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Does Cattle Grazing and Baling of Corn Residue Increase Water Erosion?

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A better understanding of the implications of corn (*Zea mays* L.) residue grazing and baling on soil and environmental quality is needed to develop sustainable integrated crop–livestock production systems. We studied how corn residue grazing and baling impacted water erosion in a rainfed and an irrigated site in Nebraska after one and seven grazing seasons, respectively. Treatments were grazing (4.4 animal unit mo [AUM] ha^{-1}), baling, and control (no residue removal) in triplicate at the rainfed site on a Yutan silty clay loam (6% slope) and light grazing (2.5 AUM ha^{-1}), heavy grazing (5 AUM ha^{-1}), baling, and control in duplicate at the irrigated site on Duroc loam and Satanta loam (5.3% slope). We measured erosion under simulated rainfall for 30 min at an intensity of 6.3 ± 1.2 cm h^{-1}. Erosion did not increase after one season of grazing at the rainfed site, but it significantly increased after seven seasons of grazing at the irrigated site. At this site, both heavy and light grazing increased runoff by 3.3 mm and sediment loss by 0.26 Mg ha^{-1}. Baling had larger effects on water erosion than grazing. Across both sites, baling reduced time to runoff start by 14 min and increased runoff by 13 mm and sediment loss by 2.7 Mg ha^{-1}. While grazing after seven seasons increased nutrient loss, baling caused larger nutrient losses at both sites. Overall, grazing caused runoff losses of sediment, C, and nutrients in the long term, but baling consistently increased such losses in both short and long term.

Abbreviations: AUM, animal unit month; EC, electrical conductivity.

Core Ideas

- **Water erosion did not increase after one season of grazing, but it significantly increased after seven seasons of grazing.**
- **Baling increased water erosion and its effects were larger than grazing.**
- **Water erosion increased as residue cover decreased.**

Corn (*Zea mays* L.) residue is an essential component of integrated crop–livestock systems (Sulc and Franzluebbers, 2014). Whether grazed or baled, residue provides a low-cost feed for ruminant livestock production (Rasby et al., 2014; Stalker et al., 2015). Corn residue grazing or baling is an increasingly common practice in the Midwest to meet the increasing demands for forage, particularly in the fall and winter months when forage supply is limited. Increased conversion of grasslands to corn and soybean (*Glycine max* L.) production and increased feed costs have augmented demands for crop residues as forage in recent years.

A better understanding of residue grazing and baling implications on soil and environmental quality is needed to support and develop sustainable crop–livestock production systems. One of the questions related to soil and water quality is: Does residue baling or grazing increase risks of water erosion under intense rainstorms? Increasing climatic fluctuations with severe drought and intense rainstorm events may increase the soil's susceptibility to water erosion if soil surface protective cover is reduced through crop residue baling or grazing (Nearing et al., 2004). Studies indicate that in the Midwest, the number of intense storms with 75 mm d^{-1} have increased by 103% in the last 50 yr (Saunders et al., 2012). For example, in the spring of 2015, intense rainstorms in the Midwestern United States were common, causing flooding and water erosion concerns. Also, prolonged droughts may degrade near-

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surface soil structural properties (i.e., aggregation), making the soil more susceptible to water erosion in subsequent years with intense rainstorms. Interactions of climatic fluctuations with soil erosion processes under the new scenarios of crop residue management, such as cattle grazing and baling, have not been much scrutinized.

Effects of grazing on water erosion can differ from those of baling as follows. First, cattle grazing normally removes between 15 and 25% of residues (Rasby et al., 2014; Stalker et al., 2015), but baling using commercial equipment often removes larger amounts (>40%). Second, cattle preferentially consume grain, leaves, and husks. Third, grazing with cattle recycles nutrients through manure deposition. Manure input can improve soil structural processes, such as aggregation, and can reduce soil erodibility (Wortmann and Shapiro, 2008), but some manure-derived nutrients (i.e., dissolved P) may also be lost through runoff. As a result, cattle grazing of residue may influence water erosion processes and associated water quality parameters differently from residue baling.

Some studies have evaluated the effects of cattle grazing of crop residues on subsequent crop yields, soil compaction, and other soil properties in Iowa (Clark et al., 2004) and Illinois (Tracy and Zhang, 2008), but implications on water erosion have not been specifically documented. Cattle grazing may increase risks of runoff loss by compacting soil, reducing macroporosity, and concomitantly reducing water infiltration. On an on-farm study in east central Nebraska, Wienhold and Gilley (2010) observed that corn residue baling at 6 ± 1 Mg ha^{-1} had no effect on runoff, but it slightly increased sediment loss (0.36 ± 0.02 Mg ha^{-1}) compared with no residue removal (0.27 ± 0.01 Mg ha^{-1}) when the total amount of residue produced was 12.9 ± 1 Mg ha^{-1}. Studies of crop residue removal from small plots also found that corn (Mirás-Avalos et al., 2009; Kenney et al., 2015), winter wheat (*Triticum aestivum* L.), and grain sorghum [*Sorghum bicolor* (L.) Moench] (Blanco-Canqui and Lal, 2009) residue removal at rates above 50% can increase sediment and nutrient losses.

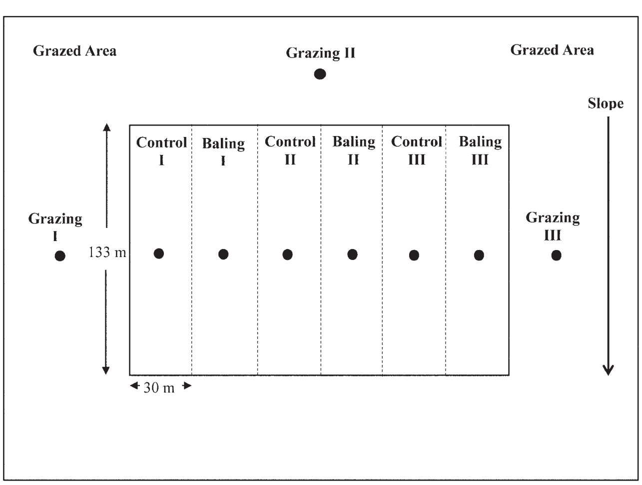

Fig. 1. Schematic representation of the plot layout within a 31-ha producer's rainfed field near Nebraska City, NE (not drawn to scale). Roman numerals I, II, and III indicate experimental blocks. The black dots represent the rainfall simulation points.

