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Does Integrating Crops with Livestock Production Impact Soil Properties and Crop Production?

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DOES INTEGRATING CROPS WITH LIVESTOCK PRODUCTION IMPACT SOIL PROPERTIES AND CROP PRODUCTION?

by

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DOES INTEGRATING CROPS WITH LIVESTOCK PRODUCTION IMPACT SOIL PROPERTIES AND CROP PRODUCTION?

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University of Nebraska, 2021

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Re-integrating crop and livestock production through cover crop (CC) and corn residue grazing could efficiently utilize resources and ensure profitability while improving environmental quality, but how this integration affects soils and crops is not well understood. We conducted two studies to address this. In the first study, we evaluated the impact of cattle (1.3-3.7 head ha^{-1}) grazing an oat (*Avena sativa* L.) CC on soil and crop yields in two adjacent irrigated no-till corn (*Zea mays* L.)-soybean (*Glycine max* L.) fields on silt loam soils in eastern Nebraska. Field I was grazed twice, while Field II was grazed thrice during a 5-yr study. Cover crop grazing reduced CC biomass by 47 to 87% without impacting soil penetration resistance, bulk density, aggregate stability, hydraulic properties, organic matter fractions, microbial biomass, and crop yields compared to non-grazed CC. In the second study, we evaluated the impact of cattle grazing of corn residue [717-807 animal unit days (AUD) ha^{-}1] and an oat CC (1354 AUD ha^{-1}) on soil compaction parameters including bulk density, penetration resistance, and initial infiltration under two rainfed no-till systems (I and II) on a silty clay loam in eastern Nebraska. System I had one year of corn residue grazing under soybean-corn without horse manure, while System II had one year of CC grazing and another year of corn residue grazing under soybean-wheat (*Triticum aestivum L*)-corn with horse manure. Dry horse manure application rate in System II averaged 3.92 Mg ha^{-1}. Oat CC was planted following wheat. Corn residue grazing did not impact bulk density, penetration resistance, and infiltration in both Systems.

Cover crop grazing in System II did not impact penetration resistance and infiltration but increased bulk density (1.43±0.04 vs 1.38±0.04 Mg m^{-3}), although the increase was below values that affect root growth. Overall, grazing of CC and corn residue has little to no impact on soil properties and crop production and, thus, it could be a viable practice to re-integrate crop with livestock production.

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CHAPTER 1. Introduction and Objectives

Introduction

There is an increasing interest in re-integrating crops with livestock, particularly in developed countries (Carvalho et al., 2018; Kronberg and Ryschawy, 2018; Kumar et al., 2019; MacLaren et al., 2019; Perez-Gutierrez and Kumar, 2019) due to the current specialization of crop and livestock production, which can lead to reduced economic returns to farmers, reduced soil resilience, and increased degradation and pollution of natural resources (Gollehon et al. 2001; Doran, 2002). These concerns in addition to increasing pressures of population growth and extreme weather events (i.e., droughts and flooding) warrant the reconsideration of current systems of food production to attain a more sustainable agriculture. Integrating crop and livestock can be achieved through a variety of strategies. One such potential strategy is through cover crop (CC) and corn residue grazing.

Grazing CCs and corn residue could provide an opportunity for producers to diversify their operations and incorporate livestock into their current crop rotations by taking advantage of the fallow period between cash crops. Integrating crop and livestock production through CC and corn residue grazing has the potential to minimize environmental harm while efficiently utilizing resources ensuring profitability for the producer and conservation of natural resources. The advantages of integrated crop-livestock systems such as CC and corn residue grazing include more efficient nutrient cycling (Maughan et al., 2009; George et al., 2013; Garrett et al., 2017; MacLaren et al., 2018), possible enhanced soil properties (Faé et al., 2009; Maughan et al., 2009; George et al., 2013; Garrett et al., 2017), increased forage availability (Drewnoski et al., 2018), reduced herbicide applications (Tracy and Davis, 2009; MacLaren et al., 2018) and a more diversified income for farmers with potential economic gains (Garrett et al., 2017; Kumar et al., 2019).

Literature has discussed the potential benefits from CCs for suppresing pests and weeds, alleviating compaction (Williams & Weil, 2004), improving nutrient cycling (Snapp et al., 2005), enhancing soil structure and microbial properties (Blanco-Canqui et al., 2015), reducing soil erosion and agrochemical runoff, and possibly providing economic benefits (Bergtold et al., 2017). However, research on CC grazing impacts on soil and crop production is lacking. Cover crops can provide high quality forage (Drewnoski et al., 2018; Farney et al., 2018; Han et al., 2018; Deen et al., 2019). Thus, grazing CCs could reduce feed costs by providing needed forage and create an incentive for CC adoption. Corn residue is also a cost-effective and underutilized feed source (Redfearn et al., 2019). Corn residue grazing could be a relatively inexpensive and efficient feed source. The question is whether CCs and corn residue can be grazed without adversely affecting the soil ecosystem services. Concerns among producers exist that CC and corn residue grazing could degrade soil properties, cause soil compaction, and reduce subsequent crop yields. As Lull (1959) noted, “what is needed is an animal that can graze with its feet off the ground,” but does research support or dispute the compaction concern of CC and corn residue grazing? Beyond compaction concerns, a more comprehensive research on CC and corn residue grazing impacts on soil physical, chemical, and biological properties is needed. Many fertile soils evolved with grazing animals; therefore, grazing can be a tool to possibly improve soil ecosystem services under proper management.

A recent review focusing on crop residue grazing found no significant negative impacts on soil properties nor crop yields (Rakkar and Blanco-Canqui, 2018), but a complete understanding of how soil and crops respond to CC grazing is limited. Since CC grazing does not remove root biomass and moderate grazing still leaves some shoot material intact on the surface of the soil, CC grazing could prove more beneficial than crop residue grazing to the soil system. The few short-term (≤4 yr) studies that exist suggest CC grazing has little to no impact on soil and crop production (Franzluebbers & Stuedemann, 2007, 2008a, 2008b; Faé et al, 2009; Schomberg et al, 2014; Blanco-Canqui et al., 2020; Kelly et al., 2021). However, these studies often only evaluated a few soil properties at a time. The scant literature suggests the need for more comprehensive research on CC grazing impacts on soil and crop production.

Objectives

The overall objective of this study is to better understand the impact of crop-livestock integration in terms of CC and corn residue grazing on soils and crop yields in eastern Nebraska. The specific objects are:

Objective 1: Determine the medium-term impact of CC grazing under two and three grazing events on soil physical, chemical, and biological properties under irrigated corn silage and high moisture corn harvest in the western US Corn Belt.

Objective 2: Determine the short-term (1-2 yr) impact of CC and corn residue grazing on soil compaction parameters including bulk density, penetration resistance, and related soil properties under two crop-livestock integrated systems.

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CHAPTER 2. Review of Literature

Cover Crops

Cover crops (CC) are receiving widespread attention from government agencies, universities, producers, and industry for their potential to improve soil properties, enhance ecosystem services, and possibly increase economic returns. Cover crops are planted between cash crop seasons when the field would otherwise be in fallow. They are used globally for a variety of reasons including soil and water conservation, N_2 fixation nutrient retention, and weed and pest management (Snapp et al., 2005; Villamel et al., 2006; Blanco-Canqui et al., 2015; Bergtold et al., 2017). Yet, despite the many well-known benefits of CCs, there is still concern among farmers on their adoption because of the added time, labor, skill, and cost of planting and terminating CCs (Drewnoski et al., 2015). This includes seed, equipment, and termination costs (Snapp et al., 2005; Bergtold et al., 2017).

Cover crops can provide a number of soil ecosystem services. These benefits include reductions in soil erosion from the aboveground surface cover and residue accumulation and improvements in soil structure (Snapp et al., 2005; Blanco-Canqui et al., 2015). The use of CCs can also increase nutrient cycling by fixing N (legume CCs), scavenging nutrients (non-legume CCs), and reducing nutrient leaching (Snapp et al., 2005; Bergtold et al., 2017; Blanco-Canqui et al., 2015). Additionally, CCs can enhance soil microbial properties and wildlife habitat (Blanco-Canqui et al., 2015). Cover crops can also be used to break pest cycles (Snapp et al., 2005) and suppress weeds (Blanco-Canqui et al., 2015). Utilizing CCs also ensures there is a living root in the soil year-round, which can alleviate compaction (Williams and Weil, 2004) and increase soil C concentration (Gale and Cambardell, 2000).

These improved soil properties can also help with enhancing ecosystem services. A healthier soil with improved hydraulic properties and reduced runoff can increase water availability to crops while also preventing excess nutrients from entering waterbodies through runoff (Snapp et al., 2005; Tonitto et al., 2006; Bergtold et al., 2017). Improved soil health has the potential to help farmers save money through increased N use and efficiency, water holding capacity, and other benefits (SARE publication, 2019). For example, legume CCs could decrease fertilizer costs by adding N to the soil while non-leguminous CCs can scavenge and capture nutrients otherwise lost to the system (Tonitto et al., 2006). In addition, CCs can suppress weeds; thereby reducing herbicide inputs (Lu et al., 2000; Tracy and Davis, 2009; Bergtold et al., 2017). While CCs can generally benefit the soil, there is also interest in the role CCs could play in crop-livestock integrated systems.

Cover Crops as Livestock Forage

There is an increasing interest in using CCs as annual forages for livestock. With economic concerns of using CCs (Snapp et al., 2005; Drewnoski et al., 2015; Bergtold et al., 2017), CC grazing could create an economic incentive to implement CCs in what would typically be a fallow period earning no income. Little research exists on the economics of CC grazing. Drewnoski et al. (2018) discussed that spring grazing winter hardy CCs could be cost effective and grazing annual forages in the fall and winter can be potential strategies since CC grazing during these time periods is outside of the traditional grazing periods for perennial pastures. In addition, there is a large amount of grassland converted to cropland. For example, in the United States (US) cropland expansion increased by 1.21 million ha nationwide between 2008 and 2011 (Lark et al., 2015), and in the US western Corn Belt, grasslands declined by about 500,000 ha between 2006 and 2011 due to cropland expansion (Wright and Wimberly, 2013). Thus, CC could provide nutritious and much needed forage for cattle (Schomberg et al., 2014; Drewnoski et al., 2018; Farney et al., 2018; Han et al., 2018; Deen et al., 2019).

Utilizing the fallow period between cash crops to graze annual CCs in rotation with cash crops is a potential alternative. Depending on the crop rotation, management, and region, CCs could be used for fall, winter, or spring grazing (Sulc and Tracy, 2007; Drewnoski et al., 2018). Fall and winter grazing of CCs is dependent on how early the previous crop is harvested before planting CCs to allow enough biomass growth before grazing. Cash crops harvested in the summer or early fall have the greatest potential to allow the subsequent CC to create enough biomass for fall and winter grazing. For example, a study in Nebraska found that 41% of the acres where producers used CCs contained wheat, seed corn, and corn silage. Planting winterkill CCs after early harvested annual crops can provide fall and winter grazing of CCs that are high in nutritive value (Drewnoski et al., 2015). A study conducted in Canada found that oat and oat-pea mixtures produced high quality forage following winter wheat (Deen et al., 2019). In addition, a study conducted in Kansas found that cover crop mixes of a grass, brassica, and legume species met the protein and energy demands for cattle (Farney et al., 2018).

Spring grazing of winter hardy CCs can also be accomplished for rotations of soybean and corn harvested for grain if proper management is used and weather is favorable (Drewnoski et al., 2018). Humid climates especially have potential to use cool-season CCs to provide nutritious forage for late winter and early spring, but biomass production is dependent on favorable weather conditions (Han et al., 2018). Thus, current literature suggests annual CCs can be used as nutritious forage for livestock.

Impacts of Cover Crop Grazing on Soil Properties

While CC grazing appears feasible, the question is: Does CC grazing negatively affect soil processes and properties? For example, some producers are concerned that CC grazing may compact soil and thus reduce subsequent crop yields due to animal grazing, trampling, and walking. Because cattle can exert similar pressures to agricultural machinery (Greenwood and McKenzie, 2001), their impact on soil physical, chemical, and biological properties must be evaluated. Here we synthesize findings from the limited published research on the impact of grazing CCs on soil properties.

Soil Compaction

To assess how CC grazing affects soil compaction, we reviewed papers that measured soil compaction indicators including bulk density and penetration resistance, which simulates root growth in the soil. According to Hamza and Anderson (2005), penetration resistance is very sensitive to animal trampling, so it is an important indicator for compaction. It is well recognized that an increase in bulk density and penetration resistance can negatively impact root development in crops. The threshold values that restrict root growth vary for bulk density depending on soil texture, but range from 1.80 g cm^{-3} for sandy soils to 1.47 g cm^{-3} for high clay soils (USDA, 2008). The threshold values that reduce root growth for penetration resistance depend on the crop and other factors but are generally considered to be from 2 to 3.5 MPa (Bengough et al., 2011; Rakkar and Blanco-Canqui, 2018).

Bulk Density

Limited literature is available on the impact of CC grazing on soil bulk density. Table 2.1 summarizes seven studies. Three of the seven studies found CC grazing increased bulk density, indicating that CC grazing may affect soil bulk density. An additional integrated study is reported in the table but not included in the above count due to sod being included in the rotation. The authors of this study found no effect on bulk density in this two-year sod followed by a cotton-peanut rotation with winter CC grazing. The authors hypothesize increased soil organic matter and increased root length and biomass as factors that may have prevented CC grazing from impacting bulk density (George et al., 2013).

One CC grazing study found that CC grazing increased bulk density by 5% compared to no grazing (1.60 vs. 1.52 Mg m^{-3}), but the increase was only significant under no-till management (Table 2.1). At the same site in Georgia, a later study reported that CC grazing increased bulk density by 6% (1.08 vs 1.02 Mg m^{-3}) after 4.5 yr but not after 0.5, 2, and 2.5 yr (Table 2.1). The latter study suggests that CC grazing effects could vary with duration of grazing. Grazing may have more effects on bulk density in the long than in the short term, although data from long-term (> 5 yr) CC grazing experiments are few (Table 2.1). Also, while bulk density increased in the above studies, such increases are not detrimental as the bulk density values are well below the threshold limiting factor for this textural class (USDA, 2008). One study of dryland cropping systems found that a non-grazed CC reduced bulk density, but grazing diminished this impact, with CC grazing having similar bulk density to the summer fallow control (Kelly et al., 2021). Outside of the US, a short-term (2 yr) study in Brazil also found that CC grazing increased bulk density, but values were also below root limiting thresholds, and a longer term (14 yr) study in Brazil found that CC grazing increased bulk density above threshold levels in the high grazing densities compared to the non-grazed control. However, low and moderate grazing density had no effect on bulk density (Table 2.1). This suggests that CC grazing at low to moderate stocking densities does not influence soil compaction.

The limited or no negative impacts of CC grazing on bulk density may be due to the following mechanisms. One, tillage operations can alleviate compaction through frequent disturbance (Raper et al., 2000; Blanco-Canqui and Ruis, 2018). Two, freeze-thaw cycles and wetting and drying cycles can naturally alleviate compaction within the soil (Jabro et al., 2013; Cui et al., 2014; Wang et al., 2020). Three, high organic matter soils could be more resistant to compaction (Soane, 1990; Diaz-Zorita and Grosso, 2000). Four, cover crops could reduce soil compaction (Kelly et al., 2021). An expanded discussion of these factors and mechanisms is presented later. It is also important to discuss the longevity of CC grazing effects after cessation of grazing, although very few studies are available on this topic. A follow-up experiment to the Georgia study discussed above found that 2 yr after grazing ended, the effect of grazing on bulk density was not significant (Franzluebbers and Stuedeman, 2013). This indicates that, while CC grazing may increase bulk density, such increase may be short lived after grazing is discontinued. The authors suggest that the high sand content (60-70%) in addition to moldboard plow and disk tillage may have led to these results. In sum, CC grazing appears to have minimal to no effect on soil bulk density and any increase in bulk density is generally below the level that can affect root penetration.

Penetration Resistance

Penetration resistance is another indicator of soil compaction (Hamza and Anderson, 2005). Similar to bulk density, studies on penetration resistance and CC grazing are few. Table 2.1 indicates that out of the five studies that measured penetration resistance, all five studies reported increases in penetration resistance from CC grazing. These findings show that CC grazing can increase penetration resistance in most cases. However, it is important to discuss the threshold levels of penetration resistance that can reduce or restrict root growth. Literature cites the penetration resistance levels that could reduce root growth vary from 2 to 3.5 MPa, depending on the crop and other factors (Bengough et al., 2011; Rakkar and Blanco-Canqui, 2018). Only two out of the five studies report penetration resistance values above this threshold level (2 MPa). One study reported values just above the threshold where CC grazing increased penetration resistance by 16% (2.2 vs. 1.9 MPa) compared to the non-grazed CC (Mullins and Burmester, 1997). However, such increase above the threshold level occurred only in the 5 to 10 cm and not in the 0 to 5 cm depth. The second study that reported penetration values above 2 MPa represents a worst-case scenario with an above-average late spring rainfall (100 mm). Despite best management practices recommending to not graze on wet soils (McKenzie and Greenwood, 2001; Bell et al., 2011), the authors decided to graze the CC regardless to measure a worst-case scenario. Cover crop grazing under the wet soil conditions led to penetration resistance levels above 2 MPa in the grazed sites compared to the non-grazed control (Schomberg et al., 2014).

Wet soil conditions can greatly influence the effect of CC grazing on soil penetration resistance (Schomberg et al., 2014), but tillage can also play a role. One study found that, under conventional disk harrow tillage, penetration resistance increased less compared to in-row disk tillage management. The authors attributed this to the additional disk passes under conventional tillage (Tollner et al., 1990). Alternatively, another study found increased penetration resistance due to CC grazing under moldboard disk plow but not under no-till (Table 2.1). This could be due to the higher soil organic C concentration under no-till compared to moldboard disk plow (Franzluebbers and Stuedemann, 2008b). Blanco-Canqui and Lal (2008) found that the higher soil organic C concentration under no-till management seemed to buffer against increases in soil compaction.

Cover crop grazing effects on penetration resistance may also vary from year to year. For example, under similar stocking rates, Faé et al. (2009) found a trend of higher penetration resistance by 7 to 15% in year one of CC grazing compared to the no CC control. However, one year later, penetration resistance in the CC grazing sites decreased to levels similar to the control. The authors attributed this variability to 1) the occurrence of freeze-thaw cycles and wetting and drying cycles and 2) the cumulative positive effects of CC root growth, which probably alleviated soil compaction from CC grazing. Note that the previous study was short term (2 yr), which may yield inconclusive results. However, Blanco-Canqui et al. (2020) also found penetration resistance increased in 2 yr of grazing, but not the 1 and 3 yr of grazing. Overall, CC grazing can increase penetration resistance, but these increases in penetration resistance values are typically below the threshold that would affect root growth.

Soil Structure

Aggregate stability is a sensitive indicator to changes in soil structure; however, there is scant literature on this soil property and CC grazing. Only four studies measured changes in wet aggregate stability (Table 2.2). Two studies found no effect of CC grazing on soil structure (Blanco-Canqui et al., 2020; Kelly et al., 2021), but another study reported CC grazing reduced wet aggregate stability by 13% (0.89 mm vs. 1.01) for the 0 to 3 cm depth and by 27% compared to non-grazed CC (1.01 vs 1.28 mm) for the 3 to 6 cm depth after 2.5 yr (Table 2.2). The authors reported no interaction between tillage system and CC grazing, indicating that tillage system did not influence the effect of CC grazing on wet aggregate stability (Franzluebbers and Stuedemann, 2008a). The fourth study found that high density grazing decreased wet aggregate stability by 81% compared to non-grazing, but low and moderate grazing densities had no impact on water stable aggregates (Bonetti et al., 2019). The decrease in wet aggregate stability could be due to cattle hooves crushing soil aggregates near the soil surface. A review of cattle grazing on pastureland found that aggregate stability typically decreases due to hoof action breaking up aggregates (Greenwood and McKenzie, 2001). Since studies on croplands generally found no effect of cattle grazing of crop residues on wet aggregate stability (Clark et al., 2004; Rakkar et al., 2017), long-term (year-round) grazing of pastureland might have a greater impact on wet aggregate stability than short-term cropland grazing (Rakkar et al., 2017).

Evaluating the impact of integrated systems on wet aggregate stability can give insight into how CC grazing compares to monoculture systems. Maughan et al. (2009) conducted a study comparing an oat-corn winter CC grazed system to a non-grazed continuous corn system with no CC (control) and found that CC grazing increased wet aggregate stability compared to the control (Maughan et al., 2009). The study found that the CC grazed system had 46% higher mean weight diameter of water-stable aggregates compared to the control (0.226 vs. 0.155 mm). This study points to the importance of CCs to maintain or increase soil aggregate stability. Living plants produce active root growth, and these roots add C into the soil from root decay and bind aggregates through root fungal hyphae (Amézketa, 1999; Greenwood and McKenzie, 2001; Sokol et al., 2019; Gale and Cambardella, 2020). Aboveground biomass is also a factor influencing the impact of CC grazing on aggregation. Residue on the soil surface can protect the soil from cattle hoof action and maintain soil aggregate stability (Greenwood and McKenzie, 2001). These studies, though few, seem to indicate that CC grazing can have mixed effects on soil wet aggregate stability.

Soil Water Infiltration

Soil water infiltration is an indicator of soil structure and porosity. Greenwood and McKenzie (2001) reported that water infiltration is one of the most sensitive soil properties to animal grazing due to its dependence on soil porosity. Despite the importance of water infiltration, there are only three studies on CC grazing and soil water infiltration (Table 2.2). One study reported, CC grazing reduced water infiltration rate in two of the seven sampling events, where infiltration rate was 46% lower due to CC grazing (Table 2.2). The authors suggest that soil water content could have contributed to the decline in water infiltration rate. The authors found that high soil water contents led to the greatest reductions in infiltration rates (Franzluebbers and Stuedemann, 2008a). Thus, high soil water content may have a greater influence on decreased infiltration rates than CC grazing. A long-term (14 yr) study in Brazil found that CC grazing decreased infiltration rate under high density grazing, but low to moderate density grazing had no impact compared to the non-grazed control (Table 2.2). However, there was a trend of lower infiltration rate with increased grazing density. The authors attributed the decreased infiltration rate to increased bulk density in the high-density grazing. The reduction in residue cover after grazing may have also reduced water infiltration. The high-density grazing reduced residue cover by 92%, whereas the moderate grazing density reduced residue cover by about 50% (Bonetti et al., 2019). Another study found that CC grazing reduced water infiltration in only one out of three yr., thus CC grazing impacts on water infiltration may be variable (Blanco-Canqui et al., 2020).

Other studies, while not explicitly evaluating CC grazing, also found little to no significant impact on water infiltration due to cattle grazing. A study in North Dakota found that swath grazing oat and triticale/sorghum straw during the winter had no effect on infiltration rate compared to perennial grass grazing by cattle. The authors suggest that this was due to frozen soil at the time of grazing (Liebig et al., 2011). In addition to soil conditions impacting CC grazing and water infiltration rate, residue cover may also play an important role. For example, a study in Australia found that grazing crop residue decreased residue cover to 38%, which reduced infiltration rates (Allan et al., 2016). Decreased water infiltration due to grazing has even been observed in grazed perennial pastures. Greenwood and McKenzie (2001) suggest that the combined effects of trampling and defoliation from cattle grazing compact the surface soil and reduce residue cover, thus leading to decreases in infiltration. In short, under the current limited literature, there seems to be no significant detrimental effect of CC grazing on soil water infiltration, especially at low to moderate stocking densities.

Water Content

Soil water content is a critical soil property that can influence crop production. Five CC grazing studies reported water content in addition to an integrated study with a two-year sod and cotton-peanut rotation with winter CC grazing (George et al., 2013). First, a short-term (2 yr) study in Ohio found no difference in soil water content between the CC grazed sites and the no CC, non-grazed control. A short-term (2-yr) dryland study in the US High and Central Plains found CC grazing did not reduce soil water any more than the non-grazed CC (Table 2.2). Additionally, a study in Georgia reported reduced water content in three of the seven sampling events under CC grazing compared to non-grazed CC. Specifically, two of the three cases where soil water content was reduced occurred with summer sampling regarding the summer grazed CC (Franzluebbers and Stuedemann, 2008a). Thus, the reduced soil water content in the grazed treatments could be due to greater summer soil water evaporation where grazing has removed more residue. This was consistent with the lower yields in the summer sorghum crop under no-till CC grazing compared with no CC grazing (Table 2.5). The increased evaporation from residue removal from CC grazing could have contributed to the reduction in yields.

While the Georgia study found water content reductions from CC grazing potentially impacted yields, a study in Brazil did not find this to be the case. Although soil water content was lower in the grazed sites compared to the non-grazed sites, CC grazing did not reduce subsequent soybean yield. The authors attributed the reduction in residue cover from CC grazing to the reduced soil water content (Peterson et al., 2019). On average, CC grazing reduced residual biomass by 54% compared to the non-grazed sites (Carvalho et al., 2018). Despite the higher soil organic matter in the grazed sites (Assmann et al., 2014; Peterson et al., 2019), it appears the greater residual biomass cover in the non-grazed sites had the greatest influence on retaining soil water content. A follow-up study on the Brazil experiment found that the low to moderate grazing densities had higher soil available water content compared to the higher density grazing that caused decreased water content between -1 and -10 kPa. The authors attributed this increased soil water content to greater porosity from low to moderate density grazing that increased root growth without compressing and compacting the soil like in the higher stocking density (Bonetti et al., 2019).

The integrated study mentioned above (George et al., 2013) found that soil water content was greater in the grazed sites compared with the non-grazed sites at the 30 and 100 cm depth during mid-season cotton production. The authors credited the increased soil water content to increased cotton root biomass during this stage of plant growth (Loison et al., 2012). In addition, in the irrigated treatments, soil water was greater in the grazed plots compared to the non-grazed plots. This could be due to the increased soil organic matter in the grazed, non-irrigated plots (George et al., 2013). Thus, the possible enhancements in soil C under CC grazing could lead to increases in soil water content. Results on the impact of CC grazing on soil water content (Table 2.2) are variable, but residue cover left after CC grazing and possible increased compaction could play a role in the response of soil water content to CC grazing.

Soil Organic Matter and Carbon Fractions

Soil organic matter and C are important indicators of soil quality and influence many soil properties and processes. Cover crop grazing has the potential to improve organic matter through the aboveground and belowground CC biomass (Blanco-Canqui et al., 2015; Sokol et al., 2019; Gale and Cambardella, 2020; Xu et al., 2021) and cattle additions from manure (Drinkwater et al., 1998; Peacock et al., 2001; Russelle et al., 2007; Drewnoski et al., 2016; Rakkar and Blanco-Canqui 2018). Although organic matter is vital to soil health and soil ecosystem services, there is little research on CC grazing impacts on organic matter and C. As summarized in Table 2.3, while CC grazing generally does not reduce organic matter and C, there are some inconsistent findings on the impact of CC grazing on organic matter, soil C, and their fractions.

