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Does cover crop grazing damage soils and reduce crop yields?

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Abstract

Cover crop (CC) grazing can be a potential strategy to support livestock and crop production while enhancing soil ecosystem services, but research on this potential multi-functionality of CCs is limited. We assessed 3-yr cereal rye (*Secale cereale* L.) CC grazing impacts on soil compaction, structure, water infiltration, fertility, and crop yields on an on-farm irrigated strip-till continuous corn (*Zea mays* L.) silage experiment on a sandy loam with <1% slope in west-central Nebraska. Treatments were: (a) non-grazed CC, (b) grazed CC, and (c) no CC. Across the 3 yr, cattle grazed CCs at 5.9 AUM ha^{-1} with grazing occurring over a 4-mo period during winter and/or spring, depending on the year. We measured soil properties within 5 d after grazing ended in spring before tilling and planting corn. Cattle grazing resulted in a 92% decrease of CC biomass, compared with non-grazed CCs. Grazing did not affect soil penetration resistance (compaction parameter), bulk density, aggregate stability, pH, and concentration of organic matter and nutrients except in the 2nd yr where it reduced cumulative infiltration by 80% and increased penetration resistance from 1.23 to 1.72 MPa but such increase was below root growth thresholds (<2 MPa). Cover crop grazing had no negative effect on corn silage yields although data were variable. Overall, CC grazing for 3 yr had small and variable effects on soils and crop yields, indicating that it can be a management option to support livestock production but more long-term data from different tillage and cropping systems, and climates are needed to further understand CC grazing implications.

1 | INTRODUCTION

Cover crop (CC) grazing can be a potential strategy to support crop and livestock production, diversify agroecosystems, enhance soil ecosystem services, and improve overall agricultural sustainability (Lemaire, Franzluebbers, Carvalho, & Dedieu, 2014; Sulc & Franzluebbers, 2014). This strategy could also further support the growing interest in integrated crop–livestock systems (Liebig et al., 2017; Sulc & Franzluebbers, 2014). Increased conversion of grasslands to croplands coupled with climatic fluctuations have heightened increased pressure on the utilization

Abbreviations: AUM, animal unit month; CC, cover crop.

of crop residues and silage for feed (Wimberly et al., 2017). Moderate grazing of CCs can provide supplemental forage. For example, small grain cereal grass (i.e., cereal rye, *Secale cereale* L.; oat, *Avena sativa* L.) CCs, alone or mixed with legumes (i.e., hairy vetch, *Vicia villosa* L.) and *Brassicas* (i.e., turnip, *Brassica rapa* L., radish, *Raphanus raphanistrum* L.) can be a source of high-quality forage, reducing the need for perennial forage sources (Franzluebbers et al., 2008). Some farmers are reluctant to adopt CCs since no direct economic return is obtained from not grazing CCs. Thus, growing CCs for grazing could be an opportunity to improve farm economics while enhancing soil ecosystem services (Schomberg et al., 2014; Siri-Prieto, Reeves, & Raper, 2009).

It is well recognized that unrestricted grazing of croplands or pasturelands can have negative effects on soil properties and agronomic production, but short-term or moderate grazing of CCs may not have such negative effects (Franzluebbers & Stuedemann, 2007). Indeed, grazing of CCs may increase the multi-functionality of CCs (Blanco-Canqui et al., 2015b; Schipanski et al., 2014). First, CC grazing reduces the amount of CC residue left on the soil surface, but the role of CCs in protecting soil from erosion and maintaining soil properties may not be compromised if sufficient CC cover is left after grazing. Second, grazing livestock returns manure to soil. It is well documented that animal manure addition can enhance soil biological activity, soil C and nutrient cycling, improve soil fertility, reduce soil's susceptibility to compaction, and improve water retention capacity, among other benefits (Blanco-Canqui, Hergert, & Nielsen, 2015a). Animal manure return, in the long term, could partly offset any potential negative effect of CC biomass grazing on soil properties. Third, grazing of CCs does not remove belowground (root) biomass. Cover crop roots can stabilize soil, improve soil properties, and contribute to soil C accumulation. Indeed, crop roots are responsible for 70% of the total soil organic C, suggesting that roots can be more important to soil C accumulation than aboveground biomass (Wilhelm, Johnson, Voorhees, & Linden, 2004).

Based on the above considerations, grazing of CCs appears to be feasible to meet soil ecosystem service thresholds and economic returns. However, research data on the potential impacts of such practice on soils and crops are limited. One of the questions is: Can CCs be grazed without negatively affecting soil properties and productivity in different soils and climatic conditions? Concerns exist that grazing of CCs with large ruminants such as cattle, may compact soil and adversely affect soil processes (i.e., water infiltration, macroporosity, aggregation, C cycling) and concomitantly reduce soil productivity or crop yields in subsequent years.