Grazing for extended periods of time may increase water erosion. A study conducted near El Reno, OK reported that grazing wheat–wheat–fallow and wheat–wheat–summer legumes increased losses of runoff and associated-sediment nutrients when growing wheat was grazed during winter and spring and when legumes were grazed between mid-July and mid-September (Daniel et al., 2006). Impacts of cattle grazing of pastures or grasslands on water and nutrient erosion have been more widely studied than crop residue grazing. Studies in Wisconsin (Vadas et al., 2015), Iowa (Schwarte et al., 2011), Oklahoma (Daniel et al., 2006), and Montana (Emmerich and Heitschmidt, 2002) have found that grazing of pastures can increase sediment and nutrient losses in runoff.

While it is well recognized that crop residues protect the soil surface and reduce water erosion (Lindstrom, 1986), site-specific information on the magnitude to which grazing and baling affect water erosion is scanty. Yet, this additional information can be useful for managing crop–livestock production systems. For example, little or no information exists on the magnitude of differences in runoff, sediment, and nutrient losses between baling and different grazing intensities. It is expected that grazing may have smaller effects on water erosion relative to residue baling, but the magnitude of effects may depend on soil type, topography, and grazing intensity. The objectives of this study were to (i) assess the impacts of corn residue grazing on runoff, sediment, and nutrient losses in a rainfed and an irrigated site in Nebraska and (ii) compare differences in runoff, sediment, and nutrient losses between residue grazing and baling. Our hypothesis was that grazing will increase runoff, sediment, and nutrient losses compared with no grazing, but such losses under grazing will be lower than those under baling.

MATERIALS AND METHODS

Description of the Experimental Sites and Management

This study was conducted in early spring 2015 using two ongoing corn residue grazing and baling experiments in eastern and west central Nebraska. The first site was an on-farm experiment located in eastern Nebraska about 16 km south of Nebraska City, NE (40.68° N lat, 95.86° W long; Fig. 1). The second site was located in west central Nebraska at the University of Nebraska-Lincoln's West Central Water Resources Field Laboratory near Brule, NE (41.09° N lat, 101.89° W long; Fig. 2). The site near Nebraska City is rainfed under no-till corn–soybean rotation, whereas the site near Brule is sprinkler irrigated under no-till continuous corn. The dominant soil series at the Nebraska City site, according to the USDA classification system, is Yutan silty clay loam (fine-silty, mixed, superactive, mesic Mollic Hapludalfs). This site is in a region with an elevation of 312 m with a mean annual precipitation of 861 mm. Two dominant soil series are present at the Brule site including Duroc loam (fine-silty, mixed, superactive, mesic Pachic Haplustolls) and Satanta loam (fine-loamy, mixed, superactive, mesic Aridic Argiustolls).

The elevation at the Brule site is 1056 m with a mean annual precipitation of 475 mm.

The experiment at the Nebraska City site was established in fall 2014 within a 31-ha producer's field after corn harvest (Fig. 1). Corn yield for the entire field (31 ha) was 13.1 Mg ha^{-1}. Estimated corn residue yield using a harvest index of 0.55 for eastern Nebraska was 10.7 Mg ha^{-1}. The experiment had three crop residue treatments, including control (no residue removal), grazing, and baling as shown in Fig. 1. The baled and control plots in triplicate were placed next to each other and fenced with electric wire during the grazing period to restrict cattle from the surrounding grazed area. Three grazed areas within the larger grazed area were each located next to each replication of baled and control treatments and were used as replications for the grazed treatment (Fig. 1). Corn residue in the baling treatment was raked using a V-rake (VR 1224; Vemeer Corp., Pella, IA) and then baled using a round baler (569 Premium; John Deere Co., Moline, IL) after grain harvest in the fall. The grazing treatment was stocked at a rate of 4.4 AUM ha^{-1}. Cows grazed corn residue for 87 d from 25 Oct. 2014 to 20 Jan. 2015. We do not have the exact amount of residue baled from the baled plots in the fall. However, we measured the quantity of corn residue remaining in each treatment plot in spring 2015 during the present study. Residue was measured in a 0.78-m^2 area from three points within each treatment plot. All of the residue found inside a circular rod of 1 m diam. was collected, weighed, oven dried at 60°C, and dry matter computed. The mean corn residue amount was 2.2 ± 1.2 Mg ha^{-1} (mean ± SD) under baled plots, 7.0 ± 0.7 Mg ha^{-1} under grazed plots, and 7.0 ± 1.8 Mg ha^{-1} under control plots.

The site near Brule was established in November 2008 and is under one full center pivot (65 ha) irrigation system (Fig. 2). The design was a randomized complete block with four corn residue management treatments in duplicate including 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 for a total of eight equally pie-shaped plots (Fig. 2). The area of each treatment plot was 8.1 ha (Fig. 2). Plots were fenced to restrict the cattle within the grazing plots and to prevent animal interference with corn residue treatments. Cows were introduced to and removed from all plots assigned to grazing treatments simultaneously each year. Cows (442 kg) grazed corn residue for an average of 62 d. The start and end dates of grazing varied slightly due to weather conditions affecting corn harvest date but averaged from early December to early February. Corn residue in baling treatment was raked into windrows using a V-rake (H&S HDII-17; H&S Manufacturing Co., Marchshfield, WI) and then baled using a round baler (Hesston 2856A; AGCO Manufacturing Co., Duluth, GA) after grain harvest in the fall. Residue baled was weighed, and then a subsample for each replicate was oven dried at 60°C and dry matter was computed. Additional details on experiment establishment and management of this research site were reported in a companion paper by Stalker et al. (2015).

