Impacts of Corn Residue Grazing and Baling on Wind Erosion Potential in a Semiarid Environment

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Implications of corn (*Zea mays* L.) residue grazing and baling on wind erosion in integrated crop–livestock systems are not well understood. This study (i) determined soil properties affecting wind erosion potential including dry aggregate-size distribution, geometric mean diameter (GMD), geometric standard deviation of dry aggregates, and wind-erodible fraction (WEF), (ii) correlated these properties with soil organic C (SOC) and particulate organic matter (POM), and (iii) simulated soil loss using the Single-event Wind Erosion Evaluation Program (SWEEP) model after 7 and 8 yr of irrigated no-till corn residue management in a semiarid region in west-central Nebraska. Residue treatments were: control (no residue removal), light grazing (2.5 animal unit months [AUM] ha^{-1}), heavy grazing (5.0 AUM ha^{-1}), and baling. We simulated soil loss for a 3-h windstorm with a wind velocity of 13 m s^{-1}. Soil properties differed in spring but not in fall. Baling reduced 6.3- to 45-mm macroaggregates by 37% and GMD by 80% and increased WEF by 25% relative to the control. Light and heavy grazing, after 8 yr, significantly reduced 6.3- to 14-mm macroaggregates 43% compared with the control and tended to reduce GMD and increase WEF, although not statistically significant. As residue cover decreased, GMD decreased and WEF increased. Residue removal did not reduce SOC and POM concentrations, but soil erodibility decreased as POM increased. Simulation showed that soil erodibility increased as residue cover decreased in spring, and baling increased the wind erosion potential. Overall, residue baling increases the wind erosion potential but residue grazing has smaller effects in this semiarid environment.

Abbreviations: AUM, animal unit month; GMD, geometric mean diameter of dry aggregates; GSD, geometric standard deviation; SOC, soil organic carbon; POM, particulate organic matter; WEF, wind-erodible fraction.

Corn residues provide numerous services for crop and livestock production, biofuel production, protection of soil, and environmental quality. For example, corn residues are considered an inexpensive cattle feed source in times when the availability of forage is limited. Residues are grazed by livestock, baled as animal feed, and mixed with ethanol co-products (i.e., distillers grains) for cattle feed. Corn residues are also potential feedstocks for the production of second-generation biofuels. The long-term impacts of grazing and baling of corn residues on soil services have not yet been fully investigated (Nelson et al., 2015).

One of the services that should be further considered prior to residue removal is wind erosion control. Particularly in semiarid regions such as the central Great Plains, the presence of abundant crop residue cover is essential for controlling wind erosion. Recent estimates have shown that removal of corn residues at rates as low as 10 to 30% could increase the risks of wind erosion in semiarid regions, depending on the amount of residue produced (Miner et al., 2013). Wind erosion is a major factor affecting soil degradation in semiarid environments. Crop residues left

Core Ideas

- **Corn residue baling increased the wind-erodible fraction relative to no baling.**
- **Cattle grazing of corn residues had smaller effects on wind erosion than baling.**
- **As residue cover decreased, the wind-erodible fraction increased.**
- **Soil erodibility decreased as particulate organic matter increased.**
- **Simulated soil loss showed that baling increased the wind erosion potential.**

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on the soil surface as standing stalks and broken coarse residues protect the soil from wind erosion, but heavy grazing and baling reduce the amount of residue left on the soil surface. Reduced residue cover in combination with the increasing climatic fluctuations (i.e., droughts) could adversely affect near-surface soil structural quality and increase the susceptibility of the soil to erosion, reducing soil productivity in the long term.

Changes in dry soil aggregate-size distribution are dynamic indicators of wind erosion potential. The smaller the dry soil aggregates, the greater the soil's susceptibility to wind erosion because microaggregates <0.1 mm in diameter require a lower threshold wind speed to initiate soil movement compared with macroaggregates (Chepil, 1950). Aggregates >0.1 mm have a higher threshold friction velocity (Chepil, 1951). Dry soil aggregates in relation to wind erosion are classified into three categories including creep-size (0.84–2-mm diameter) aggregates, saltation-size (0.10–0.84-mm) aggregates, and suspension-size (<0.10-mm diameter) aggregates (Chepil, 1950). The percentage of aggregates <0.84 mm is often referred to as the *wind-erodible fraction* (WEF). This fraction is the most susceptible to wind erosion and is generally used as an indicator of wind erosion potential. Quantifying changes in the dry aggregate-size distribution and WEF following baling and grazing of crop residues is thus critical for assessing how these practices could affect wind erosion risks in wind-erosion-prone environments.

Recent studies have evaluated changes in WEF under mechanical removal of corn residues (Osborne et al., 2014; Jin et al., 2015). However, information on the effects of residue grazing on the wind erosion potential is extremely limited. Cattle grazing generally removes fewer residues than baling and may thus have less of a negative impact on increasing wind erosion risks. Furthermore, information on the effects of crop residue removal on wind erosion is particularly needed in semiarid regions such as the central Great Plains, where wind erosion risks are high.

It is also important to understand the soil properties that influence the formation and stability of dry aggregates. Soil aggregation is often correlated with changes in the SOC concentration (Blanco-Canqui et al., 2013). Because SOC is a function of crop residue inputs, removal of the aboveground biomass by grazing and baling may reduce SOC levels in the long term. A reduction in SOC levels due to residue removal could thus be one of the main mechanisms for any rapid deterioration of soil structural quality near the surface. The most biologically active fraction of organic matter in the soil is POM. Because POM consists of easily decomposable or young organic material, it may change more rapidly than total organic C in response to management shifts. Changes in the POM concentration may be an indicator of changes in the dry aggregate-size distribution.

Under grazed fields, animal manure inputs should be considered because they can alter the soil C dynamics. The return of C with manure can minimize or offset the soil C lost due to residue grazing. The removal of residues by cattle grazing may not reduce soil C levels and affect soil aggregate properties compared with residue baling if soil C is returned with manure additions. The SOC is the result of the balance of C inputs and outputs. Corn residue grazing-induced changes in SOC and POM concentrations and their relations with GMD and WEF are not well documented.

Using simulation models to predict soil loss is important to understand how changes in soil properties and surface residue cover due to residue baling and grazing can affect the wind erosion potential. Prediction is also important for the extrapolation of point measurements to field or regional scales. The SWEEP model, a stand-alone companion product of the Wind Erosion Prediction System (WEPS), is a process-based submodel designed to simulate soil surface erodibility and wind erosion soil loss from cultivated agricultural lands as affected by weather, soil properties, and land management (Hagen, 1991; Wagner, 2013). The SWEEP model was developed for simulating single-day windstorm events under given surface conditions and consists of the erosion prediction component of WEPS with a graphical user interface. It can predict potential wind erosion given the field surface properties for a specific day at the location of interest, and it can thus estimate the probability of a wind erosion event following residue baling or grazing.

