Disrud LA (1970) Modified rotary sieve for improved accuracy. *Soil Science*, **190**, 207–210.

Mengel DB, Wilson DW, Huber DM (1982) Placement of nitrogen fertilizer for no-till and conventional tillage corn. *Agronomy Journal*, **74**, 515–518.

Nelson RG, Walsh M, Sheehan JJ, Graham R (2004) Methodology for estimating removable quantities of agricultural residues for bioenergy and bioproduct use. *Applied Biochemistry and Biotechnology*, **113**, 13–26.

NOAA (2013) An interpretation of the origins of the 2012 central Great Plains drought. Available at: http://cpo.noaa.gov/sites/cpo/Reports/MAPP/drought/2012%20drought%20report/DTF_Interpretation_of_2012_Drought_FINAL_2-pager_April_25b.pdf (accessed 12 February 2012).

Perlack RD, Wright LL, Turnhollow AF, Graham RL, Stokes BJ, Erbach DC (2005) Biomass as feedstock for a bioenergy and bioproducts industry: the technical feasibility of a billion-ton annual supply. Oak Ridge, TN: Oak Ridge National Laboratory. pp59.

Pi H, Sharratt B, Feng G, Lei J, Li X, Zheng Z (2016) Validation of SWEEP for creep, saltation, and suspension in a desert–oasis ecotone. *Aeolian Research*, **20**, 157–168.

Rhoton FE, Shipitalo MJ, Lindbo DL (2002) Runoff and soil loss from midwestern and southeastern US silt loam soils as affected by tillage practice and soil organic matter content. *Soil and Tillage Research*, **66**, 1–11.

Sarath G, Mitchell RB, Sattler SE, Funnell D, Pedersen JF, Graybosch RA, Vogel KP (2008) Opportunities and roadblocks in utilizing forages and small grains for liquid fuels. *Journal of Industrial Microbiology and Biotechnology*, **35**, 343–354.

SAS Institute (2011) Online doc. 9.3. SAS Institute Inc., Cary, NC. Available at: http://support.sas.com/documentation/93/index.html (accessed 21 January 2015).

SPSS Science (1998) SigmaScan Pro 5.0 User's Guide. SPSS Science, Chicago, IL.

Tatarko J (2001) Soil aggregation and wind erosion: processes and measurements. *Annals of Arid Zone*, **40**, 303–322.

Wagner LE (2013) A history of wind erosion prediction models in the United States Department of Agriculture: the Wind Erosion Prediction System (WEPS). *Aeolian Research*, **10**, 9–24.

Wagner LE, Ding D (1994) Representing aggregate size distributions as modified lognormal distributions. *Transactions of the American Society of Agricultural Engineers*, **37**, 815–821.

Wagner LE, Yu Y (1991) Digitization of profile meter photographs. *Transactions of American Society of Agricultural Engineers*, **34**, 412–416.

Wang L, Shi ZH, Wu GL, Fang NF (2014) Freeze/thaw and soil moisture effects on wind erosion. *Geomorphology*, **207**, 141–148.

Wilhelm WW, Johnson JMF, Karlen D, Lightle D (2007) Corn stover to sustain soil organic carbon further constrains biomass supply. *Agronomy Journal*, **99**, 1665–1667.

Wuest SB, Caesar-TonThat TC, Wright SF, Williams JD (2005) Organic matter addition, N, and residue burning effects on infiltration, biological, and physical properties of an intensively tilled silt-loam soil. *Soil and Tillage Research*, **84**, 154–167.