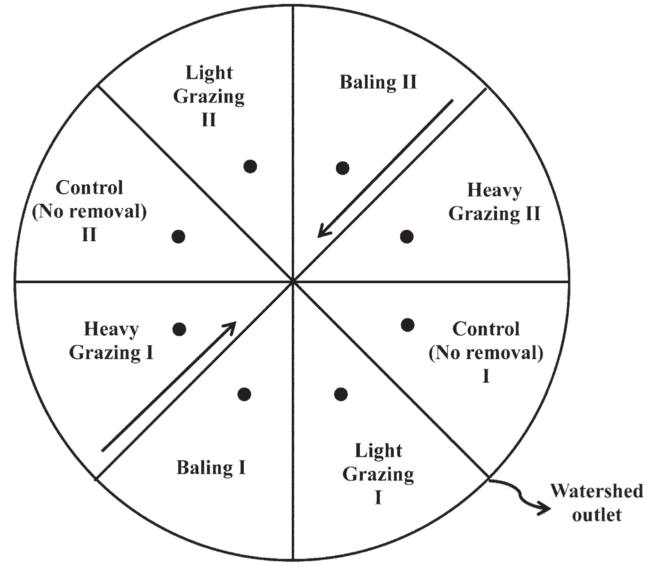

Fig. 2. Schematic representation of the experimental layout of the plots on a 65-ha under a center pivot irrigated field near Brule, NE (not drawn to scale). Roman numerals I and II indicate experimental blocks. The black dots represent the rainfall simulation points. The two long arrows indicate the approximate slope direction in this watershed cornfield.

At the Brule site, corn grain yields averaged from 2009 to 2014 were 9.2 ± 0.8 Mg ha^{-1} under control, 9.5 ± 0.8 Mg ha^{-1} under light grazing, 9.7 ± 0.7 Mg ha^{-1} under heavy grazing, and 9.4 ± 1.0 Mg ha^{-1} under baled plots. Residue amount produced in each plot was measured in fall 2008, 2010, and 2011. Each plot was sampled at 10 random locations. Residue was measured in a 0.5-m^2 quadrat (65.6 by 76.2 cm) centered on the row (76.2-cm row spacing) after corn harvest. Stalks were clipped to ground level, and all residues within the quadrat were collected. Residue amounts produced in 2009, 2012, 2013, and 2014 were estimated from the harvest index as measured data were not available. We used a harvest index of 0.52, which was obtained from measured data on grain and residue yield collected in 2008, 2010, and 2011 for this site. Table 1 shows the corn residue yield for each treatment by year. Averaged across years and treatments, residue yield at this site was 8.6 ± 0.9 Mg ha^{-1}. Averaged across years, the amount of residue baled from the baled plots was 3.6 ± 1.2 Mg ha^{-1}, which corresponded to 43 ± 15% of residue removal (Table 1).

Similar to the Nebraska City site, we also measured the corn residue amount remaining in each treatment plot at the Brule site in spring 2015. The corn residue amount was 14.43 ± 4.81 Mg ha^{-1} under control, 9.68 ± 3.51 Mg ha^{-1} under light grazing, 4.71 ± 3.27 Mg ha^{-1} under heavy grazing, and 2.70 ± 2.27 Mg ha^{-1} under baled plots. Because these values are the total amount of residue, they may include some residue (i.e., stalks) accumulated over time.

Furthermore, in spring 2015, residue cover was measured in all of the plots at both sites. It was measured by the line-transect method using a 30.5-m-long (100 ft) measuring tape (Shelton and Jasa, 2009). The tape was stretched and laid out diagonally at about a 45° angle across corn stalk rows to capture the variability of residue cover between rows. Residue hits or misses were

Table 1. Residue yield and amount of residue baled at the Brule site managed under irrigated no-till continuous corn.

Year	Control	Light grazing	Heavy grazing	Baling	Residue baled from the baled treatment	
		Mg ha^{-1}			Mg ha^{-1}	%
2008	8.07	7.4	7.42	7.89	5.13	65
2009	7.20	7.48	7.85	7.20	1.53	21
2010	9.07	9.32	9.98	8.76	4.39	50
2011	10.09	8.94	9.28	9.60	2.70	28
2012	8.95	9.42	9.05	8.49	4.07	48
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	8.56	8.57	8.72	8.45	3.61	43

evaluated at each 0.305-m (1-ft) mark of the 100-ft-long tape. The percent residue cover equals the total number of residue hits out of the 100 point evaluations. This measurement was repeated at three points in each plot in a zig-zag pattern.

Water Erosion Measurements

Impacts of corn residue grazing and baling on runoff, sediment, and nutrient losses were studied under simulated rainfall in early spring 2015, which was after one winter of residue grazing at the Nebraska City site and after seven winters of residue grazing at the Brule site. Dry and wet run rainfall simulations were performed. The dry simulation run was conducted in each plot followed by a wet simulation run 24 h later. The dry run was performed to ensure that all treatment plots had similar antecedent soil–water content before water erosion measurements. The gravimetric water content of the soil before the wet run did not significantly differ among treatments at each site. Gravimetric water content was 28.5 ± 1.0 kg kg^{-1} (mean $\pm$ SD) at the Nebraska City site and 15.0 ± 2.2 kg kg^{-1} at the Brule site. Data were collected only during the wet run. The soil slopes at the rainfall simulation sites were 5.99 ± 0.78% at Nebraska City and 5.28 ± 0.97% at Brule.

A portable and single-nozzle rainfall simulator developed by Humphry et al. (2002) was used in this study. Rainfall was applied from a 2.5-m height through a TeeJet 1/2 HH-SS50WSQ nozzle (Spraying Systems Co., Wheaton, IL). The nozzle and related plumbing, in-line filter, pressure gauge, and electrical wiring were all assembled in a 3- by 3- by 3-m aluminum frame (Humphry et al., 2002). Simulated rainfall during both the dry and wet runs was applied for 30 min to each runoff plot at an intensity of 6.28 ± 1.18 cm h^{-1} at both sites. This simulated rainfall applied for 30 min portrayed a 2-yr return period for the Nebraska City site and a 3-yr return period for the Brule site (Hershfield, 1961). The rainfall intensity during simulation was measured using four rain gauges placed around the runoff plot, which were installed within each treatment plot (Fig. 1 and 2). Water used for the simulations had an electrical conductivity (EC) of 1.93 dS m^{-1} and a pH of 8.1 at the Brule site and an EC of 0.65 dS m^{-1} and a pH of 7.8 at the Nebraska City site.

The runoff plot had dimensions of 0.52 by 1.06 m and was enclosed by a rectangular runoff box driven to a 10-cm depth into the soil. Cumulative runoff was collected via a trough made from a PVC pipe cut in half lengthwise and placed at the downslope of each plot to direct runoff to a plastic bucket placed in a soil pit. For each simulated rainfall event, we measured time to runoff start and total runoff volume at the end of simulation (30 min). Runoff collected in buckets was combined into a larger container where the runoff water was vigorously stirred to uniformly distribute the sediment before collecting two separate 1-L runoff samples for laboratory analysis. The runoff subsamples were stored in coolers and transported to the laboratory. The first runoff subsample was used to determine sediment and sediment-associated C and N concentrations, while the second subsample was used to determine the concentration of nutrients in runoff.