Simulation of soil erosion using WEPS and SWEEP has undergone extensive field and wind tunnel testing and validation. A number of studies have reported a satisfactory agreement (i.e., r^2 = 0.87–0.98) between measured and WEPS-simulated erosion (Buschiazzo and Zobeck, 2008; Funk et al., 2004; Liu et al., 2014). Hagen (2004) found "reasonable agreement" (r^2 = 0.71) between measured and WEPS-simulated erosion values for 46 windstorm events in six states. Similarly, Pi et al. (2016) validated SWEEP in a desert–oasis ecotone in China and reported that SWEEP can provide adequate estimates of wind erosion.

The objectives of this study were to: (i) quantify soil properties affecting wind erosion potential including dry aggregate-size distribution, GMD, geometric standard deviation (GSD), and WEF, (ii) correlate the measured soil erodibility properties with residue cover and SOC and POM concentrations, and (iii) determine potential wind erosion using the SWEEP model based on the measured soil aggregate properties and surface residue levels as affected by residue grazing and baling in an semiarid irrigated no-till continuous corn system in west-central Nebraska after a significant amount of time under grazing and baling management (7 and 8 yr).

METHODS

Experimental Site Description

This study was conducted on an ongoing crop residue management experiment in west-central Nebraska in spring 2014, spring 2015, and fall 2015. The experimental site was located at the University of Nebraska-Lincoln's West Central Water Resources Field Laboratory near Brule, NE (41.09° N, 101.89° W). This experiment is managed under no-till continuous corn and is sprinkler irrigated. The two dominant soil series at the experimental field are Duroc loam (a fine-silty, mixed, superactive, mesic Pachic Haplustoll) and a Satanta loam (a fine-loamy, mixed, superactive, mesic Aridic Argiustoll). The site is in a semiarid region with a mean annual precipitation of 475 mm at an elevation of 1056 m.

The experiment was established in fall 2008 and is under one full center-pivot (65-ha) irrigation system. It consisted of four corn residue removal treatments in duplicate including a control (no residue removal), light grazing (stocking rate of 2.5 AUM ha^{-1}), heavy grazing (stocking rate of 5.0 AUM ha^{-1}), and residue removal by baling. The experiment is laid out in a randomized complete block design. The center-pivot irrigated circle was divided into eight equal-size pie-shaped plots to accommodate the four treatments. Fences were used around the grazed plots to prevent cattle interference to neighboring treatments. Beef cows grazed the corresponding treatments from late November to early February each year. Cows were introduced to and removed from both light- and heavy-grazed plots simultaneously each year. Corn residue on the baled plots was raked into windrows using a V-rake (H&S HDII-17, H&S Manufacturing Co.) and baled using a round baler (Hesston 2856A, AGCO Manufacturing Co.) after grain harvest in the fall of each year. Baling was done so that the rake did not contact the soil surface, and the proportion of area affected by the tires was not quantified although tire tracks were avoided during sampling. The bales were weighed, and a residue subsample was oven dried at 60°C to compute the dry matter. Further details on the experiment establishment and management were described by Stalker et al. (2015).

Corn grain yield was determined from each treatment each year since experiment establishment (Stalker et al., 2015). The residue yield for the years prior to our study (2013 and 2014) is reported in Table 1, estimated from the harvest index because measured residue yield data for 2013 and 2014 were not available. We used a harvest index of 0.52, which was obtained from measured data on grain and residue yield collected prior to 2013 from this experiment (Stalker et al., 2015). In spring 2014 and 2015, residue cover was measured in all the plots by the line-transect method using a 30.5-m (100-ft) measuring tape. The tape was stretched diagonally at about a 45° angle across the corn stalk rows for representative measurements across rows of corn. Each 0.305-m (1-ft) mark of the 30.5-m (100-ft) marks above residue was counted on the tape. The residue cover percentage is the total number of marks above residue of the 100 marks of the tape (Fig. 1). This measurement was repeated at three points in each plot in a zig-zag pattern.

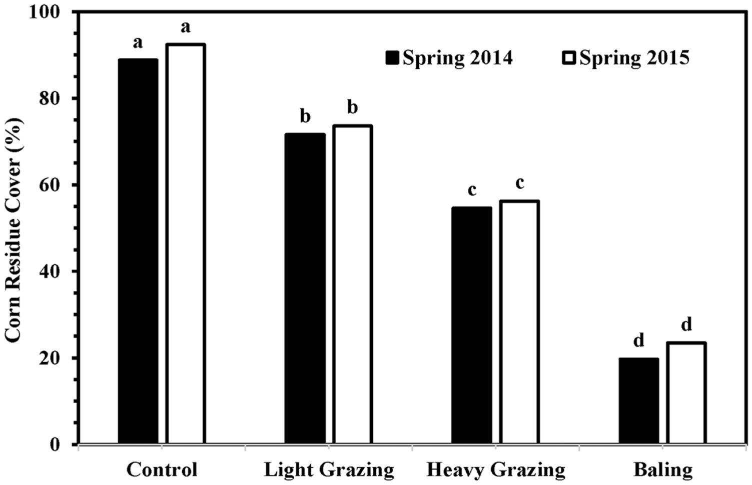

Fig. 1. Corn residue cover determined at the time of soil sampling for the evaluation of wind erosion potential under an irrigated no-till continuous corn system in west-central Nebraska. Means with different lowercase letters within the same year are significantly different.

Soil Sampling

Bulk soil samples were collected in spring 2014, spring 2015, and fall 2015 from each treatment plot for the determination of soil properties affecting the wind erosion potential including the dry aggregate-size distribution, GMD, GSD, WEF, particle-size distribution, and concentrations of SOC and POM. The SOC and POM were measured to study their correlations with dry aggregate-size properties. Soil samples in spring were collected before corn planting, while those in fall were collected in November after corn harvest and before residue baling or grazing. The soil samples were collected from the 0- to 5-cm depth using a flat-base shovel from five points within each plot. The 5-cm depth was used to assure that larger clods were included in the sample. Samples from the five points were placed in a single rectangular tray. The total weight of the soil sample in the tray was about 2.5 kg.

Table 1. Residue yield under four residue removal treatments and amount of residue baled prior to soil sampling in an irrigated no-till continuous corn system in west-central Nebraska.