Core Ideas

- Rye cover crop grazing increased soil penetration resistance in 1 of 3 yr.
- Increase in penetration resistance was below root growth thresholds (<2 MPa).
- Rye cover crop grazing did not affect organic matter and other soil properties.
- Grazing did not significantly affect corn silage yields in any of the 3 yr.
- Rye cover crop grazing can be a potential option to support livestock production.

Studies of CC grazing effects on soil properties and crop yields are very few. The few available data suggest that CC grazing may not have large effects on soils and crops. In Georgia, in a 3-yr study, Franzluebbers and Stuedemann (2007) reported that grazing a cereal rye CC with cattle at a stocking rate of 3.1–5.5 cow–calf pairs per hectare reduced the yield of summer grain crops including grain sorghum (*Sorghum bicolor* L.) and corn by 23% and reduced standing grain–crop dry matter by 26% under no-till, but not under conventional tillage. Grazing pearl millet (*Pennisetum glaucum* L. R. Br.) increased wheat dry matter yield by about 25% under both tillage systems. In a related study, under no-till and conventional tillage systems, Franzluebbers and Stuedemann (2008) reported that cattle grazing resulting in disappearance of about 90% of the aboveground biomass produced by CCs for 2.5 yr had small or no negative effects on subsequent grain sorghum, corn, and winter wheat crop yields, and soil bulk density and aggregate stability. They also found that CC grazing increased penetration resistance in the 0- to 10-cm depth under conventional tillage but not under no-till. For the same study, Franzluebbers and Stuedemann (2015) found that cumulative stocks of soil C and N fractions for the 0- to 30-cm depth did not differ with CC grazing after 7 yr. In Ohio, Fae et al. (2009) found that grazing of annual ryegrass (*Lolium multiflorum* L.) and a mixture of cereal rye and oat managed under no-till corn silage system increased soil penetration resistance by 7–15% the 1st year but had no effect 1 yr later. The same study showed that grazing of CCs did not affect subsequent corn silage yield.

While the few available studies suggest that grazing of CCs may not negatively affect soils and crop production, more research data are needed from different soil types, tillage systems, cropping systems, and climatic conditions. For example, planting CCs in corn silage systems is critically important to protect the soil after corn silage harvest, which leaves soil practically bare (Krueger, Ochsner, Porter, & Baker, 2011). The question is: does grazing CCs

TABLE 1 Precipitation and air temperature by year and month for the on-farm cover crop grazing experiments in west central Nebraska

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Precipitation, mm													
2015	7	12	0	76	110	69	65	81	32	52	17	7	528
2016	12	20	17	136	99	83	98	22	24	39	20	16	586
2017	17	13	46	57	84	11	132	91	121	79	2	14	667
2018	27	22	18	37	186	96	58	43	11	73	23	30	624
Temperature, °C													
2015	−3	−2	6	10	13	21	23	21	20	12	4	−1	
2016	−2	1	6	9	14	23	24	23	19	13	6	−4	
2017	−4	2	7	10	14	22	26	21	19	10	5	−4	
2018	−5	−6	4	6	18	23	24	22	20	9	1	−3	

from corn silage systems eliminate the benefits of CCs for mitigating the potential adverse impacts of corn silage harvest on soil properties?. Data to answer this question, particularly in irrigated corn silage systems, are unavailable. Thus, the objective of this paper was to assess the 3-yr impact of grazing of cereal rye CC on soil compaction, water-stable aggregation, water infiltration, soil fertility, and crop yields on an on-farm experiment under irrigated strip-till continuous corn silage on a sandy loam in west-central Nebraska.

2 | MATERIALS AND METHODS

2.1 | Description of the site and management

This 3-yr rye CC grazing study was conducted as an on-farm experiment in west-central Nebraska. The site (40°22′40″ N, 96°0′34″ W) was located near North Platte, NE. Mean precipitation and temperature by year and month are reported in Table 1. The soil was a Wann fine sandy loam (coarse-loamy, mixed, superactive, mesic Fluvaquentic Haplustolls) with <1% slope. The site was under sprinkler irrigated, strip-till, and continuous corn silage (Table 2) and it had been managed under strip-till continuous corn without CCs for at least 10 yr prior to the CC experiment establishment.

The CC grazing experiment had three treatments: (a) no CC, (b) non-grazed CC, and (c) grazed CC with three replications. The non-grazed CC and no-CC treatments in a randomized complete block design were fenced with metal fences to prevent cattle access during CC grazing. The rest of the field around the fenced area, which was 51 ha was grazed. The size of no-CC and non-grazed CC plots (a total of six plots) was 12 by 33 m. Three permanent locations without borders within the grazed area adjacent to three sides of the fenced rectangular area were used as pseudoreplicates (three replications) for the CC grazing treatment. The size of three grazed locations was the same as for the no-CC and non-grazed CC plots. We measured soil, crop yield, and CC biomass on the same locations year after year. Additional details of the pseudoreplication and statistical approach are described in the section of statistical analysis.