Total Soil Organic Matter or Total Carbon

Three studies evaluated the impact of CC grazing on total organic C and one on organic matter. Three additional studies assessed the impact of integrated CC grazing systems on total organic C and organic matter. Generally, CC grazing had little to no impact on total organic C and organic matter (Table 2.3). One study analyzed total organic C within water-stable aggregates and found that, at the 0 to 3 cm depth, CC grazing under no-till reduced total organic C by 18% compared to the non-grazed sites (10.7 vs. 12.6 g kg^{-1}); however, there was no effect on CC grazing and total organic C under conventional tillage. Alternatively, the authors found that at a depth of 3 to 6 cm total organic C was 20% higher under grazed compared to non-grazed (4.1 vs. 3.3 g kg^{-1}) and at 6 to 12 cm, total organic C was 8% higher under grazing compared to non-grazed (2.5 vs. 2.3 g kg^{-1}) (Table 2.3). While longer term research is needed, the authors hypothesized that animal traffic could have led to the decrease in total organic C at the surface depth, but that aggregates may have protected the organic C at the lower depths (Franzluebbers and Stuedeman, 2008b). However, two yr after the experiment ended, there were no measured effects on total organic C (Franzluebbers and Stuedeman, 2013). Thus, impacts from CC grazing did not persist after grazing was completed. Other studies found no effect of CC grazing on total organic C. In a long-term (9 yr.) study in Brazil, total organic C only decreased in the high-density grazing treatment but saw no differences in total organic C in the moderate to low grazing densities compared to the non-grazed control (Table 2.3). The authors believe the higher residue removal from high density grazing may have contributed to the reduction in total organic C. They reported that the high-density grazing had 30% less C additions, this includes CC roots, shoots, and cattle manure, compared to the other grazing densities (Assmann et al., 2014)

An integrated sod and CC grazing rotation in Florida also found variable results of CC grazing on soil organic matter. The authors found soil organic matter was greater under the grazed irrigated sites after 1 and 2 yr but soil organic matter was lower after 1, 2, and 3 yr at the grazed non-irrigated sites (Table 2.3). The increased organic matter in the grazed irrigation plots matches the greater root length and surface area of the cotton plants in the grazed plots (Loison et al., 2012). The authors hypothesized that the increased soil organic matter from grazing may have been due to the addition of roots or the greater soil microbial biomass also found at these sites could have stimulated soil organic matter accumulation (George et al., 2013). Roots supply soil C to the soil in addition to enhancing soil microbial biomass (Sokol et al., 2019; Gale and Cambardella, 2020; Xu et al., 2021). While some studies found variable impacts of CC grazing and total organic C, an integrated CC grazing study in Illinois found that CC grazing had no impact on total organic C after 5 yr (Tracy and Zhang, 2008; Maughan et al., 2009). The authors determined that the benefits of the integrated system with diverse rotation and a winter CC outweighed the potential negative disturbances from cattle traffic (Tracy and Zhang, 2008; Maughan et al., 2009). Additionally, a 2 yr study in Ohio found no effect on total organic C after 1 and 2 yr of CC grazing compared to a no CC contorl (Table 2.3). Thus, the effect of CC grazing on soil organic C is little to none.

Particulate Organic Matter/Carbon

Another important fraction of soil organic matter is particulate organic matter. It includes the fraction of soil organic material that is readily available and decomposed for use by soil microorganisms, which makes it quick to respond to management (Kantola et al., 2017). Similar to total organic C, CC grazing has variable effects on particulate organic matter. Four studies evaluated the impact of CC grazing on particulate organic matter with one other integrated CC grazing experiment reporting particulate organic C. One study found that at the 0 to 3 cm depth CC grazing lowered particulate organic matter by 19% in the summer CC compared to the non-grazed summer CC (8.4 vs 10.4 g kg^{-1}) but grazing had no effect on the winter CC and no other depth of the summer CC (Table 2.3). The authors had no explanation for why the winter CC particulate organic matter was not impacted by CC grazing (Franzluebbers and Stuedeman, 2008b), but this study suggests only the surface soil was impacted by cattle grazing. In addition, the authors found no residual effect of CC grazing on particulate organic matter 2 yr after grazing ended (Table 2.3). Similar to total organic C, a long-term (9 yr) study in Brazil found that moderate to low CC grazing densities had no impact on particulate organic matter compared to non-grazed sites; however, high density grazing did lower particulate organic matter concentration (Table 2.3). The authors contribute this reduction in particulate organic matter to the reduced residue cover under high density grazing (Assmann et al., 2014). Another study found that particulate organic C was greater after 2 yr in the CC grazed site compared to the control (3.52 vs. 2.87 kg m^{-3}) (Table 2.3). However, in a longer-term study (5 yr) in Illinois, the authors found that CC grazing had no impact on particulate organic C (Table 2.3). Their findings show that animal traffic does not degrade labile organic matter. Overall, the impact of CC grazing on particulate organic matter are variable, but generally show little to no effect.

Soil Fertility Properties

Soil fertility is a critical soil property that can influence crop productivity. Therefore, understanding the impact CC grazing could have on soil fertility properties is important. Livestock manure and urine deposition could enhance soil fertility (Drinkwater et al., 1998; Russelle et al., 2007; Drewnoski et al., 2016; Rakkar and Blanco-Canqui 2018). While cattle remove some CC biomass from grazing, much of the nutrients consumed are excreted (Rakkar and Blanco-Canqui, 2018). Additionally, the above-ground trampled CC biomass and below-ground root biomass could improve fertility as well. However, changes in soil physical properties and soil water, as described above, can influence nutrient cycling. Four studies report the effect of CC grazing on soil fertility (Table 2.3) with three additional integrated CC grazing studies. One study in Table 2.3 found that CC grazing had variable effects on nitrate-N. Franzluebbers and Stuedemann (2013a) note that inorganic soil N is influenced by many biogeochemical processes in the soil and outside environmental factors, which may contribute to variable results. Overall, they concluded CC grazing had no effect on inorganic soil N concentration (Franzluebbers and Stuedemann, 2013a). This is consistent with results from the same study that found no effect on total N and particulate organic N after 6 yr from CC grazing (Franzluebbers and Stuedemann, 2015). In addition, a long-term (6 yr) study in Brazil found no effect of CC grazing on soil K compared to the non-grazed site, but did find high density grazing reduced soil P (Table 2.3). Overall, it CC grazing can have little to no impact on soil fertility.

An integrated two-year sod rotation followed by an annual rotation with grazed winter CCs found that nitrate-N concentration was greater in the grazed non-irrigated site; soil P was greater in the non-grazed non-irrigated site; and soil K was greater in the grazed sites of both the irrigated and non-irrigated areas. The authors suggest that the non-irrigated site shows more nutrient accumulation because of a decreased chance of leaching of nitrate and potassium. In addition, with lower levels of soil organic matter in the non-irrigated sites, it is less likely that P was adsorbed to organic matter. In addition, the enhanced microbial biomass activity in the non-irrigated sites may also be responsible for greater nutrient cycling and mineralization in addition to manure additions enhancing soil C and N (George et al., 2013).

Cover crop grazing had variable effects on soil macronutrients, and the effects of CC grazing on other N fractions in the soil are also inconsistent. Table 2.3 shows a study where total N was 6% lower in the grazed sites compared to the non-grazed sites under no-tillage (2.93 vs. 3.12 g kg^{-1}). However, under conventional tillage, CC grazing had no impact on total N and there were no effects at all other depths for both tillage managements. The authors hypothesize that grazing reduced surface residue of N under no-till and cattle depositions may have enhanced gaseous loss of N (Franzluebbers and Stuedemann, 2008b). Additionally, the authors found no residual effects of CC grazing on total N after taking measurements 2 yr after grazing was terminated (Franzluebbers and Stuedemann, 2013). Two studies in Brazil found that low to moderate CC grazing densities did not affect total N compared to the non-grazed sites whereas high grazing density decreased total N (Table 2.3). This suggests CC grazing at moderate to light stocking densities does not impact total N. A study in Illinois found that the CC grazed system had higher levels of total N compared to the no CC control after 4 yr (Tracy and Zhang, 2008) and 5 yr (Maughan et al., 2009). The authors suggest the addition of N fertilizers for the corn and oat cash crop may have contributed to the increased soil N, in addition to the winter CC scavenging and recycling N (Maughan et al., 2009). Although there is little literature on the topic, CC grazing seems to have limited effects on soil fertility.

Soil Microbial Biomass

The biological component of the soil plays a critical role in soil quality and ecosystem services as soil microbes mediate many soil processes. In addition, soil organisms are sensitive to management and correlate well with soil functions, so are considered good indicators of a healthy soil (Doran and Zeiss, 2000; Schloter et al., 2003; Bünemann et al., 2018). Despite the importance of soil biota, there is little research on the impact of CC grazing on soil biological properties. The studies that do exist focus on soil microbial biomass, which gives an estimate of the total amount of microbes in the soil.

Table 2.4 summaries three studies that evaluated the effects of CC grazing on soil microbial biomass. Also, note that there are three other studies in Table 2.4 comparing integrated systems, which will be discussed next. The first study in Georgia, at a depth of 0 to 3 cm, soil microbial biomass C tended to be lower in the grazed summer CC compared to the non-grazed summer CC (1019 vs. 1176 mg kg^{-1}). The reduction of soil microbial biomass in the grazed summer CC could be related to the reduction in particulate organic C also observed in the grazed summer CC (Franzluebbers and Stuedemann, 2008b). In a follow-up study 2 yr after grazing ceased, the authors found no residual effect of CC grazing on soil microbial biomass except for an increase under CC grazing at the 3-6 cm depth under no-till (Table 2.4). A study in Ohio found no impact of CC grazing on soil microbial biomass after 2 yr (Faé et al., 2009). The third study, located in Brazil, found that soil microbial biomass was greater in the CC grazed sites compared to the non-grazed sites (Table 2.4). Cattle manure is known to increase soil microbial biomass and activity in the soil (Frostegard et al., 1997; Peacock et al., 2001) and roots can contribute C to feed soil microorganisms (Hinsinger et al., 2009; Sokol et al., 2019; Gale and Cambardella, 2020).

Since only three CC grazing studies assessed the impact of CC grazing on soil microbial biomass, additional integrated systems will be discussed. The first is a study in Illinois under an oat-corn winter CC grazing system that found no effect of CC grazing on soil microbial biomass in 1, 2, or 3 yr, but soil microbial biomass was higher than the no CC, non-grazed continuous corn control after 4 yr (Tracy and Zhang, 2008) and 5 yr (Maughan et al., 2009). The enhanced aggregate stability and C fractions in the winter CC grazed system may have contributed to the higher soil microbial biomass in this system (Tracy and Zhang, 2008; Maughan et al., 2009). The second integrated study is in

Florida under a two-year sod, cotton-peanut rotation with a grazed winter CC. The authors found soil microbial biomass increased in the grazed non-irrigated treatment compared to the non-grazed non-irrigated control whereas there was no effect of soil microbial biomass and CC grazing in the irrigated treatment. The authors suggest that the greater soil microbial biomass in the grazed non-irrigated treatments could be due to the increased soil organic matter or the increased soil water content in this treatment, potentially stimulating soil microbes. This could be why grazing did not impact the irrigated treatments (George et al., 2013). Despite the few studies that analyzed soil microbial biomass and CC grazing, it can be concluded that CC grazing generally has little to no impact on soil microbial biomass compared to non-grazed CC.

Impacts of Cover Crop Grazing on Crop Yields

Evaluating the impact of CC grazing on crop production is essential to assess the viability of this management practice and its potential impact on agricultural production. Ten studies on CC grazing impacts on crop yields are summarized in Table 2.5, with three additional studies reporting on integrated systems, which will be discussed separately, for a total of thirteen studies. Of the ten CC grazing studies, seven found no effect of CC grazing on crop yields and three found variable effects (Table 2.5).

The three studies that found variable results give insight to the factors that can impact the effect of CC grazing on crop yields. The first study in Georgia had two rotations: summer grain with winter CC and winter grain with summer CC. The authors found no effect of CC grazing on the winter grain for all 4 yr of the study. However, averaged over 4 yr and under no-till management the summer grain yield was lower under CC grazing. The authors hypothesize that the greater accumulation of residues under non-grazed no-till may have been beneficial to the summer grain yield whereas the grazed no-till sites had less residue cover and greater soil water evaporation (Franzluebbers and Stuedemann, 2007). The second study was also in Georgia and found no effect on cotton yield in the 1, 2, and 3 yr of the study, but cotton yield decreased under CC grazing in the 4 yr. The authors hypothesize that an above average late spring rainfall (100 mm) created a worst-case scenario that increased penetration resistance, which led to the decrease in yield under grazing for this year (Schomberg et al., 2014). The final study, conducted in Alabama, found CC grazing decreased cotton yields in the 1 and 3 yr of the study, but increased yields in the 2 yr. The authors note that severe drought in the 2 and 3 yr of the study may have impacted yield, specifically in 2 yr when annual precipitation decreased by 47% compared to the 1 yr (Mullins and Burmester, 1997). In general, under ideal grazing conditions, CC grazing appears to have no effect on the subsequent cash crop (Hill et al., 2004; Flores et al., 2007; Faé et al., 2009; Peterson et al., 2019). However, other studies found variable impacts of CC grazing on crop yields depending on summer residue management, wet soil conditions during grazing, or drought.

Three of the studies in Table 2.5 are integrated studies that compare an integrated system to a control. A study in Illinois compared an oat-corn CC grazing system to a non-grazed continuous corn control without CCs and found that corn yield tended to increase in the integrated CC grazing system compared to the no CC control. The authors suggested the higher corn yields could have been due to a variety of factors including the increase in labile C and N, manure deposition from grazing, or the more diverse crop rotation in the CC grazing system (Tracy and Zhang, 2008; Maughan et al., 2009). In a study in Florida with a two-year sod rotation followed by a cotton-peanut rotation with winter CC grazing found that cotton yield increased over the 4 yr study in the non-irrigated sites but found no effect on yield in the irrigated sites. The authors contributed the increase in non-irrigated sites to improved fertility from cattle manure and CC soil organic matter additions (George et al., 2013). In addition, another experiment at this site found that grazed sites had greater cotton root length and surface area (Loison et al., 2012). Thus, integrated systems involving CC grazing may improve yields compared to conventional rotations with no CC due to more diverse rotations and potentially improved fertility from CC grazing.

Overall, out of the thirteen studies evaluated, ten found no negative effects of CC grazing on subsequent crop yields. This is similar to findings in a review on crop residue grazing and crop yields, where six of the eleven studies found no negative effect on crop production. The review found that crop yields were only impacted under thawed soil conditions or under some sheep grazing rotations (Rakkar and Blanco-Canqui 2018). Similarly, CC grazing impacts on crop yields occurred when soil was wet, drought conditions, or reduced residue increasing soil water evaporation during summer CC grazing.

Factors Affecting Cover Crop Grazing Effects on Soils and Crop Production

The few studies on the impact of CC grazing on soil properties and crop production indicate CC grazing has little to no negative effect on soil and crop production. The potential factors that may explain the small or no effect deserve discussion. Some of the factors that can affect the impact of CC grazing on soil and crop production are discussed below.

Stocking Rate and Density

Stocking rate refers to the number of animals in an area for a certain amount of time. The available studies on CC grazing and soil properties were generally conducted by grazing cattle based on the weights of the animals and forage or residue availability (Wilson et al, 2004; Wyatt et al., 2013; Drewnoski et al., 2018). While there are no CC grazing studies that evaluated the impact of different stocking rates, a corn residue grazing study found increasing stocking rates could lead to negative impacts on soil properties and crop production. Rakkar et al. (2017) found that fall grazing corn residues at a stocking rate of 4.4-6.2 animal unit-months (AUM) ha^{-1} did not negatively impact soil properties, but spring grazing at a stocking rate of 9.3-13.0 AUM ha^{-1} did increase penetration resistance by 1.3 to 3.4 times compared to the control (1.5 vs. 0.25 MPa) in a no-till corn-soybean rotation in eastern Nebraska after 16 yr. The increase in penetration resistance was, however, below the root growth threshold limit (2 MPa) for most row crops. Studies specifically assessing CC grazing impacts on soils and crop production under different stocking rates are unavailable, but such studies are needed to develop CC grazing recommendations.

Stocking density refers to the concentration of animals in a certain area, often measured by post-grazing forage height. Stocking density could affect how evenly cattle impact soils and crop production, but this has been researched little in temperate climates. However, some research exists in subtropical regions such as in Brazil. In a long term (6 yr) CC grazing study, Carvalho et al. (2010) argued that increasing stocking density reduces residue amount, although nutrient cycling, through manure additions, could counteract the potential negative effects of residue removal. It is well known that cattle manure can increase microbial biomass and activity in the soil (Fraser et al., 1988; Frostegard et al., 1997; Peacock et al., 2001) and contribute to soil fertility (Drinkwater et al., 1998; Russelle et al., 2007; Drewnoski et al., 2016). Also, moderate grazing density can improve soil microbial biomass whereas high density grazing can degrade microbial biomass (Souza et al., 2008; Carvalho et al., 2010). In addition, after 9 yr at this study, they found high density grazing reduced soil C and N fractions while low to moderate grazing increased soil C and N fractions (Assman et al., 2014). After 14 yr, the same study in Brazil found that high density CC grazing increased bulk density and decreased water infiltration and water retention, but moderate to light grazing densities did not impact bulk density nor infiltration while it increased plant available water content (Bonetti et al., 2019). This long-term study in Brazil indicated that moderate CC grazing density offered the greatest benefits to soil properties while not degrading soil or crop production. The authors of this study evaluated stocking density based on sward heights.

Similar studies are needed in temperate climates to better understand the soil impacts of stocking density when grazing CCs in different climatic conditions.

Soil Water Content

The soil water content during CC grazing will influence CC grazing effects on soil properties. As soil water content increases, so does the soils susceptibility to deform and compact. Soil consistency (Atterberg limit), which reflects the interaction of soil water content and soil texture will determine the plasticity and the extent to which a soil is deformed under applied forces such as animal traffic (Hamza and Anderson, 2005). Soil conditions including texture and water content can also have an impact on soil compaction (Peng et al., 2004). Soil water content during grazing should be considered when designing a CC grazing rotation. Grazing livestock on thawed, wet soil, such as the case in spring, can have a more negative impact on soil compaction compared to grazing when the soil is frozen or dry.

A study in Iowa found that grazing corn residues when the soil was wet and thawed had no effect on bulk density or aggregate stability but increased soil penetration resistance, although such increase was below the threshold level (Clark et al., 2004). However, impacts of grazing unfrozen ground were only seen in the upper 10 cm of the soil and tillage or freeze-thaw cycles may mitigate any negative effects before planting (Clark et al., 2004). In addition, a CC grazing study in Georgia found that grazing rye in the spring following an above average late spring rainfall (100 mm) increased penetration resistance above the root growth threshold limit (2 MPa) compared to the non-grazed control (1.6 MPa). The authors concluded that the increased soil compaction led to reductions in cotton yield following the wet spring grazing. They further noted that cattle should have been moved to a dry pasture until the soil dried to prevent compaction but were interested in observing a worst-case scenario (Schomberg et al., 2014). However, the authors did not measure penetration resistance at the beginning of this study; therefore, it is possible the effect of CC grazing could have accumulated over the years as well. Nonetheless, studies from grazing pasturelands have also shown that grazing when soil is wet can lead to degradation of soil properties (McKenzie and Greenwood, 2001; Bell et al., 2011). When grazing on non-frozen ground, caution should be taken if the soil is too wet as increasing soil moisture increases the chance of compaction when grazing (Hamza and Anderson, 2005).

Number of Years under Cover Crop Grazing

Cover crop grazing could increase risks of soil degradation with an increase in the number of years of grazing due to the potential cumulative effects of animal traffic with time (Greenwood and McKenzie, 2001; Hamza and Anderson, 2005). Two studies found that CC grazing increased bulk density after 3 or 4 yr of grazing, but not in the initial years (Table 2,1). This suggests the adverse soil effects of CC grazing may develop in the long term, or the soil at these sites was resistant to compaction. Greenwood and McKenzie (2001) noted that residue cover, high organic matter, and roots can make a soil resistant to grazing compaction. Other studies did not find CC grazing effect on soil physical properties increased over time. It is possible increased soil organic matter and root additions may have made the soil resistant to compaction (George et al., 2013). In addition, natural cycles like freeze thaw could have alleviated the compaction found in the initial year of an Ohio study (Table 2.1). However, these studies are short-term (2 yr), thus longer-term studies are needed to determine the potential cumulative effects of CC grazing on soil physical properties. There are a lot of factors that could be interacting to influence CC grazing effect on soil physical properties. These include residue cover, roots, tillage, and natural cycles—all of which will be discussed later. While medium-term (3-5 yr) CC grazing studies showed potential cumulative effects of CC grazing on soil physical properties, there seems to be little impact of CC grazing on soil chemical and biological properties, regardless of number of CC grazing years.

Cover Crop Biomass Production

Cover crop biomass is a key component of CC grazing as it determines stocking rate, time of grazing, and length of grazing. Humid regions have the potential to achieve high amounts of CC biomass (4 to 6 Mg ha^{-1}), especially with rye and sorghum CC (Ruis et al., 2019). These regions provide ample warmth and moisture for CC production for grazing with little to no negative impact on soil properties (Franzluebbers and Stuedemann, 2008a,b; Sulc and Franzluebbers, 2014). For semiarid temperate regions, CC mixes and single-species stands of oat or rye are a popular choice for large CC biomass growth (2 to 5 Mg ha^{-1}). However, in some areas of the semiarid region were adequate soil moisture is a concern (<500 mm of mean annual precipitation), CC production could lead to decreases in plant available water, and thus decreased yields of cash crops (Ruis et al., 2019). While these regions are limited by moisture, there are still rotations that can make CC grazing a viable option (Sulc and Franzluebbers, 2014). For example, a study in Texas grazed winter rye in rotation with cotton to provide supplemental forage for an adjacent warm-season pasture. This system was found to be more water and N efficient and enhanced soil properties compared to a cotton monoculture system (Acosta-Martínez et al, 2004, 2010; Allen et al., 2005).

Since adequate CC biomass production is needed for grazing, there are some practices that can be utilized to potentially increase CC biomass. These practices include planting CCs with a drill instead of broadcast seeding (Ruis et al., 2019). In addition, altering crop rotations slightly allows for greater CC biomass growth. For example, CC grazing in fall can be accomplished with winter-kill CCs after harvest of winter wheat, corn silage, seed corn, or popcorn. Alternatively, winter hardy CCs after grain harvest of soybean and corn can be utilized for winter and spring CC grazing (Sulc and Franzluebbers, 2014; Drewnoski et al., 2018). Growing adequate CC biomass for grazing could be accomplished by utilizing proper planting practices and crop rotations that allow for longer CC growing seasons.

When CC grazing, care should be taken to leave sufficient cover to protect the soil. For comparison, in corn residue grazing, moderate grazing removes no more than 30% of residue cover. However, a rye CC grazing study found that grazing removed 75% of rye residue compared to the non-grazed sites at the time of cotton planting (1.7 Mg ha^{-1} vs. 6.7 Mg ha^{-1}) (Schomberg et al., 2014). However, Franzluebbers and Stuedemann (2008a,b) found that grazing about 90% of available biomass from winter and summer CCs had little to no negative impacts on soil properties. Another study in Ohio found that CC grazing annual ryegrass left 85% cover while grazing oat and winter rye left 77%

cover. Compared to the control of no cover crop (38% cover), the grazed CC sites left significantly more residue to protect the soil (Faé et al., 2009). In addition, an experiment in Georgia estimated that CC grazing reduced biomass by 55% but saw no effect on soil bulk density or yields of the subsequent crop (Hill et al., 2004). There are studies that report reductions in soil water content possibly due to CC grazing reducing residue cover (Franzluebbers and Stuedemann, 2008a; Peterson et al., 2019); however, these reductions had little to no impact on subsequent crop yields. While CC grazing can potentially reduce residue cover anywhere from 15 to 75%, it generally does not result in negative impacts on soil properties nor crop yields.

Belowground Biomass Production: Cover Crop Roots

While the livestock graze the aboveground biomass of CCs, the belowground biomass remains and could provide potential benefits to the soil. Cover crops contribute a living root to the soil when otherwise the soil would be in fallow, which is critical for C and nutrient cycling, food source for microbes, improved soil aggregation, and possible compaction alleviation. In a CC site compared to a no CC control, Faé et al. (2009) found that the CC sites had three- to five-fold greater root biomass compared to the sites with no CCs. This finding illustrates the importance root biomass could play on soil properties and shows the role CC grazing plays in ensuring a living root is in the soil year-round. One benefit from CC roots is soil compaction alleviation. A study in Maryland found that soybean roots took advantage of the root channels left behind by the previous decomposing CC roots (forage radish and rye). Under drought conditions, which caused greater soil compaction, subsequent soybean yields were significantly increased where

CCs were grown (Williams and Weil, 2004). The authors suggested the rye CC left a thick mulch on the surface of the soil, which led to increased surface soil moisture whereas the forage radish root channels where used by the soybean crop to spread its roots in an otherwise compacted soil (Williams and Weil, 2004). This demonstrates the effectiveness of belowground CC root growth to improve soil compaction.

A short-term dryland CC grazing study found the non-grazed CC reduced bulk density compared to the summer fallow control. Additionally, the grazed and non-grazed CC had improved aggregate stability compared to the fallow control (Kelly et al., 2021). In a review of the role pasture roots play in grazing compaction, it is suggested that the growth and decay of roots could increase the structural stability of the soil by enhancing aggregation and increasing porosity (Greenwood and McKenzie, 2001). In addition to alleviating compaction, roots can also increase plant available water (Vannoppen et al., 2015), aid in accumulating macronutrients (Rosolm et al., 2002), and increase soil C fractions (Sokol et al., 2019; Gale and Cambardella, 2020). Roots have also been found to indirectly reduce soil erosion through improvements in soil aggregation, organic matter, infiltration rate, and water content (Vannoppen et al., 2015). The beneficial roles roots can have on soil properties is not well researched, but the research that is available shows roots have the potential to reduce erosion and improve soil properties. Thus, CC roots could play an important role in CC grazing effects on soil properties and crop production.

Tillage

Tillage can have large impacts on soil and crop production; therefore, it is important to assess how tillage may interact with CC grazing. Specifically, tillage seems to play a role in CC grazing impacts on soil compaction. Some authors report that tillage could potentially alleviate compaction from annual disturbance (Raper et al., 2000; Blanco-Canqui and Ruis, 2018). Thus, tillage management in a CC grazing system could impact compaction. One study in Georgia found bulk density and penetration resistance increases from CC grazing were higher under conservation tillage compared to conventional tillage (Tollner et al., 1990). Another study in Georgia found that with conventional moldboard disk tillage there was a trend of lower bulk densities due to CC grazing and a trend of higher bulk densities under no-till management. However, penetration resistance increased from CC grazing under conventional tillage, but had no effect under no-till. Thus, this study reported no significant interaction between tillage and CC grazing and no-till generally had lower bulk density values compared to conventional tillage (Franzluebbers and Stuedemann, 2008a). Based on these two studies there does appear to be a possibility that conservation tillage may alleviate negative effects of CC grazing on bulk density.

Similar trends are observed in CC grazing impacts on penetration resistance. A study in Illinois (Maughan et al., 2009) found that increases in penetration resistance after 1 yr of grazing were not observed in subsequent years of CC grazing. The authors believe tillage potentially alleviated compaction from CC grazing. Although a no-till study in Ohio also found that penetration resistance tended to increase in 1 yr after grazing but this increase did not persist following 2 yr of grazing (Faé et al., 2009). Therefore, it is difficult to determine that tillage alone contributed to the alleviation of compaction when other factors like freeze-thaw and root production could have also played a role.

While tillage may influence compaction parameters under CC grazing, there seems to be no effect on aggregate stability, expressed as mean weight diameter of water stable aggregates. Franzluebbers and Stuedemann (2008a) found no interaction between conventional moldboard disk tillage and no-till with CC grazing in their 4 yr study in Georgia. In addition, Maughan et al. (2009) found no interaction between tillage and CC grazing as well. While the integrated corn-oat site with CC grazing had greater aggregate stability than the no CC, non-grazed continuous corn control, the perennial pasture had higher mean weight diameter of water stable aggregates than the CC grazed site. The authors suggested because the pasture received no disturbance from tillage and since the perennial grasses had a greater root biomass, then soil aggregates were larger in the perennial pasture than the CC grazed site and the control (Maughan et al., 2009).

Tillage and CC grazing interactions were little to none for soil chemical properties and crop yields. Franzluebbers and Stuedemann (2008b) found that, under no-till, CC grazing reduced total organic C and total N compared to conventional moldboard disk tillage. The authors suggest grazing may have reduced residue cover and thus reduced total C and N slightly. Further, the authors found that tillage had the greatest impact on total C and N, with no-till typically having higher amounts of C and N compared to conventional moldboard disk tillage. However, the decreased sorghum yields in the no-till, CC grazed plots may have been due to increased soil water evaporation from reduced residue cover from grazing (Franzluebbers and Stuedemann, 2007). Another study evaluated four different tillage systems (chisel+disk, paratill with and without disking, and no-till) in a 3 yr cotton-peanut-cotton rotation with winter CC grazing. The authors found that paratill without disking produced optimum infiltration, penetration resistance, and bulk density results. In addition, this tillage system increased surface levels of soil organic C and N by 38% and 56%, respectively, and found paratilling produced the highest yields (Siri-Prieto et al., 2007a,b). Although studies that assess tillage and CC grazing interactions are few, it seems that tillage does play a potential role in the effect of CC grazing on soil and crop production, with some tillage potentially alleviating soil compaction from grazing. However, across CC grazing studies, conservation tillage, especially no-till, generally had lower compaction values and greater concentrations of C and N, regardless of grazing treatment.