	Residue yield				Residue baled from the baled treatment	
Year	Control	Light grazing	Heavy grazing	Baling		
	Mg ha^{-1}				Mg ha^{-1}	%
2013	8.40	8.58	8.68	7.94	4.27	54
2014	8.16	8.87	8.79	9.23	3.20	35
Mean	8.28	8.72	8.73	8.58	3.61	43

The bulk soil samples were dried in a forced-air oven at 25°C for 72 h. A subsample was taken for the measurement of SOC and POM concentrations. The dry aggregate-size distribution was determined by dry sieving the bulk soil samples using a Ro-Tap sieve shaker (Nimmo and Perkins, 2002; López et al., 2007; Jin et al., 2015). The air-dry soil samples were placed on top of a stack of sieves with openings of 45, 14, 6.3, 2, 0.84, and 0.425 mm arranged in descending order. The samples were mechanically sieved for 5 min at 278 oscillations min^{-1}. Then, aggregates remaining on each sieve were transferred to preweighed containers and weighed to compute the fraction of aggregates within each aggregate-size class (<0.425, 0.425–0.84, 0.84–2, 2–6.3, 6.3–14, 14–45, and >45 mm) by dividing the amount of aggregates in each sieve by the total amount of the bulk sample. After this, GMD and GSD (an indicator of the distribution pattern of soil aggregate size) were computed based on the amount of soil remaining in each sieve and the openings of sieves as a description of the aggregate-size distribution (Nimmo and Perkins, 2002). In addition, WEF as the percentage of aggregates <0.84 mm in diameter was computed.

The particle-size distribution was determined on a portion of the air-dry samples by the hydrometer method (Gee and Or, 2002; Table 2). Soil organic C concentration was determined on the air-dry soil, which was crushed and ground in a roller mill for 24 h before analyzing total organic C by dry combustion in a CN analyzer (Nelson and Sommers, 1996). Prior to analysis of SOC, the soil pH was determined with a pH meter on a 1:2 suspension (Thomas, 1996). Soil pH did not significantly differ among the four residue treatments, but the pH values were >7.0 (7.49 ± 0.18; mean ± SD), which suggests the presence of carbonates. Soil samples were pretreated with and without 10% (v/v) HCl to separate carbonates or inorganic C. The SOC concentration was analyzed in the acid-treated samples. Total POM was determined on air-dry soil samples by the weight loss on ignition technique (Cambardella et al., 2001). Air-dry soil samples were crushed to pass through a 2-mm sieve, mixed with sodium hexametaphosphate for 24 h, mechanically stirred in a multimixer, and sieved in water using a sieve with 0.053-mm openings. The sample retained on the sieve was oven dried at 60°C and then ignited in a muffle furnace at 450°C for 4 h to determine total POM by loss on ignition. Total POM was considered to be the difference in soil mass before and after ignition divided by the initial mass of the soil.

Simulation of Soil Loss by Wind Erosion

The SWEEP model (Version 1.3.9) was used to simulate wind erosion for each of the four treatments by varying only the field-measured soil parameters that affect wind erosion (i.e., GMD, GSD, and residue characteristics). Simulation parameters used are listed in Table 3. The soil surface conditions simulated represent those conditions at the time of soil sampling. The other parameters were either assumed or calculated as representative of the time and conditions of the cropping system for the study area and held constant across sampling periods to better isolate the effects of the measured treatment parameters on the wind erosion potential. Because residue cover can potentially protect aggregates from breakdown by exposure to weather forces, initial simulations were performed without the measured plant residue

Table 2. Mean particle-size distribution in plots under four residue removal treatments in an irrigated no-till continuous corn system in west-central Nebraska.

Treatment	Sand	Silt	Clay	Textural class
		g kg^{-1}		
Control	563 ± 8†	244 ± 15	193 ± 7	sandy loam
Light grazing	654 ± 64	173 ± 43	173 ± 21	sandy loam
Heavy grazing	664 ± 49	163 ± 42	173 ± 7	sandy loam
Baling	614 ± 144	197 ± 115	189 ± 29	sandy loam
$P > F$	ns‡	ns	ns	

† Mean ± standard deviation.

‡ ns, not significant at the 0.10 probability level.

Table 3. Parameter values used for the Single-event Wind Erosion Evaluation Program (SWEEP) simulations.

SWEEP Tab	Parameter†	Source‡	Value§
Field	*x* length and *y* length, m	assumed	805
	angle, ° from north	assumed	0
	wind barriers	assumed	0
Biomass¶	residue average height, m	measured	0.0762
	residue stem area index, m^2 m^{-2}	calculated	0.0036
	residue leaf area index, m^2 m^{-2}	assumed	0
	residue flat cover, m^2 m^{-2}	measured	varies
	row spacing, m	measured	0.3
	seed placement	measured	ridge
Soil layers	number of layers	assumed	1
	thickness, mm	assumed	250
	sand fraction	measured	0.624
	very fine sand fraction	assumed	0.5
	silt fraction	measured	0.182
	clay fraction	measured	0.194
	rock volume fraction	assumed	0
	dry bulk density, Mg m^{-3}	calculated	1.5
	average aggregate density, Mg m^{-3}	calculated	1.6
	average dry aggregate stability, ln(J kg^{-1})	calculated	1.5
	geometric mean diam. of aggregate sizes, mm	measured	varies
	geometric SD of aggregate sizes	measured	varies
	minimum aggregate size, mm	calculated	0.01
	maximum aggregate size, mm	calculated	45
	soil wilting point water content, Mg Mg^{-1}	calculated	0.077
Soil surface#	Allmaras random roughness, mm	assumed	4
	ridge height, mm	assumed	0
	ridge spacing, mm	measured	762
	ridge width, mm	assumed	0
	ridge orientation, ° from north	assumed	0
	hourly surface water content, Mg Mg^{-1}	assumed	0
Weather	air density, kg m^{-3}	calculated	1.2
	wind direction, ° from north	assumed	270
	anemometer height, m	assumed	10
	aerodynamic roughness, mm	assumed	10
	Zo location flag	assumed	station
	wind table, m s^{-1}	assumed	13 for 3 h

† Parameters are defined in the SWEEP user's manual (available as part of the WEPS model download at http://www.ars.usda.gov/services/software/download.htm?softwareid=415).

‡ Calculated values were based on prediction equations in the SWEEP user's manual.

§ The term *varies* indicates that values used were based on the GMD and GSD values and Fig. 1 (residue cover) for the treatments.

¶ For the bare surface, all biomass parameters were set to zero. No growing biomass was simulated.

Crusts, dikes, and snow were assumed to not be present for this study, and those values were set to zero.