Cereal rye CC was planted after corn silage harvest in all years (Table 2). Each year (2015, 2016, and 2017), 1.4 cow—calf pairs per hectare grazed CCs between 15 March and 15 April and 2.5 cow—calf pairs per hectare grazed CCs between 15 April and 15 May. It is estimated that each cow weighed 612 kg with calf weight approximately 68 kg. In addition, in winter 2016 and 2017, about 1 yearling heifer per hectare grazed CCs for 2 mo with the duration depending on the weather. It is estimated that each yearling heifer weighed 295 kg. Thus, the stocking rate was 5.23 animal unit month (AUM) per hectare in 2015 and 6.53 AUM per hectare in 2016 and 2017 (Jenkins, 2014). Between CC termination with herbicides and corn planting in spring, the site was strip tilled to a depth of 18 cm using an Orthman 1tRIPr precision strip till machine (Orthman Manufacturing, Inc.). Cover crop was fertilized and irrigated once to facilitate establishment. Table 2 describes more details on the experiment management.

2.2 | Measurements

We assessed CC grazing effects on soil compaction, water stable aggregation, water infiltration, and soil fertility within 5 d after grazing ended in mid-spring each year before tilling and planting corn. We measured penetration resistance and soil bulk density to assess soil compaction risks and wet aggregate stability to assess soil aggregation. All soil properties except water infiltration were measured for the 0- to 10-cm and 10- to 20-cm soil depths.

We measured penetration resistance at 10 points within each treatment plot using a hand cone penetrometer (Eijkelkamp Co.; Lowery & Morrison, 2002) and readings

TABLE 2 Information on the management of the on-farm cover crop grazing experiment in an irrigated, strip-till, and continuous corn silage system in west-central Nebraska

Field activities	Management details
Strip tillage	• 24 May in 2016 • 23 May in 2017 • 1 June in 2018
Corn planting dates	• 25 May in 2016 • 25 May in 2017 • 2 June in 2018
Corn fertilization	• 63–79 kg N ha^{-1} as urea-ammonium nitrate as 32–00–00 • 16 kg P ha^{-1} as 6–24–6 and 10–34–00
Crop irrigation	400 mm per year
Corn silage harvest	• 20 Sept. in 2015 • 21 Sept. in 2016 • 14 Sept. in 2017
Cover crop planting dates	• After corn silage harvest: • 20 Sept. in 2015 • 22 Sept. in 2016 • 15 Sept. in 2017
Cover crop species and seeding rate	Cereal rye at a seeding rate of 94 kg ha^{-1} each year
Cover crop fertilization	Fertilized with 39 kg N ha^{-1} as urea each year
Cover crop irrigation	Irrigated once with 9 mm of water at establishment
Stocking rate	5.23 animal unit month (AUM) per ha in 2015 and 6.53 AUM per ha in 2016 and 2017
Grazing duration	• 20 March–20 May each year (5 cow–calf pairs ha^{-1}) • Late December–15 March in 2016 and 2017 (1.2 yearling heifers ha^{-1})
Cover crop termination method and date	Glyphosate [*N*-(phosphonomethyl) glycine] at a rate of 0.71 kg ha^{-1} between 24 and 25 May prior to planting corn
Additional information	In 2018, corn was partially damaged by hailstorm in early July and August

were divided by the cone area to express results in megapascal. Soil bulk density was determined by collecting 20-cm long soil cores using a hand probe and then slicing the cores to 0- to 10-cm and 10- to 20-cm depth intervals. A fraction of the sample from each soil core was dried at 105 °C for 24 h to determine gravimetric water content and then bulk density for each depth interval by the core method (Grossman & Reinsch, 2002; Topp & Ferre, 2002). The penetration resistance values were adjusted for differences in gravimetric water content when correlations between penetration resistance and gravimetric water content were significant. The adjustment procedures followed those by Busscher, Bauer, Camp, and Sojka (1997) and Blanco-Canqui et al. (2005).

Ponded water infiltration was measured at one point within each plot using the double ring infiltrometer method (Reynolds et al., 2002). Metal rings were inserted into the soil to a depth of 10 cm. The diameter was 75 cm for the outer ring and 25 cm for the inner ring. The water level drop in the inner ring was monitored at the following times: 1, 2, 3, 4, 5, 10, 20, 40, 60, 90, 120, 150, and 180 min. Water was added back to the original level when the water level in the inner ring dropped to 3 cm above the soil surface. Infiltration rates and cumulative infiltration were computed, but only the latter is reported in this paper as our main goal was to quantify the total amount of water that can infiltrate into the soil.