Natural Soil Processes: Natural Freeze-Thaw and Wet-Dry Cycles

The role of natural cycles such as freeze-thaw and wet-dry could have in CC grazing is not well researched. In any year, depending on the climate of the area, soils undergo multiple wet and dry and freeze-thaw cycles. This could occur in just the upper few centimeters of the soil or extend meters deep into the profile. Natural cycles of freeze-thaw and wet and dry are noted as possible factors of natural amelioration with the potential to improve soil physical properties in cropland soils (Lampurlanés and Cantero-Martínez, 2003; Jabro et al., 2013; Cui et al., 2014; Wang et al., 2020) and pastureland soils (Mapfumo et al., 1998; Greenwood and McKenzie, 2001). Studies on CC grazing impacts on soil properties noted freeze-thaw cycles as a possible natural solution to alleviate potentially negative effects of CC grazing. For example, a study in Ohio (Faé et al. 2009) and Illinois (Maughan et al., 2009) found penetration resistance initially increased under CC grazing, but these increases were not seen in following years, possibly due to natural freeze-thaw processes. Similar, wet-dry cycles in Brazil could also improve soil physical properties by reducing soil bulk density and increasing porosity. Authors of a long-term (14 yr) CC grazing study in Brazil specifically attributed Brazil's wet-dry cycles for the decrease in bulk density noted between the end of CC grazing to the end of the soybean growing season (Bonetti et al., 2019). Physical changes in the soil through wet and dry cycles will be more pronounced depending on the clay mineralogy, specifically shrink-swell clays. Nonetheless, depending on the region, these natural cycles could play a role in the impact of CC grazing on soil properties and crop production.

Conclusion

Literature review indicates that CC grazing has little to no impact on soil properties and crop yield. Cover crop grazing generally increased penetration resistance, but had little to no impact on bulk density. In general, studies showed relatively no impact of CC grazing on soil C and N fractions and soil microbial biomass, but more long-term studies are needed to better evaluate this potential impact. In the majority of studies, CC grazing did not impact crop yield, except for CC grazing under wet soil conditions or CC grazing in the summer that lead to reduced residue cover and increased soil water evaporation, and thus reduced crop yields. Based on this review of the literature, more research is still needed on integrated crop-livestock production systems, specifically CC grazing, to evaluate its impact on soil and crop production. Cover crop grazing could be an opportunity to take advantage of fallow periods between cash crops while providing a potential economic incentive for producers to plant CCs. However, the impacts of CC and corn residue grazing on soil and crop production must be further evaluated.

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Table 2.1. Cover crop grazing impacts on soil compaction parameters

Location	**Duration (yr)**	**Rotation**	**Cover Crop**	**Grazing Period (days)**	**Stocking Rate**	**Soil Type**	**Tillage**	**Grazing Impacts Summary**		**Citation**
								Bulk Density	**Penetration Resistance**	
Watkinsville, Georgia Georgia	4.5	Sorghum-corn-winter CC and wheat-summer CC	Winter cereal rye and summer pearl millet	Winter (26-49) and summer (31-77)	Winter (3.1-6.0) and summer (3.3-6.7) calf head ha^{-1}	Sandy loam, sandy clay loam	No-till and conventional tillage (moldboard initially then disk)	-No effect in 0.5, 2, and 2.5 yr -↑ after 4.5 yr -After 6 yr, no residual effect	-Avg. across 10 sampling events, ↑ under grazed, more so in conventional tillage than no-till	Franzluebbers and Stuedemann (2008a; 2013)
Watkinsville, Georgia	4	Cotton and winter CC	Rye	March-April (<10 days per paddock)	225-300 kg heifers (35-40 cows)	Sandy loam and sandy clay loam	No-till	NA	-↑ following above average rain in spring	Schomberg et al. (2014)
Watkinsville, Georgia	3	Soybean and winter CC	Rye	December to mid-April	4 stockers (200-350 kg) ha^{-1}	Sandy loam	No-till and chisel/ disk till	-No effect	-↑	Tollner et al. (1990

Moultrie, Georgia	3	Cotton and peanut and winter CC	Rye or ryegrass	Mid to late January to Late March/early April (57-84 days)	2.5 calf head ha^{-1}		Conventional tillage and strip tillage	-No effect	NA	Hill et al. (2004)
Belle Mina, Alabama	3	Cotton, winter CC	Wheat	Late Jan./early Feb. to early April (35-65 days)	Not reported	Silt loam	Strip tillage	NA	-↑ after 3 yr -Slightly above threshold	Mullins and Burmester (1997)
Pana, Illinois	4	Oat-CC mix-corn, and continuous corn control	Cereal rye, oat, and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and cultivation	NA	-No effect after 2 and 3 yr	Tracy and Zhang (2008)
Pana, Illinois	5	Oat-CC mix-corn, and continuous corn control	Cereal rye, oat, and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and spring cultivation	NA	-Avg. across 4 yr, CC grazed oat-corn system ↑ compared to control	Maughan et al. (2009)

Columbus, Ohio	2	Corn silage-CC mix and no CC control	Two mixes: annual ryegrass & winter rye & oat	20 Nov. 2006-4 Jan. 2007 and 26 March-10 Apr. 2007 (3 days per paddock)	2-3 heifers ha^{-1} (1152 kg live wt ha^{-1})	Silt loam and silty clay loam	No-till	NA	-↑ in spring 1 yr ($p<0.10$) -Not above threshold -No effect after fall 1 yr and spring 2 yr	Faé et al. (2009)
Marianna, Florida	4	2 yr of bahiagrass, peanut, cotton, CC (irrigated and non-irrigated)	Oats and rye	Late April to early May	1.5 cow/calf pairs ha^{-1} (1 yr) & 2.2 cow/calf pairs ha^{-1} (2-3 yr)	Sandy loam	Strip till	-No effect after 3, 4, and 5 yr	NA	George et al. (2013)
São Miguel das Missões district, Rio Grande do Sul, Brazil	2	Soybean and winter CC mix	Black oat and Italian ryegrass	June to October	1297, 928, 601 & 342 kg live weight ha^{-1}	Clayey	No-till	-↑ after 2 yr	NA	Flores et al. (2007; 2008)

São Miguel das Missões district, Rio Grande do Sul, Brazil	14	Soybean and winter CC mix	Black oat and Italian ryegrass	June to October	1297, 928, 601 & 342 kg live weight ha^{-1}	Clayey	No-till	-↑ in high density -No effect in low & moderate density	NA	Bonetti et al. (2019)
North Platte, Nebraska	3	Corn silage and CC (irrigated)	Cereal rye	15 March to 15 April	5.23 AUM in 1 yr & 6.53 AUM for 2-3 yr	Sandy loam	Strip till	-No effect	-No effect in 1 and 3 yr	Blanco-Canqui et al. (2020)
Western Kansas & Nebraska, Eastern Colorado	2	Summer CC and winter wheat	Mix of cool season grasses, legumes, & forbs	May and July (~28 days)	307 to 1052 kg live weight ha^{-1}	Silt or clay loam	No-till	-No effect	NA	Kelly et al. (2021)

Table 2.2. Cover crop grazing impacts on soil physical properties

Location	**Duration (yr)**	**Rotation**	**Cover Crop**	**Grazing Period (days)**	**Stocking Rate**	**Soil Type**	**Tillage**	**Grazing Impacts Summary**			**Citation**
								Soil Structure	**Soil Infiltration**	**Soil Water Content**	
Watkinsville, Georgia Georgia	4	Sorghum-corn- CC and wheat-summer CC	Cereal rye (winter) and pearl millet (summer)	Winter (26-49) and summer (31-77)	Winter (3.1-6.0) and summer (3.3-6.7) calf head ha^{-1}	Sandy loam, sandy clay loam	No-till and conventional tillage (moldboard initially then disk)	-After 2.5 yr at 0-3 cm water stable aggregates ↓ -After 2.5 yr and 3-6 cm aggregates ↓	-Three out of seven sampling events, ↓	-Two out of seven sampling events, ↓	Franzluebbers and Studemann (2008a)
Columbus, Ohio	2	Corn silage- CC mixes and no CC control	Two CC mixes: annual ryegrass and winter rye and oat mix	20 Nov. 2006-4 Jan. 2007 and 26 March-10 Apr. 2007 (3 days per paddock)	2-3 heifers ha^{-1} (1152 kg live wt ha^{-1})	Silt loam and silty clay loam	No-till	NA	NA	-No effect	Faé et al. (2009)

São Miguel das Missões district, Rio Grande do Sul, Brazil	14	Soybean and CC mix	Black oat and Italian ryegrass	June to October	4.4, 3.3, 2.0, and 1.1 steers ha^{-1}	Clayey	No-till	-No effect in low to moderate density -Reduced in high density	-↓ under high grazing density -No effect under low and moderate grazing density	-High to moderate density ↓ water content -Low to moderate density ↑ water content	Bonetti et al. (2019)
São Miguel das Missões district, Rio Grande do Sul, Brazil	16	Soybean and CC mix	Black oat and Italian ryegrass	June to October	4.4, 3.3, 2.0, and 1.1 steers ha^{-1}	Clayey	No-till	NA	NA	-Water content ↓ in grazed sites	Peterson et al. (2019)
North Platte, Nebraska	3	Corn silage and CC (irrigated)	Cereal rye	15 March to 15 April	5.23 AUM in 1 yr and 6.53 AUM for 2 and 3 yr	Sandy loam	Strip till	-No effect	-No effect in 1 and 3 yr -↓ in 2 yr	NA	Blanco-Canqui et al. (2020)

Western Kansas & Nebraska, Eastern Colorado	2	Summer CC and winter wheat	Mix of cool season grasses, legumes, & forbs	May and July (~28 days)	307 to 1052 kg live weight ha^{-1}	Silt or clay loam	No-till	-No effect	NA	-No effect	Kelly et al. (2021)
Pana, Illinois	5	Oat-CC mix-corn, and continuous corn control	Cereal rye and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and spring cultivation	-After 5 yr, mean weight diameter ↑ compared to control	NA	NA	Maughan et al. (2009)
Marianna, Florida	4	2-yr of bahiagrass, peanut, cotton, CC (irrigated and non-irrigated)	Oats and rye	Late April to early May	1.5cow/calf pairs ha^{-1} (2007) and 2.2 cow/calf pairs ha^{-1} (2008-2010)	Sandy loam	Strip till	NA	NA	-↑ in grazed, non-irrigated sites	George et al. (2013)

Table 2.3. Cover crop grazing impacts on soil chemical properties

Location	**Duration (yr)**	**Rotation**	**Cover Crop**	**Grazing Period (days)**	**Stocking Rate**	**Soil Type**	**Tillage**	**Grazing Impacts Summary**			**Citation**
								Carbon Fractions	**Nitrogen Fractions**	**Fertility Properties**	
Watkinsville, Georgia	4	Sorghum-corn-CC and wheat-summer CC	Cereal rye (winter) and pearl millet (summer)	Winter (26-49) and summer (31-77)	Winter (3.1-6.0) and summer (3.3-6.7) calf head ha^{-1}	Sandy loam, sandy clay loam	No-till (NT) and conventional tillage (CT) (moldboard initially then disk)	-Avg. over 3 yr, TOC ↓ at 0-3 cm under NT (no effect under CT) -Averaged over 3 yr, TOC ↑ at the 3-6 cm & 6-12 cm -No residual effect on TOC after 6 yr -POM ↓ in summer CC but not winter CC at 0-3 cm -No effect at all other depths	-Avg. over 3 yr, TN ↓ at 0-3 cm in NT (no effect in CT) -No effect on TN at all other depths -No residual effect on TN after 6 yr	-↑ nitrate-N levels after 1, 3, and 4 yr -↓ nitrate-N levels after 6 yr	Franzluebbers and Stuedemann (2008b; 2013a)

								-No residual effect on POM after 6 yr			
Columbus, Ohio	2	Corn silage-CC mixes and no CC control	Two CC mixes: annual ryegrass and winter rye and oat mix	20 Nov. 2006-4 Jan. 2007, & 26 March-10 Apr. 2007 (3 days per paddock)	2-3 heifers ha^{-1} (1152 kg live wt ha^{-1})	Silt loam and silty clay loam	No-till	-No effect after 1 or 2 yr on TOC -POM ↑ in grazed CC than no CC, non-grazed control	NA	NA	Faé et al. (2009)
São Miguel das Missões district, Rio Grande do Sul, Brazil	6	Soybean and CC mix	Black oat and Italian ryegrass	June to October	4.4, 3.3, 2.0, and 1.1 steers ha^{-1}	Clayey	No-till	-No effect on TOC from moderate grazing -↓ in TOC from high grazing	-No effect on TN from moderate grazing -After 3 yr, ↓ in TN from high grazing	-No effect on available P -No effect on available K	Carvalho et al. (2010)

São Miguel das Missões district, Rio Grande do Sul, Brazil	9	Soybean and CC mix	Black oat and Italian ryegrass	June to October	4.4, 3.3, 2.0, and 1.1 steers ha^{-1}	Clayey	No-till	-No effect on TOC from moderate grazing -↓ in TOC from high grazing -No effect on POM from moderate grazing -↓ in POM from high grazing	-No effect on TN from moderate grazing -↓ in TN from high grazing -No effect on PON from moderate grazing -↓ in PON from high grazing	NA	Assmann et al. (2014)
North Platte, Nebraska	3	Corn silage and CC (irrigated)	Cereal rye	15 March to 15 April	5.23 AUM in 1 yr and 6.53 AUM for 2 and 3 yr	Sandy loam	Strip till	-No effect on OM	NA	-No effect	Blanco-Canqui et al. (2020)
Western Kansas & Nebraska	2	Summer CC and winter wheat	Mix of cool season grasses,	May and July (~28 days)	307 to 1052 kg live	Silt or clay loam	No-till	-No effect on SOC -No effect on POM C	-No effect on total N	-No effect on available P	Kelly et al. (2021)

, Eastern Colorado			legumes, & forbs		weight ha^{-1}				-No effect on potential mineralizable N		
Pana, Illinois	4	Oat-CC mix-corn, and continuous corn control	Cereal rye and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and spring cultivation	-No effect on TOC after 4 yr	-TN ↑ after 4 yr compared to no CC, non-grazed control	NA	Tracy and Zhang (2008)
Pana, Illinois	5	Oat-CC mix-corn, and continuous corn control	Cereal rye and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and spring cultivation	-No effect on TOC after 5 yr -No effect on POM-C after 5 yr	-TN ↑ after 5 yr compared to no CC, non-grazed control -No effect on POM-N after 5 yr	NA	Maughan et al. (2009)
Marianna, Florida	4	2-yr of bahiagrass, peanut, cotton, CC (irrigated	Oats and rye	Late April to early May	1.5cow/calf pairs ha^{-1} (2007) and 2.2 cow/cal	Sandy loam	Strip till	-OM ↑ after 1 & 2 yr (irrigated) -No effect on OM in 3 yr (irrigated)	NA	-Nitrate-N ↑ in grazed (non-irrigated) -P ↑ in non-	George et al. (2013)

		and non-irrigated)			f pairs ha^{-1} (2008-2010)			-OM ↓ after 1, 2, & 3 yr (non-irrigated)		grazed (non-irrigated) -K ↑ in grazed (irrigated and non-irrigated)	

Table 2.4. Cover crop grazing impacts on soil biological properties

Location	Duration (yr)	Rotation	Cover Crop	Grazing Period (days)	Stocking Rate	Soil Type	Tillage	Soil Microbial Biomass (SMB)	Citation
Watkinsville, Georgia	4	Sorghum-corn-CC and wheat-summer CC	Cereal rye (winter) and pearl millet (summer)	Winter (26-49) and summer (31-77)	Winter (3.1-6.0) and summer (3.3-6.7) calf head ha^{-1}	Sandy loam, sandy clay loam	No-till and conventional tillage (moldboard initially then disk)	-Avg. across 3 yr, SMB ↓ in summer CC -Avg. across 7 yrs, no residual effect except for an ↑ at 3-6 cm under no-till	Franzluebbers and Stuedemann (2008b; 20013b, 2015)
Columbus, Ohio	2	Corn silage-CC mixes and no CC control	Two CC mixes: annual ryegrass and winter rye and oat mix	20 Nov. 2006 to 4 Jan. 2007, and from 26 March to 10 Apr. 2007 (3 days per paddock)	2-3 heifers ha^{-1} (1152 kg live wt ha^{-1})	Silt loam and silty clay loam	No-till	-No effect after 1 and 2 yr	Faé et al. (2009)
São Miguel das Missões district, Rio Grande do Sul, Brazil	4	Soybean and CC mix	Black oat and Italian ryegrass	June to October	4.4, 3.3, 2.0, and 1.1 steers ha^{-1}	Clayey	No-till	-↑ in moderate and high intensity grazing	Souza et al. (2008)

Pana, Illinois	4	Oat-CC mix-corn, and continuous corn control	Cereal rye and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and spring cultivation	-No effect after 1, 2, or 3 yr -↑ than control after 4 yr	Tracy and Zhang (2008)
Pana, Illinois	5	Oat-CC mix-corn, and continuous corn control	Cereal rye and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and spring cultivation	-↑ compared to control	Maughan et al. (2009)
Marianna, Florida	4	2-yr of bahiagrass, peanut, cotton, CC (irrigated and non-irrigated)	Oats and rye	Late April to early May	1.5cow/calf pairs ha^{-1} (2007) and 2.2 cow/calf pairs ha^{-1} (2008-2010)	Sandy loam	Strip till	-↑ in grazed under non-irrigated -No effect in irrigated plots	George et al. (2013)

Table 2.5. Cover crop grazing impacts on crop production and yield

Location	**Duration (yrs)**	**Rotation**	**Cover Crop**	**Grazing Period (days)**	**Stocking Rate**	**Soil Type**	**Tillage**	**Yield**	**Citation**
Watkinsville, Georgia	4	Sorghum-corn-CC and wheat-summer CC	Cereal rye (winter) and pearl millet (summer)	Winter (26-49) and summer (31-77)	Winter (3.1-6.0) and summer (3.3-6.7) calf head ha^{-1}	Sandy loam, sandy clay loam	No-till and conventional tillage (moldboard initially then disk)	-No effect on winter wheat for 4 yrs -Sorghum yield ↓ in 1 and 3 yr under no-till -No effect on corn in 4 yr -Avg over 4 yr, summer grain ↓ under no-till	Franzluebbers and Stuedemann (2007)
Watkinsville, Georgia	3	Soybean and CC	Rye	December-mid April	4 stockers (200-350 kg) ha^{-1}	Sandy loam	No-till and chisel/ disk till	-No effect	Tollner et al. (1990)
Watkinsville, GA	4	Cotton and CC	Rye	March-April (<10 days per paddock)	225-300 kg heifers (35-40 cows)	Sandy loam and sandy clay loam	No-till	-No effect 1, 2, & 3 yr -↓ in cotton 4 yr (above avg. rainfall)	Schomberg et al. (2014)

Moultrie, Georgia	3	Cotton and peanut and CC	Rye or ryegrass	Mid to late January to Late March/early April (57-84 days)	10 steers/heifers per 4 ha…2.5 calf head ha^{-1}	???	Conventional tillage and strip tillage	-No effect on cotton or peanut	Hill et al. (2004)
Belle Mina, Alabama	3	Cotton, CC	Wheat	Late Jan./early Feb. to early April (35 to 65 days)	Not reported	Silt loam	Strip tillage	-Cotton yield ↓ 1 & 3 yr -Cotton yield ↑ 2 yr (severe drought 2 and 3 yr)	Mullins and Burmester (1997)
Columbus, Ohio	2	Corn silage- CC mixes and no CC control	Two CC mixes: annual ryegrass and winter rye and oat mix	20 Nov. 2006-4 Jan. 2007, and 26 March-10 Apr. 2007 (3 days per paddock)	2-3 heifers ha^{-1} (1152 kg live wt ha^{-1})	Silt loam and silty clay loam	No-till	-No effect on corn silage	Faé et al. (2009)
São Miguel das Missões district, Rio Grande	2	Soybean and CC mix	Black oat and Italian ryegrass	July to November (120 days)	1297, 928, 601 & 342 kg live weight ha^{-1}	Clayey	No-till	-No effect on soybean	Flores et al. (2007)

do Sul, Brazil									
São Miguel das Missões district, Rio Grande do Sul, Brazil	16	Soybean and CC mix	Black oat and Italian ryegrass	June to October	4.4, 3.3, 2.0, and 1.1 steers ha^{-1}	Clayey	No-till	-No effect on soybean	Peterson et al. (2019)
North Platte, Nebraska	3	Corn silage and CC (irrigated)	Cereal rye	15 March to 15 April	5.23 AUM in 1 yr and 6.53 AUM for 2 and 3 yr	Sandy loam	Strip till	-No effect on corn silage	Blanco-Canqui et al. (2020)
Western Kansas & Nebraska, Eastern Colorado	2	Summer CC and winter wheat	Mix of cool season grasses, legumes, & forbs	May and July (~28 days)	307 to 1052 kg live weight ha^{-1}	Silt or clay loam	No-till	-No effect on winter wheat	Kelly et al. (2021)
Pana, Illinois	4	Oat-CC mix-corn, and continuous corn control	Cereal rye and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel or disk and cultivation	-No effect	Tracy and Zhang (2008)

Pana, Illinois	5	Oat-CC mix-corn, and continuous corn control	Cereal rye and turnip	Nov.-March (5-10 days per paddock)	1 head ha^{-1}	Silty clay loam	Chisel plowing or disking and field cultivation in spring	-No effect	Maughan et al. (2009)
Marianna, Florida	4	2-yr of bahiagrass, peanut, cotton, winter CC (irrigated and non-irrigated)	Oat and rye	Late April to early May	1.5cow/calf pairs ha^{-1} (2007) and 2.2 cow/calf pairs ha^{-1} (2008-2010)	Sandy loam	Strip till unless field was too rough after grazing so had to be tilled	-↑ cotton yield over 4 yrs except 2010 (non-irrigated) -No effect (irrigated)	George et al. (2013)

CHAPTER 3. Cover crop grazing impacts on soil properties and crop yields under irrigated no-till corn-soybean

Abstract

Cover crop (CC) grazing can be a strategy to re-integrate crops with livestock, but how this integration affects soils and crop yields is still unclear. We studied cattle (1.3-3.7 steers ha^{-1}) grazing impact of oat (*Avena sativa* L.) CC on properties of a silt loam in a field-scale irrigated no-till corn (*Zea mays* L.)-soybean (*Glycine max* L.) experiment in eastern Nebraska. Each rotation was present each year in two adjacent fields. Field I was grazed twice, while Field II was grazed thrice during a 5-yr study. Treatments were arranged in a split-plot design with corn harvest [corn silage and high moisture corn (HMC)] as main plots, and no CC, non-grazed CC, and grazed CC as split plots. Corn silage was harvested 15 d before HMC, while HMC was harvested about 25 d before dry corn. Cover crop grazing reduced CC biomass by 47 to 87% without impacting soil penetration resistance, bulk density, aggregate stability, hydraulic properties, organic matter, particulate organic matter, microbial biomass, and crop yields compared to non-grazed CC. Corn silage harvest negatively impacted most near-surface soil properties but not yields compared to HMC. Cover crop did not offset the negative impacts of corn silage except for increasing soil microbial biomass. Corn silage-induced decrease in soil organic matter and microbial biomass partly explained the decrease in soil dry and wet aggregate size. In conclusion, CC grazing had no impact on soil properties and yields, but corn silage adversely impacted soil properties under our study conditions.

Introduction

Historically, farms were diversified with both crop and livestock production. However, many modern farms, particularly in developed nations, are now specialized to produce only crops or livestock. The current specialization and increased grassland to cropland conversion (Wright & Wimberly, 2013) reduce economic returns and increase concerns of degradation and pollution of natural resources (Abson, 2019). These concerns have prompted interest in re-integrating crops with livestock production to efficiently utilize resources and ensure profitability while improving environmental quality (MacLaren, Storkey, Strauss, Swanepoel, & Dehnen-Schmutz, 2018; Kronberg & Ryschawy, 2019).

One potential practice of integration could be through CC grazing. Grazing of CCs could supply forage for cattle (Drewnoski et al., 2018) while still capturing the benefits of CCs (Snapp et al., 2005). However, concerns exist among producers that CC grazing could degrade soil properties, cause soil compaction, and reduce subsequent crop yields. The limited research data suggest CC grazing may have little or no negative impact on soil properties and crop production (Franzluebbers & Stuedemann, 2008a, 2008b; Faé, Sulc, Barker, Dick, & Eastridge, 2009; Schomberg et al., 2014; Blanco-Canqui et al., 2020). Some authors found CC grazing increased compaction without impacting yields, (Faé et al., 2009; Blanco-Canqui et al., 2020), whereas others found no negative impact on compaction nor yields (Tracy & Zhang, 2008). In a few cases, CC grazing could reduce yields due to wet soil conditions during grazing (Schomberg et al., 2014) or increased evaporation from reduced residue cover (Franzluebbers & Stuedemann, 2007).

Aside from potential risks of soil compaction, incorporating and grazing CCs may not only diversify traditional cash crop rotations but also enhance some soil properties such as soil organic matter and microbial biomass through manure and aboveground and belowground CC biomass additions (Faé et al., 2009; Franzluebbers & Stuedemann, 2008b). In previous CC grazing studies, disappearance of aboveground biomass has ranged from around 15 to 75% of CC biomass, most likely due to both consumption and trampling (Franzluebbers & Stuedemann, 2008a, 2008b; Faé et al., 2009; Schomberg et al., 2014; Blanco-Canqui et al., 2020). However, CC grazing does not remove the belowground (root) biomass (Ribeiro, Dieckow, Piva, & Bratti, 2020). The latter can contribute more to essential soil functions than aboveground biomass (Sokol, Kuebbing, Karlsen-Ayala, & Bradford, 2019). Research on plant roots, in general, shows roots can alleviate soil compaction (Williams & Weil, 2004) and improve soil organic matter (Rosolem, Foloni, & Tiritan, 2002; Sokol, et al., 2019) and resistance of the soil to erosion (Vannoppen, Vanmaercke, De Baets, & Poesen, 2015). Thus, if CC grazing is managed properly, CCs could serve a dual purpose: soil conservation and livestock feed, but more research from different CC management scenarios is needed to confirm this.

Cover crops could be especially useful in corn silage rotations. Unlike corn grain harvest, corn silage harvest removes almost all aboveground biomass, leaving significantly less residue than corn grain harvest. This can increase soil erosion risks, reduce soil organic matter, and degrade soil properties, thereby reducing the productivity of the soil. Studies show that addition of CCs to corn silage rotations can offset the adverse effects of silage harvest by increasing organic matter fractions, scavenging N, and improving related soil properties (Faé et al., 2009; Liesch, Krueger, & Ochsner, 2011; Moore, Wiedenhoeft, Kaspar, & Cambardella, 2014; Ketterings et al., 2015). However, how CC grazing influences the effectiveness of CCs to offset the adverse impacts of corn silage harvest on soils is unclear.

Short-term research (≤4 yr) suggests CC grazing could be a strategy to integrate crop and livestock production, but longer-term studies are needed. Additionally, the few studies that exist on CC grazing (Franzluebbers & Stuedemann, 2008a, 2008b; Faé et al, 2009; Schomberg et al, 2014; Blanco-Canqui et al., 2020) only assessed a few soil properties at a time. Additional studies can further advance our understanding of how CC grazing impacts soil properties and crop production. Thus, the objective of this study was to evaluate the impact of CC grazing under two and three grazing events on soil properties, and crop yields under irrigated no-till corn silage and high moisture corn (HMC) harvest in the western US Corn Belt.

