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Soil Physical and Hydrological Properties, and Greenhouse Gas Emissions under Integrated Crop-Livestock Agroecosystems

Navdeep Singh
South Dakota State University

SOIL PHYSICAL AND HYDROLOGICAL PROPERTIES, AND GREENHOUSE GAS EMISSIONS UNDER INTEGRATED CROP-LIVESTOCK AGROECOSYSTEMS

BY

NAVDEEP SINGH

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DISSERTATION ACCEPTANCE PAGE

Navdeep Singh

This dissertation is approved as a creditable and independent investigation by a candidate for the Doctor of Philosophy degree and is acceptable for meeting the dissertation requirements for this degree. Acceptance of this does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Sandeep Kumar
Advisor Date

David Wright
Department Head Date

Dean, Graduate School Date

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ABBREVIATIONS

ANOVA	Analysis of Variance
C	Carbon
C: N	Carbon: Nitrogen ratio
CH_4	Methane
CO_2	Carbon dioxide
CT	Computed tomography
d	Index of agreement
EC	Electrical conductivity
GC	Gas chromatograph
GHG	Greenhouse gas
h	Water pressure head
K_s	Green-Ampt estimated saturated hydraulic conductivity
K_{sat}	Saturated hydraulic conductivity
l	Pore connectivity parameter
N	Nitrogen
N_2O	Nitrous oxide
NO_3^-	Nitrate
NSE	Nash-Sutcliffe modelling efficiency
PSD	Pore size distribution
q_s	Water infiltration
R^2	Coefficient of determination
RMSE	Root Mean Square Error
rpm	Revolutions per minute
S	Sorptivity
S_e	Effective saturation
SOC	Soil organic carbon
SOM	Soil organic matter
SPR	Soil penetration resistance
SWR	Soil water retention
t	Time
TN	Total nitrogen
w	Gravimetric soil water content
WSA	Wet aggregate stability
θ	Volumetric soil water content
θ_s	Saturated soil water content
θ_r	Residual soil water content
Γ	Connection probability
ρ_b	Soil bulk density
τ	Tortuosity
Ψ_m	Matric potential

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ABSTRACT

SOIL PHYSICAL AND HYDROLOGICAL PROPERTIES, AND GREENHOUSE GAS EMISSIONS UNDER INTEGRATED CROP-LIVESTOCK AGROECOSYSTEMS

NAVDEEP SINGH

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Cover crops (CCs) and grazing play a critical role in successful implementation of the integrated crop-livestock system (ICLS) because they can have a direct impact on soils and greenhouse gas emissions. The objectives of this study were to (i) evaluate the short-term impacts of CCs [grass dominated cover crops (GdC) and legume dominated cover crops (LdC)] and grazed CCs and corn (*Zea mays* L.) residue under oat (*Avena sativa* L.)–CC–corn rotation on soil physical and hydrological properties; (ii) quantify the architecture of soil pores using X-ray computed tomography (CT) for soils managed under long-term ICLS, native grazed pasture and corn-soybean cropping system, and to examine relationships between CT-measured pore parameters and soil hydro-physical properties; (iii) evaluate the impact of CCs (GdC and LdC) and grazed CCs and corn residue under oats-CCs-corn rotation on soil surface carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) fluxes; and (iv) simulate water content and temperature for soils using HYDRUS model under grass dominated CC, cattle grazed-grass dominated CC and bare soils under ICLS.

Cover crops reduced soil bulk density (ρ_b) and soil penetration resistance (SPR) at 0-10 and 10-20 cm depths and, in general, increased soil water retention (SWR) and total porosity compared to the no cover crops. Cattle grazing generally increased the ρ_b and SPR at both depths, however, the values of SPR did not surpass the critical values which

indicated that the grazing did not have an adverse effect on soils in terms of root proliferation. Retention of water and total pore space in soil was reduced due to the grazing. Long-term ICLS enhanced CT-measured macroporosity (0.084 mm^3 mm^{-3}) and reduced ρ_b (1.18 Mg m^{-3}) compared to the corn-soybean cropping system (0.012 mm^3 mm^{-3}; 1.51 Mg m^{-3}). The increased proportion of pore volume contained in the largest pore cluster and higher connected porosity under long-term ICLS significantly enhanced saturated hydraulic conductivity (K_{sat}) of the soils compared to the corn-soybean cropping system. The GdC+G appeared to reduce cumulative CO_2 (4042 kg C ha^{-1}) and N_2O (1499 g N ha^{-1}) fluxes compared to the LdC+G (4819 kg C $ha^{-1}$for CO_2 and 2017 g N ha^{-1} for N_2O), indicating the superiority of GdC+G over the LdC+G in reducing the greenhouse gas (GHG) fluxes in short-term. Cumulative CH_4 flux was not affected by ICLS. The HYDRUS model was used to simulate soil water content and soil temperature from the GdC, GdC+G and no cover crop and G (NC) treatments. The model was calibrated using data from 2017 and then validated with data from 2018 growing season. The R^2 and index of agreement (d) values for simulations of soil water content varied from 0.26–0.78 and 0.52–0.89, respectively during the validation period. The corresponding values for soil temperature were 0.48–0.99 and 0.80–0.99, respectively. The model performed better in simulating soil temperature compared to that of the soil water content over the study period.

This study illustrates that cover cropping in shorter duration (2-3 yr) enhanced some soil physical attributes, however, grazing cover crops and crop residue had small or neutral effects on soils. The CT-study represented the benefits of long-term ICLS for maintaining or improving soil pore connectivity and other parameters critical for soil water transport. The GHG study showed that, in general, cover crops and grazing of cover crop and corn residue did not impact CO_2, N_2O and CH_4 fluxes in short-term. Long-term studies are required to capture the influence of management practices such as ICLS on GHG fluxes. The modeling study showed that owing to the satisfactory performance of HYDRUS in simulating soil water content and temperature under ICLS, and this model can act as a promising tool in simulating the long-term benefits of conservation practices that involve diverse CCs and grazing CCs and crop residue in enhancing the soil moisture conservation. Overall, the results of this study indicate that integrating livestock grazing in the row crop rotations that involve diverse CCs can improve soil physical and hydrological properties and has a potential to mitigate greenhouse gas emissions.

CHAPTER 1

INTRODUCTION

Rapid conversion of grasslands to croplands, and expansion of row crop agriculture and monocropping have been observed in the Northern Great Plains (Wright and Wimberly, 2013; Clay *et al.*, 2014; Kumar *et al.*, 2019). This historical conversion of land-use from native vegetation to croplands resulted in sharp declines in soil organic carbon, reduced soil quality, and hence led to a significant source of atmospheric CO_2 emissions and erosion. According to Spawn *et al.* (2019), grassland to cropland conversion across the United States during 2008-2012 caused an average release of 55.0 Mg C ha^{-1} that resulted in total emissions of 38.8 Tg C yr^{-1}, with > 90% of these emissions originating from soil organic carbon (SOC) stocks. Due to this conversion, the area under corn (*Zea mays* L.) and soybean (*Glycine max* L.) increased from 8.3 to 10.4 and 4.7 to 8.4 million acres in South Dakota (SD) and North Dakota (ND), respectively, between 2004 to 2014 (Wimberly *et al.*, 2017). Degraded soil physical conditions in terms of reduced aggregate stability have been observed in both monoculture corn and corn–soybean cropping systems that could result in unsustainable levels of erosion (Liebig *et al.*, 2002) and increased vulnerability to drought (Wright and Wimberly, 2013). Further, when these cropping systems are accompanied by crop residue removal for off-farm uses, it could lead to increased water erosion (Acharya and Blanco-Canqui, 2018). Therefore, incorporation of diverse cover crops, and grazing cover crops and crop residue under integrated crop-livestock system (ICLS) can be an alternate option for enhancing SOC and hence the soil physical and hydrological properties (de Moraes *et al.*, 2014; Rakkar and Blanco-Canqui, 2018; de Andrade Bonetti *et al.*, 2019).

Integrated crop-livestock system is a practice of using crops and livestock on a single farm in a way that they complement each other spatiotemporally, concurrently, or separately and in rotation or in succession (de Moraes *et al.*, 2014). A few examples of commonly implemented ICLS in the U.S. include animal grazing of cover crops (CC) within cash crop rotations, crop residue grazing, silvopasture and agroforestry (crops grown for grain harvesting among young trees or forage planting for grazing), sod based crop rotation (perennial forage for grazing with crops), and dual purpose cereal crops (harvesting for grains followed by grazing e.g. corn) (Sulc and Franzluebbers, 2014). Adoption of ICLS offers some major benefits in certain areas that include greater outputs and relatively fewer inputs, expense reduction and increased ecosystem services (Gil *et al.*, 2016). The recoupling of crops and livestock (the ICLS) can also play a prominent role in mitigating greenhouse gas (GHG) emissions (Salton *et al.*, 2014; Buller *et al.*, 2015). However, livestock grazing under ICLS can also significantly impact soil structural attributes (Drewry *et al.*, 2008). High external pressures exerted by animals or farm machinery can lead to the problems such as increased soil compaction due to increased bulk density and penetration resistance, and reduced macroporosity and water infiltration rates (Abdalla *et al.*, 2018; Byrnes *et al.*, 2018). Increased soil compaction creates a hindrance to root growth and obstructs the movement of air and water throughout the profile which limits the aeration to the plant roots. Also, ICLS can increase GHG emissions because livestock production also contributes to atmospheric CH_4 mainly by enteric fermentation and through addition of manure in the soils, accounting for about 20 to 25% of the global rise of atmospheric CH_4 (Lassey, 2007; Hargreaves *et al.*, 2015).