The wet aggregate stability was determined by the modified wet sieving method of Yoder (1936). A portion of the soil samples collected with the hand probe for the 0- to 10-cm and 10- to 20-cm soil depths was used. The soil sample was air-dried and sieved through sieves with 8-mm openings. Fifty grams of the air-dried and sieved sample were weighed, placed on top of a stack of sieves, saturated by capillarity for 10 min, sieved in water for another 10 min, aggregates from each sieve placed in glass beakers, dried at 105 °C for 24 h, weighed, and mean weight diameter of water stable aggregates computed (Nimmo & Perkins, 2002). The stack of sieves consisted of 4.75-, 2-, 1-, 0.5-, and 0.25-mm opening sieves arranged in a descending order. The aggregates were sieved in water using a mechanical sieving device with an up–down stroke of 3 cm at a rate of 30 strokes per minute. The amount of aggregates retained in each sieve was corrected for sand by mixing the oven-dried aggregates with 30 ml of 0.5% Na hexametaphosphate to disperse soil aggregates, sieving the mix through sieves with 53-µm opening, oven-drying the recovered sand, and correcting the amount of aggregates for sand content (Nimmo & Perkins, 2002).

Soil fertility properties including pH, organic matter, nitrate, exchangeable K, and phosphate were determined using a fraction of the bulk soil samples collected in spring before planting corn. The air-dried soil sample was passed through a 2-mm sieve. Soil pH was measured by a digital pH meter on soil and water slurry in 1:1 ratio (Watson & Brown, 1998). Soil organic matter concentration was analyzed by loss on ignition (Combs & Nathan, 1998). Briefly, 5 g of air-dried soil were oven dried at 105 °C for 2 h. Next, the oven-dried samples were weighed, heated to 360 °C for 2 h, and weighed again. The difference between the two dryings was divided by the dry weight minus tare to compute organic matter concentration. Nitrate-N concentration was determined using 5 g of soil sample mixed with 15 ml calcium phosphate-extracting solution, which was then filtered into glass test tubes for the determination of nitrate using the Cd reduction procedure (Gelderman & Beegle, 1998). We measured phosphate by the Mehlich-3 extraction procedure (Frank, Beegle, & Denning, 1998). The percent transmittance was recorded in a soil solution using Lachat QuickChem at 880 nm and standard curve established to compute P. Potassium concentration was determined using the ammonium acetate method in filtered samples by the inductively coupled plasma (Warncke & Brown, 1998).

We also quantified CC standing biomass within 5 d after grazing ended. We clipped CC to the soil surface from two 0.25-m^2 quadrats from each CC plot. The CC biomass was oven dried to 60 °C for 3 d to determine the amount of biomass. We did not quantify CC biomass production at the beginning of CC grazing. To quantify the amount of corn silage grain and residues, two parallel 5.3-m rows near the center of each plot were harvested manually. The corn ears and residue samples were weighed in the field and subsamples brought to the laboratory to determine water content. Corn silage yield was reported at a moisture content of 650 g kg^{-1}.

2.3 | Statistical analysis

Since the CC grazed treatment was not randomized as a treatment with the CC and no CC treatments, the CC grazed field was considered as a separate unreplicated experiment with three pseudoreplicates. Data were then analyzed using an analysis of variance for combining separate experiments in which treatments were nested in experiment (Kent Eskridge, personal communication, 2020). The experimental error for testing experiment effect was based on replicates only from the CC and no CC plots. Since all plots (no CC, CC, and CC grazed) were measured in each year, year was considered a stripped factor across all experimental units. This analysis resulted in the following model terms: expt rep(expt) trt(expt) rep×trt(expt) year×expt year×rep(expt) year×trt(expt) year×rep×trt(expt). Tests assumed rep(expt) was fixed and any interaction with rep was random and Satterthwaite's correction was used to estimate the denominator degrees of freedom for the F tests. Data on soil properties by depth and crop yields were analyzed using PROC MIXED in SAS to compute the ANOVA and LSMEANS (SAS Institute, 2019). All tests in LSMEANS were evaluated at the .05 probability level unless otherwise noted in the paper.

While we recognize that the pseudoreplication of the CC grazing treatment is not a true replication, note that the amount of CC biomass removed by cattle, as reported next, was similar among the three pseudoreplicates, which strongly suggests that animals spent nearly the same amount of time in each pseudoreplicate. Additionally, we visually observed that animal traffic (i.e., hoof prints) in the each pseudoreplicate of the grazed area was relatively uniform. Also, the similarities in soil textural class (sandy loam), slope (<1%), and history of management for the whole field prior to experiment establishment lend support to the assumption that soils across the no CC, CC, and grazed CC plots did not significantly differ.