The sediment concentration was determined by the evaporation method (Blanco-Canqui et al., 2004). The runoff subsamples were dried at 60°C in an oven, and sediment concentration was determined. Next, for the determination of sediment-associated C and N concentrations, the oven-dried sediment was finely ground, passed through 0.25-mm sieve, and analyzed for soil organic C and total N by the dry combustion method in a CHN Thermo Scientific Flash analyzer (Nelson and Sommers, 1996). Total P and K were analyzed on unfiltered runoff water samples. The water samples were digested using the alkaline persulfate method (Patton and Kryskalla, 2003), and digest samples were analyzed for P and K concentrations using ICP-AES (Kovar, 2003). Total N concentration was determined using high-temperature combustion (HTC) technology with chemiluminescence detection following the method EN-12260 (Teledyne-Teckmar Instrumentation, 1996). The concentrations of NH_4^+–N and NO_3^-–N in runoff were determined on filtered samples using flow injection analysis methods 4500-NH_3 and 4500-NO_3^-, respectively (Rice et al., 2012). Additionally, the pH of runoff water was determined using the 4500-H electrometric method, while EC was determined using the 2520 B test method (Rice et al., 2012). The runoff depth for each plot was computed using the runoff amount collected and the plot dimensions. Losses of sediment, sediment-associated C and N, and runoff nutrients in kilograms per hectare were computed from the data on concentration (mg L^{-1}), total runoff volume, and runoff plot area.

Soil Sampling and Analysis of Near-Surface Soil Properties

Soil properties including bulk density, wet aggregate stability, and concentration of soil organic C and total N were determined for the 0- to 5-cm depth to establish correlations with water erosion parameters for both sites. Soil was sampled from each plot at the time of rainfall simulations. Bulk density was determined using the core method on soil samples collected in cores (Grossman and Reinsch, 2002). Bulk soil samples were collected for the determination of wet aggregate stability and of the concentration of soil organic C and total N. The bulk samples were gently broken by hand and air-dried for 72 h. A fraction of the air-dried samples was sieved through 4.75- and 8-mm sieves for wet aggregate stability analysis, which was determined on 50 g of 4.75- to 8-mm air-dried aggregates by the wet sieving method using an automated sieving machine (Nimmo and Perkins, 2002). The method consisted of placing the aggregates on top of a stack of sieves with openings of 4.75, 2, 1, 0.5, and 0.25 mm in diameter placed in a water tank, saturating the aggregates by capillarity for 10 min, sieving in water for 10 min, oven drying the aggregates at 105°C, and computing wet aggregate stability as the mean weight diameter of the aggregates (Nimmo and Perkins, 2002). Sand correction was performed in each aggregate size fraction. Another portion of the air samples from each depth interval was roller milled to determine organic C and total N concentrations in a CN analyzer (Vario Max; Elementar Americas, Mount Laurel, NJ) by the dry combustion method (900°C; Nelson and Sommers, 1996).

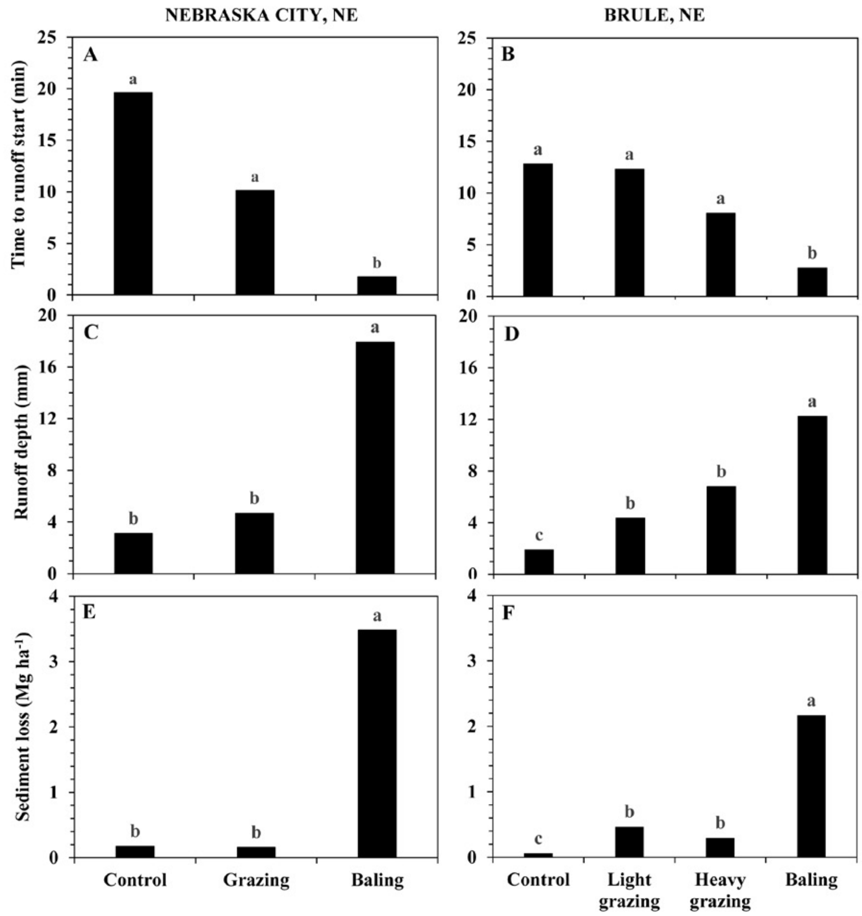

Fig. 3. Corn residue grazing and baling effects on time to runoff initiation (a, b), runoff depth (c, d), and sediment loss (e, f) for both the Nebraska City and Brule study sites in Nebraska. Bars followed by different letters are significantly different at a *P* value of ≤0.05.

Statistical Analysis

Data on water erosion parameters and soil properties were analyzed as a completely randomized block design using the PROC MIXED procedure in SAS (SAS Institute, 2015). Before the use of PROC MIXED, data were tested for normality using the Shapiro–Wilk test in PROC UNIVARIATE in SAS. Correlations and regression fits were performed using PROC CORR in SAS. The treatment differences were compared using the least significant difference separation test. Statistical significance was tested at the 0.05 probability level unless specifically noted otherwise.