Materials and Methods

Site Description and Experimental Design

We conducted this study on two adjacent field-scale CC grazing experiments (Field I and II) established in 2015 at the Eastern Nebraska Research and Education Center of the University of Nebraska-Lincoln near Mead, NE (41°10'15.07''N 96°29'43.98''W). Each experimental field was 21 ha managed under sprinkler irrigated no-till corn-soybean rotation for 5 yr (2015-2020). The mean annual temperature is 10 ^{o}C and the mean annual precipitation for the study fields is 817 mm (Table 3.1). The soil is Tomek silt loam with

0 to 2% slopes (Fine, smectitic, mesic Pachic Argiudolls) and Filbert silt loam with 0 to 2% slopes (Fine, smectitic, mesic Vertic Argialbolls).

Each phase of the corn-soybean rotation was present each year, one phase in each field. Treatments were arranged in a split-plot design with corn harvest (corn silage and HMC) as main plots, and no CC, non-grazed CC, and grazed CC as split plots in each field. The size of each main plot was 96 m by 923 m, while the split plots were 6 m wide (8 crop rows) by 923 m long (Figure 1). The grazed split plots were on the outer ends of each field to allow cattle easy access to 8 ha of total grazed area (Figure 1). Figure 1 shows our soil and plant sampling area in the CC grazed area. Corn was harvested as silage around September 1st and as HMC (about 32% moisture) around September 15th, about 25 d before the typical dry corn harvest in the region. Oat CC was drilled at 108 kg ha^{-1} immediately after each corn harvest (silage or HMC). We planted CCs only after corn harvest and not after soybeans. All treatments (six) received 44.8 kg N ha^{-1} as ammonium nitrate following CC planting.

Cover crop grazing events differed between the two fields during the 5-yr experiment. Field I was grazed twice while Field II was grazed thrice. The two CC grazing events in Field I occurred in fall 2016 and 2018, while the three CC grazing events in Field II occurred in fall 2015, 2017, and 2019 (Table 3.2). Cattle grazed from November to December at 1.3 to 3.7 steers ha^{-1} stocking rates (Table 3.2). The stocking rate was based on a target grazing period of 70 d and accounted for the CC biomass under corn silage and CC plus corn residue biomass under HMC. For the HMC, we estimated corn residue available for grazing of 3.6 kg per 25.5 kg corn grain harvested (Watson, MacDonald, Erickson, Kononoff, & Klopfensein, 2015). In the first two years, the forage allowance was about 11.6 kg $steer^{-1}$ d^{-1} and, in the latter three years, it was increased to about 17.7 kg $steer^{-1}$ d^{-1}. Table 3.2 shows the details of the steer body weights, stocking rates, amount of forage allocated, and the actual grazing period achieved. Cattle were removed from all treatments when forage became limiting in a given treatment. However, in 2016 cattle were removed early due to ice cover limiting access to the forage. Because of the importance of weather conditions during grazing, Table 3.2 also reports the percent of grazing days with precipitation and the percent of grazing days with temperatures at or below 0 ^{o}C.

Measurements

We conducted field measurements and sampled soil after the last grazing event in each field, which was in late spring of 2019 for Field I, and late spring of 2020 for Field II. Each field was sampled under standing soybean. Because this field-scale grazing experiment was not replicated, each 923 m long field was divided into three sections (307.5 m long) for measurement purposes (Figure 1). The three sections were used as pseudoreplicates for all the measurements.

Soil Compaction Parameters

We measured soil penetration resistance and bulk density to evaluate soil compaction. Penetration resistance was measured using a hand cone penetrometer (Eijkelkamp Co., Giesbeek, the Netherlands) at 0 to 5 and 5 to 10 cm soil depths. It was measured at 30 points on the shoulder of crop rows within each section for a total of 90 data points per treatment. Data were converted to cone index (MPa) by dividing the reading in kg cm^{-2} by the cone area. At the time of penetration resistance measurements, we sampled soil with a hand probe at the same depths for water content (Topp & Ferré, 2002). Penetration resistance was not significantly correlated with water content ($p > 0.05$). We collected intact 5- by 5-cm soil cores on the shoulder of rows at the above depths to determine bulk density, by the core method (Grossman & Reinsch, 2002).

Soil Hydraulic Properties

Water infiltration was measured by a single ring infiltrometer (Reynolds, Elrick, & Youngs, 2002). Surface residue was removed and a 25-cm diameter metal ring was inserted between rows into the soil 10 cm deep. One measurement per pseudoreplicate was done. Water infiltration was measured at different time intervals for a total of 180 min. Water retention was determined from the cores sampled for bulk density. The cores were trimmed at both ends and the bottom of the core was covered with a cheesecloth, weighed, and saturated with water using a Marriote bottle for 72 h. The saturated cores were placed in the pressure extractors to determine volumetric water content at -0.033 MPa matric potential (Dane & Hopmans, 2002). After the cores reached equilibrium in about a week, we weighed, the cores and oven dried a sub-sample at 105 °C for 24 h to determine water content (Dane & Hopmans, 2002). The remaining sample in each core was air dried for 72 h, passed through a 2-mm sieve, and placed in 5.2-cm diameter metal rings to determine volumetric water content at -1.5 MPa matric potential on the high-pressure extractors (Dane & Hopmans, 2002). At equilibrium, we weighed the samples and oven-dried at 105 ^{o}C for 24 h to determine water content. We computed available water as the difference in volumetric water content between field capacity (-0.033 MPa) and permanent wilting point (-1.5 MPa).

Soil Wet and Dry Aggregate Stability

Wet aggregate stability was determined by wet sieving to assess water erosion potential (Nimmo & Perkins, 2002). We sampled soil with a shovel and split into three depths (0 to 5, 5 to 10, and 10 to 20 cm). Samples were broken by hand to break large clods and peds, dried in a forced air oven for 72 h, and passed through an 8-mm sieve. Fifty grams of the air-dried sample were placed on the filter paper on top of a stack of sieves for saturation through capillary action. The stack of sieves, organized from largest to smallest sieve size (4.75, 2, 1, 0.5, 0.25 mm), was placed in a water tank. The top sieve was just in contact with water in the tank during soil saturation for 10 min. After saturation, the filter paper was removed and the sample was sieved for 10 min using a mechanical sieving machine at the rate of 30 strokes min^{-1}. Then, the soil from each sieve was transferred to pre-weighed beakers and dried in the oven for 48 h at 105 ^{o}C. Samples were corrected for sand content by adding 30 mL of 0.5% Na hexa-meta phosphate for 24 h to disperse the soil aggregates. The dispersed soil was then passed through a 53-µm sieve and the sand and fine gravel were oven-dried for 24 h at 105 ^{o}C and weighed for the correction before computing mean weight diameter of water-stable aggregates (Nimmo & Perkins, 2002).

Dry aggregate stability was determined by dry sieving to assess wind erosion potential (Nimmo & Perkins, 2002). We sampled soil with a flat base shovel from 0 to 5 cm soil depth. Soil samples were dried in a forced air oven for 72 h. Two sub-samples of 1 kg each were placed in the Ro-Tap sieve shaker (RX-29 model, W.S. Tyler, Ohio) with a set of sieves in descending order of 45, 14, 6.3, 2, 0.84, and 0.425 mm for mechanical sieving for 5 min at 278 oscillations minute^{-1}. The dry aggregates in each sieve were weighed and wind erodible fraction computed as a percentage of the dry aggregates < 0.84 mm in diameter (Chepil, 1952).

Soil Organic Matter Fractions

Organic matter and particulate organic matter (POM) concentrations were determined on a fraction of soil samples collected for wet aggregate stability. Soil organic matter was analyzed by loss on ignition (Combs & Nathan, 1998). Soil was oven-dried at 105 ^{o}C for 2 h, and a 5-g soil sample was weighed and heated to 360 ^{o}C for 2 h and weighed again. Soil organic matter concentration was calculated by the difference between the two dryings divided by the dry weight. Particulate organic matter was determined by loss on ignition method (Cambardella, Gajda, Doran, Wienhold, & Kettler, 2001). Thirty grams of soil were dispersed with 0.5% Na hexa-meta phosphate and shaken for 18 h on a mechanical shaker (Model E6010, Eberbach Corp., MI). The dispersed samples were passed through a 53-µm sieve. The material remaining on the sieves was transferred into tins and dried at 60 ^{o}C for 48 h and weighed. The tins were placed in a muffle furnace at 450 ^{o}C for 4 h and weighed again.

Soil Microbial Biomass

Soil biological parameters including microbial biomass and community structure were determined by the method of direct hydrolysis, derivation, and extraction of fatty acid methyl esters (FAMEs) from soil microorganisms (Grigera, Drijber, & Wienhold, 2007) at the 0 to 5 and 5 to 10 cm depths. A 10-g air-dried soil sample (passed through an

8 mm sieve) was weighed and placed into a 50 ml teflon centrifuge tube. In addition, a 5-g sample placed in the oven for 24 h at 105 ºC was used to determine water content and adjust sample dry weight. Ten ml of MeOH-KOH were added to the soil and shaken to split the fatty acid chains from the head group and repeated with another 10 ml. Tubes were then placed into a water bath at 37 °C for 1 h while shaking every 15 min. About 2 ml of 1N acetic acid were added to ensure the pH is neutral. Then, five ml of hexane were added, mixed, and the tubes were loaded to the centrifuge for 10 min at 6000 rpm. The fatty acid-hexane solution was then separated at the top of the tube and transferred to a pyrex tube. The extraction was repeated with another 5 ml of hexane.

The fatty acid-hexane solution was filtered and evaporated under N_2, benzene and mixed. The solution was evaporated to dry, re-dissolved, and transferred to an amber vial for analysis on a gas chromatograph (Hewlett-Packard Company, Palo Alto, CA) with the carrier gas as He and with C19:0 (0.05 mg/ml) as an internal standard. The sum of 19 FAME biomarkers was used to identify total microbial biomass (total FAME) (C16:0) and microbial communities including bacteria (iC14:0, iC15:0, aC15:0, C15:0, iC16:0, iC17:0, aC17:0, C17:0), arbuscular mycorrhizal fungi (C16:1cis11), saprophytic fungi (C18:2cis9,12), and eukaryotes (C20:3, C20:4, C20:5).

Cover Crop Biomass and Crop Yield

We collected CC biomass from 10 random locations within the grazed CC treatment and six random locations within the non-grazed CCs. Each sampling location was 0.91 by 0.57 m. The CC was clipped to the soil surface and dried in a forced air oven for 48 h to determine CC biomass amount. Cover crop biomass was measured before grazing (pre-grazed) and after grazing (post-graze). No post-grazing CC biomass was measured in

2015 for the first grazing event in Field II. Corn residue in HMC was collected post grazing from 10 random locations within the grazed treatment and six random locations within the non-grazed treatment. Each sampling location was 0.76 by 0.76 m. The stalks were clipped to the second node, the upper portion of the stalks was collected, and all other corn residue within the area was collected and oven dried at 60 °C for 48 h to determine corn residue amount.

Corn silage, HMC, and soybean yields were collected by hand within each pseudoreplicate. Yields were collected from three separate 5.33 m-long rows per pseudoreplicate. Corn silage was harvested by cutting the plants at the first node. Subsamples were oven dried at 60 °C for 48 h and weighed. Corn silage yield per hectare was calculated based on corn ear and stalk dry matter. High moisture corn was hand harvested by cutting plants at the second node. Corn ears were removed, and ear and remaining plant residue (husk, leaf, and stalk) were weighed separately. Three corn plants and three ears were taken as a subsample from each 5.33 m bundle, and were oven dried at 60 °C for 48 h. The grain was shelled from the cob, then cobs and grain were placed back in the oven for another 24 h, or until dry. The grain dry matter content was used to calculate HMC grain yield. Soybean was hand harvested and oven dried at 60 °C for 48 h. Samples were threshed and grain collected to determine yield.

Statistical Analysis

Statistical analysis was conducted by field (Field I and Field II) as grazing events differed between the two fields. Because of the large-scale nature of this field experiment, the treatments were not replicated. Thus, the three sections of each experimental field, as specified earlier, were used as pseudoreplicates for the data analysis by PROC MIXED in SAS (SAS Institute, 2020). The two main plots (corn silage and HMC) and split plots (no CC, non-grazed CC, and grazed CC) were the fixed factors while replicates (pseudoreplicates) were the random factors. Data were normally distributed as per the Shapiro-Wilk test in PROC UNIVARIATE in SAS. We analyzed correlations among soil properties across all treatments by PROC CORR in SAS. Data analysis was performed by soil depth. Treatment effects were studied using LSMEANS. Treatment effects, normality, and correlations were considered significant at the 0.05 probability.

Results and Discussion

Cover Crop and Corn Residue Biomass

Cover crop grazing consistently reduced CC biomass (Table 3.3). In Field I, CC grazing reduced CC biomass by 47% for the first grazing event and 83% for the second in corn silage; and 87% for the first grazing event and 83% for the second under HMC. In Field II, CC grazing reduced CC biomass by 87% in the second grazing event and 83% in the third in corn silage; and 64% in the second grazing event and 81% in the third in HMC (Table 3.3). As stated earlier, in this field, CC biomass was not quantified in the first grazing event. Under HMC, grazing reduced corn residue in both fields from 18% to 23%. Cover crop grazing probably reduced CC biomass and corn residue amount by consumption and trampling. For example, if we assume the steers consumed 2.5% of their body weight each day, then only 34 ± 14% of the CC biomass disappearance would have been from intake under corn silage and 31 ± 26% of the CC and corn residue disappearance would have been from intake under HMC. This suggests that the majority of biomass disappearance was due to trampling.

Cover crop biomass production was greater in corn silage than in HMC (Table 3.3). In Field II, CC yielded 4-7 times higher in silage than HMC. In Field I, CC yielded 1-4 times higher in silage than in HMC. The higher CC biomass production in corn silage is attributed to differences in planting dates. Cover crop after corn silage harvest was planted earlier and thus had more growing degree days than CC after HMC. Also, corn silage harvest leaves little to no surface residue, which can increase soil temperature and promote germination (Licht & Al-Kaisi, 2005), thereby increasing CC biomass production under corn silage relative to HMC.

Cover Crop Grazing Impacts on Soil Properties

Corn harvest (silage vs HMC) significantly affected soil properties ($p < 0.05$). However, CC grazing did not significantly ($p > 0.05$) affect soil properties compared with the non-grazed CC (Tables 3.4-3.7; Figures 3.2-3.3). The corn harvest × CC treatment interaction was not significant ($p > 0.05$). As indicated earlier, soil properties included bulk density (Table 3.4), penetration resistance (Table 3.4), wet aggregate stability expressed as mean weight diameter of water-stable aggregates (Table 3.4), dry aggregate stability expressed as wind erodible fraction (Figure 3.2), water infiltration (Figure 3.3), volumetric water content at -0.03 and -1.5 MPa (Table 3.5), organic matter and POM concentrations (Table 3.6), and microbial biomass (Table 3.7).

The lack of effects of CC grazing on bulk density and penetration resistance (Table 3.4) suggests that CC grazing may not cause soil compaction. This finding may be due to the following factors. First, CC was planted and grazed only after the corn phase of the corn-soybean rotation (every other year grazing), which possibly reduced potential cumulative effects of grazing. Second, our experiment is an on deep loess and high organic matter soil (42 g kg^{-1} organic matter for the 0 to 20 cm depth). High organic matter soils can be less susceptible to compaction than low organic matter soils (Hamza & Anderson, 2005). Third, in this experiment, cattle grazed in late fall when soils are drier compared to spring (Table 3.1-3.2). Clark et al. (2004) found that corn residue grazing in spring can compact soil more in wet soil conditions. Fourth, natural freeze-thaw and wetting-drying cycles, which are prevalent in this region, possibly alleviated any soil compaction (Jabro, Iverson, Evans, Allen, & Stevens, 2013).

The lack of impact of CC grazing on water infiltration (Figure 3) or water retention (Table 3.5) suggests CC grazing may not reduce the ability of CCs to capture and retain water. Literature is limited on CC grazing and soil hydraulic properties. On a similar study in west central Nebraska, Blanco-Canqui et al. (2020) reported that winter rye CC grazing had variable impacts on water infiltration during a 3-yr study. Additionally, in our experiment, the limited or no effect of CC grazing on wet (Table 3.4) or dry aggregate stability (Figure 3.1) suggests that CC grazing may not degrade soil structural stability, which is important for erosion control, soil organic matter protection, water movement, and other dynamic processes (Ramesh et al., 2019).

The limited or no effects of CC grazing on soil organic matter and POM agree with previous studies (Franzluebbers & Stuedemann, 2008b; Faé et al., 2009; Blanco-Canqui et al., 2020). In this experiment, because CC was grazed every other year (only two and three grazing events), opportunity to accumulate manure or CC residues that might influence organic matter was limited. We hypothesize that, in the long term, CC grazing would increase organic matter fractions by trampling residues into the soil and manure addition (Rakkar & Blanco-Canqui, 2018). It is worth noting that, in this study, the presence of CC had large and significant effects on increasing soil microbial biomass compared to no CC in both fields (Table 3.6). This finding agrees with a review by Kim, Zaboloy, Guan, & Villamil (2020) which found CCs can increase soil microbial biomass and activity, attributed to the above and belowground CC biomass input.

Overall, findings suggest that CC grazing has limited or no impacts on soil properties in the short term and are consistent with the few previous studies on CC grazing (Franzluebbers & Stuedeman, 2008a, 2008b; Faé et al., 2009; Schomberg et al., 2014; Blanco-Canqui et al., 2020). We suggest that while CC grazing reduced CC aboveground biomass, some residue probably remained in the soil due to trampling. Also, the belowground root biomass may have prevented negative effects of CC grazing (Sokol et al., 2019; Ribeiro et al., 2020).

Cover Crop Grazing Impacts on Crop Yields

Cover crop grazing had no impact on subsequent soybean yields (Table 3.8) and little to no impact on corn yields (Table 3.9). When averaged across all years, CC grazing had no impact on crop yields (Tables 3.8-3.9). The lack of CC grazing impact on soil properties (Table 3.10) may explain the limited effects of CC grazing on yields (Table 3.8-3.9). Also, most previous studies found no effects of CC grazing on crop yields (Faé et al., 2009; Blanco-Canqui et al., 2020). Literature also indicates, in a few cases, CC grazing could reduce yields due to compaction when CCs are grazed in wet soil conditions (Schomberg et al., 2014) or when evaporation is high due to reduced residue cover (Franzluebbers and Stuedemann, 2007). Unlike previous studies, our experiment was irrigated, grazed in late fall, and did not experience excessively wet grazing conditions (Table 3.2). Overall, CC grazing appears to have no impact on crop yields.

Corn Silage Impacts on Soils and Crop Yields

While CC grazing had no negative impacts on soil properties, corn silage had significant negative impacts on near-surface soil properties compared to HMC. Corn silage increased penetration resistance (Table 3.4) and wind erodible fraction (Figure 3.2), while it reduced wet aggregate stability (Table 3.4), organic matter and POM concentrations (Table 3.6), and microbial biomass (Table 3.7) in both fields. In one of the two fields, corn silage also increased bulk density at the 5 to 10 cm depth (Table 3.4) and reduced volumetric water content at -0.033 and -1.5 MPa for the 0 to 5 cm depth (Table 3.5). The addition of CC did not offset the negative impacts of corn silage except for an increase in microbial biomass (Table 3.10). This somewhat contradicts previous literature that cereal rye CC following corn silage can improve soil organic matter, structure, and hydraulic properties (Liesch et al., 2011; Moore et al., 2014). However, our study not only used a winterkill CC of oat but also CC planted every other year, which may have limited CC benefits.

Corn silage increased penetration resistance by 1.36 times (1.32 vs 1.80 MPa) in Field I and by 1.46 times (0.94 vs 1.37 MPa) in Field II when averaged across both 0 to 5 cm and 5 to 10 cm depths (Table 3.4). It also increased bulk density by 1.04 times but only for the 5 to 10 cm depth in Field II (Table 3.4). In both fields, corn silage reduced the mean weight diameter of water-stable aggregates by 1.86 times for the 0 to 5 cm depth (Table 3.4), and increased wind erodible fraction by 1.95 times (Figure 3.2). Furthermore, corn silage reduced volumetric water content by 1.12 times at -0.033 MPa and 1.14 times at -1.5 MPa at the 0 to 5 cm depth in Field II. However, corn silage did not affect plant available water (Table 3.5) nor water infiltration (Figure 3.3). While CC grazing had no impact on organic matter fractions, corn silage reduced organic matter and POM concentrations compared to HMC (Table 3.6). In both fields at the 0 to 5 cm depth, corn silage reduced soil organic matter concentration by 1.12 times in Field I and 1.22 times in Field II. Additionally, in both fields, corn silage reduced POM by 1.39 times in Field I and 1.52 times in Field II at the 0 to 5 cm depth and 1.16 times at the 5 to 10 cm depth in Field II (Table 3.6).

These results indicate that corn silage can have greater impacts than CC grazing. For example, corn silage increased soil compaction risks unlike CC grazing. This is expected as corn silage harvest not only removes most residues but also requires additional machinery and passes through the field. The increase in penetration resistance values were, however, below the crop root-limiting threshold of 2 MPa (Bengough, McKenzie, Hallett, & Valentine, 2011). The corn silage-induced decrease in organic matter concentration may have contributed to the increased compaction (Hamza & Anderson, 2005). The increase in wind erodible fraction and reduction in wet aggregate stability with corn silage harvest suggests that this practice can increase water and wind erosion potential compared to HMC (Table 3.4; Figure 3.2).

The reduced microbial biomass under silage is attributed to the biomass removal and reduced soil organic matter. In addition, the increased penetration resistance and decreased wet and dry aggregate stability may have disrupted soil microbial habitats (Gupta & Germida, 2015). Corn silage with CC had, however, higher microbial biomass than corn silage without CC (Table 3.10), suggesting that CC may partly offset the adverse effects of corn silage on soil microbial biomass. Despite the negative impacts of corn silage on soil properties compared to HMC (Table 3.10), corn silage did not have any negative effects on subsequent soybean yields (Table 3.8). This study was an irrigated, no-till, corn-soybean rotation with relatively high soil organic matter (Table 3.6). Therefore, the high organic matter concentration and use of irrigation water may have buffered against any negative soil impacts of corn silage on soybean yields.

Interrelationships among Soil Properties

Correlations among soil properties across all treatments and replications (n=18) were significant, particularly at the 0 to 5 cm soil depth (Table 3.11). The significant correlations were most likely due to the large corn silage-induced changes in soil properties. Table 3.11 shows soil organic matter, POM, and various microbial biomass were correlated with dry (wind erodible fraction) and wet aggregate stability, suggesting increases in organic matter fractions and microbial biomass can improve soil aggregate stability. These results are consistent with literature showing that organic matter and soil microorganisms play a large role in creating and maintaining soil aggregates (Bronick & Lal, 2005; Gupta & Germida, 2015; Lehmann, Zheng, & Rillig, 2018; Ramesh et al., 2019). Additionally, the negative correlation of organic matter fractions with bulk density and penetration resistance in both fields suggests increasing organic matter can be a strategy to reduce compaction risks (Table 3.11) as supported by literature (Hamza &

Anderson, 2005). Also, increases in microbial biomass were correlated with penetration resistance for both fields (Table 3.11). This suggests, similar to organic matter, the importance of microbial communities to promote soil aggregation and contribute to reduced soil compaction. It should also be noted that wind erodible fraction increased while wet aggregate stability decreased with an increase in penetration resistance (Table 3.11), which corroborates the adverse effects of increased compaction on reducing soil aggregation.

Conclusions

Cover crop grazing (1.3-3.7 steers ha^{-1} stocking rates) had no impacts on soil compaction, erosion potential, hydraulic properties, organic matter, POM, and microbial biomass after two (Field I) and three (Field II) CC grazing events during 5 yr in an irrigated no-till corn-soybean rotation in eastern Nebraska. Similarly, CC grazing had no effect on crop yields when averaged across all years. In contrast, corn silage had detrimental impacts on soil properties. Corn silage increased soil compaction and wind and water erosion potential, while it reduced organic matter, POM, and microbial biomass compared to HMC although it did not reduce subsequent crop yields. In general, CC did not offset the negative impacts of corn silage on soil properties. Corn-silage induced decreases in soil organic matter and microbial biomass explained some of the decreases in soil aggregate stability and increases in soil compaction risks. Overall, CC grazing could be an option to integrate crop and livestock without adversely impacting soil or crop production, but corn harvest as silage can negatively impact soil properties under the conditions of this study.

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Table 3.1. Mean air temperatures (ºC) and precipitation (mm) from 2015 to 2020 at the Eastern Nebraska Research and Extension Center, near Mead, NE.

	2015	2016	2017	2018	2019	2020	Average
Mean Temperature							
	---------------------ºC---------------------						
Jan.	-3	-5	-3	-6	-5	-4	-4
Feb.	-7	0	2	-5	-8	-2	-3
Mar.	6	8	5	4	1	6	5
Apr.	12	12	11	6	11	10	10
May	16	16	16	20	13	15	16
June	22	25	20	20	22	26	23
July	24	24	25	24	25	25	25
Aug.	22	23	21	23	23	23	23
Sept.	21	16	18	19	21	17	19
Oct.	13	13	12	10	9	9	11
Nov.	6	7	4	0	2	6	4
Dec.	1	-4	-3	-2	-1	-2	-2
Annual Average	11	11	11	9	9	11	10
Precipitation							
	---------------------mm---------------------						
Jan.	3	15	4	8	2	19	9
Feb.	6	8	5	6	2	1	5
Mar.	20	30	50	103	52	32	48
Apr.	94	157	112	5	34	7	68
May	185	174	169	63	193	43	138

June	180	95	72	198	122	32	117
July	103	123	41	87	67	63	81
Aug.	173	208	129	99	72	43	121
Sept.	101	20	71	233	91	39	93
Oct.	13	40	117	60	169	13	69
Nov.	45	28	5	20	21	12	22
Dec.	106	29	1	90	64	4	49
Annual Total	1029	927	776	972	889	308	817

Table 3.2. Information on grazing events, steer initial weights, stocking rates, forage allocation, grazing duration, percent of grazing days with precipitation, and percent of grazing days at or below 0 °C for each of the two experimental fields of cover crop (CC) grazing under irrigated no-till corn-soybean rotation in eastern Nebraska during the 5 yr of management. Note that Field I had two grazing events while Field II had three grazing events.

	Grazing Events		**Steers Initial Weight**	**Stocking Rates (steers ha^{-1})**		**Forage Allocated† (kg steer $^{-1}$ d^{-1})**		**Grazing Duration**	**Grazing Days with Precipitation**	**Grazing Days ≤0°C**
Year	**Field I**	**Field II**	**kg**	**Corn Silage**	**HMC***	**Corn Silage‡**	**HMC§**	**Days**	**--------------%---------------**	
2015	ng¶	Grazed	230	3.7	2.9	11.4	2.6 + 8.8	62	31	37
2016	Grazed	ng	251	2.8	2.8	11.7	2.7 + 8.8	42	14	31
2017	ng	Grazed	247	1.9	2.0	18.2	4.7 + 14	48	8	19
2018	Grazed	ng	238	1.5	2.4	17.6	8.4 + 9.0	30	20	60
2019	ng	Grazed	245	1.3	1.7	17.5	2.0 + 15	69	23	45

*HMC, high moisture corn

† Forage allocated for a target grazing period of 70 days

‡ CC biomass allocated

§ CC + corn residue biomass allocated

¶ ng, not grazed

Table 3.3. Cover crop (CC) and corn residue biomass (Mg ha^{-1}) in each field under irrigated no-till corn-soybean rotation in eastern Nebraska. The CC was planted immediately following corn harvest. Corn silage was harvested about 15 d before high moisture corn (HMC). Pre-grazed CC biomass is the biomass sampled prior to grazing and used to calculate stocking rates. Post-grazed CC and corn residue is the biomass remaining after grazing. Note that all treatments received 44.8 kg N ha^{-1} by ammonium nitrate following CC planting.