Soil porosity, which can be influenced by ICLS, plays a major role in the transmission and retention of fluids and gases in the soil (Eynard *et al.*, 2004). Soil porosity and pore-size distribution are usually simply estimated by traditional water retention methods. However, these methods do not provide information of unconnected pores (Rab *et al.*, 2014) and pore morphology (Gantzer and Anderson, 2002). Conversely, computed tomography (CT) imaging techniques are fast, robust, non-invasive and provide a unique opportunity to quantify detailed pore morphological parameters and permit three-dimensional visualization of soil structural properties (Carlson *et al.*, 2003) on a micrometer scale (Hapca *et al.*, 2015). Although not measured through CT scanning, Bonetti *et al.* (2018) observed an increase in the macroporosity after the implementation of ICLS due to the greater root development under ICLS.

Process-based models can integrate various processes across the soil-plant-atmospheric continuum and can help explain the mechanisms pertaining to soil water movement, GHG emissions, crop growth and development among others under different management interventions. Models can provide useful information regarding the long-term benefits of the best management practices in enhancing soil and water conservation. Numerical models such as HYDRUS have the ability to analyze and predict water flow, storage and water movement processes in vadose zone very accurately due to the flexibility of selecting boundary conditions and soil hydraulic functions (Saito *et al.*, 2006). It has been applied successfully in various studies for predicting soil moisture content and water and heat transport under diverse conditions (Li *et al.*, 2017; Wang *et al.*, 2018; Baek *et al.*, 2020).

Study Objectives

The purpose of this study was to evaluate soil physical and hydrological properties, greenhouse gas fluxes, soil water and temperature regime for soils managed under ICLS to determine whether the ICLS can be used as a management practice to benefit the soils and environment. The objectives of this study were evaluated in four sub-studies as outlined below. Specific objectives were developed separately for each study.

Study 1. This study was entitled “soil hydrological properties as influenced by cover crops and grazing under a short-term integrated crop-livestock system” with the specific objective being measurement and comparison of bulk density, penetration resistance, soil water retention, pore size distributions and water infiltration among grass dominated CC (GdC), cattle grazed GdC (GdC+G), legume dominated CC (LdC), cattle grazed LdC (LdC+G), and no CC (NC) treatments.

Study 2. This study was entitled “crop-livestock integration impacted X-ray-computed-tomography (CT)-measured near-surface soil pore parameters” with the specific objectives being (i) to quantify the architecture of soil pores using X-ray CT for soils under long-term integrated crop-livestock system (ICLS), native grazed pasture (NGP) and corn-soybean cropping system (CNT), and (ii) to determine the correlation between CT-measured pore parameters and soil hydro-physical properties.

Study 3. This study was entitled “short-term grazing of cover crops and maize residue impacts on soil greenhouse gas fluxes in two Mollisols” with the specific objective being measurement and comparison of soil surface carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) fluxes among grass dominated CC (GdC), cattle grazed GdC (GdC+G), legume dominated CC (LdC), cattle grazed LdC (LdC+G), and no CC (NC) treatments.

Study 4. This study was entitled "modeling soil water and thermal regime under integrated crop-livestock system with HYDRUS" with the specific objective was to simulate soil water content and temperature using HYDRUS model from cover cropped, grazed and bare soils under integrated crop-livestock systems.

All the four studies were written independently in the format of journal manuscripts for publication purposes. Study 3 is published in *Journal of Environmental Quality*.

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CHAPTER 2

LITERATURE REVIEW

A recent agricultural land use change from grassland to cropland has been occurred in Northern Great Plains. A total of 7.3 million acres of uncultivated land was converted to croplands from 2008 to 2012 in the USA with a net cropland expansion of 3 million acres (Lark *et al.*, 2015). Majority of this shift was detected in the states of South Dakota and North Dakota, predominantly in the east of the Missouri river (Wright and Wimberly, 2013; Lark *et al.*, 2015). During the period of 2006-2012, South Dakota lost 4.6 million acres of grassland as a consequence of hike in cropland acreage (Reitsma *et al.*, 2015). This conversion has triggered many problems in the agroecosystems such as destruction of wildlife habitat, unstable soil structure due to lower root density in croplands, reduced water infiltration, increased erosion, elevated nutrient discharge to surface as well as ground water and degraded environmental quality (Claassen *et al.*, 2010; Reitsma *et al.*, 2015; Wimberly *et al.*, 2017). To address this issue, adoption of diverse, robust and ecologically sustainable management practices is required which have an ability to maintain and improve agricultural productivity simultaneously reducing adverse impacts on environment. Coupling of crops and animals on a single farm, also known as integrated crop livestock system (ICLS), can be one of the alternatives for enhancing the soils and environmental quality. This literature review chapter discusses the impacts of ICLS on soil physical and hydrological properties, and greenhouse gas emissions. This chapter has been divided below in different subsections separately.

2.1. Integrated Crop-Livestock System

Integrated crop-livestock system is a practice of using crops and livestock on a single farm in a way that they complement each other spatiotemporally, concurrently, or separately and in rotation or in succession (de Moraes *et al.*, 2014). In the past century, many factors like industrialization, specialization and low labor caused decoupling of crops and livestock. Advancement of tractor models in the 1920s, possible promotion of specialization by government policies, increased demand of synthetic fertilizers were some of the drivers those caused separation of the two (disintegration of crop and livestock) (Hilimire, 2011). Various studies have shown that combining livestock with the cropping systems can improve nutrient cycling (Nie *et al.*, 2016), soil structure (Sulc and Tracy, 2007), enhance diversification in agricultural systems (Lemaire *et al.*, 2014), improve soil tilth and fertility (Russelle *et al.*, 2007), preserve natural resources and environmental quality (Lemaire *et al.*, 2014), enhance ecosystem services and farm profitability (Russelle *et al.*, 2007). Some of the ICLS adopted in the United States involve grazing of cover crops, grazing of crop residue after harvest and grazing of annual crops swathed for winter feed (Liebig *et al.*, 2011). Other common ICLS that are being observed in the US are grass-based crop rotation, cover crop grazing within cash-crop rotation, livestock grazing of crop residues, grass intercropping, dual-purpose cereal crops, and silvopasture (Sulc and Franzluebbers, 2014). In our study, the ICLS system involves the crop rotations managed with cover crops, and cattle grazing of cover crops and row crop residues. Therefore, the impacts of cover crops and grazing cover crops on soil properties have been discussed.

2.2. Soil Physical and Hydrological Properties

Changes in soil physical and hydrological properties influence all the ecosystem services delivered by soils those include food, fuel, fiber, nutrient cycling, water filtration, erosion control, biodiversity, soil C dynamics and sequestration and many more (Blanco-Canqui and Ruis, 2018). The fundamental soil processes are mediated by soil physical and hydrological properties. For instance, soil compaction is influenced by bulk density, aeration by soil pore size distribution, runoff and erosion by texture, infiltration rate, aggregate stability and erodibility and soil warming by heat capacity (Lal, 2011). Furthermore, the movement and availability of water, air and nutrients for plant growth is defined by soil physical and hydrological properties and management practices. Soil physical environment plays a vital role in the crop growth, establishment and production. For example, soil physical properties such as bulk density, penetration resistance, pore size distribution modulate the seed germination, seedling emergence, root growth and crop production. Soil porosity and water retention characteristics directly control a number of soil physical indices involving plant available water, soil aeration capacity and field capacity (Reynolds *et al.*, 2009). Pore size distribution of the soils govern a number of critical soil processes those including gas diffusion and flow of water, transport and reaction of nutrients and chemicals, protection of soil carbon and other nutrients at micro-scale, accommodation of roots and macro and micro fauna, enzyme activities, among others (Blanco-Canqui and Ruis, 2018). The presence of interconnected pores or pathways, their architecture and size distribution dictate the ability of soil to transmit water. Water infiltration in the soils plays a major role in regulating the water supply to the rhizosphere, which directly influences crop production. Agricultural drainage, nutrient leaching, groundwater recharge, surface runoff velocities, soil erosion, among others, are governed by the water infiltration in the soils. Soil hydrological properties give an indication about the structure of the soil porous system consisting of pores of diverse geometry, sizes, and connectivity (Rousseva *et al.*, 2017). Thus, soil hydrological properties are essential to understand the transmission properties and water balance in soils. Furthermore, the hydro-physical soil attributes are required as input data in various models generally used to predict, estimate and assess the phenomena that dictate the flow of water in the surface stream, subsurface or groundwater system at various scales. Therefore, soil physical and hydrological parameters are very important to study as these properties strongly impact agronomical, ecological and pedological processes that directly influence ecosystem services at landscape and watershed scales (Lal, 2011).

2.2.1. Impacts of Cover Crops and Grazing under ICLS on Soil Physical and Hydrological Properties

Soil physical and hydrological properties are generally influenced by management practices such as tillage, traffic, mulching, cover-cropping, grazing of cover crops and crop residue, among others. Cover crops can be defined as spatially-close growing plants that aid in protection of soil and improve soil health (Fageria *et al.* (2005). Cover crops have shown positive effects on soil properties (Villamil *et al.*, 2006a; Jokela *et al.*, 2009; Stavi *et al.*, 2012). In a long-term study (15 yr.) conducted by Blanco-Canqui *et al.* (2012), cover crops increased aggregate stability, water content and decreased maximum compactibility of mesic Udic Argiustolls. In another long-term study of 13 yr., Steele *et al.* (2012) found that winter annual cereal cover crops increased aggregate stability of fine silty soils. Abdollahi and Munkholm (2014) showed that continuous use of cover crops for five years decreased penetration resistance and ameliorated plow pan compaction at 20-40 cm soil depth. Water infiltration rates and soil aggregate stability were enhanced by cultivating cover crops and following no-till practices (Mitchell *et al.*, 2017). Abdollahi *et al.* (2014) established that planting of cover crops increased soil macroporosity thereby enhancing air and water flow through the soil which resulted in improved root growth. There are several other studies which show positive impact of cover crops on soil structural properties in terms of improved soil aggregation, decreased bulk density, penetration resistance, enhanced water infiltration and macroporosity (Jokela *et al.*, 2009; Chen and Weil, 2010; Blanco-Canqui *et al.*, 2011; Stavi *et al.*, 2012; Blanco-Canqui *et al.*, 2013; Haruna and Nkongolo, 2015; Alvarez *et al.*, 2017). On the other hand, some studies, particularly short duration studies, found no significant impact of cover crops on physical properties of soil. A three-year study conducted by Welch *et al.* (2016) demonstrated that cover crops did not affect soil physical properties and were unable to reduce soil compaction. Similarly, Mubiru and Coyne (2009) reported that soil bulk density remained unaffected when they cultivated four different cover crop species into fallow in degraded soils in a two-year study period. In another two-year study conducted by Carof *et al.* (2007) on loamy soils under no-till management, cover crops showed no effect on soil hydraulic conductivity, however macroporosity was enhanced. There are also other studies that reported minimal or no influence of cover crops on soil physical properties (e.g., Kaspar *et al.*, 2001; Sainju *et al.*, 2003). Cover crops thus have a variable impact on soil properties (Fronning *et al.*, 2008).