(bare soil) to observe the effects of the treatments on soil erosion as a result of differences in GMD and GSD alone. The soil particle size used in the model was the average of all plots (sand = 624 g kg^{-1}, silt = 182 g kg^{-1}, and clay = 194 g kg^{-1}). The simulations also assumed an 805- by 805-m square field, no wind barriers, no crust on the soil surface, and a fairly low random roughness of 4 mm (Allmaras et al., 1966). The assumptions of no crust and low random roughness were made so that they would not suppress erosion and therefore simulated erosion differences would primarily be a result of the treatment effects on the measured aggregation and residue parameters as outlined in the study objectives. While we did not measure crusting, field observations showed no visible differences in crusting in this loamy no-till soil. All other input parameters for the SWEEP model were determined from measured soil properties (e.g., sand, silt, clay, and organic matter) according to the estimation equations in the SWEEP user's manual (available as part of the WEPS model download at www.ars.usda.gov/services/software/download.htm?softwareid=415).

All simulations of soil loss were conducted for a single windstorm event with a wind velocity of 13 m s^{-1} and a duration of 3 h. The wind velocity of 13 m s^{-1} was chosen so that relative differences in wind erosion could be observed. Using a lower wind speed would have shown little or no erosion loss and thus no observable differences in erosion. Note that the probability of a 13 m s^{-1} or greater wind speed at the nearest SWEEP weather station (Sidney, NE, Municipal Airport, NOAA Automated Surface Observing System [ASOS]) is 2.1% in April. This probability means that on average ~15 h (2.1% of 720 h in the month) in April have wind speeds of 13 m s^{-1} or greater. These 15 h may all occur in 1 d or they may be spread out across multiple days (more than one windstorm). This indicates that 13 m s^{-1} (46.7 km h^{-1}) winds in April are not uncommon at the study site. April has historically the most erosive winds at this location. November is the fall month with the greatest probability of a 13 m s^{-1} or greater wind speed at 1.4% for the Sidney station.

In addition to the bare soil simulations, the measured biomass information was input into the SWEEP model along with the measured GMD and GSD for each time that residue was measured (i.e., spring 2014 and 2015). Residue stem area index was calculated by the SWEEP model by multiplying the average stem diameter (60 mm) by the stem height (76.2 mm) by the stem population (7.9 plants m^{-1}). Stem diameter was taken from He (2015), height was assumed to be the harvest cutting height, and stem population was the planting population. Standing residue leaf area index and growing crop parameters were assumed to be zero under all treatments because the leaf parts of the plants were removed during harvest and no growing crop was present. Residue cover data obtained with the line-transect method, as indicated above, were used (Fig. 1).

Furthermore, we determined the threshold wind velocity (which is the wind velocity, measured at a 10-m height, at which soil erosion initiates) and the probability of how often wind velocities exceeding the threshold could be expected for the sampling month. These parameters were based on the measured surface conditions and historical wind parameters for the nearest weather station within the SWEEP model weather database. The nearest SWEEP weather station to the study site was the Municipal Airport ASOS station in Sydney, NE, which is approximately 92 km from the study site and is more similar to the overall landscape at Brule than other stations in the region. Regardless of the weather station used, the focus of our simulation was on the differences in wind erosion potential among the four treatments rather than the exact representation of wind speeds at the experimental site. Threshold wind velocities are determined in SWEEP by automatically increasing the wind speed in 1 m s^{-1} increments (beginning with 1 m s^{-1}) until soil loss is obtained for the simulated field soil and vegetation conditions. The first occurrence of soil loss is considered the threshold wind speed in SWEEP.

Statistical Analysis

Data on measured soil properties and simulated soil loss were analyzed using PROC MIXED in SAS (SAS Institute, 2015). Residue management treatments and sampling time were considered as fixed factors, while replications were random variables. Data were tested for normality prior to analysis of treatments using PROC UNIVARIATE in SAS. To study correlations of GMD and WEF with residue cover and SOC and POM concentrations, PROC CORR in SAS was used. The differences among treatments and the significance of correlations were studied at the 0.10 probability level.

RESULTS AND DISCUSSION

Treatment effects on wind erodibility parameters including dry aggregate-size distribution, GMD, and WEF were significant (Tables 4–5). Because the treatment × sampling time interaction was significant for some erodibility parameters, the data are discussed by sampling time. Treatments had significant effects on all the aforementioned wind erodibility parameters in the spring sampling but not in the fall (Tables 1–2). Treatments had no effects on GSD at any sampling time.

Dry Aggregate-Size Distribution

Corn residue grazing and baling effects on the dry aggregate-size distribution varied with the aggregate-size class (Table 4). In spring 2014, baled and lightly grazed plots had a 35% greater proportion of 0.425- to 0.84-mm small aggregates than heavily grazed and control (non-baled and non-grazed) plots. At the same sampling time, the control and grazed plots had 2.9 times more 14- to 45-mm aggregates than the baled plots. In spring 2015, similar to spring 2014, baled plots had a greater (78%) proportion of 0.425- to 0.84-mm aggregates. At the same time, control plots had a 43% greater proportion of 6.3- to 14-mm aggregates compared with baled and grazed plots. These results indicate that baling, in general, increased the amount of small aggregates and reduced the amount of large aggregates in spring. In other words, large aggregates (0.84–45 mm) broke down

Table 4. Fraction of dry aggregates in different aggregate-size classes for four residue removal treatments in an irrigated no-till continuous corn system on a semiarid soil in west-central Nebraska.

Treatment	Dry aggregate-size distribution						
	<0.425 mm	0.425–0.84 mm	0.84–2.00 mm	2.00–6.30 mm	6.3–14 mm	14–45 mm	>45 mm
				Spring 2014			
Control	0.22 a†	0.20 b	0.13 a	0.18 a	0.11 a	0.12 a	0.04 a
Light grazing	0.22 a	0.29 a	0.15 a	0.17 a	0.10 a	0.07 ab	0.00 a
Heavy grazing	0.23 a	0.23 b	0.16 a	0.20 a	0.11 a	0.07 ab	0.00 a
Baling	0.22 a	0.29 a	0.18 a	0.21 a	0.07 a	0.03 b	0.00 a
				Spring 2015			
Control	0.26 a	0.09 b	0.13 a	0.24 a	0.15 a	0.13 a	0.00 a
Light grazing	0.28 a	0.13 ab	0.15 a	0.21 a	0.11 b	0.07 a	0.05 a
Heavy grazing	0.29 a	0.14 ab	0.17 a	0.22 a	0.10 b	0.08 a	0.00 a
Baling	0.29 a	0.16 a	0.16 a	0.21 a	0.10 b	0.08 a	0.00 a
				Fall 2015			
Control	0.21 a	0.12 a	0.13 a	0.24 a	0.16 a	0.13 a	0.01 a
Light grazing	0.25 a	0.13 a	0.13 a	0.23 a	0.14 a	0.11 a	0.01 a
Heavy grazing	0.24 a	0.09 a	0.11 a	0.18 a	0.13 a	0.18 a	0.07 a
Baling	0.24 a	0.12 a	0.15 a	0.24 a	0.14 a	0.09 a	0.02 a

† Means followed by lowercase letters within the same column and sampling time are not significantly different.

into smaller aggregates ($\leq$0.84 mm) due to baling. Grazing had smaller effects than baling, but it reduced the amount of large (6.3–14 mm) aggregates relative to the control in spring 2015.