	Cover Crop Biomass (Mg ha^{-1})						Corn Residue Biomass† (Mg ha^{-1})		
	Corn Silage			HMC			HMC		
Year	**Non-grazed CC**	**Pre-grazed CC**	**Post-grazed CC**	**Non-grazed CC**	**Pre-grazed CC**	**Post-grazed CC**	**Non-grazed residue**	**Pre-grazed residue**	**Post-grazed residue**
Two Grazing Events (Field I)									
2016	2.06	2.56	1.35	0.67	0.61	0.08	8.76	8.69	.
2018	2.15	2.06	0.36	2.03	1.59	0.27	9.09	9.30	7.02
Three Grazing Events (Field II)									
2015	2.00	3.21	.	0.58	0.59	.	8.67	8.94	.
2017	2.18	2.69	0.36	0.72	0.74	0.27	8.77	9.11	7.04
2019	1.88	1.73	0.29	0.25	0.27	0.05	8.18	8.84	7.27

† Corn residue biomass only reported for high moisture corn treatments

Table 3.4. Means and standard deviations for bulk density, penetration resistance, and mean weight diameter of water stable aggregates (MWD) for two soil depths for a cover crop (CC) grazing experiment under irrigated no-till corn-soybean rotation in eastern Nebraska. Means with different lowercase letters under the same soil depth interval differ significantly at p<0.05.

Treatment	Bulk Density (Mg m^{-3})	Penetration Resistance (MPa)	MWD (mm)
Two Grazing Events (Field I)			
0-5 cm depth			
No CC	1.08±0.06	1.70±0.32	0.58±0.26
Non-grazed CC	1.12±0.09	1.52±0.28	0.71±0.39
Grazed CC	1.10±0.08	1.59±0.28	0.56±0.28
High Moisture Corn	1.08±0.09	1.38±0.11b	0.86±0.25a
Corn Silage	1.10±0.06	1.83±0.23a	0.37±0.05b
5-10 cm depth			
No CC	1.46±0.07	1.62±0.37	0.70±0.20
Non-grazed CC	1.47±0.10	1.47±0.34	0.74±0.22
Grazed CC	1.45±0.03	1.42±0.22	0.63±0.10
High Moisture Corn	1.44±0.05	1.26±0.15b	0.76±0.21
Corn Silage	1.48±0.08	1.76±0.20a	0.62±0.11
Three Grazing Events (Field II)			
0-5 cm depth			
No CC	1.15±0.12	1.12±0.39	0.82±0.42
Non-grazed CC	1.09±0.08	1.08±0.23	0.73±0.26
Grazed CC	1.14±0.08	1.11±0.21	0.98±0.31
High Moisture Corn	1.12±0.09	0.88±0.14b	1.04±0.35a
Corn Silage	1.13±0.10	1.33±0.15a	0.64±0.16b
5-10 cm depth			
No CC	1.32±0.09	1.28±0.41	0.76±0.37
Non-grazed CC	1.30±0.08	1.22±0.34	0.60±0.18
Grazed CC	1.30±0.08	1.13±0.15	1.21±1.16
High Moisture Corn	1.28±0.07b	1.00±0.14b	1.06±0.99
Corn Silage	1.33±0.09a	1.42±0.28a	0.65±0.18

Table 3.5. Means and standard deviations for volumetric water content at -0.033 and -1.5 MPa matric potential, and plant available water for the 0 to 5 cm soil depth in a cover crop grazing (CC) experiment under irrigated no-till corn-soybean rotation in eastern Nebraska. Means with different lowercase letters differ significantly at $p<0.05$.

Treatments	**Volumetric water content**		**Available water**
	-0.033 MPa	**-1.5 MPa**	
	----------------------cm^3 cm^{-3}----------------------		
Two Grazing Events (Field I)			
No CC	0.27±0.02	0.16±0.01	0.11±0.02
Non-grazed CC	0.26±0.02	0.16±0.02	0.10±0.01
Grazed CC	0.25±0.01	0.16±0.01	0.10±0.01
High Moisture Corn	0.26±0.02	0.16±0.02	0.10±0.02
Corn Silage	0.27±0.02	0.16±0.01	0.10±0.02
Three Grazing Events (Field II)			
No CC	0.27±0.03	0.16±0.01	0.11±0.02
Non-grazed CC	0.26±0.02	0.15±0.02	0.11±0.01
Grazed CC	0.26±0.02	0.15±0.03	0.12±0.02
High Moisture Corn	0.28±0.02a	0.16±0.02a	0.12±0.02
Corn Silage	0.25±0.01b	0.14±0.01b	0.11±0.01

Table 3.6. Means and standard deviations for organic matter and particulate organic matter concentration for three soil depths for a cover crop (CC) grazing experiment under irrigated no-till corn-soybean rotation in eastern Nebraska. Means with different lowercase letters under the same soil depth interval differ significantly at p<0.05.

Treatment	Organic Matter	Particulate Organic Matter
	%	g kg^{-1}
	Two Grazing Events (Field I)	
	0-5 cm depth	
No CC	4.5±0.9	16.4±4.2
Non-grazed CC	4.1±0.8	17.7±5.5
Grazed CC	4.4±0.8	15.6±2.5
High Moisture Corn	4.6±0.8a	19.3±3.7a
Corn Silage	4.1±0.6b	13.9±2.2b
	5-10 cm depth	
No CC	4.2±0.6	9.1±2.4a
Non-grazed CC	4.1±0.7	7.9±2.7ab
Grazed CC	4.0±0.4	6.9±0.9b
High Moisture Corn	4.1±0.6	8.5±2.3
Corn Silage	4.0±0.5	7.4±2.1
	10-20 cm depth	
No CC	3.7±0.5	4.5±2.3
Non-grazed CC	3.6±0.7	4.3±1.5
Grazed CC	3.7±0.4	4.0±1.5
High Moisture Corn	3.6±0.4	4.1±1.5
Corn Silage	3.6±0.6	4.4±1.9
	Three Grazing Events (Field II)	
	0-5 cm depth	
No CC	5.1±1.0	23.2±8.6
Non-grazed CC	4.9±0.7	23.3±7.0
Grazed CC	5.0±0.7	23.5±7.1
High Moisture Corn	5.5±0.6a	28.1±4.7a
Corn Silage	4.5±0.5b	18.5±5.8b
	5-10 cm depth	
No CC	4.1±0.6	10.2±4.2b
Non-grazed CC	4.0±0.6	12.8±5.0a
Grazed CC	3.8±0.3	9.4±2.8b
High Moisture Corn	4.0±0.5	11.6±4.8a

Corn Silage	3.9±0.6	10.0±3.5b
	10-20 cm depth	
No CC	3.8±0.5	3.6±1.3
Non-grazed CC	3.6±0.4	3.5±1.1
Grazed CC	3.6±0.2	4.2±1.1
High Moisture Corn	3.6±0.4	3.6±1.3
Corn Silage	3.7±0.4	3.9±1.1

Table 3.7. Means and standard deviations for total microbial biomass and microbial communities for two soil depths for a cover crop grazing (CC) experiment under irrigated no-till corn-soybean rotation in eastern Nebraska. Means with different lowercase letters under the same soil depth interval differ significantly at p<0.05.

Treatment	**Total FAME**	**Bacteria**	**Micro-eukaryotes**	**Arbuscular Mycorrhiza**	**Saprophytic Fungi**
	------------------------------ nmol g^{-1} of soil -------------------------------				
Two Grazing Events (Field I)					
0-5 cm depth					
No CC	130±19.0b	45.5±6.4b	2.8±0.8	5.0±1.3	6.1±1.6b
Non-grazed CC	150±16.1a	53.0±4.8a	2.7±0.8	5.5±1.2	8.9±3.1ab
Grazed CC	160±16.6a	55.5±3.3a	2.8±0.5	5.8±1.2	10.2±5.8a
High Moisture Corn	158±18.4a	53.9±5.1a	3.2±0.5a	6.4±0.8a	11.2±4.0a
Corn Silage	135±16.8b	48.7±6.8b	2.3±0.5b	4.5±0.6b	5.7±1.3b
5-10 cm depth					
No CC	78.4±7.8	31.3±2.7	1.5±0.2	3.4±0.6	2.0±0.5
Non-grazed CC	80.7±10.0	32.0±2.9	1.4±0.3	3.4±0.8	2.5±0.5
Grazed CC	74.6±10.9	30.2±3.9	1.3±0.2	3.3±0.5	2.2±0.4
High Moisture Corn	78.0±11.8	30.8±4.0	1.5±0.2a	3.7±0.4a	2.3±0.5
Corn Silage	77.8±7.0	31.5±2.1	1.3±0.2b	3.0±0.6b	2.2±0.5
Three Grazing Events (Field II)					
0-5 cm depth					
No CC	113±24.3	45.5±4.3b	1.5±0.4	3.7±1.1b	3.5±1.5
Non-grazed CC	133±13.5	52.4±4.3a	1.9±0.5	4.6±0.8a	4.9±1.0
Grazed CC	131±22.5	51.3±7.2ab	1.7±0.5	4.3±1.2ab	4.8±2.1
High Moisture Corn	138±18.1a	53.1±6.0a	2.0±0.4a	4.9±1.1a	5.3±1.6a
Corn Silage	114±18.6b	46.4±6.1b	1.4±0.4b	3.6±0.6b	3.4±1.0b
5-10 cm depth					
No CC	63.2±5.9	26.8±2.2	0.8±0.3	2.9±1.2	1.5±0.3b
Non-grazed CC	72.6±9.9	30.5±3.3	1.2±0.3	2.8±0.7	2.1±0.3a
Grazed CC	68.0±8.8	28.7±4.4	1.0±0.1	3.0±0.8	1.9±0.4ab
High Moisture Corn	68.1±10.7	28.4±4.1	1.1±0.3	2.6±0.8	1.9±0.5
Corn Silage	67.7±7.0	28.9±3.1	0.9±0.2	3.2±1.0	1.8±0.5

Table 3.8. Means and standard deviations for soybean grain yields for a cover crop (CC) grazing experiment under irrigated no-till corn-soybean rotation in eastern Nebraska. An additional year (2020) is shown to capture any effects following the last CC grazing event (2019). Means with different lowercase letters differ significantly at $p<0.05$. na denotes non-applicable as the crop was not present for that year in the rotation.

Year	**Treatment**	**Soybean Yield**	
		----------------------------------Mg ha^{-1}-------------------------------------	
		Two Grazing Events (Field I)	**Three Grazing Events (Field II)**
2015	No CC	5.2±0.2	na
	Non-grazed CC	5.1±0.3	na
	Grazed CC	4.9±0.3	na
	High Moisture Corn	5.0±0.3	na
	Corn Silage	5.1±0.3	na
2016	No CC	na	4.7±0.3
	Non-grazed CC	na	4.4±0.3
	Grazed CC	na	4.6±0.2
	High Moisture Corn	na	4.5±0.2
	Corn Silage	na	4.7±0.3
2017	No CC	4.0±0.3	na
	Non-grazed CC	3.8±0.3	na
	Grazed CC	3.7±0.3	na
	High Moisture Corn	3.8±0.3	na

	Corn Silage	3.9±0.3	na
2018	No CC	na	3.8±0.4
	Non-grazed CC	na	3.7±0.2
	Grazed CC	na	3.8±0.2
	High Moisture Corn	na	3.7±0.3
	Corn Silage	na	3.9±0.2
2019	No CC	3.5±0.6	na
	Non-grazed CC	3.6±0.4	na
	Grazed CC	3.6±0.6	na
	High Moisture Corn	3.6±0.5	na
	Corn Silage	3.6±0.4	na
2020	No CC	na	2.7±0.4
	Non-grazed CC	na	2.8±0.5
	Grazed CC	na	2.6±0.5
	High Moisture Corn	na	2.6±0.5b
	Corn Silage	na	2.8±0.4a
Across years	No CC	4.2±0.8	3.8±0.9
	Non-grazed CC	4.2±0.7	3.7±0.7
	Grazed CC	4.1±0.7	3.7±0.9

	High Moisture Corn	4.1±0.7	3.6±0.8
	Corn Silage	4.2±0.8	3.8±0.8

Table 3.9. Means and standard deviations for corn silage dry matter yields, and high moisture corn (HMC) grain yields for a cover crop (CC) grazing experiment under irrigated no-till corn-soybean rotation in eastern Nebraska. An additional year (2020) is shown to capture any effects following the last CC grazing event (2019). Means with different lowercase letters differ significantly at p<0.05. na denotes non-applicable as the crop was not present for that year in the rotation

Year	**Treatment**	**High Moisture Corn and Corn Silage Yields**			
		HMC	**Corn Silage**	**HMC**	**Corn Silage**
		---------------------------------- Mg ha^{-1} ----------------------------------			
		Two Grazing Events (Field I)		**Three Grazing Events (Field II)**	
2015	No CC	na	na	13.0±1.2	17.1±0.7
	Non-grazed CC	na	na	12.8±1.0	17.3±0.7
	Grazed CC	na	na	13.6±0.4	18.8±0.6
2016	No CC	12.3±0.8	20.6±2.2	na	na
	Non-grazed CC	12.8±0.5	19.6±1.9	na	na
	Grazed CC	12.2±1.3	20.6±1.0	na	na
2017	No CC	na	na	14.6±0.3	21.8±0.9
	Non-grazed CC	na	na	14.6±0.6	20.7±1.5
	Grazed CC	na	na	15.0±1.0	20.8±1.4
2018	No CC	10.9±0.7c	20.2±0.6	na	na
	Non-grazed CC	11.8±0.3b	19.8±1.6	na	na
	Grazed CC	13.0±0.1a	19.0±3.0	na	na
2019	No CC	na	na	13.7±1.1a	20.4±0.9
	Non-grazed CC	na	na	13.6±1.2a	20.8±1.5
	Grazed CC	na	na	13.3±1.3b	20.8±1.4
2020	No CC	10.7±0.3	18.4±0.7	na	na

	Non-grazed CC	9.95±0.9	19.0±0.7	na	na
	Grazed CC	10.7±0.4	19.6±0.6	na	na
Across years	No CC	11.3±0.9	19.7±1.1	13.8±1.1	19.8±2.6
	Non-grazed CC	11.5±1.3	19.5±1.3	13.7±1.2	19.6±2.2
	Grazed CC	11.9±1.2	19.7±1.8	13.9±1.1	20.1±1.4

Table 3.10. Summary of soil and crop response under cover crop (CC) grazing and corn silage and high moisture corn harvest managed under irrigated no-till corn-soybean rotation in eastern Nebraska. Crop yields are averaged across all years. Differences significant at $p<0.05$. ns, not significant; VWC, volumetric water content; na, non-applicable

Parameters	Impact of CC grazing compared to non-grazed CC	Impact of CC grazing compared to no CC	Impact of silage compared to high moisture corn	Impact of silage with CC compared to silage without CC
Soil Properties				
Penetration Resistance	ns	ns	Increased†‡§¶	ns
Bulk Density	ns	ns	Increased‡¶	ns
Wet Aggregate Stability	ns	ns	Reduced†§¶	ns
Dry Aggregate Stability	ns	ns	Increased†§¶	ns
Cumulative Infiltration	ns	ns	ns	ns
VWC at -0.033 MPa	ns	ns	Reduced†¶	ns
VWC at -1.5 MPa	ns	ns	Reduced†¶	ns
Plant Available Water	ns	ns	ns	ns
Organic Matter	ns	ns	Reduced†§¶	ns
Particulate Organic Matter	ns	ns	Reduced†‡§¶	ns
Microbial Biomass	ns	Increased†§	Reduced†‡§¶	Increased†§¶
Crop Yields				
Soybean	ns	ns	ns	ns

Corn Silage	ns	ns	na	na
High Moisture Corn	ns	ns	na	na

† 0 to 5 cm depth

‡ 5 to 10 cm depth

§ Two CC grazing events (Field I)

¶ Three CC grazing events (Field II)

Table 3.11. Correlation coefficients ($n = 18$) between different soil properties at the 0 to 5 cm soil depth.† Differences significant at $p<0.05$.

Two Grazing Events (Field I)										
	BD	**PR**	**WAS**	**WEF**	**VWC at -0.033 MPa**	**VWC at -1.5 MPa**	**PAW**	**Infiltration**	**SOM**	**POM**
BD	-	-	-	-	-	-	-	-	-	-
PR	0.24	-	-	-	-	-	-	-	-	-
WAS	-0.11	-0.66*	-	-	-	-	-	-	-	-
WEF	0.24	0.76*	-0.78*	-	-	-	-	-	-	-
VWC at -0.033 MPa	0.25	0.18	-0.09	0.06	-	-	-	-	-	-
VWC at -1.5 MPa	0.19	0.42	0.02	-0.01	0.62*	-	-	-	-	-
PAW	0.16	-0.10	-0.21	0.18	0.68*	-0.11	-	-	-	-
Infiltration	0.09	-0.25	0.65*	-0.39	0.02	0.13	-0.22	-	-	-
SOM	-0.69*	-0.34	0.26	-0.48*	0.02	0.13	-0.08	0.09	-	-
POM	-0.45	-0.69*	0.68*	-0.59*	-0.37	-0.43	-0.09	0.31	0.48*	-
FAME	-0.10	-0.47*	0.58*	-0.67*	-0.35	0.00	-0.52*	0.46*	0.23	0.31
Bacteria	-0.21	-0.39	0.44	-0.56*	-0.29	-0.06	-0.37	0.41	0.30	0.26
Eukaryotes	0.16	-0.46	0.60*	-0.67*	0.06	0.26	-0.13	0.33	0.33	0.32
AMF	0.07	-0.67*	0.73*	-0.88*	-0.01	0.08	-0.17	0.45	0.23	0.36
Saprophytic Fungi	-0.05	-0.57*	0.73*	-0.72*	-0.36	-0.01	-0.56*	0.54	0.13	0.41
Three Grazing Events (Field II)										
	BD	**PR**	**WAS**	**WEF**	**VWC at -0.033 MPa**	**VWC at -1.5 MPa**	**PAW**	**Infiltration**	**SOM**	**POM**
BD	-	-	-	-	-	-	-	-	-	-
PR	-0.08	-	-	-	-	-	-	-	-	-
WAS	0.18	-0.61*	-	-	-	-	-	-	-	-

WEF	0.22	0.74*	-0.55*	-	-	-	-	-	-	-
VWC at -0.033 MPa	0.34	-0.78*	0.59*	-0.69*	-	-	-	-	-	-
VWC at -1.5 MPa	0.49*	-0.57*	0.32	-0.46	0.71*	-	-	-	-	-
PAW	-0.08	-0.44	0.46	-0.43	0.60*	-0.15	-	-	-	-
Infiltration	-0.10	0.16	-0.10	0.12	-0.30	-0.22	-0.17	-	-	-
SOM	-0.36	-0.49*	0.56*	-0.64*	0.51*	0.18	0.50*	-0.42	-	-
POM	-0.46	-0.46	0.51*	-0.68*	0.45	0.15	0.46	-0.41	0.96*	-
FAME	-0.08	-0.59*	0.68*	-0.48*	0.45	0.14	0.47*	0.05	0.62*	0.63*
Bacteria	0.00	-0.60*	0.62*	-0.39	0.41	0.13	0.43	0.12	0.50*	0.48*
Eukaryotes	-0.18	-0.50*	0.57*	-0.60*	0.45	0.15	0.47	0.01	0.71*	0.75*
AMF	0.16	-0.72*	0.59*	-0.61*	0.51*	0.55*	0.09	0.16	0.27	0.34
Saprophytic Fungi	0.13	-0.60*	0.70*	-0.54*	0.51*	0.26	0.42	0.13	0.50*	0.52*

†BD, bulk density; PR, penetration resistance; WAS, wet aggregate stability; WEF, wind erodible fraction; FC, VWC, volumetric water content; PAW, plant available water; Infiltration, total cumulative infiltration; SOM, soil organic matter; POM, particulate organic matter; FAME, total fatty acid methyl ester; AMF, arbuscular mycorrhizal fungi

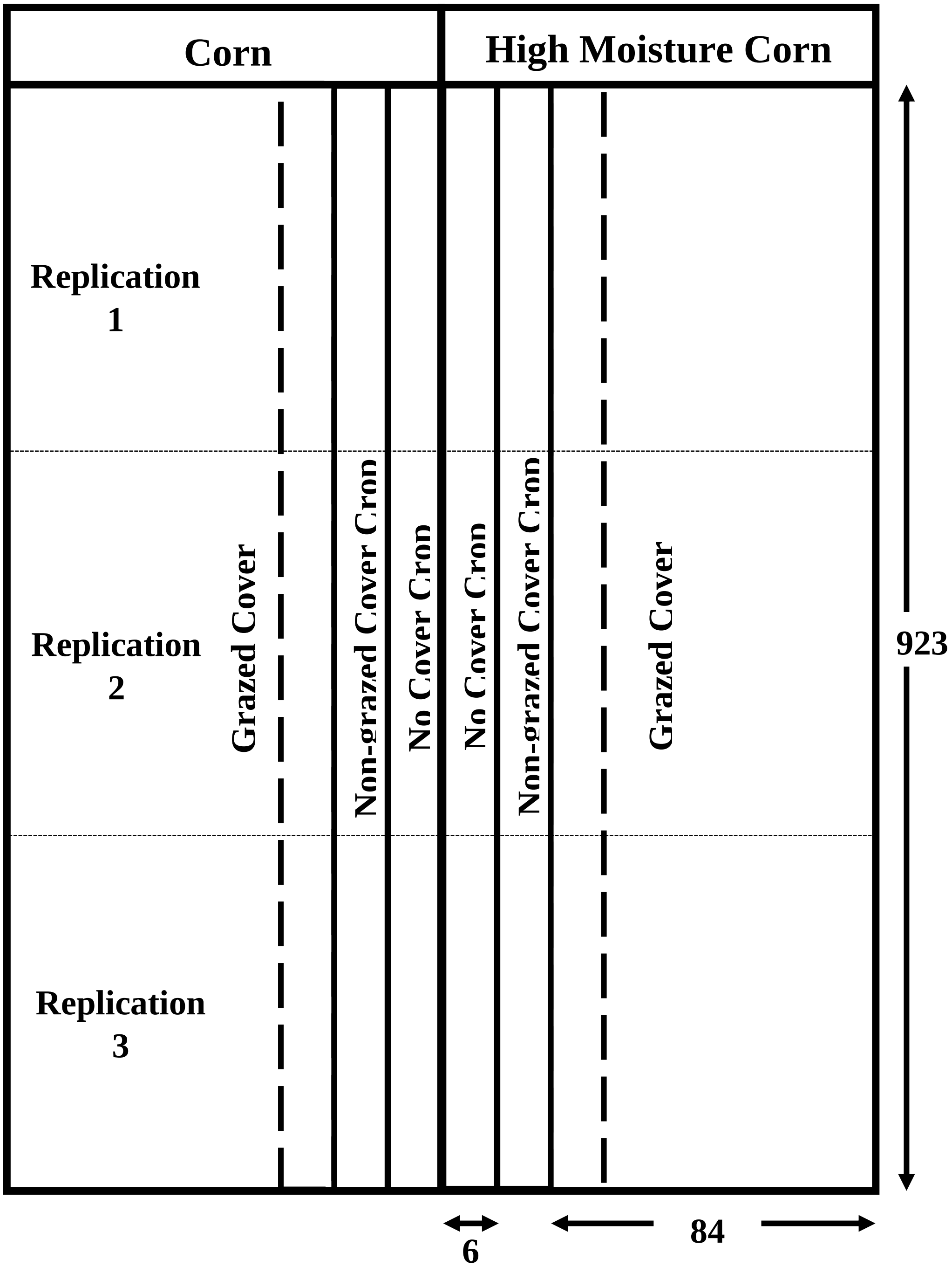

Figure 3.1. Diagram showing the layout of one of two field experiments with two main plots (corn silage and high moisture corn) and three split plots [no cover crop (CC), non-grazed CC, and grazed CC]. Replicates represent pseudoreplicates. The plant and soil sampling area for the grazed CC treatments is shown with dashed lines as we sampled only a section of the total grazed CC area. Diagram is not to scale.

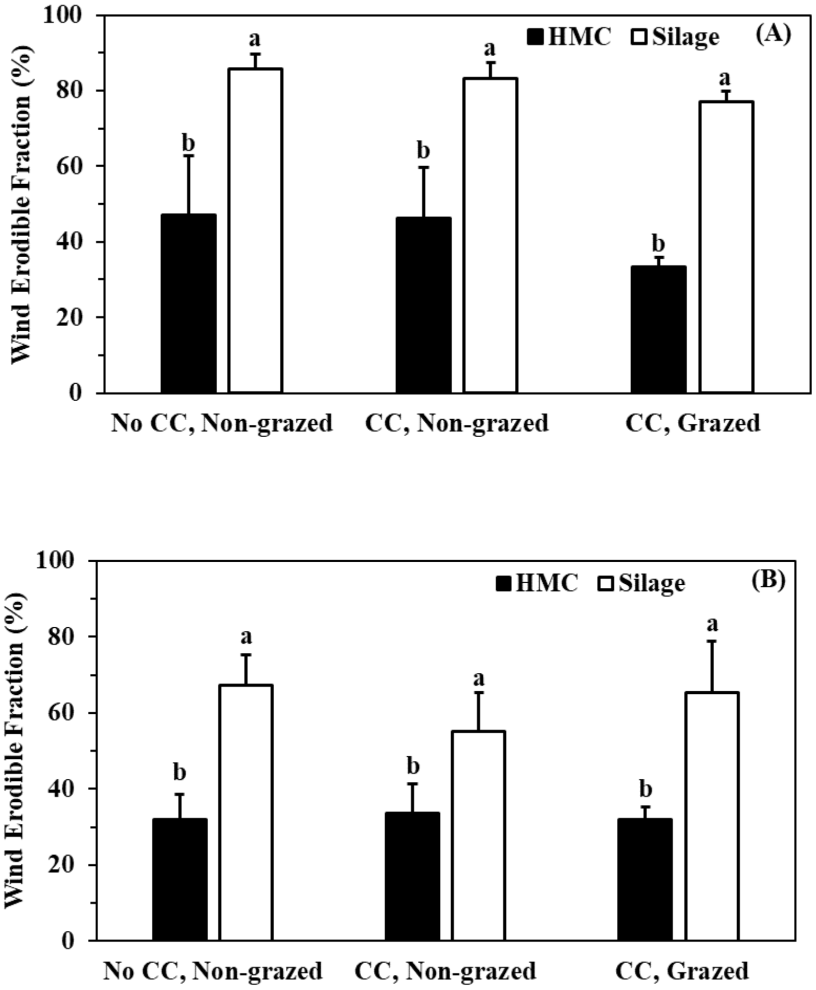

Figure 3.2. Cover crop (CC) grazing and corn silage versus high moisture corn (HMC) harvest impacts on wind erodible fraction (<0.84 mm dry aggregates) under irrigated no-till corn-soybean rotation in eastern Nebraska for Field I (A) and Field II (B). Bars with different lowercase letters differ significantly at $p<0.05$. Error bars are the standard deviation of the mean.