Livestock grazing can significantly impact soil structural attributes (Drewry *et al.*, 2008). High external pressures exerted by animals or farm machinery can lead to the problems such as soil compaction, increased bulk density, penetration resistance and reduced macroporosity and water infiltration rate (Cade-Menun *et al.*, 2017; Abdalla *et al.*, 2018). Increased soil compaction creates a hindrance to root growth and obstructs the movement of air and water throughout the profile which leads to limited aeration of the plant roots (Calonego *et al.*, 2017). Soil physical disintegration and compression by the animal trampling mainly depend upon stocking rate (Sousa Neto *et al.*, 2014), duration of grazing period, soil moisture content (Drewry *et al.*, 2008), soil texture (Bilotta *et al.*, 2007) and species of the grazing animal (Poffenbarger, 2010). Pulido *et al.* (2016) conducted a study to assess the impact of heavy grazing on soil quality and found an increase in soil bulk density in 5-10 cm depth in the enclosures having animal stocking rates higher than 1AUha^{-1}. Similar results were observed in the 12 year study done by Pulido *et al.* (2016), where continuously grazed watersheds showed an increase of 8% in soil bulk density. Likewise, various other studies had revealed that livestock treading can lead to increased bulk density and soil compaction (Hamza and Anderson, 2005; Drewry *et al.*, 2008; Iglesias *et al.*, 2014; Liebig *et al.*, 2014), reduced infiltration rates and hydraulic conductivity (Pietola *et al.*, 2005; Reszkowska *et al.*, 2011; Stavi *et al.*, 2011) and reduced porosity (Martınez and Zinck, 2004; González-BarriosA *et al.*, 2010; Stavi *et al.*, 2011).

Cover crops and their grazing by the livestock, which are important components of an ICLS, help in maintaining and improving soil physical and hydrological properties (Franzluebbers and Stuedemann, 2008; Blanco-Canqui *et al.*, 2012; Blanco-Canqui *et al.*, 2015; Alvarez *et al.*, 2017; Calonego *et al.*, 2017; Mitchell *et al.*, 2017). However, in some of the studies, cover crops and grazing did not have any significant effect on the soil properties (Welch *et al.*, 2016; Rakkar *et al.*, 2017) as soil physical behavior depends on various factors such as soil type, cropping systems, climatic conditions, stocking intensity, soil moisture content, time period of the study, management operations, among others. A study conducted by Moreira *et al.* (2012) showed that the physical quality of an Oxisol improved after 8 years of an ICLS and attributed it to the physical quality of resilience. Haruna and Nkongolo (2015) evaluated the effects of cereal rye cover crop management on soil physical and biological properties and found 3.5% decrease in soil bulk density in the plots having cover crop as compared with no-cover crop. Liebig *et al.* (2011) assessed the impacts of livestock hoof traffic on soil water infiltration rates in central North Dakota, USA and found that infiltration rate was not affected by no, low and high hoof traffic at three, six, and nine years after initiation of the study in integrated annual cropping systems, where winter grazing was used.

2.3. Soil Porosity

2.3.1. X-ray Computed Tomography Approach for Measuring Soil Porosity

The X-ray Computed Tomography (CT), first developed by Hounsfield (1975) for medical imaging, is a robust, non-invasive imaging technique that permits tridimensional visualization of soil structural properties (Rab *et al.*, 2014; Carducci *et al.*, 2016). Kumar *et al.* (2010) used X-ray CT to measure soil macroporosity and coarse mesoporosity in grass buffer and grazed pasture systems and found that macroporosity was 13 times greater in the buffer than that in the pastures in upper 10 cm soil. Jarvis *et al.* (2017) used

X-ray tomography to analyze soil pore space arrangement of a silt loam at 65 μm resolution in the harrowed and ploughed layers and reported a strong relationship between the percolating fraction and the imaged porosity. Müller *et al.* (2018) parameterized hydrological properties of macropores on the basis of imaged macropore arrangement of an Andosol and a Gleysol and found that the movement of water via macropores is supervised by tortuosity, connectivity and macropore size distribution, that can be attained by X-ray CT. Parvin *et al.* (2017) derived soil water retention curve by two techniques, X-ray CT and evaporation method and reported that X-ray CT was able to examine the pores, which were not detected by the evaporation, due to which evaporation method gave lower volume of macropores than they actually were. Rab *et al.* (2014) conducted a study to examine the usefulness of X-ray CT to examine the macroporosity and found an increase and decrease in mean pore diameter by increasing volume of soil to be measured and increasing the scan resolution, respectively. They concluded that X-ray CT is an effective tool to describe soil porosity from macro- to micro-scale, provided that sampling and analysis methodologies are followed according to the research questions. Various researchers used this technique to examine pore size distribution (Monga *et al.*, 2008; Houston *et al.*, 2017; Jarvis *et al.*, 2017), macropore space organization (Rab *et al.*, 2014; Bottinelli *et al.*, 2016; Martínez *et al.*, 2017; Müller *et al.*, 2018), spatial variability of soil structure (Carducci *et al.*, 2016), aggregate structure analysis (Gao *et al.*, 2017), fractal properties of soils (Martín-Sotoca *et al.*, 2016).

2.3.2. Cover Crops and Grazing under ICLS Influences on Soil Porosity

Soil structure and aggregation are highly influenced by the cattle grazing under ICLS depending upon different grazing management practices followed (Allen *et al.*, 2007; Liebig *et al.*, 2012b; Sulc and Franzluebbers, 2014). As the soil matrix exhibit a complex stratified arrangement, a thorough and precise study of spatial arrangement of soil solids will be beneficial in quantifying the impacts of cover crops and grazing on soil structure under ICLS. Integrated crop-livestock systems can increase soil organic matter as Franzluebbers *et al.* (2012) suggested that pore connectivity may be positively influenced by greater soil organic carbon in grazed systems, which compensates for the negative influence of the greater compaction caused by animal traffic. Bonetti *et al.* (2018) evaluated soil physical attributes in an ICLS and reported that after ICLS implementation, the values of soil macroporosity increased in the grazed and nongrazed areas. They postulated that the ICLS had no negative effects on total porosity, macroporosity, microporosity and soil bulk density. However intensive grazing can reduce soil due to increased soil bulk density. For instance, de Andrade Bonetti *et al.* (2019) examined the impact of animal trampling on soil physical attributes after 14 yrs. of ICLS implementation and observed that intensive animal trampling decreased total porosity and macroporosity and increased the bulk density. Villamil *et al.* (2006b) studied the use of winter cover crops such as hairy vetch (*Vicia villosa* Roth) and cereal rye (*Secale cereale* L.), in a corn –soybean rotation and reported an increase in total and storage porosity along with plant available water in the cropping sequences those including winter CCs. Abdollahi *et al.* (2014) established that planting of CCs increased soil macroporosity thereby enhancing air and water flow through the soil, which resulted in improved root growth.

2.4. Impacts of ICLS on Greenhouse Gas Emissions

2.4.1. Agricultural Emissions

The global annual mean air temperature rose by 0.85°C between 1880 and 2012 (Pachauri *et al.*, 2014). This warming has primarily been caused by increased anthropogenic emissions of long-lived greenhouse gases (GHGs) such as carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4). Agriculture contributed 10% of total U.S. GHG emissions in 2018 (USEPA, 2019). The GHG emissions from agriculture come mainly from agricultural soils, livestock, and rice production. Soils act as sources and sinks for GHG emissions. Agricultural soils are known to be the largest anthropogenic source of N_2O (Reay *et al.*, 2012). The N_2O and CO_2 emissions in any given cropping system are influenced by the fluctuations in the soil environmental characteristics, e.g., soil moisture and temperature, in conjunction with management effects (Negassa *et al.*, 2015) as the microbial activities are directly controlled by these soil variables. The N_2O fluxes are related primarily with the availability of mineral N and C sources in soil for the denitrifier bacterial communities, soil structure, microbial community composition, soil pH (Abalos *et al.*, 2014), precipitation events, temperature and fertilizer-N applications, whereas the water filled pore space, temperature fluctuations, intensity of tillage and extent of plant residue incorporation in the soil are the major factors influencing soil CO_2 emissions (Hoben *et al.*, 2011; Abdalla *et al.*, 2014). The factors mainly temperature and precipitation are dependent on seasonal weather patterns. Although, N_2O emissions from agriculture are much lower than CO_2, but the very large global warming potential makes N_2O a major contributor to climate change. NO_3^- in soil is subject to many biological processes such as N uptake by crops, N immobilization by soil biota, movement below the root zone following large precipitation events, and conversion to nitric oxide, N_2O, and N_2 by soil denitrifies (Drury *et al.*, 2014). Nitrification and denitrification processes in the agricultural soils are affected by various soil variables and are considered as the major sources of N_2O emissions (Guardia *et al.*, 2016a).