RESULTS

Losses of Runoff and Sediment

Time to runoff start (Fig. 3a and 3b), runoff depth (Fig. 3c and 3d), and sediment concentration (Fig. 3e and 3f) significantly differed among treatments at both the Nebraska City and Brule sites. At the Nebraska City site, differences were, however, significant only between baling and the rest of treatments (Fig. 3a, 3c, and 3e). At this site, runoff from baled plots started 13 min earlier compared with that of the average from the grazed and control (no residue removal) plots. At the Brule site, runoff from baled plots started 8 min earlier compared with that of the average from the light grazed, heavy grazed, and control plots. Time to runoff initiation occurred in the following order: control ≥ grazed > baled at Nebraska City (Fig. 3a) and control ≥ light grazing ≥ heavy grazing > baled at Brule (Fig. 3b). Grazing tended to reduce time to runoff initiation relative to the control, but differences were not statistically significant at the two sites.

Runoff depth also differed among treatments at both sites (Fig. 3c and 3d). At the Nebraska City site, grazing did not increase runoff loss compared with that of the control, and both grazing and control had less runoff loss than that of baling (Fig. 3c). Baling increased runoff loss by 4.8 times (17.9 vs. 3.8 mm) compared with the average across the control and grazing treatments. At the Brule site, however, grazing increased runoff loss compared with that of the control (Fig. 3d). At this site, both light and heavy grazing increased runoff, on average, by 2.7 times (5.2 vs. 1.9 mm) compared with that of the control. At the same site, baling had a large and significant effect on runoff loss. It increased runoff loss by 2.2 times (12.2 vs. 5.6 mm) compared with the average across light and heavy grazing and by 6.4 times (12.2 vs. 1.9 mm) compared with that of the control. At the Brule site, runoff loss gradually increased in the following order: baled > heavy grazing = light grazing > control.

Treatment effects on sediment loss mirrored those on runoff loss (Fig. 3e and 3f). At the Nebraska City site, while differences in sediment loss between grazing and control did not

Table 2. Grazing and baling effects on loss of sediment-associated nutrients for two corn residue grazing and baling experimental sites in eastern and west central Nebraska.

Site	Treatments	Sediment-associated nutrients† Total C	Total N
		kg ha^{-1}	
Nebraska City (eastern Nebraska)	Control	3.61b	0.36b
	Grazing	4.09b	0.41b
	Baling	60.87a	6.33a
Brule (west central Nebraska)	Control	1.06b	0.14b
	Light grazing	10.01a	0.93a
	Heavy grazing	6.56a	0.56a
	Baling	25.11a	2.23a

† Means followed by different letters in a column within a site are significantly different at $P \leq 0.05$.

differ, control and grazed plots had less sediment loss than baled plots (Fig. 3e). At this site, sediment loss from baled plots was 20 times (3.48 vs. 0.17 Mg ha^{-1}) greater than the average across grazed and control plots. Similarly, at the Brule site, sediment loss from baled plots was 6.8 times (2.17 Mg ha^{-1}) greater than the average across light and heavy grazing (0.32 Mg ha^{-1}) and 36 times that of the control (0.06 Mg ha^{-1}; Fig. 3f). At the same site, grazing had small and significant effects on sediment loss (Fig. 3f). Both light and heavy grazing increased sediment loss by 5.3 times relative to that of the control (Fig. 3f).

Losses of Sediment-Associated Carbon and Nitrogen and Runoff Nutrients

Losses of sediment-associated total C and total N also differed among treatments (Table 2). At the Nebraska City site, grazing did not increase the losses of sediment-associated C and N compared with control. Baling, however, increased losses of sediment C and N by 16 times compared with the average across grazed and control plots (Table 2). At the Brule site, baling as well as grazing increased the loss of sediment C and N relative to the control. Baling and light and heavy grazing increased losses of C in sediment from 1.06 kg ha^{-1} (control) to an average of 18.89 kg ha^{-1} (Table 2). They also increased losses of total N in sediment from 0.14 kg ha^{-1} (control) to an average of 1.24 kg ha^{-1} (Table 2). Similar to runoff and sediment loss, baling caused a larger loss of sediment C (25 vs. 8 times) and N (16 vs. 5 times) than grazing.

Runoff pH and EC values did not differ among treatments within each site except that the control had a slightly higher EC than the grazing and baling at the Nebraska City site. Differences in runoff nutrient loss among treatments were significant (Table 3). Baling consistently caused losses of runoff nutrients at both sites. At the Nebraska City site, baling increased the loss of K^+ by 4.9 times, NO_3–N by 5 times, NH_4–N by 6 times, and total N by 7.2 times. At the Brule site, it increased the loss of K^+ by 3 times, NO_3–N by 6 times, NH_4–N and total P by 3.5 times, and total N by 5.7 times (Table 3). Grazing did not increase nutrient loss at the Nebraska City site, but at the Brule site, both light and heavy grazing increased the loss of K^+ by 2.9 times, NO_3–N by 2.5 times, and total N by 2.8 times. Grazing did not, however, increase losses of NH_4–N or total P at the Brule site. Light and heavy grazing had similar effects on increasing the losses of total N, NO_3–N, and K^+ than baling. It is important to indicate that losses of runoff nutrients, particularly total P and NH_4–N, due to baling and grazing were numerically and statistically significant; the amount (kg ha^{-1}) of such losses was small (Table 4). The K^+ concentration in runoff at the Brule site was larger than that at the Nebraska City site, corroborating that semiarid soils can contain more K than soils from regions with higher precipitation.

Relationship of Runoff, Sediment, and Nutrient Loss with Residue Cover and Soil Properties

Baling and grazing reduced the percentage of residue cover at both sites (Table 4). At the Nebraska City site, the percentage of residue cover existed in the following order: control (72%) > grazing (57%) > baling (39%). At the Brule site, the percentage of residue cover averaged across 6 yr was in the following order: control (88%) > light grazing (75%) > heavy grazing (66%) > baling (42%). Losses of runoff, sediment, sediment-associated C, and runoff nutrients were related to the amount of residue cover left in each plot at both sites (Fig. 4). Residue cover was linearly correlated with time to runoff initiation (Fig. 4a and 4b). Residue cover was exponentially correlated with runoff depth at the Brule site (Fig. 4c) and linearly correlated at the Nebraska City site (Fig. 4d). Similarly, residue cover was linearly correlated with sediment-associated C at the Nebraska City site. (Fig. 4h). Losses of sediment concentration were not significantly correlated with residue cover (Fig. 4e and 4f). While residue cover was not correlated with sediment-associated C at the Brule site

Table 3. Grazing and baling effects on loss of nutrients in runoff for two experimental sites in eastern and west central Nebraska.