3 | RESULTS AND DISCUSSION

3.1 | Rye cover crop standing biomass amount

In the 1st year (2016), standing biomass between grazed and non-grazed rye CC did not statistically differ due to cattle breaking through the fence and grazing the CC in the non-grazed CC treatment plots for about 1 d in mid-spring (Figure 1). We acknowledge that the cattle breaking for about 1 d in spring may have affected soil and crop yield results during the 1st year (2016). In 2017 and 2018, CC standing biomass under CC grazed plots was about 8% of that in non-grazed CCs (Figure 1), suggesting that livestock grazing of CCs resulted in significant reduction in aboveground biomass amount due to consumption, trampling, and removal of leaf area potentially affecting plant growth. The low standard deviation in the amount of CC biomass

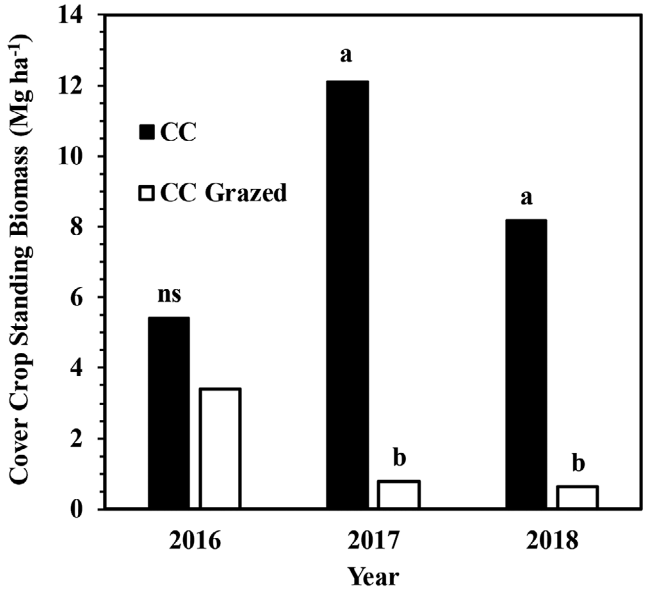

FIGURE 1 Cover crop (CC) standing biomass in an irrigated, strip-till, and continuous corn silage system in west-central Nebraska. Bars followed by different letters within the same year are significantly different. ns indicates non-significant difference

removed among the three CC grazed sampling areas (pseudoreplicates) suggest that cattle most probably spent the same amount of time in all portions of the CC grazed field. The reduction in CC biomass amount in this study was similar to that reported in Georgia by Franzluebbers and Stuedemann (2007) where cattle stocked at a rate of 3.1 to 5.5 cow–calf pairs per hectare resulted in a significant reduction in pearl millet summer CC and cereal rye winter CC biomass amount in a 4-yr study. Additional studies reporting standing CC biomass after grazing are scant to compare with the results of our study.

Non-grazed CC biomass production was, averaged across years, 8.6 ± 3.3 Mg ha^{-1}. Cereal rye CC production was as high as 12.1 Mg ha^{-1} in 2017. The amount of CC biomass produced in this corn silage system was much higher than reported (<3 Mg ha^{-1}) in corn grain systems in the region (Blanco-Canqui, Sindelar, & Wortmann, 2017; Sindelar, Blanco-Canqui, Virginia, & Ferguson, 2019; Koehler-Cole et al., 2020). The higher CC biomass production is attributed to the early planting of CCs in the corn silage system, which allows for more growing degree days for the CC compared with corn grain systems in which CCs are typically planted in mid-fall (late October or early November). Cover crop in our experiment was planted in late summer (Table 2). It is also important to note that in this experiment, cereal rye was fertilized with N and irrigated once at establishment, which most probably resulted in increased CC biomass production relative to studies in which CCs are not typically fertilized nor irrigated.

3.2 | Soil compaction

Changes in soil bulk density and penetration resistance were used to evaluate rye CC grazing impacts on soil compaction. Cover crop grazing had no effect on soil bulk density in any year (Table 3). However, it had some effects on penetration resistance (Table 3). It did not affect penetration resistance in the 1st year but increased it by 40% (1.13 vs. 1.72 MPa) in the 0- to 10-cm soil depth during the 2nd year and by 31% (1.39 vs. 1.82 MPa) in the 10- to 20-cm depth during the 3rd year compared with non-grazed CC and no CC. No differences in CC standing biomass between grazed and non-grazed CCs (Figure 1) may explain the lack of CC grazing effects on soil compaction in the 1st year (Table 3). The increased penetration resistance under CC grazing in spring 2017 and not in spring 2018 for the 0- to 10-cm depth did not appear to be related to differences in precipitation during the grazing months. Grazing when soils are wet can cause more compaction than when soils are relatively dry. Note that mean precipitation in March through May was 187 mm in 2017 and 241 mm in 2018 (Table 1).