2.4.2. Impacts of Cover Crops and Grazing under ICLS on GHG Emissions

Cover crops and grazing, being the main components of ICLS, influence the emission of GHGs from soil. It has been found that growing leguminous cover crops is beneficial in reducing the N_2O emissions by decreasing the availability of nitrate (Christopher and Lal, 2007; Sauer *et al.*, 2009) and by allowing reduction of N fertilizer use (Jensen and Hauggaard-Nielsen, 2003). The type of cover crop species (legume, non-legume or a mixture of both) may affect N_2O emissions from soils in different ways (Kim *et al.*, 2013). Use of leguminous cover crops that do not require N fertilization in a cropping system may help limit N_2O emissions, but the documented effects of cover crops on N_2O emissions have been mixed (Cavigelli *et al.*, 2012); some studies have found cover crops to increase (Petersen *et al.*, 2011) or have no consistent effect (Smith *et al.*, 2011) on N_2O emissions. An additional N is provided to the soil by legume cover crops either alone or in combination with non-legumes, that can lead to increased transpiration thereby affecting soil moisture conditions which may likely influence N_2O emissions (Peyrard *et al.*, 2016). The nonlegume cover crops, e.g. winter cereals, could help reduce N_2O emissions, as they extract soil N more efficiently compared to legumes, due to their deep roots (Kallenbach *et al.*, 2010). The magnitude of the emissions depends on the chemical composition and the quantity of plant residue added to the soil (Garcia-Ruiz and Baggs, 2007). The contents of C and N in plant residue are important variables in determining the N mineralization kinetics in the soil and thus also can affect soil N_2O emissions, which tend to be greater when the added crop residues (legumes) have a low C:N ratio (Huang *et al.*, 2004). A short-term increase in N_2O emissions was revealed by a meta-analysis, due to the incorporation of cover crop (especially legume) in agricultural soils (Basche *et al.*, 2014). Furthermore, the higher C: N ratio of non-legume residues than that of legumes, may supply energy (C) for denitrifiers, that can lead to higher N_2O losses (Sarkodie-Addo *et al.*, 2003). In this context, the abundance of denitrifying microorganisms is increased by the presence of cereal residues (Gao *et al.*, 2016), consequently raising denitrification losses when soil conditions are favorable (elevated NO_3 availability and soil moisture following rainfall) (Baral *et al.*, 2016). For better crop production and proficient utilization of resources, the usage of blends of cereals and legumes has been urged to combine the synergism of the individual species (Hwang *et al.*, 2015). The addition of cover crops to the conventional cropping systems can help enhance SOC and N sequestration potentials and thus can mitigate climate change (Liebig *et al.*, 2012a). N_2O emissions can be reduced by cover crops as they deplete the NO_3^- pool, which is the principal substrate for denitrification (Liebig *et al.*, 2015). On the other hand, during their growth phase, labile C and N is released by the cover crops through root exudates and rhizodeposition, which can stimulate microbial activity and increase N_2O emissions (Gul and Whalen, 2013; Mitchell *et al.*, 2013). Very few studies have focused on the emissions of CH_4 to the atmosphere as influenced by the cover crops. Cover crops can impact the CH_4 emissions depending upon some factors such as soil aeration, presence of alternative electron acceptor, SOM abundance and make-up, vegetation type and methanogenic population (Chiavegato, 2014). Sanz-Cobena *et al.* (2014) conducted a study to investigate the effect of cover crop planting on greenhouse gas emissions and did not find any statistical differences were found between different cover crop treatments and noticed that one legume cover crop treatment acted as both a source as well as sink in different seasons. Other studies (Guardia *et al.*, 2016a; Guardia *et al.*, 2016b) have also found no significant impact of cover crops on the emissions of CH_4.

Production and consumption of GHGs in soil are microbial processes and the fluxes of these gases from grassland soils are interdependent on grazing management (Chiavegato *et al.*, 2015). The emission of N_2O is highly variable spatiotemporally within a grassland ecosystem, due to the heterogeneous distribution of urine and dung patches and variability of edaphic properties that control soil water status. Cai and Akiyama (2016) reported that N_2O release from animal excreta is due to the enhanced nitrification and denitrification. The ICLS added more C in soil and lowered CO_2 and N_2O emissions as compared to no tillage, conventional tillage and permanent pasture systems, thus found to be highly efficient system by Salton *et al.* (2014). Studies have also shown that better grazing management reduces CO_2 emissions through carbon (C) sequestration on grazing lands (Conant *et al.*, 2001) and due to decreased leaf area index (Bremer *et al.*, 1998). The CH_4 emissions from the grazing livestock mainly come from enteric fermentation (Gerber *et al.*, 2013). Microbial activity on the deposited cow dung over the soil surface can also act as a source of CH_4 emissions. Mixed results regarding the emission of this gas as influenced by grazing have been reported in the previous studies. Some studies have shown that grazing can have an adverse effect on the absorption of CH_4 into soils (Chen *et al.*, 2011; Salton *et al.*, 2014). The ICLS can also reduce the absorption rate of CH_4 (Dong *et al.*, 2000; Liu *et al.*, 2007; Schönbach *et al.*, 2012). On the other hand, no significant impact of grazing on the emissions of CH_4 have also been demonstrated by some studies (Chen *et al.*, 2011; Tang *et al.*, 2013). Liebig *et al.* (2010) conducted a study in Northern Great Plains of USA to investigate the net global warming potential as influenced by moderately grazed pasture, heavily grazed pasture and heavily grazed crested wheatgrass and observed that the grazing had no significant impact on CH_4 fluxes and acted only as small sinks of CH_4.

2.5. HYDRUS Model for Simulating Soil Water Content and Temperature

To understand various features of hydrology that include soil water flow, deep drainage, infiltration, evaporation, soil moisture storage, water uptake by plant roots, groundwater recharge, runoff, and erosion, the knowledge of variably saturated zones is crucial. As soil system is very complex, the utilization of modeling techniques to simulate the fate of water in variably saturated zones is essential. HYDRUS (Simunek *et al.*, 2005) and 2D/3D (Šimůnek *et al.*, 2006)] model efficiently simulates water, solute, heat and gas flow in unsaturated and partially or fully saturated porous media. For simulating saturated and unsaturated flow of water, this model uses the Richards' equation, which includes a sink term to describe absorption of water by plant roots. For solute and heat movement, it solves Fickian-based advection-dispersion equations. Zhao *et al.* (2016) tested the performance of HYDRUS by using an extended freezing code to simulate the heat and water movement in freezing and thawing soils and showed that the freezing module can effectively predict water and heat flow in frozen as well as in unfrozen soils. They concluded that the influence of land management practices and freezing and thawing on soils can be precisely simulated by freezing module in HYDRUS. Du *et al.* (2017) used HYDRUS model to find the processes involved in soil water and vapor flow and reported that soil temperature gradient was the main force that led to vapor movement in the desert soils and matric potential gradient developed by the rainfall caused the movement of the liquid soil water near the surface. Yu *et al.* (2016) examined the effect of twelve cover crops having diverse root systems on soil hydraulic conductivity and their influence on surface runoff using HYDRUS and found that cover crops with highly dense roots and coarse root axes increase hydraulic conductivity of soil and effectually decrease surface runoff.

HYDRUS model has been used invariably by various researchers across the world for different purposes such as to simulate the heat and water movement in freezing and thawing soils (Zhao *et al.*, 2016), to examine water flow and water loss in soils planted with direct seeded rice (Li *et al.*, 2014), to quantify nutrient leaching as influenced by winter cover cropping (Honegger and Kalita, 2015), to study soil moisture dynamics (Chen *et al.*, 2014; Kodešová *et al.*, 2014), soil temperature dynamics (Kodešová *et al.*, 2014), water uptake by plant roots (Deb *et al.*, 2013), testing of heat sensor (Saito *et al.*, 2007), coupled movement of liquid water, vapor and heat in unsaturated soils (Deb *et al.*, 2011), among others.

2.6. Research Gaps

The literature reviewed reveals that previous studies have evaluated the impacts of cover crops and grazing on soil physical properties and GHG emissions separately under diverse environmental conditions. However, there are some research gaps among the studies those are mentioned below as.

1. Previous studies have explored the impacts of cover crops and grazing separately on soils and environmental quality, however, studies that assessed the impacts of cover crops and grazing under an ICLS on soil physical and hydrological properties and GHG emissions are very limited.

2. Very few studies have studied soil pore parameters in the soils managed under long-term ICLS using X-ray CT scanning technique, that can provide spatial and geometrical characteristics of soil pores.

3. Little is known about the behavior of soil water and temperature regime under an ICLS.

Therefore, the present study will take an opportunity to fill the above mentioned research gaps with the major goal of the study was to assess the impacts of cover crops and grazing cover crops and row crop residue under integrated crop-livestock system on soil physical (e.g., bulk density, penetration resistance, water stable aggregates, porosity) and hydrological properties (water retention, saturated hydraulic conductivity, infiltration rate), and GHG emissions.

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CHAPTER 3

SOIL HYDROLOGICAL PROPERTIES AS INFLUENCED BY COVER CROPS AND GRAZING UNDER A SHORT-TERM INTEGRATED CROP-LIVESTOCK SYSTEM

ABSTRACT

Cover crops and grazing play a critical role in successful implementation of the integrated crop-livestock system (ICLS) because they can have a direct impact on soils. The present study was conducted to assess the impacts of cover crops and grazing on soil physical and hydrological properties. Two sites [northern Brookings (Brookings-N) and northwestern Brookings (Brookings-NW)] were established in 2016 and 2017, respectively, in South Dakota. Specific objective was to evaluate the impact of cover crops (CCs) and grazed CCs under oat (*Avena sativa* L.)–CCs–corn (*Zea mays* L.) rotation on soil physical and hydrological properties. Study treatments included (i) legume-dominated CC (LdC), (ii) cattle-grazed LdC (LdC+G), (iii) grass-dominated CC (GdC), (iv) cattle-grazed GdC (GdC+G), and (v) without CC or grazing (NC). Cover crops had lower soil bulk density (ρ_b) and soil penetration resistance (SPR) at 0-10 and 10-20 cm depths and, in general, higher soil water retention (SWR) and total porosity compared to the NC at either site. Cattle grazing generally increased the ρ_b and SPR at both depths, however, the SPR did not surpass the critical values for root proliferation at either depth. Soil water retention and total porosity were decreased in response to the grazing. In conclusion, cover cropping in our shorter duration (2-3 yr) study) enhanced some soil physical attributes, however, grazing cover crops and crop residue had small or neutral effects on soils.