Site	Treatments	pH	EC†	Total N	Total P	NO_3–N	NH_4–N	K^+
						kg ha^{-1}		
Nebraska City (eastern Nebraska)	Control	7.3	0.73a‡	0.09b	0.037a	0.02b	0.05b	0.33b
	Grazing	7.3	0.66b	0.20b	0.035a	0.05ab	0.07b	0.56ab
	Baling	7.0	0.64b	0.65a	0.089a	0.10a	0.30a	1.63a
Brule (west central Nebraska)	Control	8.0	2.07a	0.33c	0.002b	0.27c	0.002b	0.85b
	Light grazing	7.8	2.07a	0.81b	0.001b	0.49b	0.001b	2.05a
	Heavy grazing	7.9	2.05a	1.06b	0.003b	0.85b	0.003ab	2.90a
	Baling	8.0	2.05a	1.87a	0.007a	1.60a	0.007a	2.57a

† EC, electrical conductivity.

‡ Means followed by different letters in a column within a site are significantly different at $P \leq 0.05$.

(Fig. 4g), it was linearly correlated at the Nebraska City site (Fig. 4h). At the Nebraska City site, losses of sediment (Fig. 4e) and sediment-associated C (Fig. 4g) abruptly decreased with an increase in residue cover from baling to grazed and control plots, indicating that baling greatly increased losses of sediment and C compared with grazing and control.

Near-surface soil properties related to soil erodibility are reported in Table 5. At the Nebraska City site, grazing increased bulk density by about 10% relative to the control, but baling had no effects. At the same site, baling reduced wet soil aggregate stability by 48% compared with control and grazing treatments (Table 5). At the Brule site, soil properties did not statistically differ among the four treatments, but baling tended to increase bulk density and reduce the mean weight diameter of the water-stable aggregates and the soil organic C concentration compared with the rest of the treatments (Table 5). Also, light and heavy grazing tended to increase soil organic C and total N concentration compared with baling and control. At the Brule site, soil bulk density was significantly correlated with sediment loss (Fig. 5A) and runoff depth (Fig. 5B). Correlations between soil properties and water erosion parameters were not statistically significant at the Nebraska City site.

DISCUSSION

The increased water erosion after seven grazing seasons at the Brule site but no increase in water erosion after one grazing season at the Nebraska City site appear to suggest that consecutive grazing events may increase the risks of water erosion in the long term. We did not, however, monitor water erosion every year before this study at the Brule site to ascertain if grazing increased water erosion with time. The increased water erosion with grazing at the Brule site is primarily attributed to the reduced residue cover due to grazing, as differences in measured near-surface soil properties among treatments were not significant (Table 5). The effect of reduced residue cover on increasing water erosion is well documented (Lindstrom, 1986; Blanco-Canqui and Lal, 2009). While studies specifically assessing the impacts of corn residue grazing by livestock on water erosion are practically unavailable, those assessing the effects of grazing pastures or crops other than corn found a consistent increase in water erosion due to grazing (Mwendera et al., 1997; Daniel et al., 2006; Evans, 2005). In spring 2015, during this study, residue cover under light and heavy grazed plots was, on average, 26% lower than under the control (Table 4). Despite the relatively high percentage of residue cover (72% for light grazing and 55% for heavy grazing; Table 4), grazed plots still had higher losses of runoff, sediment, and nutrients compared with the control (89% cover).

Losses of runoff, sediment, and nutrients between light grazing (2.5 AUM ha^{-1}) and heavy grazing (5.0 AUM ha^{-1}) did not, however, significantly differ, which suggests that water erosion did not increase with an increase in grazing intensity under the conditions of this study. There was a trend for rapid runoff initiation and increased runoff losses under heavy grazing relative to light grazing, but differences were not statistically significant.

Table 4. Percent residue cover measured using the line-transect method for each treatment at both Nebraska City and Brule sites in spring.

Year	Nebraska City, NE			
	Control	Grazing	Baling	
2015†	72	57	39	
	Brule, NE			
	Control	Light grazing	Heavy grazing	Baling
2010	79	61	55	30
2011	90	80	60	53
2012	88	78	76	41
2013	83	74	64	52
2014	99	87	86	58
2015†	89	72	55	19
Mean	88	75	66	42

† This is the year when this study of rainfall simulation was conducted at both sites.

We expected that grazing intensity would increase water erosion. In pasturelands or rangelands, an increase in grazing intensity is widely known to increase water erosion (Meehan and Platts, 1978; Thurow et al., 1988; Mwendera et al., 1997; Cournane et al., 2011). We hypothesize that the use of higher stocking rates than 5.0 AUM ha^{-1} can increase water erosion compared with 2.5 AUM ha^{-1}.

The lack of significant grazing effects at the Nebraska City site may be due to the following reasons: 1. One grazing event may not be sufficient to significantly increase the risks of water erosion. Grazing can have cumulative negative effects on soil hydraulic properties in the long term (Koala et al., 2015). 2. At this site, residue cover under grazed plots was 15% lower than that in control plots, which indicates that the decrease in residue cover due to grazing at this site was smaller than the average at the Brule site (26%) (Table 4). It is also worthwhile to mention, however, that grazing at the Nebraska City site tended to reduce time to runoff start and increase losses of runoff, sediment-associated C and N, and runoff nutrients relative to the control, although differences were not statistically significant after one grazing event.

The significant grazing effect on water erosion at the Brule site was much smaller than the baling effect at both sites (Fig. 3). Baling of corn residues had large effects on water erosion and water quality parameters in both rainfed and irrigated environments. These large effects of baling are attributed to (i) the reduced residue cover and (ii) degradation of near-surface soil properties.