The level of increase in penetration resistance in the 2nd year deserves discussion. Cover crop grazing increased penetration resistance in the 2nd year, but the increase in penetration resistance values was generally below the threshold levels that can restrict root growth and crop production (Table 3). Threshold levels of compaction vary between 2 and 4 MPa, depending on soil and crop type (Atwell, 1993; Bengough, McKenzie, Hallett, & Valentine, 2011). It is important to clarify that while the penetration resistance values under CC grazed plots were below the threshold levels, they could still have some adverse effect on root growth. Unger and Kaspar (1994) discussed that root growth may be affected with penetration resistance values as low as 1 MPa.

In general, our results also indicate that in years when CC grazing increases penetration resistance, such increase can be relatively small and may not significantly reduce crop production as discussed later. Further monitoring of changes in penetration resistance and bulk density across multiple years is needed to determine any cumulative effects of CC grazing on soil compaction and other soil processes in the long term. It is also worth noting that while CC grazing may induce some risks of compaction, it may also reduce compaction in the long term by adding organic matter through manure input as discussed earlier. Annual addition of cattle manure to corn fields has been shown to reduce risks of soil compaction (Blanco-Canqui et al., 2015a).

Studies comparing penetration resistance between grazed and non-grazed CCs are not common. On sandy loam and sandy clay loam soils in Georgia, Franzluebbers

TABLE 3 Cover crop (CC) grazing impacts on soil physical properties in an irrigated strip-till, and continuous corn silage system in west-central Nebraska. Means with different letters within the same soil depth significantly differ. Means without letters do not significantly differ

Treatment	Depth	Bulk density	Penetration resistance	Mean weight diameter of water-stable aggregates
	cm	Mg m^{-3}	MPa	mm
2016				
No CC	0–10	1.26 ± 0.14	2.37 ± 0.57	0.60 ± 0.16
CC		1.32 ± 0.05	3.13 ± 0.13	0.69 ± 0.20
CC grazed		1.40 ± 0.01	3.14 ± 0.99	0.60 ± 0.06
No CC	10–20	1.49 ± 0.05	2.88 ± 0.63	0.63 ± 0.35
CC		1.51 ± 0.04	3.13 ± 0.56	0.67 ± 0.23
CC grazed		1.46 ± 0.03	3.28 ± 0.24	0.33 ± 0.05
2017				
No CC	0–10	1.40 ± 0.05	1.16 ± 0.20b	1.71 ± 0.62a
CC		1.53 ± 0.06	1.10 ± 0.20b	1.06 ± 0.02ab
CC grazed		1.46 ± 0.13	1.72 ± 0.38a	0.67 ± 0.35b
No CC	10–20	1.41 ± 0.14	1.43 ± 0.11	0.43 ± 0.15b
CC		1.55 ± 0.10	1.55 ± 0.37	0.66 ± 0.09a
CC grazed		1.59 ± 0.14	1.87 ± 0.36	0.49 ± 0.15b
2018				
No CC	0–10	1.21 ± 0.14	1.19 ± 0.17	0.85 ± 0.10
CC		1.32 ± 0.27	1.67 ± 1.01	1.44 ± 0.19
CC grazed		1.12 ± 0.06	1.96 ± 0.22	1.11 ± 0.58
No CC	10–20	1.44 ± 0.20	1.40 ± 0.29b	0.28 ± 0.04
CC		1.58 ± 0.01	1.38 ± 0.23b	0.38 ± 0.08
CC grazed		1.30 ± 0.11	1.82 ± 0.31a	0.34±0.18

and Stuedemann (2008) reported that CC grazing increased penetration resistance under conventional till but not under no-till management after 2.5 yr of management. In Ohio, Fae et al. (2009) found that grazing annual ryegrass, and a mixture of cereal rye and oat winter CCs increased soil penetration resistance by 7–15% in no-till corn silage production after 1 yr. Our results and those of the few previous studies suggest that CC grazing under conservation management has small and variable effects on soil compaction, indicating that CC grazing does not generally increase soil compaction.