Keywords: Soil physical and hydrological properties, Grazing, Integrated crop-livestock system, Cover crops

3.1. Introduction

Rapid conversion of grasslands to croplands and expansion of row crop agriculture and monocropping have been observed in the Northern Great Plains (Wright and Wimberly, 2013; Clay *et al.*, 2014; Kumar *et al.*, 2019). Due to this conversion, the area under corn (*Zea mays* L.) and soybean (*Glycine max* L.) increased from 8.3 to 10.4 and 4.7 to 8.4 million acres in South Dakota (SD) and North Dakota (ND), respectively, between 2004 to 2014 (Wimberly *et al.*, 2017). This historical conversion of land-use from native vegetation to croplands resulted in sharp declines in soil organic carbon, reduced soil quality, and hence led to a significant source of atmospheric CO_2 emissions and erosion. Incorporation of diverse CCs, and grazing CCs and crop residue under integrated crop-livestock system (ICLS) can be an alternate option for enhancing soil organic carbon and hence the soil physical and hydrological properties (Rakkar and Blanco-Canqui, 2018). The ICLS is a practice of using crops and livestock on a single farm in a way that they complement each other spatiotemporally, concurrently, or separately and in rotation or in succession (de Moraes *et al.*, 2014). A few examples of commonly implemented ICLS in the U.S. include animal grazing of CCs within cash crop rotations, crop residue grazing, silvopasture and agroforestry (crops grown for grain harvesting among young trees or forage planting for grazing), sod based crop rotation (perennial forage for grazing with crops), and dual purpose cereal crops (harvesting for grains followed by grazing e.g. corn) (Sulc and Franzluebbers, 2014). Being the most diversified type of farming system in the world, the ICLS exhibits the complementarity between crops and livestock, emerging out of complex interactions among soil-plant-animal-atmosphere (de Moraes *et al.*, 2014). The sustainability, functional diversity and self-sufficiency of ICLS (Tichit *et al.*, 2011) create an opportunity to enhance the efficiency of ecologically based farming systems (Hendrickson *et al.*, 2008).

Cover crops and grazing are the integral parts of an ICLS. Cover crops can be defined as spatially-close growing plants that aid in protection of soil and improve soil health (Fageria *et al.* (2005). Cover crops when used for long-term duration can increase soil water content and decrease maximum compactibility (Blanco-Canqui *et al.*, 2012). Steele *et al.* (2012) found that the application of winter annual cereal CCs for 13 years increased aggregate stability of soils. Abdollahi and Munkholm (2014) showed that continuous use of CCs for five years decreased penetration resistance and ameliorated plow pan compaction at 20-40 cm depth. Water infiltration rates and soil aggregate stability were enhanced by cultivating CCs under no-till crop rotations (Mitchell *et al.*, 2017). Abdollahi *et al.* (2014) established that planting of CCs increased soil macroporosity thereby enhancing air and water flow through the soil, which resulted in improved root growth. Several researchers have shown positive impact of CCs on soil structural properties in terms of improved soil aggregation, decreased bulk density, penetration resistance, enhanced water infiltration and macroporosity (Chen and Weil, 2010; Haruna and Nkongolo, 2015; Alvarez *et al.*, 2017). However, these CCs may not be effective for enhancing soil properties when used for shorter durations. A three-year study conducted by Welch *et al.* (2016) demonstrated that CCs did not affect soil physical properties and did not reduce the soil compaction. Similarly, Mubiru and Coyne

(2009) reported that soil bulk density remained unaffected when they cultivated four different CC species into fallow under degraded soils in a two-year study. In another two-year study conducted by Carof *et al.* (2007) under no-till management, CCs showed no effect on soil hydraulic conductivity, however increased the macroporosity. There are also other studies that reported minimal or no influence of CCs on soil physical properties (Kaspar *et al.*, 2001; Sainju *et al.*, 2003). Cover crops thus have a variable impact on soil properties and depend on site-specific soils, environment and management practices (Fronning *et al.*, 2008).

Livestock grazing, another component of ICLS can also significantly impact soil structural attributes (Drewry *et al.*, 2008). High external pressures exerted by animals or farm machinery can lead to the problems such as increased soil compaction due to increased bulk density and penetration resistance, and reduced macroporosity and water infiltration rates (Abdalla *et al.*, 2018; Byrnes *et al.*, 2018). Increased soil compaction creates a hindrance to root growth and obstructs the movement of air and water throughout the profile which limits the aeration to the plant roots. Pulido *et al.* (2016) conducted a study to assess the impact of heavy grazing on soil quality and found an increase in soil bulk density in 5-10 cm depth in the enclosures having animal stocking rates higher than 1AU ha^{-1}. Similar results were observed in the 12-year study conducted by Pulido *et al.* (2016), where continuously grazed watersheds showed an increase of 8% in soil bulk density.

There is enough body of literature available that discusses the impacts of CCs and grazing on soil properties. However, studies exploring the impacts of CCs and grazing under an ICLS on soil physical and hydrological properties are very limited. Thus, we hypothesize that multispecies CCs and grazing under an ICLS can enhance soil organic carbon and hence the soil physical and hydrological properties. The specific objective of this study was to evaluate the impact of CCs and grazed CC and corn residue under oat–CC–corn rotation on soil physical and hydrological properties.

3.2. Materials and Methods

3.2.1. Experimental Site, Treatments and Experimental Design

A field experiment to evaluate the impacts of ICLS on soil physical and hydrological properties at two sites, Brookings-north (N) and NW-Brookings-northwest (NW), was conducted at the research farm of South Dakota State University, Brookings, SD, USA. Brookings-N and Brookings-NW sites were established in 2016 and 2017, respectively, and the study was conducted for two years (2018-2019) at each site. Soils at the Brookings-N (44°20'34.8"N, 96°48'14.8"W) and Brookings-NW site (44°20'14.5"N 96°48'28.8"W) were classified as Fordville (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Pachic Hapludolls) and Barnes (fine-loamy, mixed, frigid Udic Haploborolls), respectively. The basic soil physical and chemical properties of the study area are shown in Table 3.1. The experimental areas were characterized with a continental climate having warm and humid summers, and cold and snowy winters.

The experimental design at either site was a randomized complete block design comprising of five treatments viz., (i) legume dominated CC (LdC), (ii) cattle grazed LdC (LdC+G), (iii) grass dominated CC (GdC), (iv) cattle grazed GdC (GdC+G), and (v) without CC and grazing (NC) with 4 replications. The plot sizes at the Brookings-N and Brookings-NW were 18.3 m × 27.4 m, and 18.3 m × 30.5 m, respectively. The cropping system at these sites was oat (*Avena sativa* L.)-corn (*Zea mays* L.). The CC mixtures at each site were planted in 19-cm wide rows using a grain drill [John Deere 750 series grain drill (Deere and Co., Moline, Illinois, USA)] after the harvest of oats. The grazing treatment at either site included the grazing of CC and corn residue with a herd of Aberdeen Angus (*Bos taurus*), a breed of cattle commonly used for beef production in South Dakota. An electric fencing around the grazed plots was made to prevent disturbance of the ungrazed plots by grazing animals. During the grazing, the animals were present all the time in the grazed plots. The stocking rate of cattle was determined on the basis of quantity of above-ground crop biomass available in the field for grazing assuming 12.7 kg of dry matter consumed per animal per day (Uresk, 2010). Following the best management practices for livestock grazing, the aim of cattle grazing was to utilize approximately one-half of the available biomass and leave the other half on the soil to prevent soil erosion. Additional information about the study sites can be obtained from Singh *et al.* (2020).

3.2.2. Soil Sampling and Analysis

Undisturbed soil cores (7.62 cm i.d. × 7.62 cm long) were extracted from 0-10 and 10-20 cm depths to determine the soil bulk density and water retention. Soil samples from each plot were also collected with a soil auger at 0-10 cm and 10-20 cm depths from either site in 2018 and 2019 after the harvest of oats and corn. The samples were then air-dried at room temperature and sieved to 2-mm after removing all visible residues.

3.2.3. Carbon and Nitrogen Fractions

Cold and hot water extractable organic carbon and nitrogen fractions were measured based on the procedure outlined by Ghani *et al.* (2003). Briefly, 3 g of soil was mixed with 30 ml of distilled water in 50 ml polypropylene centrifuge tube, shaken on vortex shaker for 10 seconds. Soil solution was further shaken on a rotatory shaker for 30 minutes at 40 revolutions per minute (rpm). Then, the solution was centrifuged at 3000 rpm for 25 minutes at 4°C. The resulting suspension was filtered with 0.45 µm pore size syringe filters and the filtrate obtained is cold-water extractable organic carbon (CWEC) and nitrogen (CWEN). The left-over soil was again mixed with 30 ml of distilled water and was shaken on vortex shaker for 10 seconds. This soil solution was subjected to hot-water bath at 80°C for 12-15 hours, followed by shaking on vortex shaker for 10 seconds, and centrifugation at 3000 rpm for 25 minutes at 25°C. The obtained suspension was filtered with 0.45 µm pore size syringe filters and the resulting filtrate is hot-water extractable organic carbon (HWEC) and nitrogen (HWEN). The concentration of cold and hot water extractable C and N fractions was determined with the TOC-L analyzer (Shimadzu Corporation, model-TNM-L-ROHS).

3.2.4. Soil Bulk Density and Penetration Resistance

For each layer sampled, soil bulk density (ρ_b) was measured using the core method (Grossman and Reinsch, 2002). Soil penetration resistance (SPR) for both the layers was measured with an Eijkelkamp-type hand penetrometer (Herrick and Jones, 2002). The measurements were taken at five points in each plot and the average value was used to represent the SPR of each plot at each depth. Soil samples were also taken from both the depths to determine the gravimetric moisture content (*w*) to confirm whether the differences in SPR were in response to the *w* or the treatments.