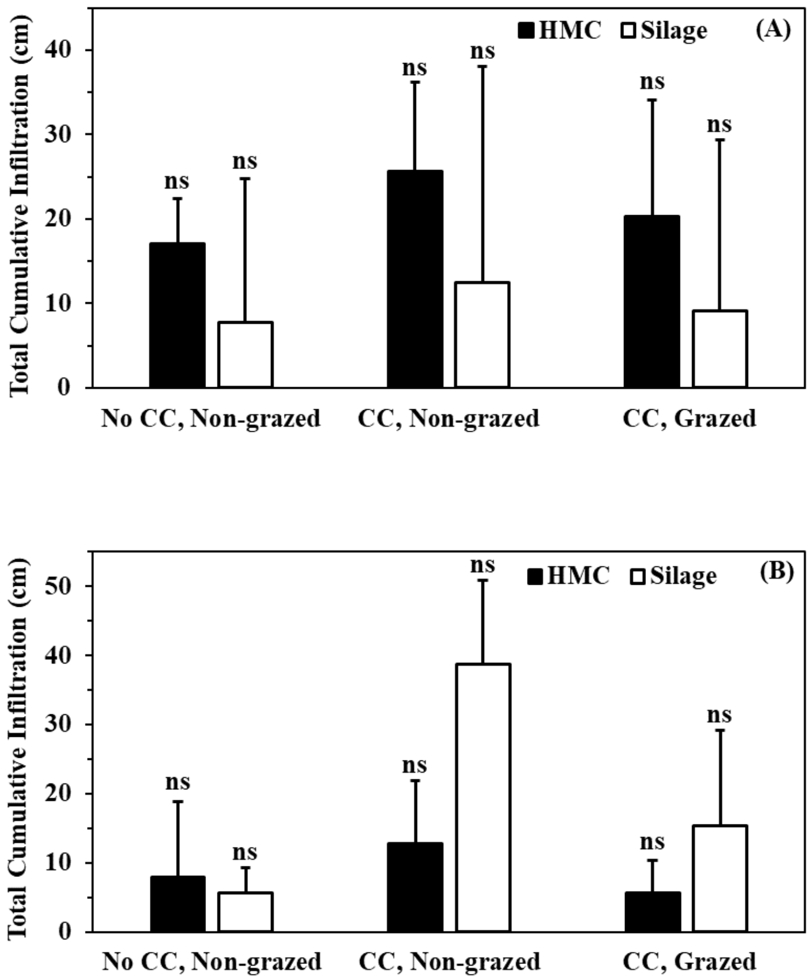

Figure 3.3. Cover crop (CC) grazing and corn silage versus high moisture corn (HMC) harvest impacts on total cumulative water infiltration under irrigated no-till corn-soybean rotation in eastern Nebraska for Field I (A) and Field II (B). Error bars are the standard deviation of the mean. ns = not significant

CHAPTER 4. Short-Term Impacts of Grazing Cover Crops and Corn Residue on Soil Compaction

Abstract

Integrating livestock into cropping systems can diversify agricultural production systems, but how this practice affects soil compaction is not clear. The objective of our study was to evaluate the short-term impact of grazing cover crops (CC) and corn residue on soil compaction parameters in two cropping systems. We studied the impact of cattle grazing of corn (*Zea mays* L.) residue [717-807 animal unit days (AUD) ha^{-1}] and an oat (*Avena sativa* L.) CC (1354 AUD ha^{-1}) on soil compaction parameters including bulk density, penetration resistance, and initial infiltration rate under two rainfed no-till systems (I and II) on a silty clay loam in eastern Nebraska. System I consisted of one year of corn residue grazing under soybean (*Glycine max* L)-corn without horse manure, while System II consisted of one year of CC grazing and another year of corn residue grazing under soybean-wheat (*Triticum aestivum* L.)-corn with horse manure. Dry horse manure application rate in System II averaged 39.2 Mg ha^{-1}. Oat CC was planted following wheat, so CC grazing only occurred in System II, whereas corn residue grazing occurred in both systems. Corn residue grazing in System I did not impact bulk density (1.38±0.05 vs 1.38±0.06 Mg m^{-3}), penetration resistance (0.72±0.11 vs. 0.81±0.14 MPa), or initial infiltration rate (8.93±1.46 vs 9.01±2.34 cm sec$^{-1/2}$). Similarly, corn residue grazing in System II did not impact bulk density (1.41±0.04 vs 1.36±0.05 Mg m^{-3}), penetration resistance (0.80±0.13 vs. 0.80±0.14 MPa), and initial infiltration rate (14.37±4.04 vs 12.75±3.01 cm sec$^{-1/2}$). Cover crop grazing in System II did not impact penetration resistance (1.26±0.14 vs. 1.06±0.07 MPa) and initial infiltration rate (7.79±2.10 vs

9.15±3.84 cm $sec^{-1/2}$), but it did increase bulk density (1.43±0.04 vs 1.38±0.04 Mg m^{-3}). However, this increase was below bulk density values that negatively affect root growth. Cover crop and corn residue grazing generally had no impact on soil compaction in the short-term (1-2 yr).

Introduction

There is renewed interest in returning livestock to graze croplands, and this integration has been shown to utilize resources more efficiently, increase forage availability, and create diversified income for farmers (MacLaren et al., 2018; Kronberg & Ryschawy, 2019). Despite the potential benefits of crop and livestock integration, increased soil compaction risks associated with livestock grazing croplands remain a concern (Cox-O'Neill et al., 2017). The adverse effects of excessive soil compaction on root growth, nutrient cycling, soil biota, water, gas, and heat fluxes, and the mineralization of soil C and N, among others are well known (Greenwood & McKenzie, 2001; Hamza & Anderson, 2005; Pandey et al., 2021). Two common soil compaction parameters include bulk density and penetration resistance. Bulk density evaluates how dense the soil is, while penetration resistance simulates root growth in the soil. Threshold values that restrict root growth for bulk density depend on soil texture, but they range from 1.80 g cm^{-3} for sandy soils to 1.47 g cm^{-3} for high clay soils (USDA, 2008). Likewise, the threshold values that reduce root growth for penetration resistance depend on the crop and other factors but are generally considered to be from 2 to 3.5 MPa (Bengough et al., 2011; Rakkar & Blanco-Canqui, 2018).

Research on cattle grazing grasslands and pasturelands is abundant (Greenwood & McKenzie, 2001), but how grazing of CC and corn residue impacts soil compaction is not well understood. The few studies on CC grazing and soil compaction show that CC grazing generally increases penetration resistance but typically such increases are below the threshold that would affect root growth (Tollner et al., 1990; Mullins & Burmester, 1997; Franzluebbers & Stuedemann, 2008; Blanco-Canqui et al., 2020). Similarly, research shows that CC grazing has minimal to no impact on bulk density and any increases are below the thresholds that can affect root growth (Tollner et al., 1990; Franzluebbers & Stuedemann, 2008; George et al., 2013; Blanco-Canqui et al., 2020).

A recent review by Rakkar & Blanco-Canqui (2018) focusing on crop residue grazing found that crop residue grazing generally increased penetration resistance and bulk density. However, increased soil compaction did not reduce crop yields and the negative effects on soil were site specific. Numerous factors could influence crop residue grazing impacts on soil compaction including soil texture, tillage system, animal stocking rate, residue production, and timing of grazing (Rakkar & Blanco-Canqui, 2018). For example, grazing corn residue on thawed and wet soils can lead to increased penetration resistance (Clark et al., 2004). In addition, in a study in Nebraska, grazing at low to moderate stocking rates (44-6.2 AUM ha^{-1}) had no impact on soil compaction, but grazing at higher stocking rates (9.3-13.0 AUM ha^{-1}) increased penetration resistance (Rakkar et al., 2017). Thus, additional research is needed to identify all factors that play a role in corn residue grazing and soil compaction.

The limited research on CC and corn residue grazing suggests that grazing croplands may increase soil compaction, specifically penetration resistance, but effects are site specific depending on stocking rate, soil water content, tillage, timing of grazing, biomass production, and natural freeze-thaw and wetting-drying cycles. Nonetheless, studies on CC and corn residue grazing in relation to soil compaction are very few to make definitive conclusions. This warrants more research for different soil types, timing of grazing, and stocking rates to determine how CC and corn residue grazing impacts soil compaction under different scenarios. The objective of our study was to evaluate the short-term impact of grazing CCs and corn residue on soil compaction parameters in two no-till cropping systems in eastern Nebraska.

Materials and Methods

Site Description and Experimental Design

A CC and corn residue grazing experiment was established in 2018 on 0.44 ha at the University of Nebraska-Lincoln, Lincoln, NE (40°49'51"N 96°39'23"W) to study the impact of crop and livestock integration on soil and crop production. Soils at the experimental site were classified as a Wymore-Askarben complex, 0 to 2% slopes with Wymore silty clay loam (Fine, smectitic, mesic Aquertic Argiudolls) and Askarben silty clay loam (Fine, smectitic, mesic Typic Argiudolls). This is a rainfed experiment with a mean annual temperature of 10.8 ^{o}C and a mean annual precipitation of 778 mm (Table 4.1).

Prior to establishment of this experiment, the study site was managed as a perennial hazelnut (*Corylus avellana L.*) orchard. Trees were removed and the site was prepared using deep tillage. Following this, no-till was implemented and the entire study area was planted to wheat in 2018. Treatments were randomized before planting the first phase of corn and soybean for the experiment in spring of 2018. To accomplish this, wheat was terminated prior to planting the first phase of corn and soybean for each cropping system. One full cropping sequence passed before incorporating grazing in the winter of 2018. The experiment had six treatment rotations; however, only a subset of treatments were used in this study. This subset was chosen for completeness of data. The systems chosen were System I (soybean-corn) and System II (soybean-wheat-corn). System II had dry horse manure applied at 2.85 to 6.28 Mg ha^{-1} following wheat. Half of each plot in each system was grazed CC and corn residue and the other half was non-grazed CC and corn residue. An oat CC was planted following wheat harvest in System II. Cattle grazed corn residue following the corn phase and grazed CC following the wheat phase. Therefore, in System I, only corn residue was grazed once while in System II, CC (the first year) and corn residue (second year). Two steers grazed from December to January. Steer weights ranged from 499 to 698 kg and stocking rates ranged from 717 to 1354 AUD ha^{-1}. Detailed steer weights, stocking rates, and grazing durations can be found in Table 4.2. Plots were 27.6 m by 30 m, whereas grazed paddocks were 4.6 m by 15 m. There were four replications for this study.

Measurements

Soil measurements were conducted in late spring and included bulk density, penetration resistance, soil temperature, and sorptivity (initial infiltration rate). Post-grazing CC and corn residue biomass was sampled from the grazed and non-grazed plots in late winter to early spring. Penetration resistance was measured in the field using a hand cone penetrometer (Eijkelkamp Co., Giesbeek, the Netherlands) at 0 to 5 and 5 to 10 cm soil depths. Ten measurements (kg cm^{-2}) were taken per plot on the shoulder of crop rows. The data were converted to cone index (MPa) by dividing by the kg cm^{-2} reading by the cone area. At the time of penetration resistance measurements, soil samples were collected using a hand probe at the same soil depths to determine gravimetric water content (Topp & Ferré, 2002) and study correlations between penetration resistance and soil water content. To determine soil bulk density, three intact soil cores (5 by 5 cm) were collected per plot on the shoulder of rows at the 0 to 5 cm depth. The cores were refrigerated at 4 °C before determining bulk density by the core method (Grossman & Reinsch, 2002). Since potential changes in soil compaction can influence soil structure and porosity, soil sorptivity was measured. Sorptivity is a parameter to measure initial water infiltration rate (Lipiec, Wójciga, & Horn, 2009). A 9.75 cm diameter by 10 cm long ring was inserted into the soil at about 2 cm at three locations per plot (Smith, 1999). Water (75 mL) was poured into the ring and the time for the water to infiltrate was recorded. Soil sorptivity was computed according to the method of Smith (1999). At the time of sorptivity measurements, we also collected soil samples with a hand probe at 0 to 5 cm to determine gravimetric water content (Topp & Ferré, 2002) and study correlations between sorptvity and soil water content.

Soil temperature was measured during spring in early afternoon. Thermometers were placed into the soil at 7.62 cm with 10 measurements taken per plot. Corn residue and CC biomass was collected post grazing using metal frames 0.25 m wide by 1 m long. Oat CC was clipped to the soil surface. Two collections were made per plot. Full field weights were taken, and a sub-sample was weighed wet and dried in a 60 °C forced air oven to determine dry matter amount of CC and corn residue biomass. Residue cover was collected using the line-transect model outlined by Shelton and Jasa (2009). A 15.24 m tape measure was laid out in each plot, and a count was made if there was residue under the tape at each 0.3 m mark. Two readings were taken per plot, averaged, divided by 15.24 m, and multiplied by 100 to get percentage of residue cover.

Statistical Analysis

Data on soil properties by depth and biomass measurements were analyzed using PROC MIXED in SAS to compute ANOVAs and LSMEANS (SAS Institute, 2020). This experiment was analyzed as a randomized complete block design. Normal distribution of data was studied using the Shapiro-Wilk test in PROC UNIVARIATE in SAS. Correlation between penetration resistance and soil water content and sorptivity and soil water content were performed using PROC CORR. This analysis showed no significant correlations. Treatment effects were differentiated using LSMEANS. Treatment effects, normality, and correlations were considered significant at the 0.05 probability level.

Results and Discussion

Cover Crop Biomass and Corn Residue Amount

Corn residue grazing in System I (soybean-corn) reduced corn residue amount by 25% while CC grazing in System II (soybean-wheat-corn) reduced the amount of CC biomass by 48% compared to non-grazing. However, in the second grazing period in System II, corn residue grazing did not reduce corn residue compared to non-grazing (Table 4.3). Because of snow cover while grazing corn residue in System II, the steers did not attempt to graze the corn residue beneath the snow, so they were removed from the paddocks. It is well known grazing of corn residue and CC reduces biomass from consumption and trampling. Cover crop grazing studies suggest grazing removes around 15 to 75% of CC biomass due to consumption and trampling (Franzluebbers & Stuedemann, 2008; Faé et al., 2009; Schomberg et al., 2014; Blanco-Canqui et al., 2020). Additionally, a review on crop residue grazing found that cattle often remove no more than 30% of crop residue (Rakkar & Blanco-Canqui, 2018). The removal of CC biomass most likely explains the increased soil temperature compared to non-grazed treatments in System II under CC grazing (11.34±0.64 vs. 10.10±1.06 ^{o}C; Table 4.3). However, grazing corn residue in both systems did not impact soil temperature (Table 4.3). It is unclear why corn residue grazing did not increase soil temperature. This could be due to corn residue grazing not significantly decreasing soil cover whereas CC grazing did significantly reduce soil cover (Table 4.3).

Soil Compaction Parameters

Corn residue grazing in both systems had no impact on bulk density, penetration resistance, and initial infiltration rate (Table 4.4). Cover crop grazing in System II, however, increased bulk density by 1.04 times (1.43±0.04 vs 1.38±0.04 Mg m^{-3}; Table 4.4), but this is not above the threshold that might affect root growth (USDA, 2008). Despite the increased bulk density, CC grazing in System II had no impact on penetration resistance and initial infiltration rate. This is not common as penetration resistance is typically a more sensitive compaction parameter than bulk density (Hamza and Anderson, 2005). However, there was a trend of increased penetration resistance (1.26±0.14 vs. 1.06±0.07 MPa) and reduced initial infiltration rate (7.79±2.10 vs 9.15±3.84 cm $sec^{-1/2}$) under CC grazing for System II. Soil conditions at time of grazing and stocking rate may explain the increase in bulk density under CC grazing but not corn residue grazing. Stocking rate was greater for CC grazing (1354 AUD ha^{-1}) than corn residue grazing (716-807 AUD ha^{-1}; Table 4.2). Also, based on visual observation, the soil in the CC plots froze later compared to the corn residue plots. Thus, since the corn residue plots froze before the CC plots, this means the soil was more likely thawed during CC grazing and frozen during at least a portion of corn residue grazing.

Overall, grazing in both systems generally had no impact on soil compaction parameters. Here we will discuss a few factors that may have contributed to grazing having little to no impact on compaction parameters. First, this is a short-term experiment (1-2 yr); therefore, there are little to no accumulated impacts of grazing. A study in Georgia found CC grazing had no impact on bulk density in the short term (<2.5 yr);

however, they did find bulk density slightly increased after 4.5 yr, but the increase was not above the threshold that may affect root growth (Franzluebbers and Stuedemann, 2008). This indicates that our experiment may be too short to pick up longer-term effects of cropland grazing and bulk density. Second, the soils at this site have shrink-swell potential; therefore, natural freeze-thaw and wetting-drying cycles could have alleviated any possible compaction prior to soil sampling (Jabro, Iverson, Evans, Allen, & Stevens, 2013). Other CC grazing studies cite these natural processes as potential mechanisms that may alleviate any compaction from cropland grazing (Faé et al. 2009; Maughan et al., 2009; Bonetti et al., 2019). Third, grazing occurred in the winter in relatively dry conditions (Table 4.1) whereas grazing in the spring or under wet conditions can increase soil compaction (Clark et al, 2004; Schomberg et al., 2014). Fourth, prior to experiment establishment in 2018, this site was managed in a perennial system, so the soil may be more resilient to compaction due to increased root biomass, soil C, and soil biota under perennial systems (DuPont et al., 2010; Balota et al., 2015).

Since compaction can alter soil structure and porosity, water infiltration is a sensitive parameter to animal grazing due to its dependency on soil structure and porosity (Greenwood and McKenzie, 2001). However, in our study, grazing CC and corn residue had no impact on sorptivity, a measure of initial water infiltration rate (Table 4.4). This is most likely because CC and corn residue grazing also had little to no impact on soil compaction (Table 4.4). Our findings are somewhat consistent with other CC grazing studies, which have found variable to no effects of CC grazing on water infiltration (Franzluebbers and Stuedemann, 2008; Blanco-Canqui, et al., 2020). These findings are also similar for crop residue grazing, which generally does not impact soil hydraulic properties (Rakkar and Blanco-Canqui, 2018). Thus, we found no impact on initial water infiltration rate from CC and corn residue grazing in this experiment.

Conclusion

Results from this study under no-till, rainfed conditions suggest that integrating crop with livestock production through CC and corn residue winter grazing had little to no impact on soil bulk density, penetration resistance, and initial water infiltration. However, more research under different soil textures, soil wetness, climate, crop rotations, and tillage systems are needed to better evaluate the impact of crop livestock integration on soil properties. Particularly, long-term research (> 5 yrs) is needed that evaluates the impact of cropland grazing under different stocking rates and densities. Nonetheless, our study results agree with the data from the few previous studies indicating that cattle grazing corn residue and CCs has little to no impact on soil compaction. This suggests crop-livestock integration through CC and corn residue winter grazing can be a viable management practice without largely impacting soil compaction parameters, at least in the short term (1-2 yr).

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Table 4.1. Monthly mean air temperatures (^{o}C) and total precipitation (mm) from 2018 to 2021 at the University of Nebraska's East Campus in Lincoln, NE.

	2018	2019	2020	2021	Monthly Average
Temperature					
-------------------------------^{o}C--------------------------------					
Jan.	-4.61	-3.79	-2.31	-1.83	-3.14
Feb.	-4.31	-6.69	-0.28	-8.54	-4.96
Mar.	4.71	1.55	6.86	8.24	5.34
Apr.	7.10	12.13	9.94	-	-
May	20.87	15.31	15.49	-	-
June	24.99	22.73	25.39	-	-
July	24.88	25.76	25.49	-	-
Aug.	23.94	23.23	23.98	-	-
Sept.	19.94	22.99	18.06	-	-
Oct.	10.13	9.01	9.81	-	-
Nov.	0.99	3.12	6.10	-	-
Dec.	-1.03	-0.15	-1.08	-	-
Annual Average	10.63	10.43	11.45	-	-
Precipitation					
-----------------------------mm--------------------------------					
Jan.	9.14	14.73	32.77	36.07	23.18
Feb.	15.49	27.94	2.79	19.56	16.45
Mar.	67.56	63.25	42.42	132.8	76.51
Apr.	7.11	26.42	19.05	-	-
May	56.64	174.2	116.3	-	-
June	192.0	111.3	78.99	-	-
July	62.48	103.4	146.6	-	-
Aug.	109.2	70.10	32.26	-	-
Sept.	180.1	87.12	40.13	-	-
Oct.	70.61	119.1	9.40	-	-
Nov.	15.49	19.05	30.48	-	-
Dec.	85.09	66.04	27.94	-	-
Annual Average	870.9	882.7	579.1	-	-

Table 4.2. Information on grazing events, steer weights, stocking rates, and average grazing durations for System I and System II in a rainfed no-till experiment in eastern Nebraska. Two steers were used in this experiment and paddock size was 0.0069 ha. To note, grazing did not occur in every year for every system. na, not applicable

Year	**Average Steer Weight (kg)**	**Stocking Rates (animal unit day ha^{-1})**		**Average Grazing Duration (days)**	
		Corn Residue	**Cover Crop**	**Corn Residue**	**Cover Crop**
System I					
2019-2020	499	717	.†	2.25	.†
System II					
2019-2020	499	na	1354	na	4.25
2020-2021	698	807	na	1.81	na

†As per the rotation, there is no cover crop in the rotation of System I.

Table 4.3. Means and standard deviations of cover crop (CC) and corn residue biomass (Mg ha^{-1}), residue cover (%), and soil temperature (°C) for System I and System II in a rainfed no-till experiment in eastern Nebraska. Means with different lowercase letters differ significantly between treatments at $p<0.05$.

Treatment	**CC Biomass**	**Corn Residue Biomass**	**CC Residue Cover**	**Corn Residue Cover**	**Soil Temperature under Corn Residue**	**Soil Temperature under CC**
	-----------Mg ha^{-1}----------		**---------------%---------------**		**-----------------°C------------------**	
System I						
Grazing	.†	8.42±1.33b	.†	82±10.28	10.93±0.50	.†
Non-grazing	.	11.29±1.91a	.	94±2.38	9.90±1.46	.
System II						
Grazing	2.15±1.07b	7.47±1.52	90±2.71b	93±6.40	8.10±0.58	11.34±0.64a
Non-grazing	4.17±1.73a	6.38±1.39	98±2.22a	94±1.71	6.54±1.19	10.10±1.06b

†As per the rotation, there is no cover crop in the rotation of System I.

Table 4.4. Means and standard deviations for bulk density, penetration resistance, and initial infiltration rate in System I and System II for the 0 to 10 cm depth for a cover crop (CC) and corn residue grazing experiment under rainfed no-till in eastern Nebraska. No bulk density data was collected for the 5 to 10 cm soil depth. Means with different lowercase letters differ significantly between treatments at p<0.05. ns, not significant; na, non-applicable

Treatment	**Bulk Density (Mg m^{-3})**		**Penetration Resistance (MPa)**		**Initial Infiltration (cm sec$^{-1/2}$)**	
	Corn Residue	**Cover Crop**	**Corn Residue**	**Cover Crop**	**Corn Residue**	**Cover Crop**
System I						
0-5 cm depth						
Grazing	1.38±0.05ns	.†	0.72±0.11ns	.†	8.93±1.46ns	.†
Non-grazing	1.38±0.06	.	0.81±0.14	.	9.01±2.34	.
5-10 cm depth						
Grazing	-	-	0.98±0.18ns	.†	na	na
Non-grazing	-	-	1.06±0.14	.	na	na
System II						
0-5 cm depth						
Grazing	1.41±0.04ns	1.43±0.04a	0.80±0.13ns	1.26±0.14ns	14.37±4.04ns	7.79±2.10ns
Non-grazing	1.36±0.05	1.38±0.04b	0.80±0.14	1.06±0.07	12.75±3.01	9.15±3.84
5-10 cm depth						
Grazing	-	-	1.28±0.08ns	1.19±0.05ns	na	na
Non-grazing	-	-	1.33±0.21	1.26±0.21	na	na

†As per the rotation, there is no cover crop in the rotation of System I.

CHAPTER 5. Extension Publications

5.1. Does Grazing Cover Crops Negatively Impact Soil and Crop Yields?

Separation of crop and livestock production can degrade soil and other natural resources while reducing economic returns. Additionally, the conversion of grassland to cropland has put a strain on forage for cattle. Grazing cover crops can be a potential option to re-integrate crops with livestock production and reverse the adverse effects of separating crops and livestock production. Grazing cover crops could still maintain the benefits from cover crops as roots and some stubble remain after grazing. Cover crop grazing has shown to improve economic returns (Franzluebbers and Stuedemann, 2007) while still capturing benefits from cover crops (Faé et al., 2009; Maughan et al., 2009); however, soil compaction risks can be a concern.

While there are few studies evaluating cover crop grazing, most of the existing studies found any shallow soil compaction that did occur was not enough to influence yields. Tillage and soil wetness could influence the impact of cover crop grazing on soil compaction. A study under strip tillage in west central Nebraska found that grazing cover crops increased soil compaction in one of three years, but it is possible strip tillage may have alleviated potential compaction in the other two years (Blanco-Canqui, et al., 2020). On the other hand, a study in Georgia found that compaction increased more when grazing under conventional tillage (disk plowing to 6-8 in.) compared to grazing under no-till (Franzluebbers and Stuedemann, 2008). This suggests conservation tillage, such as no till or strip till, could be more beneficial than conventional tillage when grazing cover crops. Another study in Georgia found cover crop grazing in the spring after an above-average rainfall increased soil compaction due to soil wetness and thus reduced cotton yields (Schomberg et al., 2014). Thus, soil wetness is also important to consider when cover crop grazing.

To further improve our understanding of how cover crop grazing may affect soil properties and crop yields, we conducted a study in 2019 and 2020 on a field-scale oat cover crop grazing experiment under an irrigated no-till corn-soybean rotation on silt loam soils in eastern Nebraska. Our results suggest that fall/winter cover crop grazing does not negatively impact soil or crop yields (Figure 1). These results are similar to other fall/winter cover crop grazing studies, but it should also be noted our study only had cover crop following the corn phase of the rotation, thus grazing only occurred every other year, possibly reducing any cumulative impacts of grazing.

Field Management

Our cover crop grazing experiment was established in 2015 at the Eastern Nebraska Research and Education Center near Mead, NE. There were two study fields in this experiment, and each field was 52 acres under center pivot irrigation and no-till. The rotation was corn-soybean, and each field was cut in half and harvested as corn silage in one-half of the field and high moisture corn in the other half of the field. Corn silage was harvested around September 1st and high moisture corn (about 32% moisture) harvested around September 15th, about 25 days before typical dry corn (about 15% moisture) harvest. A cover crop of Horsepower oat was drilled at 96 lbs per acre following corn harvest (Figure 2). Following cover crop planting, the fields received 40 lbs N per acre from ammonium nitrate. No cover crop was planted following soybean harvest.

Cattle Management

Cattle grazed from November to December at stocking rates ranging from 0.6 to 1.7 head per acre, with cattle initial weights ranging from 507 to 553 pounds throughout the study. The stocking rates were calculated based on a target grazing period of 70 days and accounted for cover crop biomass under corn silage and both cover crop biomass plus corn residue amount under high moisture corn. Forage allowance was about 25.6 pounds per steer per day in the first two years and about 39.0 pounds per steer per day in the last three years. Grazing only occurred in late fall/winter following the corn phase of the rotation with grazing durations ranged from 30 to 69 days over the 5 year experiment. Based on the rotation, grazing occurred twice in one field and three times in the other field over a five year period.

Did cover crop grazing damage soils?

Cover crop grazing had no impact on soil compaction, wind or water erosion potential (expressed as wet and dry aggregate stability), water infiltration, water retention, organic matter, particulate organic matter (fraction of organic matter readily accessible to soil microbes), or microbial biomass compared to the non-grazed cover crop (Figure 1). These findings strongly suggest that cover crop grazing does not damage soils.

Why might grazing not impact soils?

It is believed cover crop grazing had no impact on soil compaction in this experiment because:

1) Grazing only occurred after the corn phase of the corn-soybean rotation, which reduced the frequency of grazing (every other year grazing).

2) The experiment was located on soil with high soil organic matter (4.2% within 0 to 8 inches) and soil organic matter can prevent soil compaction.

3) Grazing occurred in late fall when the soil is less likely to be wet compared to spring, with spring having more rainfall.

4) Natural freeze-thaw and wetting-drying soil cycles can naturally break up any potential soil compaction.

Cover crop grazing removed about 47 to 87% of cover crop biomass due to cattle intake and trampling (Figure 3). However, much of the biomass removed was actually incorporated into the soil surface from trampling, retaining cover crop residue within the system. Additionally, cattle intake removes little nutrients from the system, as cattle excrete most of the nutrients consumed during grazing. For these reasons above, we believe cover crop grazing in this study may have had no negative impact on soil properties due to the addition of trampled cover crop aboveground biomass, cover crop root biomass, and infrequency of grazing (every other year).

Did cover crop grazing impact crop yields?

Cover crop grazing had no impact on soybean or corn yields (Figure 1), which is similar to previous cover crop grazing experiments. Only two studies report yield decreases from cover crop grazing during wet soil conditions in spring (Schomberg et al. 2014) or increased soil water evaporation from summer cover crop grazing reducing residue cover (Franzluebbers and Stuedemann, 2007). Our study site was irrigated and grazed in fall/winter.

Should I graze my cover crops?

- In this study, cover crop grazing had no impact on soil compaction, wind or water erosion potential, water infiltration, water retention, organic matter, particulate organic matter, or microbial biomass compared to the non-grazed cover crop. Therefore, based on the conditions of this study, fall/winter cover crop grazing had no negative impacts on soil properties. Additionally, cover crop grazing had no impact on crop yields.
- In previous studies, cover crop grazing can have some impact on soil compaction, depending on tillage system and soil conditions at time of grazing. Based on what little research is available, it is suggested conservation tillage, such as no till or strip till, may prevent possible accumulated impacts of compaction, but conventional tillage should be avoided.
- Based on our experiment and others, cover crop grazing could be a strategy to re-integrate crop and livestock production without largely degrading soil properties or impacting crop yields.