Non-grazed CCs in this study had no effect on bulk density and penetration resistance relative to no CC. These short-term (3 yr) results suggest that addition of CC to conservation tillage systems may have small or no effects on soil compaction similar to CC grazing. The previous studies found that CC could generally reduce soil compaction compared with no CC. For example, after 4 and 5 yr, Villamil, Bollero, Darmody, Simmons, and Bullock (2006) reported that cereal rye and hairy vetch winter CC reduced near-surface (5 cm) penetration resistance in no-till corn–soybean systems. Similarly, after 10 yr, Abdollahi, Munkholm, and Garbout (2014) found that fodder radish CC reduced subsoil compaction under three tillage systems (no-till, harrowing, and moldboard plow) and attributed the reduction in compaction to biopore formation and soil structural development. The positive effects of CCs on reducing soil compaction found in previous studies may be due to more years of CC use (>4 yr) than in our study (<3 yr). They may also be due to the use of different types of CCs. One of the mechanisms by which CCs can reduce risks of soil compaction or soil compactibility in the long term is through accumulation of soil organic matter (Blanco-Canqui et al., 2015b).

3.3 | Soil structure and water infiltration

Cover crop grazing had no effect on wet aggregate stability expressed as mean weight diameter of water-stable aggregates compared with non-grazed CC in any year (Table 3), indicating that CC grazing did not negatively affect soil aggregate formation and stability in the short term. However, CC grazing had some effects on water infiltration. It reduced water infiltration by 80% in the 2nd year, but not in the 1st and 3rd year compared with CC and no-CC

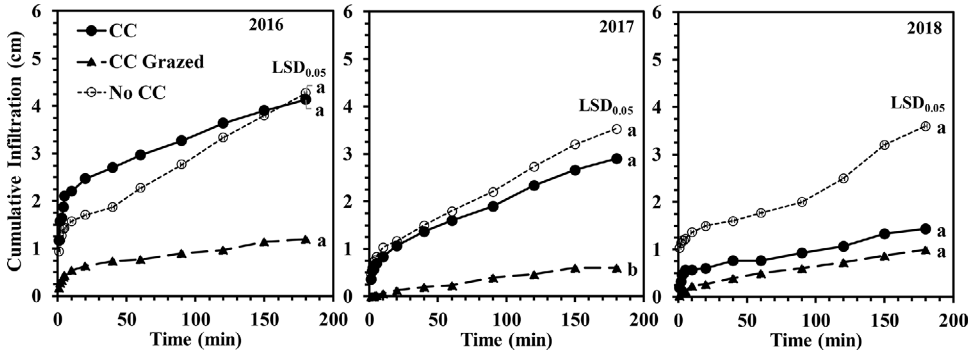

FIGURE 2 Cover crop (CC) grazing impact on cumulative water infiltration measured for 3 yr in an irrigated, strip-till, continuous corn silage in west-central Nebraska. Different letters in each year indicate significant differences among treatments after 3 h of water infiltration measurement

TABLE 4 Cover crop (CC) grazing impacts on soil fertility properties (mean ± SD) measured after 3 yr for two soil depths in an irrigated, strip-till, and continuous corn silage system in west-central Nebraska. Differences among treatments were not significant for any soil property

Treatment	pH	Organic matter	Nitrate	Exchangeable K	Phosphate
		g kg^{-1}	mg kg^{-1}		
0- to 10-cm depth					
No CC	8.3 ± 0.2	22 ± 4	23 ± 7.3	288 ± 76	121 ± 99
CC	8.0 ± 0.5	27 ± 8	22 ± 10.9	266 ± 82	81 ± 38
CC grazed	7.8 ± 0.2	28 ± 7	25 ± 12.7	305 ± 115	119 ± 60
10- to 20-cm depth					
No CC	8.0 ± 0.4	28 ± 8	22 ± 14.9	310 ± 40	126 ± 40
CC	7.9 ± 0.4	29 ± 6	12 ± 3.3	251 ± 61	87 ± 57
CC grazed	8.0 ± 0.3	29 ± 3	14 ± 8.1	299 ± 168	124 ± 72

(Figure 2). Based on these results, CC grazing effects on water infiltration can be variable from year to year. The decrease in water infiltration in 1 of 3 yr suggests that CC grazing at a stocking rate of about 5.9 AUM per hectare could adversely affect the amount of water capture in some years. Studies reporting effects of cattle grazing of CCs on infiltration are few. Similar to our study, Franzluebbers and Stuedemann (2008) reported that CC grazing tended (p = .07) to reduce water infiltration rate by 19% under no-till and conventional tillage cropping systems in Georgia during a 4-yr study. Studies on main crop residue grazing such as corn residues in our study region generally found no changes in aggregate stability and water infiltration in the short (Blanco-Canqui et al., 2016) and long (Rakkar et al., 2017) term at stocking rates as high as 13 AUM ha^{-1}. Overall, these findings suggest that CC grazing, similar to crop residue grazing, may have small or no effects on soil compaction, aggregation, and infiltration.