3.2.5. Infiltration Rate and Model Fitted Parameters

Water infiltration rate was measured using a single-ring infiltrometer with 25.4 cm inner diameter and 20 cm in height using a constant-head method until a steady state was achieved (Reynolds *et al.*, 2002). The measured infiltration data was fitted with a physically based infiltration model, Green and Ampt (1911). Green-Ampt infiltration model was fit to infiltration data as a function of time. The Green-Ampt infiltration model was modified by Philip (1957) for time (*t*) vs. cumulative infiltration (*I*), and is given as:

$$t = \frac{I}{K_s} - \frac{\left[S^2 \ln\left(1 + \frac{2IK_s}{S^2}\right) \right]}{2K_s^2}$$

where *t* is time (h), *I* is the cumulative infiltration (mm), *S* is the sorptivity (mm $h^{-0.5}$), and K_s is the saturated hydraulic conductivity (mm h^{-1}). The procedures proposed by Clothier and Scotter (2002) were followed to estimate the *S* and K_s parameters based on the cumulative infiltration. The initial *S* parameter was estimated from the ratio of initial infiltration and $(time)^{0.5}$, and the initial K_s value was the steady state infiltration rate (mm h^{-1}). The sorptivity (*S*) parameter is related to initial infiltration rate, which strongly depends upon the antecedent soil water content.

The *S* and K_s parameters can be estimated to describe infiltration data.

3.2.6. Soil Water Retention and Pore-Size Distribution

A cheesecloth was fixed at the bottom of each soil core extracted from 0-10 cm depth, and the cores were saturated with water by capillarity, drained and weighed at eight (0, -0.4, -1.0, -2.5, -5.0, -10.0, -20.0 and -30.0 kPa) matric potentials (ψ_m) using a combination of tension table and pressure plate extractors (Soil moisture Equipment Corp.) (Klute and Dirksen, 1986). Pore-size distribution (PSD) for each treatment was determined from the measured soil water retention (SWR) data. Equivalent pore radius was estimated using the capillary rise equation (Hillel, 1998). Pore-size classes based on their corresponding effective diameters were grouped into macropores (>1000 μm equivalent cylindrical diameter, ecd), coarse mesopores (60 to 1000 μm ecd), fine mesopores (10 to 60 μm ecd) and micropores (<10 μm ecd) (Jury *et al.*, 1991).

3.2.7. Statistical Analysis

Statistical comparisons of differences in soil physical and hydrological properties among different treatments for each depth were obtained using pairwise differences method (adjusted by Tukey) by a mixed model, where treatments were defined as fixed effects and the replication as random effects in SAS 9.4 (SAS, 2013). Single degree-of-freedom contrasts were also determined to compare specific treatments and were conducted as follows: grazed vs. ungrazed, CCs vs. no CCs and grazed vs. control. Significance was determined at $\alpha = 0.05$ level for all statistical analysis in this study.

3.3. Results

3.3.1. Labile Carbon and Nitrogen Fractions

At Brookings N, cold water extractable organic carbon (CWEC) was significantly higher under GdC (321.0 μg C g soil^{-1}) as compared to that under LdC (274.4 μg C g soil^{-1}) at 0-10 cm depth in 2018 (P=0.03) (Table 3.2). The values for CWEC were statistically similar among the treatments at 10-20 cm depth. However, CWEC was different for GZ vs. UG contrast, where these values were higher for UG (251.8 μg C g soil^{-1}) than the GZ (218.2 μg C g soil^{-1}) at 10-20 cm depth (Table 3.3). The CWEN was not influenced by the treatments at both the depths in 2018. Significantly higher HWEC under GdC+G (1568.3 μg C g soil^{-1}) than that under LdC+G (1370.0 μg C g soil^{-1}) and NC (1392.8 μg C g soil^{-1}) was recorded at the surface depth (P=0.04) in 2018 (Table 3.2). The HWEN was statistically similar among the treatments at both the depths. In 2019, CWEC was not influenced by the treatments at 0-10 cm depth (Table 3.4). However, at 10-20 cm depth, significantly higher CWEC was observed in GdC (267.7 μg C g soil^{-1}) as compared to that in LdC (228.3 μg C g soil^{-1}) and NC (199.0 μg C g soil^{-1}). At this depth, CWEC was different for UG vs. NC (P=0.01) and GZ vs. NC (P=0.03) contrasts, where these values were higher for UG (248.0 μg C g soil^{-1}) and GZ (239.9 μg C g soil^{-1}) when compared to the NC (199.0 μg C g soil^{-1}) (Table 3.5). The values for CWEN were statistically similar among the treatments at 0-10 and 10-20 cm depths. However, CWEN was different for GZ vs. NC contrast, where these values were higher for GZ (33.4 μg N g soil^{-1}) than the NC (26.3 μg N g soil^{-1}) at 10-20 cm depth (Table 3.5). Significantly higher HWEC was recorded in GdC (1599.3 μg C g soil^{-1}) as compared to that in LdC (1478.5 μg C g soil^{-1}) and NC (1288.0 μg C g soil^{-1}) at the surface depth. Significant differences in HWEC were observed for the contrasts UG vs. NC ($P<0.01$) and GZ vs. NC ($P<0.01$) for 0-10 cm depth. Also, HWEC was significantly enhanced in GdC (679.3 μg C g soil^{-1}) and LdC (679.6 μg C g soil^{-1}) compared to the NC (503.5 μg C g soil^{-1}) at 10-20 cm depth (Table 3.4). The values of HWEC for all three contrasts (i.e., UG vs. NC, GZ vs. UG and GZ vs. NC) were significantly different ($P<0.05$) for 10-20 cm depth and suggested greater HWEC with CCs and grazing compared to the control (Table 3.5). At surface depth, HWEN was not influenced by the treatments ($P>0.05$; Table 3.4). However, at sub-surface depth, significantly higher HWEN was recorded in LdC (85.0 μg N g soil^{-1}) compared to the NC (50.5 μg N g soil^{-1}). The values of HWEN were significantly different for the contrasts viz. UG vs. NC and GZ vs. NC, and indicated higher HWEN for UG (72.6 μg N g soil^{-1}) and GZ (68.7 μg N g soil^{-1}) than that of the NC (50.5 μg N g soil^{-1}) at sub-surface depth (Table 3.5) at Brookings-N site.

At Brookings NW, the values for CWEC were statistically similar among the treatments at 0-10 cm depth in 2018 (Table 3.2). However, CWEC was different for contrasts UG vs. NC ($P=0.02$) and GZ vs. NC ($P=0.01$), where these values were higher for UG (234.5 μg C g soil^{-1}) and GZ (238.6 μg C g soil^{-1}) when compared to the NC (203.5 μg C g soil^{-1}) at 0-10 cm depth (Table 3.3). At 10-20 cm depth, CWEC was not affected by the treatments ($P=0.49$). Cold water extractable organic nitrogen was significantly higher under GdC (34.0 μg N g soil^{-1}) and LdC (33.3 μg N g soil^{-1}) as compared to that under NC (23.9 μg N g soil^{-1}) at 0-10 cm depth in 2018 ($P<0.01$) (Table 3.2). The values of CWEN for all three contrasts (i.e., UG vs. NC, GZ vs. UG and GZ vs. NC) were significantly different ($P<0.05$) for 0-10 cm depth and showed higher

CWEN in UG (33.6 μg N g soil^{-1}) and GZ (27.4 μg N g soil^{-1}) than in the NC (23.9 μg N g soil^{-1}) (Table 3.4). The HWEC and HWEN were not influenced by the treatments at each depth in 2018 (P>0.05; Table 3.2). In general, C and N fractions were found to be statistically similar among the treatments, at both depths in 2019 at this site (P>0.05; Table 3.4).

3.3.2. Soil Bulk Density and Penetration Resistance

Soil bulk density and penetration resistance, which were used to assess the implications of CC and grazing on soil compaction at 0-10 cm and 10-20 cm depths at Brookings-N and Brookings-NW sites, are reported in Figs. 1-4. At Brookings-N, a significant reduction in ρ_b was observed under GdC (1.32 Mg m^{-3}), GdC+G (1.31 Mg m^{-3}) and LdC (1.27 Mg m^{-3}) compared to the NC (1.42 Mg m^{-3}) at 0-10 cm depth in 2018 (Fig. 1A). Significant differences in ρ_b were observed for the contrasts UG (1.30 Mg m^{-3}) vs. NC (1.42 Mg m^{-3}) (P<0.01) and GZ (1.36 Mg m^{-3}) vs. UG (1.30 Mg m^{-3}) (P=0.02) for 0-10 cm depth, except that ρ_b was not significant for GZ vs. NC contrast (Table 3.8). A similar trend was observed at 10-20 cm depth, where GdC, GdC+G, LdC, LdC+G had significantly lower ρ_b compared to the NC. The bulk density for contrasts UG vs. NC and GZ vs. NC were significant at this depth in 2018 and indicated a decrement in ρ_b with UG and GZ in comparison with NC. Soil penetration resistance (SPR) was affected by CC and grazing treatments in 2018 (Fig. 2). In the 0-10 cm soil layer, the GdC (0.68 MPa) and LdC (0.47 MPa) had significantly lower SPR compared to the NC (0.96 MPa). A significant increase in SPR under GZ (0.88 MPa) than the UG (0.58 MPa) and a significant decrease under UG (0.58 MPa) compared to the NC (0.96 MPa) were recorded in 2018 (Table 3.8). At 10-20 cm depth, SPR was not influenced by the treatments (Fig. 2B), however, the values of SPR were different for the contrasts GZ vs. UG and UG vs. NC and indicated an enhancement in SPR under GZ and reduction under UG when compared with UG and NC, respectively. In 2019, ρ_b was significantly lower under LdC (1.21 Mg m^{-3}) and LdC+G (1.20 Mg m^{-3}) compared to the NC (1.27 Mg m^{-3}) at surface depth (Fig. 1C). The values of SPR for contrast UG vs. NC were different and showed reduction in ρ_b at surface depth with cover cropping. In sub-surface soil layer, ρ_b was not affected by the treatments (Fig. 1D), however, ρ_b was different for the contrast GZ vs. UG and showed higher ρ_b under GZ (1.40 Mg m^{-3}) compared to the UG (1.33 Mg m^{-3}). Cover cropping and grazing treatments showed a significant reduction in SPR at surface depth compared to the NC in 2019 (Fig. 2C). The SPR was different for the contrasts viz., UG vs. NC, GZ vs. UG and GZ vs. NC ($P<0.01$) at 0-10 cm depth, where SPR under UG and GZ was lower compared to that under NC (Table 3.8). The values of SPR were similar among the treatments at 10-20 cm depth, however, UG (1.55 MPa) showed significantly lower SPR when compared with NC (1.86 MPa).