Geometric Mean Diameter and Wind-Erodible Fraction

Corn residue baling reduced the GMD and increased the WEF in spring (Table 2). Averaged across spring 2014 and spring 2015, baling reduced the GMD by 80% and increased the WEF by 25% relative to control plots. Grazing did not significantly affect the GMD and WEF compared with the control (Table 5). However, while differences between grazing and control treatments were not statistically significant, there was a consistent trend in the results. Numerical values of GMD were smaller and WEF was larger under light and heavy grazing compared with the control. The GMD values were in this order: control $\geq$ light grazing = heavy grazing $\geq$ baling; WEF values were in this order: control $\leq$ light grazing = heavy grazing $\leq$ baling (Table 2).

These results indicate that residue baling increases the susceptibility of the soil to wind erosion in springtime in this semiarid environment. Residue baling reduced the amount of large dry aggregates in springtime. The decreased dry soil aggregate size after residue baling agrees with results from the few studies in the western Corn Belt (Blanco-Canqui et al., 2014; Osborne et al., 2014; Jin et al., 2015), which have found reduced soil dry aggregate size when corn residue was mechanically removed at high rates from no-till continuous corn systems under rainfed (Osborne et al., 2014; Jin et al., 2015) and irrigated (Blanco-Canqui et al., 2014) conditions.

The results also indicate that grazing for 7 and 8 yr had smaller effects than baling on wind erosion risks. The decrease in the amount of large (6.3–14-mm) aggregates in spring 2015

Table 5. Cattle grazing and baling impacts on the geometric mean diameter (GMD) of dry soil aggregates, geometric standard deviation (GSD) of dry soil aggregates, wind-erodible fraction (WEF), simulated soil loss under bare soil, and simulated soil loss under soil plus actual amounts of residues in an irrigated no-till continuous corn system in west central Nebraska.

Treatment	Year	GMD	GSD	WEF	Simulated wind erosion loss†	
					Bare soil	Soil + residue
		mm		%	kg m^{-2}	
Control	spring 2014	1.24 a‡	15.01 a	42.84 b	4.55 b	0.00 b
Light grazing		0.85 ab	11.31 a	50.93 a	4.68 ab	0.00 b
Heavy grazing		0.92 ab	11.79 a	45.37 ab	4.65 ab	0.00 b
Baling		0.71 b	9.08 a	51.00 a	4.74 a	1.04 a
Control	spring 2015	1.40 a	16.88 a	34.26 b	4.52 b	0.00 b
Light grazing		0.92 ab	17.23 a	41.80 a	4.66 a	0.00 b
Heavy grazing		0.80 ab	14.44 a	42.49 a	4.67 a	0.00 b
Baling		0.76 b	14.63 a	45.36 a	4.69 a	0.92 a
Control	fall 2015	1.55 a	13.64 a	32.68 b	4.45 a	
Light grazing		1.12 a	14.78 a	37.97 a	4.59 a	
Heavy grazing		2.13 a	20.78 a	32.29 b	4.24 b	
Baling		1.21 a	14.38 a	35.88 ab	4.56 a	

† Loss as simulated with SWEEP for a 3-h, 13 m s^{-1} windstorm.

‡ Means followed by different lowercase letters within the same column and sampling time are significantly different.

under light and heavy grazing relative to the control suggests that grazing could increase the wind erosion potential (Table 4). Although statistically not significant, grazing also tended to reduce the GMD and increase the WEF (Table 5) compared with the control. This trend suggests that grazing could significantly increase wind erosion risks in the longer term (>8 yr), which strongly suggests the need to continuously monitor the wind erodibility parameters for this experiment. Studies assessing wind erosion potential under different corn residue grazing intensities are unavailable to compare with our study results. However, studies from grasslands (Vermeire et al., 2005) and rangelands (Aubault et al., 2015) have reported increased risks of wind erosion under intensive animal grazing.

It is notable that, while not significant, heavy grazing in spring 2014 showed a larger GMD and smaller WEF than light grazing. This result was opposite to what was observed in spring 2015, when heavy grazing had a smaller GMD and larger WEF than light grazing. These opposing trends were also observed for simulated soil loss (discussed below). One would intuitively expect less cover to result in smaller aggregates due to more direct exposure to the weathering forces of wet–dry, freeze–thaw, and freeze-drying. However, such trends could be a result of the spatial variability in soils or the heavier grazing traffic resulting in compression of the soil into larger aggregates.

Our results also suggest that soil aggregate behavior changed from spring to fall. The increased canopy cover during the corn growing season and fallen residues on the soil surface, combined with favorable climatic conditions in summer and early fall, probably improved soil aggregate properties of the baled and grazed plots, reducing their susceptibility to wind erosion. Table 5 indicates that the GMD and WEF of the grazed and baled plots in fall were nearly similar to the level of the control in spring. This indicates that the near-surface soil structural quality of the grazed and baled plots rebounded in fall, recovering to a level similar to that of the control plots. Our results indicate that residue grazing and baling effects on soil aggregate properties are temporally variable and depend on the sampling time. In the study region, the risks of wind erosion are the highest in late winter and early spring when winds are frequent and strong. The significant residue removal impact on soil aggregate disintegration during spring thus coincides with the time when soils are at high risk of wind erosion.