Losses of runoff, sediment, and nutrients increased with a decrease in residue cover due to baling at both sites (Fig. 4). This functional relationship corroborated the role of residues in reducing water erosion (Lindstrom, 1986; Blanco-Canqui and Lal, 2009). During this study, the residue cover under baled plots was 1.8 times (39 vs. 72%) lower at the Nebraska City site and 4.7 times (19 vs. 89%) lower at the Brule site relative to the control plots. These results indicate that baling of residues with commercial equipment in producer's fields greatly reduces residue cover (<39%), which was not sufficient to control water erosion to the level of no residue removal in both rainfed and irrigated environments. The amount of residue present under baled plots in the spring of 2015 (2.2 ± 1.2 Mg ha^{-1} at the Nebraska City site and 2.7 ± 2.3 Mg ha^{-1} at the Brule site) indicates that more than 2.7 Mg ha^{-1} of residue should be left on the soil if water erosion reduction to a level similar to the control is the goal. Previous studies also found that residue baling at high rates increases water erosion (Lindstrom, 1986; Blanco-Canqui and Lal, 2009; Wienhold and Gilley, 2010; Kenney et al., 2015).

The increased water erosion with baling can also be partly explained by the reduced wet soil aggregate stability. At the Nebraska City site, the mean weight diameter of water-stable aggregates under baling decreased by 30% compared with that of the control (Table 5). At the Brule site, the mean weight diameter of aggregates also tended to decrease with baling. Aggregate stability is one of the most sensitive indicators of soil erodibility (Bryan, 2000; Lehrsch, 1998). A decrease in wet aggregate stability directly increases water erosion risks because unstable aggregates rapidly disintegrate under raindrop impacts (Bryan, 2000). Soil bulk density, which is inversely proportional to porosity, is another property that can explain the increased water erosion (Hamza and Anderson, 2005). At both sites, compared with the control, baling tended to increase bulk density, although differences were not statistically significant. At the Brule site, runoff and sediment losses increased with an increase in bulk density (Fig. 5). Similarly, at the Nebraska City site, higher bulk density and lower aggregate stability under baled plots (Table 5) corresponded with higher losses of runoff, sediment, and nutrients (Fig. 3; Table 3). An increase in bulk density increases the risks of runoff and sediment losses by reducing macroporosity (Parker et al., 1995).

The significant loss of rainfall as runoff deserves discussion. Under baling, 53% of rainfall applied was lost as runoff at the Nebraska City site and 42% was lost at the Brule site. Grazing in the long term also caused loss (19%) of rainfall as runoff at the Brule site, but this loss was smaller than for baling. Runoff loss can have at least two consequences. 1. It can adversely affect water resources by reducing precipitation or irrigation capture and recharge of groundwater. Capturing precipitation or irrigation water through increased infiltration and storage is important, particularly in water-limited regions. 2. Runoff

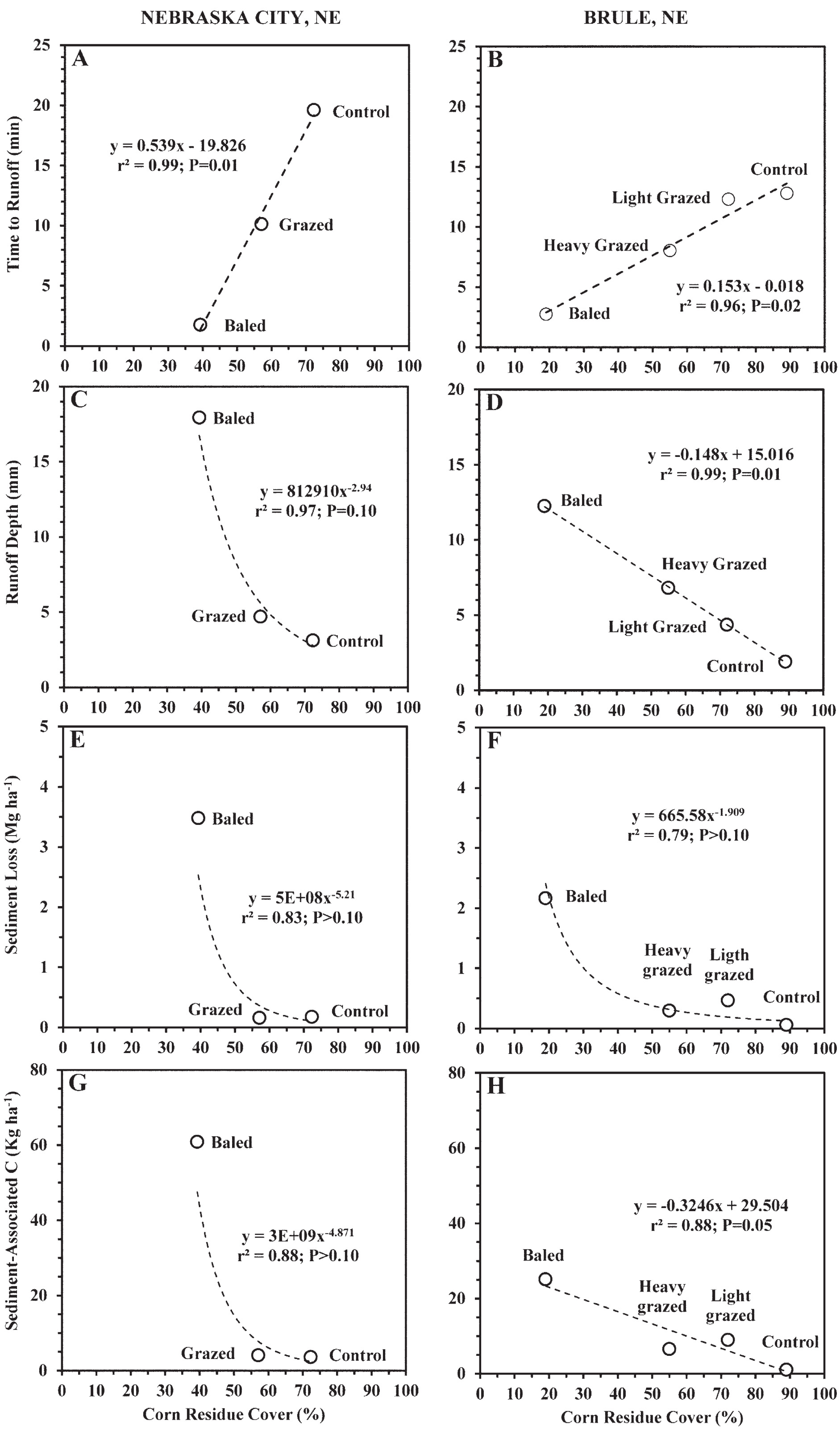

Fig. 4. Relationship of corn residue cover with time to runoff initiation (a, b), runoff depth (c, d), and sediment loss (e, f) for both the Nebraska City and Brule study sites in Nebraska.