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Additional Resources

Soil impacts of planting oats after corn silage and high moisture corn (https://youtu.be/t9QfXrYAJig)

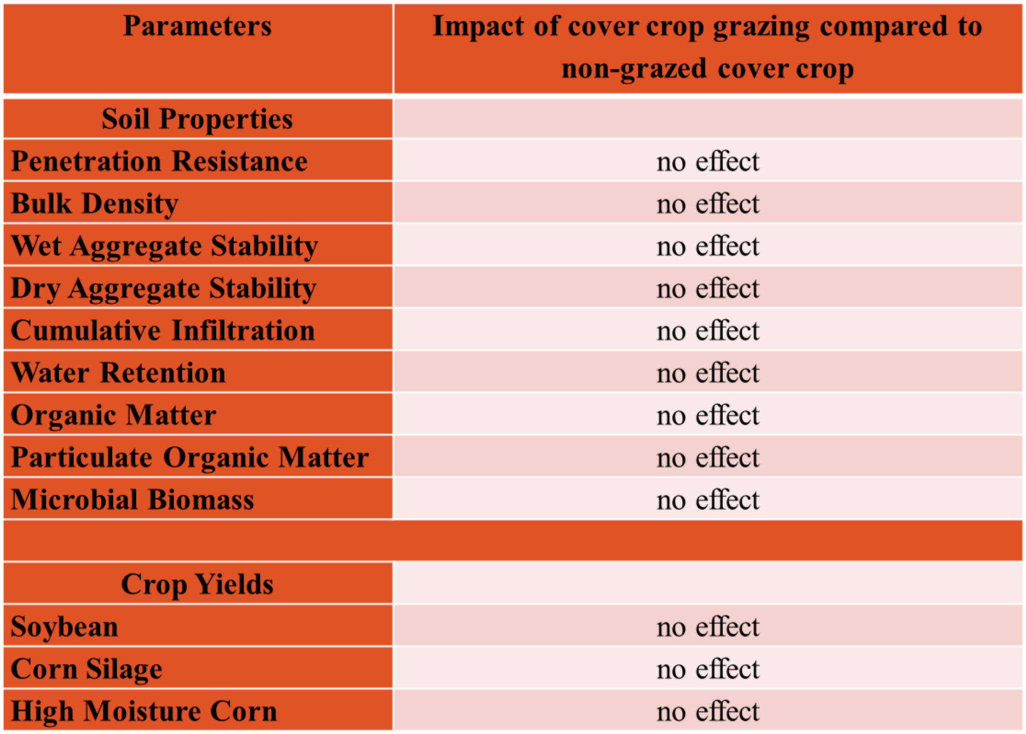
Grazing potential and economics of planting oats after corn silage and high moisture corn (https://youtu.be/oGnbI5tPdSE)

Cover crop grazing: impacts on soils and crop yields (https://cropwatch.unl.edu/2019/cover-crop-grazing-impacts-soils-and-crop-yields)

Double-cropped cool-season annuals (cover crops) for late fall and early spring forage (https://beef.unl.edu/double-cropped-cool-season-annuals)

Effects and economics of grazing cover crops in a three-year non-irrigated rotation (https://cropwatch.unl.edu/2021/effects-and-economics-grazing-cover-crops-three-year-non-irrigated-rotation)

Check herbicide restrictions before planting and using cover crops (https://cropwatch.unl.edu/2019/check-herbicide-restrictions-planting-and-using-cover-crops)



Parameters	**Impact of cover crop grazing compared to non-grazed cover crop**
Soil Properties	
Penetration Resistance	no effect
Bulk Density	no effect
Wet Aggregate Stability	no effect
Dry Aggregate Stability	no effect
Cumulative Infiltration	no effect
Water Retention	no effect
Organic Matter	no effect
Particulate Organic Matter	no effect
Microbial Biomass	no effect
Crop Yields	
Soybean	no effect
Corn Silage	no effect
High Moisture Corn	no effect

Figure 5.1.1. Summary table of soil and crop response to cover crop grazing compared to non-grazed cover crop. Penetration resistance and bulk density are soil compaction parameters. Wet and dry aggregate stability are indicators of water and wind erosion. Particulate organic matter is the fraction of organic matter readily accessible for soil microbes to use.

Figure 5.1.2. Oat cover crop biomass in October compared to the no cover crop control for high moisture corn (left) and corn silage (right). (Photos by Mary Drewnoski)

Figure 5.1.3. Cattle grazing oat cover crop and corn residue in November following high moisture corn (left) and grazing cover crop following corn silage (right). Grazing reduced cover crop biomass by 47 to 87% under corn silage. Grazing reduced cover crop biomass by 64 to 87% and reduced corn residue by 18 to 23% under high moisture corn. (Photos by McKenna Brinton)

5.2. Can Cover Crops Offset the Negative Impacts of Corn Silage?

Corn harvested as corn silage is used as feed for cattle. However, harvesting corn for silage removes nearly all aboveground biomass (Figure 1), and this can be detrimental to soil. In this experiment, compared to high moisture corn, corn silage increased soil compaction and wind and water erosion potential (expressed as dry and wet aggregate stability) while reducing water retention, organic matter fractions, and microbial biomass (Figure 2). Despite degrading most near-surface soil properties, corn silage did not negatively impact subsequent soybean yields (Figure 2). Our study site was irrigated and had soils with high organic matter concentration (4.2% in the upper 8 inches), possibly offsetting the potential for yield decreases under corn silage, despite the negative impact of corn silage on soil properties.

Published studies show that winter rye cover crops can offset adverse effects of corn silage harvest by increasing organic matter fractions and microbial biomass, improving soil structure, reducing erosion, scavenging N, and increasing water movement in the soil (Faé et al., 2009; Krueger et al., 2011; Liesch et al, 2011; Moore et al., 2014; Ketterings et al., 2015). However, in our experiment, except for an increase in microbial biomass, the oat cover crop did not offset the negative effects of corn silage. This could be because our experiment used a winterkill cover crop of oat planted every other year, which may have limited cover crop benefits.

Field Management

This study site was established in 2015 at the Eastern Nebraska Research and Education Center near Mead, NE. This experiment had two study fields (Field I and Field II), and each was 52 acres under center pivot irrigation with no-till and a corn-soybean rotation. During the corn phase, each field was cut in half, with half of the field harvested as corn silage around September 1st and the other half of the field harvested as high moisture corn (32% moisture) around September 15th. Following corn harvest, a cover crop of Horsepower oat was drilled at 96 lbs per acre and received 40 lbs N per acre from ammonium nitrate.

How did corn silage impact soil properties and crop yields?

Compaction

Corn silage increased penetration resistance (soil compaction parameter) at both the 0 to 2 and 2 to 4 inches depth. However, values did not increase above what would restrict root growth. Additionally, in one field at the 2 to 4 inches depth, corn silage increased bulk density (compaction parameter) compared to high moisture corn. These results are expected as corn silage harvest requires additional machinery and passes in the field. Also, soil organic matter can buffer against compaction, but corn silage reduced organic matter concentration near the soil surface.

Organic Matter Fractions

For the 0 to 2 inches soil depth, corn silage reduced soil organic matter and particulate organic matter. Particulate organic matter is the fraction of soil organic matter that is readily accessible for microbes to use. In Field I, soil organic matter concentration was 4.6% under high moisture corn and 4.1% under corn silage. In Field II, soil organic matter was 5.5% under high moisture corn and 4.5% under corn silage. There were no significant differences in organic matter fractions at the 2 to 8 inches depth.

Erosion

Wind erosion potential was expressed as dry aggregate stability and water erosion potential was expressed as wet aggregate stability. Compared to high moisture corn, corn silage increased wind erosion potential, most likely due to the reduced residue cover (Figure 1 and 4). At the 0 to 2 inches depth, corn silage reduced wet aggregate stability, which is a parameter of soil structure. Degraded soil structure (Figure 3), represented as wet aggregate stability, can increase soil water erosion risks. Organic matter and soil microbial biomass are known to improve soil structure and aggregation by building and maintaining soil aggregates. Thus, the degradation of soil structure for the 0 to 2 inches soil depth could be due to the reduction in soil organic matter concentration and microbial biomass for this same depth.

Soil Water

Corn silage also reduced soil water content compared to high moisture corn, most likely due to reduced residue cover (Figure 1), thus increasing soil water evaporation. Additionally, while corn silage had no impact on water infiltration, corn silage did reduce water retention compared to high moisture corn in one of the two fields. This is most likely due to corn silage-induced reduction in soil organic matter concentration, reduction in soil porosity (increased bulk density), and reduction in soil aggregate stability, among others.

Soil Biology

Compared to high moisture corn, corn silage significantly reduced soil microbial biomass for the 0 to 2 and 2 to 4 inches soil depth. This is concerning, as soil microorganisms are critical to the health of the soil as they mediate many soil functions and processes, including decomposition of plant residues, cycling of nutrients, and binding soil aggregates to improve soil structure, which can improve water infiltration and resist against compaction and erosion.

Crop Yields

Despite the multiple negative impacts of corn silage on soil physical, chemical, and biological properties, corn silage had no negative impact on subsequent soybean yields (Figure 2). One would expect with the large negative impacts corn silage had on soil properties that crop yields would be reduced. However, this study was conducted on deep loess soils of eastern Nebraska, which are known for their inherent fertility and high soil organic matter concentration. Therefore, the soil at this study site may have prevented yield losses following corn silage. This study site was also irrigated, so despite the reduced residue cover under corn silage increasing soil evaporation and leading to soil water loss, irrigation probably offset these losses and potential yield reductions. Other soil types and management practices may show different results under corn silage harvest, but because this study site is irrigated and has overall high soil organic matter content, we believe these factors may have offset any potential reductions in yield due to corn silage.

Did the cover crop offset the negative impacts of corn silage?

The oat cover crop did little to overcome the negative impacts of corn silage; however, corn silage with cover crop had greater microbial biomass than corn silage without cover crop (Figure 2). This is most likely due to the increased above and belowground cover crop biomass to support soil microorganisms. This is promising as soil microorganisms mediate many processes and functions in the soil, as discussed above. Additionally, from observation, the oat cover crop appeared to prevent erosion during its growth (Figure 4). We believe our study found little to no impact of the oat cover crop because it was only planted every other year and is winterkilled. Thus, winterkilled cover crops are unlikely to produce biomass similar to cover crops that overwinter. Previous studies that found benefits of cover cropping with corn silage used winter rye, a cover crop that overwinters. However, an oat cover crop was chosen for our study for high biomass production in the fall with no need to terminate it in the spring.

Should cover crops be used with corn silage?

- Our study found oat cover crop after corn silage harvest increased microbial biomass but did not impact other soil properties. However, other research using a winter rye cover crop after corn silage found that rye can offset damaging impacts of corn silage. In our experiment, the oat cover crop was winterkilled, possibly limiting the beneficial impact of the cover crop to offset corn silage impacts.
- Based on visual observations, the oat cover crop did reduce erosion during its growth period by covering and protecting the soil surface (Figure 4) although changes in soil aggregate stability were not significant.
- The choice of cover crop is critical and must fit the goals of your farming system, but longer live cover crop growth periods, like with cover crops that overwinter, can be beneficial.
- The silt loam loess soils of eastern Nebraska are highly erodible, as indicated in this study (Figure 1, 2, and 4). Also, a recent study of the US Corn Belt, including eastern Nebraska, found that we have lost around 35% of our topsoil, which results in around 2.8 billion dollars of economic loss annually (Thaler et al., 2021). Therefore, with corn silage harvest leaving the soil bare of residue cover (Figure 1 and 4), the hidden costs of soil erosion cannot be understated. Thus, a cover crop following corn silage can be recommended to ameliorate the negative effects of corn silage. Specifically, a cover crop that overwinters can protect the soil in the spring when winds and rainfall amount are high before main crops are established.

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Additional Resources

Planting cover crops after silage offers several benefits

(https://cropwatch.unl.edu/2017/planting-cover-crops-after-silage-offers-several-benefits)

Harvesting crop residues NebGuide

(https://extensionpublications.unl.edu/assets/pdf/g1846.pdf)

Consider nutrient removal and ground cover costs when harvesting corn for silage

(https://cropwatch.unl.edu/consider-nutrient-removal-and-ground-cover-costs-when-harvesting-corn-silage-aug-10-2012)

Figure 5.2.1. Residue cover under high moisture corn (left) and corn silage (right) during soil sampling in late spring. Residue cover remaining on the soil surface from high moisture corn harvest helps to intercept the impact of raindrops, slow the speed of runoff, and protect the soil surface from erosion, unlike the visible signs of erosion in corn silage (right). Additionally, surface residue can contribute to soil nutrients, structure and infiltration, organic matter, and feed for soil microbes.

Parameter	Impact of silage compared to high moisture corn	Impact of silage with cover crop compared to silage without cover crop
Soil Properties		
Penetration Resistance	Increased	no effect
Bulk Density	Increased	no effect
Wet Aggregate Stability	Reduced	no effect
Dry Aggregate Stability	Increased	no effect
Cumulative Infiltration	no effect	no effect
Water Retention	Reduced	no effect
Organic Matter	Reduced	no effect
Particulate Organic Matter	Reduced	no effect
Microbial Biomass	Reduced	Increased
Crop Yields		
Soybean	no effect	no effect

Figure 5.2.2. Summary table of soil and crop response of corn silage compared to high moisture corn and corn silage with oat cover crop compared to corn silage with no oat cover crop. Differences occurred at the 0 to 2 inches soil depth, except for penetration resistance, particulate organic matter, and microbial biomass, which were different in the 0 to 4 inches depth and bulk density, which was only impacted at the 2 to 4 inches depth. Penetration resistance and bulk density are soil compaction parameters. Wet and dry aggregate stability are indicators of water and wind erosion. Particulate organic matter is the fraction of organic matter readily accessible for soil microbes to use.

Figure 5.2.3. Soil aggregates of high moisture corn (left) and corn silage (right). High moisture corn harvest retains residue on the soil surface, protecting the soil from erosion and compaction, which can break apart soil aggregates and destroy soil structure.

Figure 5.2.4. Corn silage with no oat cover crop (left) compared to corn silage with oat cover crop (right). Photo taken in October. Cover crops help to intercept the impact of raindrops, slow the speed of runoff, and protect the soil surface from erosion while acting as a food source for soil microorganisms, unlike the visible signs of erosion from no cover crop (left). (photo taken by Dr. Mary Drewnoski)

CHAPTER 6. Conclusions and Remaining Questions

Conclusions

This study was conducted to better understand the impact of cover crop (CC) and corn residue grazing on soils and crop yields in eastern Nebraska. The key conclusions of this study are:

1. In the medium-term experiment, CC grazing did not impact soil physical, chemical, or biological properties or crop yields compared to non-grazed CC.
2. Corn silage negatively affected soil properties but not crop yields compared to high moisture corn.
3. Cover crop generally did not offset the adverse effects of corn silage on most soil properties.
4. In the short-term experiment, CC and corn residue grazing generally did not impact soil compaction or initial water infiltration.
5. Cover crop and corn residue grazing can be a strategy to re-integrate crop and livestock production to move toward a more agroecological approach to modern agriculture.

In our studies, CC grazing generally had no impact on soil and crop production. In previous studies, CC grazing can have some impact on soil compaction, depending on tillage system and soil conditions at time of grazing. Based on what little research is available, if CC grazing ever year, conservation tillage may prevent possible accumulated impacts of compaction, but conventional tillage should be avoided. Additionally, if possible, it is not advised to graze CCs under wet soil conditions. This is particularly of concern if grazing occurs in spring when soils are normally wet. Based on our experiment and others, CC grazing could be a strategy to re-integrate crop and livestock production without largely degrading soil properties or impacting crop yields.

Remaining Questions

This thesis project provided valuable information into the impacts of cover crop (CC) and corn residue grazing on soil and crop production. However, more research is needed as suggested below:

1. Long term (>5 yr) studies to evaluate the possible accumulated impacts of CC and corn residue grazing on soil properties.
2. More research on the impact of CC and corn residue grazing on soil properties across different climate regions, soil types, and management practices.
3. Research to evaluate how CC and corn residue grazing stocking rate and density impact soil and crop production. Stocking density and CC grazing studies are especially lacking in temperate climates. In addition, published information should report stocking rates and densities.
4. In CC and corn residue grazing experiments, care needs to be taken to record soil conditions during grazing. This includes soil water content and temperature. Soil conditions at time of grazing can play a critical role in how CC and corn residue grazing impacts soil properties and subsequent yields.
5. While research of CC grazing impacts on soil compaction is necessary, research is lacking on CC grazing impacts on soil physical properties beyond compaction.

Further, CC grazing impacts on soil fertility and biological properties is also lacking.

6. More studies with a comprehensive economic analysis of CC and corn residue grazing across regions and management practices.
7. Natural cycles (freeze-thaw and wet-dry) need more research to evaluate their possible interactions with soil properties and CC and corn residue grazing.
8. More research on the cattle response to CC grazing and CC mixes to maximize biomass growth and cattle nutritional needs.
9. More interdisciplinary and transdisciplinary research is needed that incorporates agricultural economists, animal scientists, plant scientists, soil scientists, social scientists, and producers.
10. Investigations into the social drivers behind CC and corn residue grazing are needed. Understanding the social aspect is critical to attempt to address the decision-making process of why producers may or may not adopt CC and corn residue grazing. Producer input and surveys in addition to focus groups of producers, stakeholders, and policy makers would be beneficial to identify and address knowledge gaps and better understand the social aspect of CC and corn residue grazing decision-making.

Appendices

Appendix A. East Campus Grazing Experiment Plot and Treatment Numbers

Plot	Treatment	Sequence
101	1	C+S
102	2	S+C
103	5	W+C+S (w/M)
104	3	C+S+W (w/M)
105	4	S+W+C (w/M)
106	6	W+C+S
201	4	S+W+C (w/M)
202	5	W+C+S (w/ M)
203	1	C+S
204	2	S+C
205	6	W+C+S
206	3	C+S+W (w/M)
301	2	S+C
302	3	C+S+W (w/M)
303	6	W+C+S
304	5	W+C+S (w/M)
305	1	C+S
306	4	S+W+C (w/M)
401	5	W+C+S (w/ M)
402	3	C+S+W (w/M)
403	1	C+S
404	4	S+W+C (w/M)
405	6	W+C+S
406	2	S+C

Appendix B. East Campus Grazing Experiment Penetration Resistance

Date	Depth (cm)	Plot	Trt	Rep	Grazed (GR)/Non-grazed (NG)	Hoof (H)/No hoof (NH)	Penetration Resistance (MPa)	Gravimetric Water Content (g/g)
June '19	0-5	101	1	1	GR	H	3.10	0.15
June '19	0-5	101	1	1	GR	NH	1.51	0.15
June '19	0-5	101	1	1	NG	NH	2.50	0.25
June '19	0-5	103	5	1	GR	H	2.38	0.17
June '19	0-5	103	5	1	GR	NH	3.55	0.17
June '19	0-5	103	5	1	NG	NH	2.33	0.20
June '19	0-5	104	3	1	GR	H	3.48	0.15
June '19	0-5	104	3	1	GR	NH	2.83	0.15
June '19	0-5	104	3	1	NG	NH	3.49	0.17
June '19	0-5	106	6	1	GR	H	2.45	0.13
June '19	0-5	106	6	1	GR	NH	3.04	0.13
June '19	0-5	106	6	1	NG	NH	1.89	0.16
June '19	0-5	202	5	2	GR	H	3.99	0.18
June '19	0-5	202	5	2	GR	NH	3.30	0.18
June '19	0-5	202	5	2	NG	NH	3.64	0.20
June '19	0-5	203	1	2	GR	H	2.74	0.10
June '19	0-5	203	1	2	GR	NH	3.68	0.10
June '19	0-5	203	1	2	NG	NH	1.91	0.24
June '19	0-5	205	6	2	GR	H	4.62	0.12
June '19	0-5	205	6	2	GR	NH	3.86	0.12
June '19	0-5	205	6	2	NG	NH	2.57	0.16
June '19	0-5	206	3	2	GR	H	3.02	0.17
June '19	0-5	206	3	2	GR	NH	3.93	0.17
June '19	0-5	206	3	2	NG	NH	2.35	0.18
June '19	0-5	302	3	3	GR	H	2.93	0.14
June '19	0-5	302	3	3	GR	NH	2.18	0.14
June '19	0-5	302	3	3	NG	NH	2.30	0.20
June '19	0-5	303	6	3	GR	H	2.51	0.13
June '19	0-5	303	6	3	GR	NH	3.09	0.13
June '19	0-5	303	6	3	NG	NH	1.88	0.12
June '19	0-5	304	5	3	GR	H	3.84	0.16
June '19	0-5	304	5	3	GR	NH	3.56	0.16
June '19	0-5	304	5	3	NG	NH	1.94	0.16
June '19	0-5	305	1	3	GR	H	1.07	0.16
June '19	0-5	305	1	3	GR	NH	1.54	0.16

June '19	0-5	305	1	3	NG	NH	2.38	0.24
June '19	0-5	401	5	4	GR	H	1.96	0.17
June '19	0-5	401	5	4	GR	NH	1.57	0.17
June '19	0-5	401	5	4	NG	NH	2.88	0.22
June '19	0-5	402	3	4	GR	H	2.77	0.18
June '19	0-5	402	3	4	GR	NH	3.43	0.18
June '19	0-5	402	3	4	NG	NH	2.59	0.27
June '19	0-5	403	1	4	GR	H	2.47	0.17
June '19	0-5	403	1	4	GR	NH	1.28	0.17
June '19	0-5	403	1	4	NG	NH	3.31	0.27
June '19	0-5	405	6	4	GR	H	3.52	0.16
June '19	0-5	405	6	4	GR	NH	1.77	0.16
June '19	0-5	405	6	4	NG	NH	1.47	0.15
June '19	5-10	101	1	1	GR	H	1.82	0.24
June '19	5-10	101	1	1	GR	NH	1.69	0.24
June '19	5-10	101	1	1	NG	NH	3.35	0.30
June '19	5-10	103	5	1	GR	H	4.04	0.21
June '19	5-10	103	5	1	GR	NH	1.65	0.21
June '19	5-10	103	5	1	NG	NH	3.18	0.23
June '19	5-10	104	3	1	GR	H	2.20	0.22
June '19	5-10	104	3	1	GR	NH	2.16	0.22
June '19	5-10	104	3	1	NG	NH	1.84	0.21
June '19	5-10	106	6	1	GR	H	1.75	0.20
June '19	5-10	106	6	1	GR	NH	1.69	0.20
June '19	5-10	106	6	1	NG	NH	1.78	0.18
June '19	5-10	202	5	2	GR	H	2.05	0.24
June '19	5-10	202	5	2	GR	NH	1.20	0.24
June '19	5-10	202	5	2	NG	NH	2.64	0.19
June '19	5-10	203	1	2	GR	H	4.27	0.21
June '19	5-10	203	1	2	GR	NH	2.47	0.21
June '19	5-10	203	1	2	NG	NH	1.28	0.23
June '19	5-10	205	6	2	GR	H	3.28	0.17
June '19	5-10	205	6	2	GR	NH	3.31	0.17
June '19	5-10	205	6	2	NG	NH	3.52	0.18
June '19	5-10	206	3	2	GR	H	1.50	0.24
June '19	5-10	206	3	2	GR	NH	1.77	0.24
June '19	5-10	206	3	2	NG	NH	1.47	0.19
June '19	5-10	302	3	3	GR	H	1.53	0.22
June '19	5-10	302	3	3	GR	NH	1.82	0.22
June '19	5-10	302	3	3	NG	NH	1.69	0.24

June '19	5-10	303	6	3	GR	H	2.44	0.22
June '19	5-10	303	6	3	GR	NH	3.35	0.22
June '19	5-10	303	6	3	NG	NH	4.04	0.17
June '19	5-10	304	5	3	GR	H	2.23	0.25
June '19	5-10	304	5	3	GR	NH	1.65	0.25
June '19	5-10	304	5	3	NG	NH	3.18	0.13
June '19	5-10	305	1	3	GR	H	1.29	0.22
June '19	5-10	305	1	3	GR	NH	2.20	0.22
June '19	5-10	305	1	3	NG	NH	2.16	0.28
June '19	5-10	401	5	4	GR	H	1.64	0.22
June '19	5-10	401	5	4	GR	NH	1.84	0.22
June '19	5-10	401	5	4	NG	NH	1.75	0.26
June '19	5-10	402	3	4	GR	H	1.36	0.22
June '19	5-10	402	3	4	GR	NH	1.69	0.22
June '19	5-10	402	3	4	NG	NH	1.78	0.25
June '19	5-10	403	1	4	GR	H	1.27	0.27
June '19	5-10	403	1	4	GR	NH	2.05	0.27
June '19	5-10	403	1	4	NG	NH	1.20	0.28
June '19	5-10	405	6	4	GR	H	1.98	0.21
June '19	5-10	405	6	4	GR	NH	2.64	0.21
June '19	5-10	405	6	4	NG	NH	4.27	0.20

Appendix C. East Campus Grazing Experiment Bulk Density and Water Retention VWC, volumetric water content; PAW, plant available water

Date	Depth (cm)	Plot	Trt	Rep	Grazed (GR) /Non-grazed (NGR)	Hoof (H)/ No Hoof (NH)	Bulk Density (g/cm3)	VWC -.33 bar (cm3/ cm3)	VWC -15 bar (cm3/ cm3)	PAW
June '19	0-5	101	1	1	GR	NH	1.18	0.28	0.23	0.04
June '19	0-5	101	1	1	NGR	-	1.16	0.28	0.21	0.07
June '19	0-5	101	1	1	NGR	-	1.19	0.34	0.21	0.13
June '19	0-5	101	1	1	GR	H	1.11	0.32	0.22	0.10
June '19	0-5	101	1	1	GR	H	1.14	0.33	0.20	0.13
June '19	0-5	101	1	1	GR	NH	1.12	0.34	0.22	0.12
June '19	0-5	103	5	1	NGR	-	1.33	0.29	0.23	0.06
June '19	0-5	103	5	1	GR	NH	1.16	0.29	0.20	0.09
June '19	0-5	103	5	1	GR	NH	0.99	0.35	0.20	0.16
June '19	0-5	103	5	1	GR	H	1.12	0.31	0.16	0.16
June '19	0-5	103	5	1	NGR	-	1.18	0.30	0.20	0.10
June '19	0-5	103	5	1	GR	H	1.04	0.30	0.17	0.13
June '19	0-5	104	3	1	GR	H	1.21	0.33	0.06	0.27
June '19	0-5	104	3	1	GR	NH	1.22	0.27	0.23	0.04
June '19	0-5	104	3	1	GR	NH	1.26	0.28	0.20	0.07
June '19	0-5	104	3	1	NGR	-	1.25	0.29	0.19	0.10
June '19	0-5	104	3	1	GR	H	1.19	0.29	0.22	0.07
June '19	0-5	104	3	1	NGR	-	1.15	0.25	0.19	0.06
June '19	0-5	106	6	1	GR	NH	1.30	0.32	0.21	0.11
June '19	0-5	106	6	1	NGR	-	1.30	0.27	0.21	0.06
June '19	0-5	106	6	1	GR	H	1.06	0.34	0.16	0.19
June '19	0-5	106	6	1	NGR	-	1.36	0.28	0.23	0.06
June '19	0-5	106	6	1	GR	H	1.22	0.32	0.18	0.14
June '19	0-5	106	6	1	GR	NH	1.35	0.31	0.24	0.08
June '19	0-5	202	5	2	GR	H	1.08	0.37	0.18	0.19
June '19	0-5	202	5	2	NGR	-	1.45	0.30	0.20	0.11
June '19	0-5	202	5	2	GR	H	1.19	0.35	0.22	0.13
June '19	0-5	202	5	2	GR	NH	1.30	0.31	0.23	0.08
June '19	0-5	202	5	2	NGR	-	1.41	0.28	0.22	0.06
June '19	0-5	202	5	2	GR	NH	1.30	0.30	0.20	0.10
June '19	0-5	203	1	2	GR	H	1.09	0.31	0.18	0.14
June '19	0-5	203	1	2	NGR	-	1.28	0.29	0.18	0.11
June '19	0-5	203	1	2	NGR	-	1.18	0.25	0.17	0.08
June '19	0-5	203	1	2	GR	NH	1.28	0.32	0.24	0.08