Factors Affecting Aggregate Breakdown Due to Crop Residue Removal by Baling and Grazing

Corn Residue Cover

Corn grain and residue yield did not differ among the four treatments in any year (Stalker et al., 2015), but baling after harvest in fall removed about 43% of residues in 2013 and 2014 prior to our sampling periods (Table 1). Differences in residue cover percentages among the four treatments were highly significant (Fig. 1). Averaged across spring 2014 and 2015, residue cover percentage was in this order: control (91%) > light grazing (73%) > heavy grazing (55%) > baling (22%). Control plots (no baling and no grazing) had about 22% more residue cover than lightly grazed, 36% more residue cover than heavily grazed, and 70% more residue cover than baled plots (Fig. 1). We did not measure corn residue yield in spring 2014 and 2015. However, Stalker et al. (2015), for the same experiment, measured residue yield in spring of 2009, 2010, and 2011 and reported that the residue amount remaining in spring averaged across the years was lower than in fall of the previous year by 20% for the control, 22% for light grazing, 27% for heavy grazing, and 71% for baling. The 3-yr data reported by Stalker et al. (2015) indicate that the residue amount in spring in this experiment was significantly lower than in fall for each treatment and that baling had the lowest amount of residue remaining.

Changes in wind erodibility parameters were correlated with crop residue cover. In spring 2014, the GMD increased as residue cover increased (Fig. 2A), but the WEF and residue cover were not significantly correlated (Fig. 2B). In spring 2015, both the GMD and WEF were highly correlated with the residue cover percentage. The GMD increased and the WEF decreased with an increase in residue cover (Fig. 2C and 2D). Changes in residue cover explained 60% of the variability in the GMD and 50% of the variability in the WEF in spring 2015 (Fig. 2). In other words, the size of dry soil aggregates decreased with a decrease in residue cover due to baling and grazing, indicating that residues protected the soil surface and maintained aggregate stability relative to plots with limited residue cover. Residue cover under baling fell to 22%, which resulted in a significant increase in the wind erosion potential. This finding thus suggests that 22% residue cover is insufficient to reduce wind erosion risks in this semiarid environment. However, the lack of significant differences in wind erosion potential among light grazing (73% residue cover), heavy grazing (55% residue cover), and the control (91% residue cover) suggests that a decrease in residue cover to about 55% may not significantly increase the risk of wind erosion in this region.

Soil Texture and Climate

Coarse-textured soils can be less resistant to wind erosion than fine-textured soils because the particle-size distribution has a strong influence on the soil aggregate stability (Lyles and Tatarko, 1986; Lehrsch, 1998; Dagesse, 2011). Table 2 shows that the soil textural class for the study plots was sandy loam. The high sand content of this soil may have contributed to the adverse effects of residue baling on the aggregate-size distribution. Soils with high sand content often have smaller, weaker, and less stable macroaggregates than soils with high clay content. Clay particles bind together more strongly due to their higher specific surface area and activity than sand or silt particles (Fouli et al., 2013).

The decrease in dry soil aggregate size also suggests that the reduced residue cover due to baling and grazing exposed surface soil aggregates to external climatic conditions such as raindrop impact and soil temperature and moisture fluctuations. These conditions probably contributed to rapid aggregate breakdown. Near-surface soil aggregates in semiarid environments can be especially vulnerable to disruption by raindrops, compared with

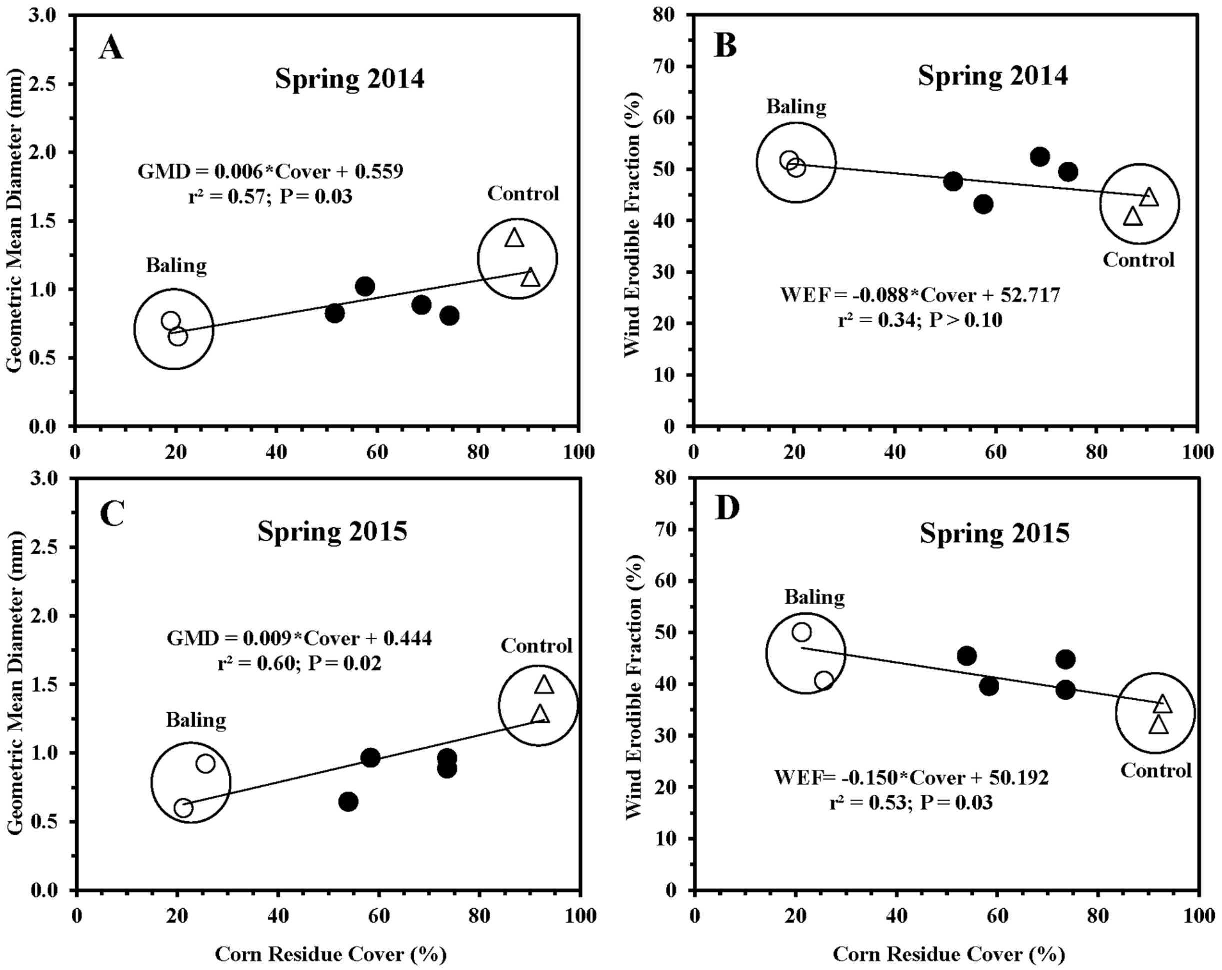

Fig. 2. Relationship of (A,C) the geometric mean diameter (GMD) and (B,D) the wind-erodible fraction (WEF) of dry soil aggregates with corn residue cover in an irrigated no-till continuous corn system in west-central Nebraska. The solid circles represent both light and heavy grazing.

soils in regions with higher precipitation, due to reduced aggregate development and organic matter content (Blanco-Canqui et al., 2016). Reduced residue cover in baled and grazed plots may have also increased fluctuations in soil temperature. While we did not monitor changes in soil temperature in this study, another study in a similar region (western Kansas) found that residue removal >50% increased the soil temperature by about 2°C in spring (Kenney et al., 2015). The same study found that the amplitude of daytime and nighttime soil temperatures in plots with limited or no residue cover in winter and spring was larger than in plots with high residue cover. Such large fluctuations in soil temperature due to residue removal can contribute to soil aggregate breakdown.