3.4 | Soil fertility and crop yields

Cover crop grazing had no effect on soil fertility parameters including pH, and concentration of organic matter, nitrate, exchangeable K, and available phosphate after 3 yr (Table 4). Similarly, CC grazing did not significantly affect crop yields in any year (Table 5). The absence of statistically significant CC grazing effects on yields is most probably due to the small and variable effects of grazing on soil properties such as compaction. Had CC grazing increased soil compaction above threshold levels that restrict root growth and reduced soil fertility such as organic matter concentration, it may have significantly reduced crop yields. Our results can have important implications for CC grazing in the region. Results suggest that even under the conditions of this CC grazing study with relatively high stocking rate (5.9 AUM ha^{-1}), CC grazing had no negative effect on crop yields.

TABLE 5 Cover crop (CC) grazing impacts on corn silage yield (mean ± SD) at 650 g kg^{-1} of moisture content in an irrigated, strip-till continuous, corn silage system in west-central Nebraska. Differences in corn silage yield among the three CC treatments were not statistically significant in any year

Cover crop	Corn silage yield 2016	2017	2018
		Mg ha^{-1}	
No CC	38.30 ± 6.58	38.58 ± 6.35	22.08 ± 6.85
CC	45.18 ± 6.70	31.20 ± 11.93	19.21 ± 6.72
CC grazed	28.32 ± 18.23	25.83 ± 5.84	19.04 ± 11.75

Concerns exist among some producers that CC grazing may compact and reduce subsequent crop yields, but our results suggest that grazing of CC may not significantly affect crop yield in the short term. Additional studies are needed to determine how CC grazing at different stocking rates (low, medium, and high) affects crop yields in the short and long term. Note that in our study, animals grazed CCs for about 4 mo, depending on the year, which can have a different effect on soil compaction and other soil and crop parameters from intensive or continuous grazing, which is not uncommon in the study region. For example, a question that needs to be answered is that whether moving cattle more frequently such as daily or weekly from field to field to reduce soil exposure to grazing impacts would be a better alternative. Also, note that in this study, the whole field was strip tilled between CC grazing and corn planting. The use of strip till may have alleviated the potential negative effects of cattle traffic-induced compaction by fracturing the compacted layers. Studies comparing how CC grazing affects crop yields and soils under different tillage systems are few. In southeastern United States, under both no-till and conventional-till systems, Franzluebbers and Stuedemann (2008) found that CC grazing had generally no significant effect on corn, soybean, and wheat yields and that yields were variable from year to year. Our results also agree with studies on crop residue grazing in the region, which generally found no large negative effects of grazing on crop yields (Baumhardt, Schwartz, Green, & MacDonald, 2009; Baumhardt, Schwartz, MacDonald, & Tolk, 2011; Stalker et al., 2015; Ulmer et al., 2019). Some studies suggested that grazing winter annuals (Siri-Prieto et al., 2009) or crop residues (Baumhardt et al., 2011) under conservation tillage followed by non-inversion tillage to manage any grazing-induced soil compaction can be opportunities to increase soil productivity and generate additional income from grazing. In general, findings from previous studies and this study suggest CC grazing does not have large negative effects on soil fertility parameters and crop yields.

4 | CONCLUSIONS

Results from this 3-yr on-farm study under a strip-till system in the western Corn Belt suggest that livestock grazing of rye CC may have small or no effects on soil properties and crop production. Rye CC grazing at a stocking rate of about 5.9 AUM ha^{-1} compacted the soil and reduced water infiltration in 1 of 3 yr, but the increase in the compaction level was below the threshold levels that can significantly restrict root growth. Effect of CC grazing on soil fertility and crop yields were not statistically significant. The small effects on soil properties and no effects on crop yields suggest that integrating CCs with livestock production can be a potential alternative in the study region under the conditions of this study. As noted earlier, we hypothesize that the use of strip till could have alleviated any potential negative effects of CC grazing on soil properties and crop yields in this study. Additional studies with more robust experimental designs are needed for a rigorous assessment of CC grazing impacts on soil ecosystem services under a wide range of soil types (coarse-, medium, and fine-textured soils), cropping systems (monocrops, short rotations, and extended rotations), and tillage systems (plow till, reduced till, and no-till). For example, a need exists to determine how livestock grazing at different stocking rates (low, medium, and high) of CCs affect soils and crop yields in the long term. Such studies can be valuable to establish the threshold levels of cattle-stocking rates for maintaining soils and crop production. We hypothesize that a higher stocking rate or density than in this study could have some adverse significant effects on soil and crop yields. There is also a need to monitor changes in soil compaction parameters and other soil properties with time within the same growing season after CC grazing ends to determine the longevity of CC grazing effects on soil properties such as compaction parameters. Overall, rye CC grazing under the conditions of this study has small or no negative effects on soil properties and crop yields in the short term (3 yr), suggesting that CC grazing can be a potential opportunity to support livestock production without adversely affecting other soil ecosystem services.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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