June '19	0-5	203	1	2	GR	NH	1.30	0.27	0.20	0.06
June '19	0-5	203	1	2	GR	H	1.16	0.29	0.19	0.10
June '19	0-5	205	6	2	NGR	-	1.35	0.25	0.20	0.05
June '19	0-5	205	6	2	GR	NH	1.24	0.32	0.23	0.09
June '19	0-5	205	6	2	NGR	-	1.30	0.29	0.18	0.11
June '19	0-5	205	6	2	GR	H	1.20	0.28	0.20	0.08
June '19	0-5	205	6	2	GR	H	1.08	0.38	0.20	0.18
June '19	0-5	205	6	2	GR	NH	1.18	0.28	0.18	0.11
June '19	0-5	206	3	2	NGR	-	1.31	0.30	0.23	0.07
June '19	0-5	206	3	2	GR	NH	1.39	0.28	0.25	0.03
June '19	0-5	206	3	2	GR	H	1.30	0.29	0.24	0.05
June '19	0-5	206	3	2	GR	H	1.26	0.26	0.20	0.06
June '19	0-5	206	3	2	GR	NH	1.29	0.29	0.20	0.09
June '19	0-5	206	3	2	NGR	-	1.35	0.28	0.19	0.09
June '19	0-5	302	3	3	GR	NH	1.36	0.27	0.21	0.06
June '19	0-5	302	3	3	GR	H	1.29	0.27	0.23	0.04
June '19	0-5	302	3	3	NGR	-	1.11	0.26	0.21	0.04
June '19	0-5	302	3	3	NGR	-	1.34	0.28	0.24	0.04
June '19	0-5	302	3	3	GR	NH	1.35	0.25	0.22	0.03
June '19	0-5	302	3	3	GR	H	1.26	0.26	0.19	0.07
June '19	0-5	303	6	3	NGR	-	1.34	0.23	0.23	0.00
June '19	0-5	303	6	3	GR	NH	1.37	0.26	0.19	0.06
June '19	0-5	303	6	3	GR	H	1.29	0.26	0.19	0.07
June '19	0-5	303	6	3	NGR	-	1.37	0.28	0.24	0.04
June '19	0-5	303	6	3	GR	NH	1.34	0.27	0.23	0.04
June '19	0-5	303	6	3	GR	H	1.14	0.24	0.18	0.06
June '19	0-5	304	5	3	GR	NH	1.23	0.28	0.21	0.07
June '19	0-5	304	5	3	GR	H	1.38	0.29	0.25	0.04
June '19	0-5	304	5	3	GR	NH	1.09	0.24	0.19	0.05
June '19	0-5	304	5	3	NGR	-	1.32	0.29	0.24	0.05
June '19	0-5	304	5	3	NGR	-	1.21	0.31	0.23	0.08
June '19	0-5	304	5	3	GR	H	1.01	0.26	0.19	0.07
June '19	0-5	305	1	3	NGR	-	1.29	0.30	0.24	0.06
June '19	0-5	305	1	3	NGR	-	1.31	0.31	0.24	0.07
June '19	0-5	305	1	3	GR	H	1.32	0.28	0.23	0.05
June '19	0-5	305	1	3	GR	NH	1.32	0.29	0.30	-0.01
June '19	0-5	305	1	3	GR	NH	1.22	0.27	0.21	0.05
June '19	0-5	305	1	3	GR	H	1.21	0.28	0.22	0.06
June '19	0-5	401	5	4	NGR	-	1.24	0.29	0.22	0.08
June '19	0-5	401	5	4	NGR	-	1.10	0.34	0.17	0.17

June '19	0-5	401	5	4	GR	H	1.05	0.26	0.20	0.06
June '19	0-5	401	5	4	GR	NH	1.19	0.27	0.22	0.06
June '19	0-5	401	5	4	GR	H	1.35	0.31	0.25	0.06
June '19	0-5	401	5	4	GR	NH	1.16	0.28	0.21	0.06
June '19	0-5	402	3	4	NGR	-	1.23	0.30	0.24	0.06
June '19	0-5	402	3	4	NGR	-	1.32	0.31	0.25	0.06
June '19	0-5	402	3	4	GR	NH	1.17	0.28	0.22	0.06
June '19	0-5	402	3	4	GR	NH	1.15	0.28	0.21	0.07
June '19	0-5	402	3	4	GR	H	1.03	0.32	0.21	0.11
June '19	0-5	402	3	4	GR	H	0.93	0.29	0.14	0.14
June '19	0-5	403	1	4	GR	NH	1.25	0.32	0.25	0.06
June '19	0-5	403	1	4	GR	H	1.04	0.29	0.21	0.09
June '19	0-5	403	1	4	GR	H	1.04	0.32	0.23	0.09
June '19	0-5	403	1	4	NGR	-	1.30	0.26	0.25	0.01
June '19	0-5	403	1	4	NGR	-	1.23	0.31	0.23	0.07
June '19	0-5	403	1	4	GR	NH	1.26	0.31	0.28	0.02
June '19	0-5	405	6	4	GR	H	1.17	0.30	0.25	0.04
June '19	0-5	405	6	4	NGR	-	1.31	0.29	0.24	0.05
June '19	0-5	405	6	4	GR	H	1.15	0.29	0.22	0.07
June '19	0-5	405	6	4	NGR	-	1.35	0.31	0.24	0.07
June '19	0-5	405	6	4	GR	NH	1.16	0.29	0.19	0.10
June '19	0-5	405	6	4	GR	NH	1.10	0.29	0.22	0.07

Appendix D. East Campus Grazing Experiment Physical and Chemical Properties

MWD, mean weight diameter; POM, particulate organic matter; OM, organic matter

Date	Depth (cm)	Plot	Rep	Trt	Grazed (GR)/ Non-grazed (NG)	Cover (%)	Erodible Fraction (kg/kg)	MWD (mm)	Total N (%)	Total C (%)	Coarse POM (g/kg)	Fine POM (g/kg)	Total POM (g/kg)	OM (%)
June '19	0-5	101	1	1	GR	41	0.42	1.25	0.23	2.31	3.64	9.92	13.56	4.3
June '19	0-5	101	1	1	NG	72	0.21	1.12	0.27	2.84	6.57	19.05	25.62	5.8
June '19	0-5	103	1	5	GR	5	0.38	1.42	0.26	2.78	10.97	12.30	23.27	5.2
June '19	0-5	103	1	5	NG	12	0.36	1.35	0.29	3.41	12.32	14.65	26.97	5.9
June '19	0-5	104	1	3	GR	39	0.33	1.64	0.24	3.13	5.95	11.57	17.53	4.8
June '19	0-5	104	1	3	NG	57	0.32	0.72	0.21	2.27	2.66	8.30	10.96	4.2
June '19	0-5	106	1	6	GR	37	0.50	0.80	0.20	2.10	4.00	14.32	18.32	4.1
June '19	0-5	106	1	6	NG	54	0.36	1.51	0.21	2.23	3.63	9.25	12.88	4.2
June '19	0-5	202	2	5	GR	5	0.30	1.44	0.23	2.49	12.29	11.96	24.25	4.6
June '19	0-5	202	2	5	NG	3	0.23	1.13	0.22	2.38	6.29	8.93	15.22	4.3
June '19	0-5	203	2	1	GR	22	0.51	1.78	0.22	2.33	5.95	9.92	15.87	4.3
June '19	0-5	203	2	1	NG	55	0.21	0.87	0.21	2.31	3.95	11.86	15.82	4.4
June '19	0-5	205	2	6	GR	4	0.44	1.16	0.21	2.23	2.99	7.31	10.31	4.1
June '19	0-5	205	2	6	NG	57	0.34	1.14	0.22	2.29	2.66	9.98	12.64	4.3
June '19	0-5	206	2	3	GR	26	0.32	1.25	0.23	2.44	4.61	9.87	14.47	4.7
June '19	0-5	206	2	3	NG	57	0.27	1.03	0.20	2.05	2.32	8.62	10.94	4
June '19	0-5	302	3	3	GR	21	0.32	1.17	0.19	2.09	4.64	9.95	14.59	4
June '19	0-5	302	3	3	NG	61	0.15	0.99	0.20	2.19	5.94	11.55	17.49	4.1
June '19	0-5	303	3	6	GR	0	0.37	1.14	0.20	2.19	4.29	8.90	13.19	3.6
June '19	0-5	303	3	6	NG	16	0.47	1.10	0.20	2.14	4.31	8.62	12.93	4
June '19	0-5	304	3	5	GR	0	0.30	1.40	0.28	3.12	22.26	14.29	36.54	6.3
June '19	0-5	304	3	5	NG	8	0.23	1.97	0.28	3.22	28.17	17.24	45.41	6.4

June '19	0-5	305	3	1	GR	27	0.25	1.79	0.22	2.42	9.98	12.31	22.29	4.8
June '19	0-5	305	3	1	NG	70	0.19	1.68	0.28	3.04	9.23	19.44	28.67	5.6
June '20	0-5	401	4	5	GR	0	0.30	1.24	0.26	2.95	20.25	12.28	32.53	5.7
June '19	0-5	401	4	5	NG	15	0.19	1.11	0.26	2.80	17.16	15.84	32.99	5.8
June '19	0-5	402	4	3	GR	24	0.51	0.88	0.25	2.65	6.33	16.98	23.31	4.8
June '19	0-5	402	4	3	NG	66	0.11	0.64	0.20	2.11	3.63	10.22	13.84	3.9
June '19	0-5	403	4	1	GR	25	0.25	1.15	0.24	2.50	4.96	14.56	19.52	4.6
June '19	0-5	403	4	1	NG	84	0.28	1.13	0.24	2.58	7.65	13.63	21.28	4.6
June '19	0-5	405	4	6	GR	1	0.25	1.62	0.28	3.01	10.95	16.26	27.22	5.6
June '19	0-5	405	4	6	NG	19	0.49	0.88	0.22	2.32	3.97	10.93	14.91	4.4

Appendix E. East Campus Grazing Experiment Soil Fertility
CEC, cation exchange capacity

Date	Depth (cm)	Plot	Rep	Trt	Grazed (GR)/ Non-grazed (NG)	pH	CEC (me/100g)	Nitrate-N (ppm)	P (ppm)	K (ppm)	Sulfate (ppm)	Ca (ppm)	Mg (ppm)	Na (ppm)
June '19	0-5	101	1	1	GR	5.9	23.6	39.5	169	859	13.3	2464	452	13
June '19	0-5	101	1	1	NG	6	19.2	22.7	115	716	11.5	2098	377	12
June '19	0-5	103	1	5	GR	6	20.8	41.8	108	805	12.2	2144	390	24
June '19	0-5	103	1	5	NG	6.1	17.7	23.8	105	853	11.1	1923	350	13
June '19	0-5	104	1	3	GR	6.3	20.4	19.6	77	762	11.2	2361	398	11
June '19	0-5	104	1	3	NG	6.1	18.7	36.4	106	865	10.2	2199	349	8
June '19	0-5	106	1	6	GR	6	20.1	34.9	81	775	11.3	2126	360	6
June '19	0-5	106	1	6	NG	6.1	19.3	27.3	77	920	11.9	2158	359	7
June '19	0-5	202	2	5	GR	6.3	18.8	14.1	136	840	14.3	2005	370	13
June '19	0-5	202	2	5	NG	6.1	17.3	11.4	98	873	13.3	1854	316	16
June '19	0-5	203	2	1	GR	6.1	19.8	25.9	81	814	12.1	2141	368	10
June '19	0-5	203	2	1	NG	5.7	18.3	51.8	77	768	10.2	2096	321	8
June '19	0-5	205	2	6	GR	5.9	20.2	42.2	73	800	11.9	2114	364	11
June '19	0-5	205	2	6	NG	5.8	18.6	24.3	85	796	10.4	2141	339	9
June '19	0-5	206	2	3	GR	5.9	21.8	33.4	82	870	11.5	2332	382	10
June '19	0-5	206	2	3	NG	5.9	18.6	33.1	101	811	10	2133	345	7
June '19	0-5	302	3	3	GR	6	20	31	75	704	11.2	2083	341	7
June '19	0-5	302	3	3	NG	6.5	17.8	12	88	903	10.8	2195	353	8
June '19	0-5	303	3	6	GR	6.1	19.8	38.8	111	732	12.9	2196	360	7
June '19	0-5	303	3	6	NG	6.3	18.2	7	89	688	13.1	2254	351	9
June '19	0-5	304	3	5	GR	6.5	17.8	21.8	128	747	12.6	2012	345	12

June '19	0-5	304	3	5	NG	6.5	17.5	8.8	146	1015	10.9	2098	342	13
June '19	0-5	305	3	1	GR	6.5	18.4	12.4	115	801	15.1	2052	341	7
June '19	0-5	305	3	1	NG	6.4	19.8	37.4	128	1071	13.8	2444	359	7
June '20	0-5	401	4	5	GR	6.4	17.1	17.1	121	742	13.2	1897	326	10
June '19	0-5	401	4	5	NG	6.4	17.4	19.5	125	951	13.8	2040	329	11
June '19	0-5	402	4	3	GR	6	22.5	33.1	94	755	13	2375	366	7
June '19	0-5	402	4	3	NG	6.2	19.1	20.3	84	818	10.1	2262	359	8
June '19	0-5	403	4	1	GR	6.3	21	21.1	86	662	10.3	2707	364	7
June '19	0-5	403	4	1	NG	6.3	20	25	95	778	10.9	2603	374	7
June '19	0-5	405	4	6	GR	6.3	21.1	41.4	96	704	11.9	2613	366	9
June '19	0-5	405	4	6	NG	6.1	18.1	30.6	74	647	10.9	2227	339	7

Appendix F. East Campus Grazing Experiment Water Infiltration

Date	Plot	Rep	Trt	Grazed (GR)/ Non-grazed (NG)	Cumulative Infiltration (cm)
June '19	101	1	1	GR	1.2
June '19	101	1	1	NG	3.6
June '19	104	1	3	GR	4.3
June '19	104	1	3	NG	3.9
June '19	106	1	6	GR	1.1
June '19	106	1	6	NG	7.1
June '19	203	2	1	GR	2.1
June '19	203	2	1	NG	7.5
June '19	205	2	6	GR	2.5
June '19	205	2	6	NG	14.9
June '19	206	2	3	GR	10.8
June '19	206	2	3	NG	5.5
June '19	302	3	3	GR	9.7
June '19	302	3	3	NG	2
June '19	304	3	5	GR	3.7
June '19	304	3	5	NG	28.2
June '19	305	3	1	GR	5.1
June '19	305	3	1	NG	17.1
June '19	402	4	3	GR	4.4
June '19	402	4	3	NG	1.6
June '19	403	4	1	GR	12.4
June '19	403	4	1	NG	1.7
June '19	405	4	6	GR	0.9
June '19	405	4	6	NG	3.3

Appendix G. East Campus Grazing Experiment Soil Compaction March 2020 VWC, volumetric water content

Date	Depth (cm)	Plot	Rep	Trt	Grazed (GR)/ Non-grazed (NGR)	Penetration Resistance (Mpa)	VWC (cm3/ cm3)	Bulk Density (g/cm3)
March '20	0-5	102	1	2	GR	0.59	0.11	1.36
March '20	0-5	102	1	2	NGR	0.71	0.16	1.30
March '20	0-5	103	1	5	GR	0.75	0.11	1.38
March '20	0-5	103	1	5	NGR	0.48	0.15	1.35
March '20	0-5	105	1	4	GR	1.25	0.11	1.43
March '20	0-5	105	1	4	NGR	1.15	0.15	1.39
March '20	0-5	106	1	6	GR	1.00	0.12	1.37
March '20	0-5	106	1	6	NGR	0.90	0.15	1.40
March '20	0-5	201	2	4	GR	1.38	0.17	1.44
March '20	0-5	201	2	4	NGR	0.98	0.17	1.39
March '20	0-5	202	2	5	GR	0.71	0.17	1.39
March '20	0-5	202	2	5	NGR	0.71	0.16	1.37
March '20	0-5	204	2	2	GR	0.68	0.14	1.36
March '20	0-5	204	2	2	NGR	0.76	0.18	1.39
March '20	0-5	205	2	6	GR	0.89	0.11	1.40
March '20	0-5	205	2	6	NGR	0.72	0.12	1.43
March '20	0-5	301	3	2	GR	0.84	0.12	1.45
March '20	0-5	301	3	2	NGR	1.02	0.16	1.45
March '20	0-5	303	3	6	GR	1.03	0.09	1.44
March '20	0-5	303	3	6	NGR	0.91	0.14	1.45
March '20	0-5	304	3	5	GR	1.10	0.12	1.43
March '20	0-5	304	3	5	NGR	0.68	0.14	1.42
March '20	0-5	306	3	4	GR	1.36	0.15	1.45
March '20	0-5	306	3	4	NGR	1.02	0.14	1.37
March '20	0-5	401	4	5	GR	1.10	0.12	1.40
March '20	0-5	401	4	5	NGR	0.86	0.17	1.41
March '20	0-5	404	4	4	GR	1.07	0.15	1.38
March '20	0-5	404	4	4	NGR	1.08	0.15	1.35
March '20	0-5	405	4	6	GR	1.07	0.16	1.37
March '20	0-5	405	4	6	NGR	1.12	0.16	1.42
March '20	0-5	406	4	2	GR	0.78	0.14	1.34
March '20	0-5	406	4	2	NGR	0.77	0.16	1.37
March '20	5-10	102	1	2	GR	0.79	0.28	.
March '20	5-10	102	1	2	NGR	0.95	0.29	.
March '20	5-10	103	1	5	GR	0.79	0.33	.
March '20	5-10	103	1	5	NGR	0.76	0.35	.

March '20	5-10	105	1	4	GR	1.16	0.29	·
March '20	5-10	105	1	4	NGR	1.13	0.31	·
March '20	5-10	106	1	6	GR	1.25	0.34	·
March '20	5-10	106	1	6	NGR	1.04	0.32	·
March '20	5-10	201	2	4	GR	1.27	0.35	·
March '20	5-10	201	2	4	NGR	1.05	0.31	·
March '20	5-10	202	2	5	GR	0.96	0.35	·
March '20	5-10	202	2	5	NGR	0.89	0.35	·
March '20	5-10	204	2	2	GR	0.86	0.32	·
March '20	5-10	204	2	2	NGR	0.99	0.31	·
March '20	5-10	205	2	6	GR	1.17	0.30	·
March '20	5-10	205	2	6	NGR	0.81	0.29	·
March '20	5-10	301	3	2	GR	1.09	0.30	·
March '20	5-10	301	3	2	NGR	1.26	0.34	·
March '20	5-10	303	3	6	GR	1.33	0.28	·
March '20	5-10	303	3	6	NGR	1.19	0.32	·
March '20	5-10	304	3	5	GR	1.26	0.30	·
March '20	5-10	304	3	5	NGR	0.94	0.33	·
March '20	5-10	306	3	4	GR	1.18	0.32	·
March '20	5-10	306	3	4	NGR	1.37	0.31	·
March '20	5-10	401	4	5	GR	1.35	0.28	·
March '20	5-10	401	4	5	NGR	1.21	0.32	·
March '20	5-10	404	4	4	GR	1.17	0.35	·
March '20	5-10	404	4	4	NGR	1.51	0.33	·
March '20	5-10	405	4	6	GR	1.44	0.32	·
March '20	5-10	405	4	6	NGR	1.40	0.33	·
March '20	5-10	406	4	2	GR	1.17	0.31	·
March '20	5-10	406	4	2	NGR	1.05	0.35	·

Appendix H. East Campus Grazing Experiment Soil Compaction Parameters June 2020

Date	Depth (cm)	Plot	Rep	Trt	Grazed (GR) /Non-grazed (NGR)	Penetration Resistance (Mpa)	Gravimetric Water Content (g/g)	Bulk Density (g/cm3)	Sorptivity (cm sec -1/2)
June '20	0-5	102	1	2	GR	2.50	0.17	1.35	8.59
June '20	0-5	102	1	2	NGR	2.37	0.18	1.36	6.77
June '20	0-5	103	1	5	GR	2.81	0.16	1.37	5.22
June '20	0-5	103	1	5	NGR	3.00	0.17	1.43	3.98
June '20	0-5	105	1	4	GR	4.15	0.13	1.44	6.08
June '20	0-5	105	1	4	NGR	3.35	0.16	1.48	5.05
June '20	0-5	106	1	6	GR	3.63	0.14	1.39	8.14
June '20	0-5	106	1	6	NGR	2.62	0.15	1.47	9.97
June '20	0-5	201	2	4	GR	4.45	0.13	1.51	5.98
June '20	0-5	201	2	4	NGR	3.60	0.18	1.57	7.68
June '20	0-5	202	2	5	GR	3.31	0.16	1.41	4.28
June '20	0-5	202	2	5	NGR	4.22	0.15	1.48	7.51
June '20	0-5	204	2	2	GR	2.70	0.15	1.41	7.84
June '20	0-5	204	2	2	NGR	2.67	0.17	1.43	10.98
June '20	0-5	205	2	6	GR	4.34	0.16	1.39	6.72
June '20	0-5	205	2	6	NGR	2.85	0.15	1.43	8.49
June '20	0-5	301	3	2	GR	2.85	0.15	1.44	8.21
June '20	0-5	301	3	2	NGR	3.32	0.15	1.42	7.22
June '20	0-5	303	3	6	GR	3.64	0.13	1.41	6.66
June '20	0-5	303	3	6	NGR	3.93	0.12	1.46	5.20
June '20	0-5	304	3	5	GR	3.66	0.14	1.34	5.66
June '20	0-5	304	3	5	NGR	3.09	0.15	1.36	5.53
June '20	0-5	306	3	4	GR	4.33	0.13	1.45	8.87
June '20	0-5	306	3	4	NGR	3.29	0.17	1.48	9.74
June '20	0-5	401	4	5	GR	4.24	0.14	1.46	4.65
June '20	0-5	401	4	5	NGR	3.44	0.15	1.44	3.97
June '20	0-5	404	4	4	GR	2.90	0.17	1.41	10.22
June '20	0-5	404	4	4	NGR	2.27	0.14	1.43	14.15
June '20	0-5	405	4	6	GR	4.16	0.14	1.40	5.02
June '20	0-5	405	4	6	NGR	3.00	0.16	1.44	4.45
June '20	0-5	406	4	2	GR	2.73	0.16	1.38	11.08
June '20	0-5	406	4	2	NGR	3.02	0.19	1.41	11.08
June '20	5-10	102	1	2	GR	2.01	0.18	·	·
June '20	5-10	102	1	2	NGR	1.68	0.20	·	·
June '20	5-10	103	1	5	GR	1.86	0.17	·	·

June '20	5-10	103	1	5	NGR	1.69	0.21	.	.
June '20	5-10	105	1	4	GR	3.40	0.16	.	.
June '20	5-10	105	1	4	NGR	1.86	0.15	.	.
June '20	5-10	106	1	6	GR	2.84	0.17	.	.
June '20	5-10	106	1	6	NGR	2.28	0.17	.	.
June '20	5-10	201	2	4	GR	3.54	0.15	.	.
June '20	5-10	201	2	4	NGR	2.70	0.18	.	.
June '20	5-10	202	2	5	GR	2.81	0.17	.	.
June '20	5-10	202	2	5	NGR	3.02	0.18	.	.
June '20	5-10	204	2	2	GR	1.99	0.17	.	.
June '20	5-10	204	2	2	NGR	2.23	0.20	.	.
June '20	5-10	205	2	6	GR	3.47	0.19	.	.
June '20	5-10	205	2	6	NGR	2.14	0.19	.	.
June '20	5-10	301	3	2	GR	2.10	0.17	.	.
June '20	5-10	301	3	2	NGR	2.52	0.17	.	.
June '20	5-10	303	3	6	GR	3.53	0.16	.	.
June '20	5-10	303	3	6	NGR	3.90	0.14	.	.
June '20	5-10	304	3	5	GR	2.72	0.17	.	.
June '20	5-10	304	3	5	NGR	2.55	0.19	.	.
June '20	5-10	306	3	4	GR	2.66	0.15	.	.
June '20	5-10	306	3	4	NGR	2.79	0.19	.	.
June '20	5-10	401	4	5	GR	3.02	0.18	.	.
June '20	5-10	401	4	5	NGR	2.85	0.18	.	.
June '20	5-10	404	4	4	GR	2.04	0.18	.	.
June '20	5-10	404	4	4	NGR	2.47	0.15	.	.
June '20	5-10	405	4	6	GR	3.22	0.16	.	.
June '20	5-10	405	4	6	NGR	2.81	0.18	.	.
June '20	5-10	406	4	2	GR	1.99	0.18	.	.
June '20	5-10	406	4	2	NGR	2.35	0.22	.	.

Appendix I. East Campus Grazing Experiment Biomass 2020

Date	Plot	Rep	Trt	Grazed (GR)/Non-grazed (NGR)	Cover (%)	Biomass (Mg/ha)	Temp (°C)
2020	102	1	2	GR	68	8.95	10.85
2020	102	1	2	NGR	95	12.34	7.80
2020	103	1	5	GR	70	9.91	10.00
2020	103	1	5	NGR	95	11.00	8.00
2020	105	1	4	GR	91	2.11	10.95
2020	105	1	4	NGR	100	5.00	10.20
2020	106	1	6	GR	72	5.20	11.30
2020	106	1	6	NGR	91	12.16	10.35
2020	201	2	4	GR	86	3.66	10.65
2020	201	2	4	NGR	95	5.80	8.60
2020	202	2	5	GR	68	6.75	9.40
2020	202	2	5	NGR	91	9.96	9.45
2020	204	2	2	GR	83	8.88	10.50
2020	204	2	2	NGR	90	11.58	10.00
2020	205	2	6	GR	69	4.21	11.85
2020	205	2	6	NGR	82	8.88	10.65
2020	301	3	2	GR	82	6.46	11.65
2020	301	3	2	NGR	94	8.51	10.95
2020	303	3	6	GR	54	2.39	13.65
2020	303	3	6	NGR	80	5.09	12.40
2020	304	3	5	GR	47	4.37	12.85
2020	304	3	5	NGR	73	5.55	10.95
2020	306	3	4	GR	92	1.21	11.95
2020	306	3	4	NGR	99	1.80	10.55
2020	401	4	5	GR	61	5.67	12.55
2020	401	4	5	NGR	85	7.19	9.85
2020	404	4	4	GR	91	1.61	11.80
2020	404	4	4	NGR	99	4.09	11.05
2020	405	4	6	GR	67	3.43	13.25
2020	405	4	6	NGR	91	9.22	11.45
2020	406	4	2	GR	93	9.39	10.70
2020	406	4	2	NGR	95	12.72	10.85

Appendix J. East Campus Grazing Experiment Biomass 2021

Date	Plot	Rep	Trt	Grazed (GR)/Non-grazed (NGR)	Biomass (Mg/ha)
2021	101	1	1	GR	8.72
2021	101	1	1	NGR	6.94
2021	104	1	3	GR	2.66
2021	104	1	3	NGR	3.68
2021	105	1	4	GR	7.07
2021	105	1	4	NGR	4.34
2021	201	2	4	GR	6.73
2021	201	2	4	NGR	6.68
2021	203	2	1	GR	7.95
2021	203	2	1	NGR	9.25
2021	206	2	3	GR	1.28
2021	206	2	3	NGR	2.12
2021	302	3	3	GR	3.77
2021	302	3	3	NGR	3.22
2021	305	3	1	GR	10.37
2021	305	3	1	NGR	9.69
2021	306	3	4	GR	9.71
2021	306	3	4	NGR	7.37
2021	402	4	3	GR	3.33
2021	402	4	3	NGR	4.61
2021	403	4	1	GR	9.14
2021	403	4	1	NGR	9.07
2021	404	4	4	GR	6.38
2021	404	4	4	NGR	7.12