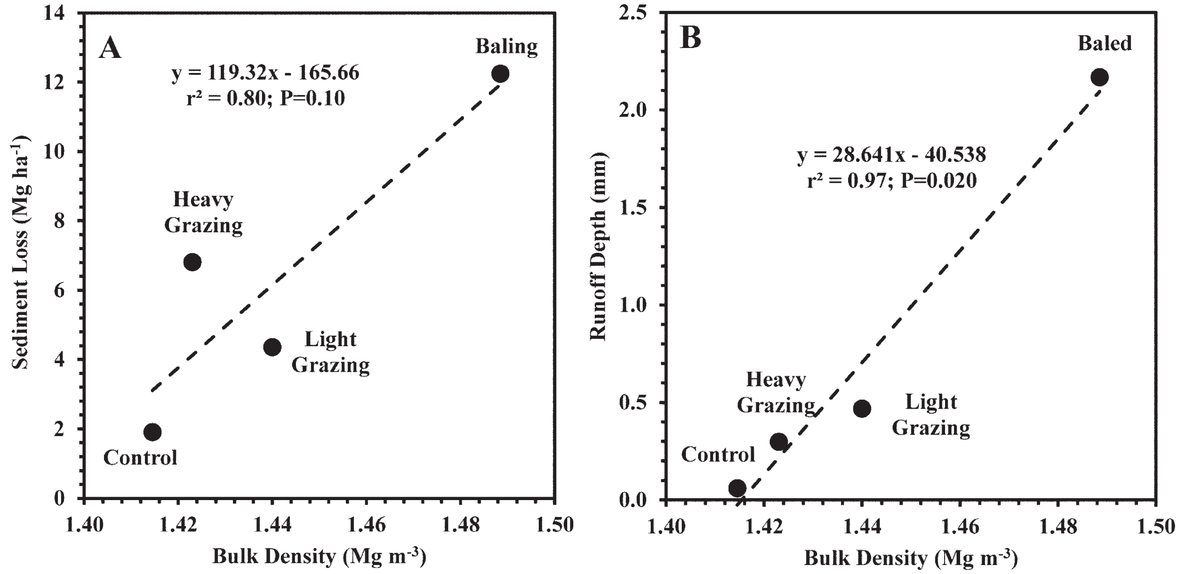

Fig. 5. Relationship of sediment loss (a) and runoff depth (b) with soil bulk density for the Brule site.

can carry nutrients along potentially contributing to increased risks of agricultural nonpoint-source pollution of downstream water sources (Wienhold and Gilley, 2010). Our results suggest that residue removal exposed soil to direct raindrop impacts, which detached soil aggregates and likely induced surface sealing, resulting in greater partitioning of rainfall into runoff.

Averaged across both sites, baling increased sediment loss by 25 times (2.8 Mg ha^{-1}) compared with the control (0.11 Mg ha^{-1}; Fig. 3e and 3f). These losses from baled plots were much greater than those reported by Wienhold and Gilley (2010) from a runoff study in a producer's field in east central Nebraska where 0.36 Mg ha^{-1} of sediment was lost from baled plots and 0.27 Mg ha^{-1} was lost from nonbaled plots. The smaller losses observed by Wienhold and Gilley (2010) may be attributed to the higher residue cover (49.5%) present in the baled plots in their study than in our study (40.5%). Results from both studies indicate nonetheless that baling corn residues from sloping fields can increase the risks of soil erosion. In this region, when forage demands are high, crop residues are sometimes baled or cattle is grazed even in some sloping croplands (Stalker et al., 2015), which could increase the soil's susceptibility to erosion.

Our results indicate that baling has the potential to increase losses of runoff, sediment, and nutrients. They also suggest that grazing corn residues with livestock in the same piece of land for various years may result in increased water erosion, but the extent will be lower than that under baling. The increased water erosion under grazing after seven grazing seasons appears to suggest the need for redesigning grazing strategies. Grazing every other year or every 2 yr may be a potential strategy for reducing the risks of erosion (Sulc and Franzluebbers, 2014).

CONCLUSIONS

This study from rainfed and irrigated sites in Nebraska indicates that cattle grazing of corn residues had no effect after one grazing season, but it caused some losses of runoff, sediment, and runoff nutrients after seven grazing seasons (7 yr) in sloping cornfields. These results suggest that grazing of corn residue in sloping croplands (~5.6% slope) may increase the risks of water erosion in the long term, but that may not be the case in the short term. Baling of residues had much larger effects on water erosion than grazing. It increased losses of runoff, sediment, and runoff nutrients in both the short and long term. Residue cover as high as 40% under baled fields was not sufficient to reduce water erosion relative to no residue removal in both sloping cornfields in the springtime. Residue removal not only caused losses of runoff, sediment, and sediment-associated C but also losses of nutrients (N, P, and K) in runoff, although the amount of loss of some runoff nutrients was relatively small. These results suggest that bal-

Table 5. Near-surface (5 cm depth) soil properties for each treatment at both Nebraska City and Brule sites in spring 2015.

Site	Treatments	Bulk density	Mean weight diameter of water-stable aggregates	Soil organic C	Total N
		Mg m^{-3}	mm	g kg^{-1}	g kg^{-1}
Nebraska City (eastern Nebraska)	Control	1.09b†	1.40a	18.33a	0.19a
	Grazing	1.19a	1.51a	18.29a	0.19a
	Baling	1.17ab	0.98b	18.72a	0.19a
Brule (west central Nebraska)	Control	1.41a	2.49a	11.19a	0.09a
	Light grazing	1.44a	2.03a	14.29a	0.14a
	Heavy grazing	1.42a	2.74a	13.59a	0.12a
	Baling	1.49a	2.08a	9.91a	0.10a

† Means followed by different letters in a column within a site are significantly different at $P \leq 0.05$.

ing of crop residues at high rates from sloping fields should not be practiced to reduce the risks of soil erosion. Losses of runoff, sediment, and nutrients increased with a decrease in residue cover as expected. Overall, this study found that baling from sloping cornfields (~5.6% slope) can have large effects on increasing water erosion, but grazing can have limited effects.

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