At Brookings-NW, ρ_b among different treatments was statistically similar at 0-10 cm depth in 2018 (Fig. 3A). The ρ_b was different for the contrast UG vs. NC and indicated reduction in ρ_b under UG (1.39 Mg m^{-3}) in comparison with NC (1.51 Mg m^{-3}) (Table 3.8). At 10-20 cm depth, no influence of treatments on ρ_b was noticed in 2018. The SPR was significantly reduced by grass and legume dominated CCs and their grazing, compared to that of the NC at surface depth (Fig. 4A). Significant differences in SPR were observed for contrasts UG vs. NC, GZ vs. UG and GZ vs. NC at this depth ($P<0.01$; Table 3.8) and indicated alleviation of soil compaction in comparison with the

NC. The values for SPR were higher for the sub-surface soil layer and LdC recorded significantly lower SPR (1.42 MPa) than the NC (2.37 MPa) in 2018. The SPR differed for all the contrasts in this layer ($P<0.05$) and showed a trend similar to that of the surface layer. In 2019, GdC (1.29 Mg m^{-3}) and LdC (1.36 Mg m^{-3}) showed a significant reduction in ρ_b compared to the NC (1.48 Mg m^{-3}) at surface depth (Fig. 3C). The values of ρ_b differed for the contrasts UG vs. NC and GZ vs. UG at this depth and indicated an increase in ρ_b in response to grazing and decrease in response to cover cropping. A similar trend in ρ_b was observed for the contrasts at sub-surface depth. The SPR was not influenced by the treatments at 0-10 cm depth in 2019, however, the values of SPR were different for contrasts UG vs. NC and GZ vs. UG and showed higher SPR under GZ (1.24 MPa) compared to the UG (1.10 MPa) and lower SPR for UG (1.10 MPa) than for NC (1.34 MPa) ($P<0.05$; Table 3.8). At 10-20 cm depth, SPR under NC (1.78 MPa) was significantly higher than that under GdC (1.36 MPa), GdC+G (1.40 MPa) and LdC (1.37 MPa) (Fig. 4D). The values of SPR differed for UG vs. NC and GZ vs. NC contrasts, and were lower under UG (1.36 MPa) and GZ (1.47 MPa) in comparison with the NC (1.78 MPa) ($P<0.01$; Table 3.8).

3.3.3. Soil Water Retention and Pore Size Distribution

At the Brookings-N site, soil water retention (SWR) differed among the treatments at six (0, -0.4, -1.0, -2.5, -5.0 and -10.0 kPa) of the eight Ψ_m in 2018 ($P < 0.05$; Fig. 5A). Water retained in soils under LdC was significantly 17, 16, 15, 14% higher at the 0, −0.4, −2.5, and −5.0 kPa Ψ_m, respectively, than the NC. The values of SWR differed for the contrast UG vs. NC and indicated that water retained at 0, −0.4, −2.5, and

−5.0 kPa Ψ_m was 13, 13, 14 and 13% greater under UG than that under NC, respectively ($P<0.05$). The SWR differed for GZ vs. UG contrast, where GZ recorded 10, 9, 9, 10 and 10% lower SWR than the UG at 0, −0.4, −1.0, −2.5, and −5.0 kPa Ψ_m, respectively (Table 3.9). In 2019, LdC retained significantly higher water at 0, −0.4, −1.0, −10.0, −20.0 and −30.0 kPa Ψ_m compared to the NC ($P<0.05$; Fig. 5B). The SWR was different for contrasts UG vs. NC and GZ vs. UG at all the eight Ψ_m and suggested greater SWR with UG than NC and lower with GZ than the UG.

At the Brookings-NW site, SWR was not affected by the treatments in 2018 ($P>0.05$; Fig. 5C). However, in 2019, the treatments influenced the SWR at all eight Ψ_m (0 to -30.0 kPa). Soils under LdC retained 17, 19, 20, 18, 17, 18, 19 and 21% more water compared to the NC at 0, −0.4, −1.0, −2.5, −5.0, −10.0, −20.0 and −30.0 kPa Ψ_m, respectively (Fig. 5D). Significantly higher SWR values were recorded in UG at 0, −0.4, −1.0, −10.0 and −20.0 kPa Ψ_m, when compared with that of NC. The SWR differed at all the eight Ψ_m for GZ vs. UG ($P<0.05$) with lower water content under GZ than that under UG (Table 3.10).

Data on the pore size distribution (PSD) under different treatments of cover cropping and grazing at Brookings-N and Brookings-NW sites for 2018 and 2019 are shown in Tables 3.11 and 3.13, respectively. At Brookings-N site, total pores were significantly influenced by the treatments ($P<0.01$) in 2018, where LdC (0.626 m^3 m^{-3}) recorded higher total pores compared to that of the NC (0.536 m^3 m^{-3}) (Table 3.11). Total pores were significant for the contrasts UG vs. NC and GZ vs. UG, showing an enhancement in soil porosity with UG (0.608 m^3 m^{-3}) compared with the NC (0.536 m^3 m^{-3}) and reduction with GZ (0.546 m^3 m^{-3}) compared to the UG (0.608 m^3 m^{-3}) (Table

3.12). In 2019, soil porosity was significantly impacted by the CC and grazing treatments. The values of macroporosity were different for the contrasts UG vs. NC and GZ vs. NC and showed significant improvement in macropores by UG (0.010 m^3 m^{-3}) and GZ (0.004 m^3 m^{-3}) treatments when compared with the NC (0.001 m^3 m^{-3}) ($P<0.03$; Table 3.14). Fine mesopores were significantly higher with LdC+G (0.062 m^3 m^{-3}) than with the GdC+G (0.041 m^3 m^{-3}) (Table 3.13). The LdC treatment significantly increased soil micropores and total pores by 15% and 22% than the NC, respectively. An increase in micropores and total pores was noticed under UG compared to the NC and a decrease in these was recorded with GZ compared to the UG ($P<0.05$; Table 3.14).

At Brookings-NW site, coarse mesopores were significantly influenced by the treatments ($P<0.01$) in 2018, where LdC (0.061 m^3 m^{-3}) recorded higher coarse mesopores compared to that of the NC (0.043 m^3 m^{-3}) (Table 3.11). The coarse mesoporosity differed for the contrasts viz., UG vs. NC and GZ vs. UG and suggested an increment in coarse mesopores with UG (0.059 m^3 m^{-3}) compared with the NC (0.043 m^3 m^{-3}) and reduction with GZ (0.037 m^3 m^{-3}) compared to the UG (0.059 m^3 m^{-3}) (Table 3.12). In general, this trend was observed in all the pore types in 2018, however, the differences were not always significant. In 2019, significantly higher coarse mesopores were recorded under UG (0.056 m^3 m^{-3}) than under NC (0.038 m^3 m^{-3}) and lower under GZ (0.036 m^3 m^{-3}) when compared with the UG (0.056 m^3 m^{-3}). Micropores and total pores were increased by LdC in comparison with the NC ($P<0.01$; Table 3.13). Cover crops significantly improved total pores (0.577 m^3 m^{-3}) compared to the NC (0.507 m^3 m^{-3}) and GZ significantly reduced these (0.508 m^3 m^{-3}) compared to the UG (0.577 m^3

m^{-3}). An identical trend was also observed in micropores, whereas it was significant only for the contrast GZ vs. UG.

3.3.4. Ponded Infiltration Measurements

Data for quasi-steady infiltration rate (q_s) and estimated Green-Ampt infiltration parameters (S and K_s) for the GdC, GdC+G, LdC, LdC+G and NC treatments at Brookings-N and Brookings-NW sites are shown in Table 3.15. Green–Ampt model fitted the measured infiltration data well with coefficients of determination (r^2) ranging from 0.98 to 0.99. At Brookings-N site, Green-Ampt estimated S parameter was not significantly different among the treatments, however, in general, higher values for this parameter were observed under cover cropping and grazing treatments than that under the NC. A similar trend was observed for K_s parameter, where UG significantly increased K_s (413.9 mm hr^{-1}) compared to that of the NC (97.7 mm hr^{-1}) (P=0.03; Table 3.16). Quasi-steady infiltration rate was significantly different for UG vs. NC contrast, where it was 3.7 times higher in UG than the NC (P=0.03). At Brookings-NW site, S parameter was 3.7 times higher for GdC than that for the NC (P=0.04). A similar trend was observed for K_s parameter; however the differences were not significant. Significantly higher q_s was recorded for the GdC (39.4 mm hr^{-1}) compared to the NC (4.3 mm hr^{-1}). The q_s was different for the contrast GZ vs. UG and indicated a significant reduction in q_s with GZ compared to the UG.