Organic Carbon and Particulate Organic Matter

In this study, residue baling and grazing after 7 and 8 yr did not reduce the SOC concentration (Table 6). While baling reduced the GMD and increased the WEF, it had no effect on SOC concentration. As a result, the GMD (Fig. 3A) and WEF (Fig. 3B) were not significantly correlated with SOC concentration ($r < 0.34$, $P > 0.10$). The GMD tended to increase and the WEF tended to decrease with an increase in SOC concentration, but, statistically, such correlations were not significant. Changes

Table 6. Concentration of soil organic C (SOC) and particulate organic matter (POM) under four residue removal treatments in an irrigated no-till continuous corn system in west-central Nebraska.

Residue	SOC	POM
	g kg^{-1}	g kg^{-1}
	Spring 2014	
Control	6.5 ± 3.3†	11.3 ± 0.1
Light grazing	8.9 ± 4.5	13.4 ± 2.2
Heavy grazing	13.2 ± 0.1	13.3 ± 1.8
Baling	8.8 ± 0.5	10.3 ± 2.2
P > *F*	ns‡	ns
	Spring 2015	
Control	11.2 ± 1.0	11.7 ± 1.9
Light grazing	14.3 ± 2.1	12.6 ± 1.2
Heavy grazing	13.6 ± 2.7	13.5 ± 1.5
Baling	9.9 ± 1.1	9.0 ± 0.5
P > *F*	ns	ns
	Fall 2015	
Control	14.8 ± 0.5	13.3 ± 0.4
Light grazing	14.3 ± 1.2	13.8 ± 0.8
Heavy grazing	14.5 ± 0.5	11.2 ± 0.9
Baling	15.3 ± 4.9	13.1 ± 7.5
P > *F*	ns	ns

† Mean ± standard deviation.

‡ ns, not significant at the 0.10 probability level.

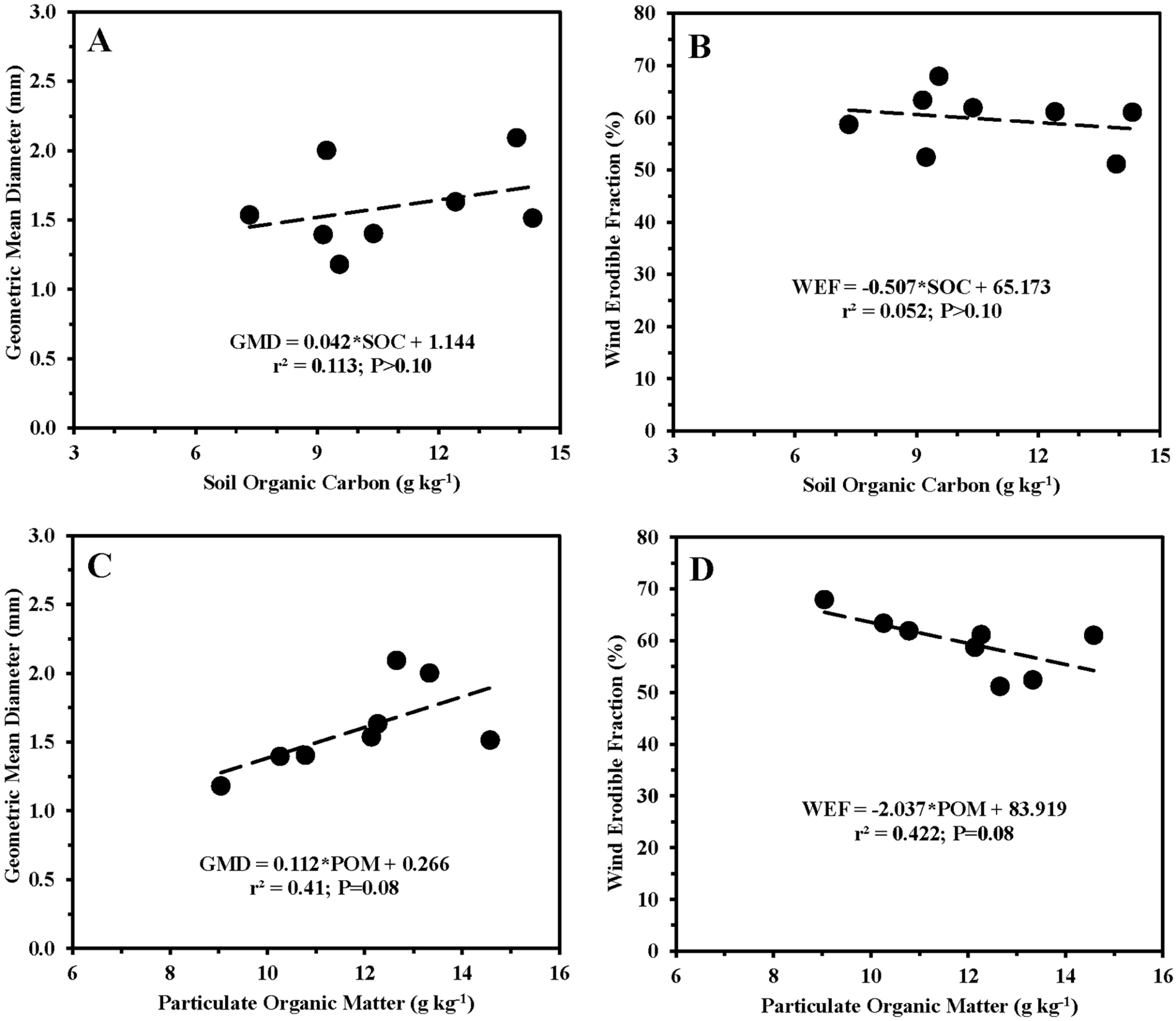

Fig. 3. Relationship of the geometric mean diameter (GMD) and the wind-erodible fraction (WEF) of dry soil aggregates with changes in (A,B) soil organic C (SOC) and (C,D) particulate organic matter (POM) concentration due to residue grazing and baling in an irrigated no-till continuous corn system in a semiarid soil in west-central Nebraska.

in the POM concentration appeared to influence the aggregate-size distribution more than SOC. Statistical differences in the POM concentrations between the control and the residue removal plots were not significant (Table 6), but the POM concentration was moderately and significantly correlated ($r = 0.64$) with the GMD and WEF. The GMD increased (Fig. 3C) whereas the WEF (Fig. 3D) decreased with an increase in POM concentration. These results suggest that POM, the microbially active fraction of the soil organic matter, probably improved the stability of macroaggregates. Our results agree with the study by Jin et al. (2015), which found that residue baling at high rates reduced POM concentrations, and this reduction was correlated with a decrease in dry aggregate size in a rainfed no-till system in eastern Nebraska. Our results also suggest that POM could be a more sensitive determinant of dry aggregate formation and stability than total organic C in this environment.

Simulated Soil Loss

Wind erodibility is increasingly controlled by soil properties as residue cover decreases. When residue production is low, such as in times of drought or if excessive removal occurs by baling or grazing, the wind erosion process is more sensitive to aggregation. The simulations by the SWEEP model were first performed for bare soil, using only soil properties (GMD and GSD), without residues, to observe the effects of the treatments on soil erodibility and loss alone. Next, the measured residue cover was added as biomass inputs in the SWEEP model.

Bare Soil

Predicted soil losses with the SWEEP model tended to follow the trends of the WEF and GMD, although differences in predicted soil loss among treatments and sampling dates were not large (Table 5). Soil loss was significant and, on average, was 4% larger under baling than under the control in spring in both years (Table 2). The increased soil loss was expected because less crop residue should mean greater breakdown of aggregates exposed to weathering. Grazing had no effect on soil loss in spring 2014, but in spring 2015, both light and heavy grazing increased soil loss compared with the control (Table 5). In fall 2015, heavy grazing appeared to have less soil loss than the other treatments, and this is attributed to the spatial variability among treatment plots in terms of soil properties as well as cattle trafficking patterns because this heavy grazing effect was not consistent with that observed in spring. These results suggest that further study is warranted into the effects of cattle traffic on aggregate formation (i.e., when wet) or breakdown (i.e., when dry). Soil loss in spring was greater than in the fall for all treatments, which is attributed to the greater exposure of the soil surface to winter weather, which tends to break down aggregates.

Soil with Residues

When the measured residue cover was added to the surface inputs of the SWEEP model, the results were straightforward. As expected, the greater the corn residue cover, the lower the soil loss. In fact, baling was the only treatment that caused soil loss in spring of 2014 (1.04 kg m^{-2}) under an average 19.7% residue cover and in spring 2015 (0.92 kg m^{-2}) under an average 23.4% residue cover. Soil loss simulated under the residue cover associated with the baled plots was much lower than soil loss without residue cover. Residues left on the surface of the control and grazed plots were high (>50%), which reduced simulated soil losses from these treatments to zero. Results using the SWEEP model appear to support the general recommendation that >30% residue cover is needed to control wind erosion (Unger, 2006; Muth et al., 2012). Although simulated losses in the spring were near the tolerable rate (T value) of 1.12 kg m^{-2}, historical weather records show that 2.1% of all winds at Sidney, NE, are >13 m s^{-1}. In this study, as discussed above, baling reduced the residue cover to about 22%, which could significantly increase wind erosion risks, while heavy grazing, which reduced the residue cover to 55%, may not significantly increase wind erosion risks.

Wind Erosion Threshold

The most erodible time of year for any location depends on the combination of wind erosivity and the erodibility of the surface. The historical records show that the most erosive winds at this study site occur in April. Thus, our simulations coinciding with our spring soil samplings are considered representative of the period with the highest erosion potential. The threshold wind speed at which wind erosion is initiated was determined using the measured soil conditions with and without residue. For bare soils, the threshold wind speed was between 8 m s^{-1} for the baled plots and 9 m s^{-1} for the other treatments. The probability of a wind event of 8 m s^{-1} or greater in April using the nearby Sidney, NE, historical weather is 18.5%, while the probability of a wind speed >9 m s^{-1} is 11.9%. For the fall treatments, the threshold was between 9 and 10 m s^{-1} with a 7.9 and 5.2% probability, respectively, of those wind speeds or greater occurring in November. This indicates that based on the historic winds at Sidney, NE, an erosion event is 129 to 134% more likely to occur in spring than in fall for bare soil conditions. When corn residue cover was included in the simulations, the threshold for wind erosion ranged from 12 m s^{-1} for the lowest residue cover of 19% (baled plots) up to 21 m s^{-1} for the highest residue cover of 92.8% (control plots). Historical records for April at Sidney show that 3.2% of the winds are >12 m s^{-1}, while only 0.03% of the winds are historically above 21 m s^{-1}. These results illustrate the importance of maintaining residue cover to control wind erosion in the study region.

CONCLUSIONS

Our results indicate that the baling of corn residues in an irrigated no-till continuous corn system on a semiarid soil in west-central Nebraska can increase the wind erosion potential. Baled plots had a greater proportion of microaggregates with a corresponding lower proportion of macroaggregates than plots without baling, suggesting that residue removal increased the susceptibility of the soil to wind erosion. Baling had greater adverse effects than grazing. Differences in wind erodibility parameters such as the GMD and WEF between grazing and control treatments were not, in general, statistically significant, but there was a consistent trend for reduced soil aggregate size under both light and heavy grazing relative to the control. This finding suggests that residue grazing may increase wind erosion risks in the longer term (>8 yr), thereby warranting further long-term monitoring. Baling effects were significant only in spring and not in fall, which suggest that corn residue baling increases the wind erosion potential in springtime when winds are high and residue cover is limited. Soil erodibility increased as corn residue cover decreased. Residue removal did not reduce SOC and POM concentrations, but the latter was moderately correlated with soil aggregate size, which suggests that the trend for decreased POM concentration due to residue removal was partly responsible for the aggregate disintegration. Predicted soil loss using the SWEEP model followed the trends of measured soil erodibility properties and showed, similar to the measured data, that baling can significantly increase wind erosion risks if the residue cover falls to about 22%. Overall, corn residue baling can increase the wind erosion potential in this semiarid environment, but grazing had smaller effects after 7 and 8 yr of management.

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