3.4. Discussion

3.4.1. Labile C and N Fractions

Soil labile C and N fractions are greatly affected by factors such as temperature and rainfall and are sensitive to management practices such as CCs and grazing. The HWEC comprises of easily available substances such as carbohydrates, phenols, and lignin monomers (Landgraf *et al.*, 2006). During the extraction of HWEC, other pools of labile nutrients such as nitrogen, sulfur and phosphorus are also extracted along with C (Ghani *et al.*, 2003). Thus, it is considered as most sensitive and consistent indicator of soil quality that responds to changes in the root zone caused by management practices. The labile C and N fractions can act as a short-term reserve of nutrients and energy for crop growth in agricultural ecosystems (Needelman *et al.*, 1999). In the present study, CCs, in general, increased the labile C and N fractions compared to the no CC. This may be due to the fact that CC and crop residue inputs provide C and N sources for microbes, resulting in the decomposition of crop residues, while lack of crop C and N inputs in the control treatment resulted in the lowest labile C and N content. Furthermore, within CC types, GdC had higher labile C contents (not always significant), which is likely due to their higher C:N ratio as compared to those of the LdC. Increase in labile C and N fractions could be due to the increase in microbial activity that can lead to improved soil physical conditions (Singh *et al.*, 2019). Grazing showed mixed responses on labile fraction of C and N in the current study. The mixed results of labile C and N fractions among the treatments are possibly due to the shorter duration of this study. The labile C and N fractions are known to be more sensitive towards the management practices. An increase in C and N fraction in response to the low intensity grazing was reported by Dubeux Jr *et al.* (2006) because a major proportion of the C inputs tended to accumulate in the labile fraction of C and N. The removal of plant biomass promotes plant regrowth hence enhance nutrient cycling within the rhizosphere (Sainepo *et al.*, 2018).

3.4.2. Soil Bulk Density and Penetration Resistance

The reduction in soil compaction indicators such as bulk density and penetration resistance due to cover-cropping may be attributed to the additions of organic residues and higher activity of micro and macro fauna and roots in the surface depth (Soane, 1990) in the CC plots compared to the NC (Figs. 1-4). Furthermore, CCs having deep tap roots such as radish (a part of the CC blends used in this study) have been known to act as a bio-drills that can penetrate the compact soil layers and alleviate the soil densification. Soil compaction can result into mechanical impedance to root growth and can negatively affect water transmission and storage and diffusion of gases through the soils, which can impair overall soil physical quality. An increase in ρ_b and SPR values was observed in the grazed treatments compared to the ungrazed ones, because of the animal trampling occurring due to the pressure from the contact of the hoof with the soil surface. The critical limit of SPR limiting root development is 2.0 MPa (da Silva *et al.*, 1994) , while the threshold limits of ρ_b for silty and sandy soils are 1.65 and 1.80 Mg m^{-3}, respectively (USDA-NRCS, 2008). In other words, the plant roots will likely show morphological changes in response to mechanical resistance offered by the compacted soil. However, it is to be noted that the soil compaction observed in response to grazing in this study was below the threshold limits of ρ_b and SPR suggested as restrictive for root growth. Thus, it can be postulated that grazing in the current study did not elevate ρ_b and SPR beyond the critical values that could limit root growth and development. Grazing of CCs and crop residue, if followed in long-term, may have added benefits in terms of manure addition, which may reduce soil compactibility, serve as a source of plant nutrients for crops and may aid in build-up of soil organic carbon. Thus, the direct manure addition might compensate the effects related to the compaction.

3.4.3. Soil Water Retention and Pore Size Distribution

The improvement in soil aggregation due to CCs compared to the NC can enhance the SWR (Blanco-Canqui *et al.*, 2015). The actively growing roots of CCs play a significant role in soil structuring by drawing the particles closer while growing in pores and releasing exudates that act as cementing agent for the aggregates formation (Calonego and Rosolem, 2011). In addition, the residues of CCs when incorporated in soil provide a carbon source for micro-organisms, which produce mucus and other organic binding agents (Rasool *et al.*, 2008) and result in better soil aggregation. This bonding process improves the soil structure and facilitates better SWR (Bronick and Lal, 2005). Changes in coarse mesoporosity and microporosity were reflected in the increase in SWR characteristics in the cover cropped soils. The results suggested an increase in total porosity of the soils under CCs (Tables 3.11 and 3.13) that could possibly be due to the creation of voids by the CC roots and subsequent improvements in soil structure. The results from our study are in agreement with Villamil *et al.* (2006), who reported an increase in soil porosity and SWR properties and reduction in ρ_b in CC soils and attributed these benefits to the additional residues and SOM in CC soils. Furthermore, high content of C and N fractions, those are labile forms of SOC may have aided in enhancing the SWR and PSD in the soils under CC compared to that of the NC.

The grazing of CC and crop residue decreased the water retained at the measured Ψ_m (Fig. 5). This could be attributed to the alteration of PSD resulting into a reduction of pore volume in response to the animal traffic while grazing, thus reducing SWR. This deformation in soil due to grazing occurs because of stress exerted by the animals over the soil surface and is governed by stress–strain relationships (Dec *et al.*, 2012). Soil deformation occurs when stress employed by the grazing livestock becomes higher than soil strength or the load bearing capacity of the soil (Peth *et al.*, 2006). The stress-strain measurements were not determined in this study; however, the deformation could be indicated by the reduction in void space and the increase in BD and SPR in response to grazing. The reduced volume of soil pores due to grazing can reduce aeration and water movement in the soils which could further lead to water and nutrient loss via runoff. However, it was observed that, although non-significant, the soils under grazed treatments retained more water compared to the NC at all the measured Ψ_m except at Brookings-NW in 2018. Rakkar *et al.*, 2019 conducted a study in the central Great Plains and reported that corn residue grazing at appropriate stocking rates based on residue production has limited impacts on most soil properties in the short term.

3.4.4. Soil Water Infiltration and Green-Ampt Estimated Parameters

Enhanced water infiltration due to CCs was linked to reduced soil compaction, evidenced by lower bulk density and penetration resistance, and increased soil porosity. Crop residue increases the C input in soil, which stabilizes soil aggregates, reduces soil bulk density, and improves soil porosity which further enhances soil water infiltration (Blanco-Canqui *et al.*, 2013). As infiltration is the key process in managing rainwater in the soil, the significant increase in water infiltration under CC can reduce the risk of water loss through runoff. In addition, keeping the residue on the soil may have increased the earthworm activity, thus, water-conducting pores (e.g., burrows) and could have resulted in higher infiltration (Lawal, 2019). Reduction in infiltration, in general, due to grazing might be due the increased soil compaction caused by the cattle hoof pressure. Other researchers have also reported a decrease in infiltration rate and soil porosity with animal traffic (Franzluebbers *et al.*, 2012). However, infiltration rate was not influenced by the short-term cattle grazing on a Typic Dystrochrept in New Zealand (Russell *et al.*, 2001). The trend for reduced infiltration with grazing of CCs and crop residue in our study is consistent with the mixed results in the literature, i.e. reduced or no change in infiltration due to animal grazing.

3.5. Conclusions/Summary

A study was conducted to investigate the influence of cover crops and grazing under a short-term integrated crop-livestock system on soil physical and hydrological properties at two sites. Cover crops, in general, reduced the soil compaction indicators (bulk density and penetration resistance) and enhanced the soil water retention and total porosity at the 0-10 and 10-20 cm for either site. The positive effects of cover crops on soil physical and hydrological attributes suggest that cover crops can improve the water flow in the soils and can reduce the risks of water erosion. Cattle grazing of cover crops and crop residue slightly densified the soil at both the depths, however, these values did not pass the critical limits for root growth. Reduction in soil pore volume in response to grazing was also observed in this study. This study concluded that cover cropping can be beneficial in improving soil physical attributes, however, grazing of cover crops and crop residue impact on these properties were minimal or neutral, indicating the potential of ICLS in improving soil physical quality.

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Table 3.1. Basic soil properties for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths at Northern and Northwestern Brookings sites.

Soil depth cm	Sand	Silt	Clay	Texture	pH	EC dS m^{-1}
	---------g kg^{-1}---------					
Northern Brookings						
0-5	48.7	24.1	27.3	Sandy clay loam	7.39	0.41
5-15	50.5	22.4	27.1	Sandy clay loam	7.75	0.35
15-30	61.2	18.2	20.6	Sandy clay loam	7.93	0.31
30-45	78.5	10.6	10.9	Sandy loam	8.13	0.28
45-60	52.7	28.2	19.0	Sandy loam	8.19	0.30
Northwestern Brookings						
0-5	64.0	19.7	16.3	Sandy loam	7.48	0.28
5-15	45.1	28.5	26.4	Loam	7.46	0.22
15-30	61.0	18.4	20.6	Sandy clay loam	7.71	0.16
30-45	65.7	16.8	17.5	Sandy loam	7.88	0.16
45-60	53.4	23.9	22.7	Sandy clay loam	8.09	0.17

Note. EC, electrical conductivity

Table 3.2. Labile soil carbon and nitrogen fractions for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites in 2018.

Treatment	CWEC (µg C g soil^{-1})		CWEN (µg N g soil^{-1})		HWEC (µg C g soil^{-1})		HWEN (µg N g soil^{-1})	
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
Northern Brookings								
GdC†	321.0a††	263.5a	35.2a	30.0a	1528.3ab	696.5a	178.4a	74.9a
GdC+G	296.7ab	219.7a	31.3a	26.3a	1568.3a	728.8a	179.4a	76.2a
LdC	274.4b	240.2a	30.6a	31.5a	1414.7bc	809.1a	161.9a	98.5a
LdC+G	284.8ab	216.8a	28.8a	25.9a	1370.0c	804.7a	147.0a	90.4a
NC	284.2ab	221.0a	31.3a	24.5a	1392.8bc	708.1a	138.4a	76.0a
P-value	0.03	0.23	0.63	0.65	0.04	0.18	0.05	0.06
Northwestern Brookings								
GdC	235.2	272.6	34.0a	45.6	1023.4	610.8	104.6	58.2
GdC+G	239.3	278.3	26.7c	30.1	917.4	557.2	113.9	57.6
LdC	233.9	241.2	33.3ab	36.5	858.7	581.5	102.6	56.5
LdC+G	237.9	281.3	28.1bc	43.7	865.4	560.4	96.1	55.5
NC	203.5	262.6	23.9c	34.0	865.5	613.7	100.1	56.4
P-value	0.11	0.49	<0.01	0.63	0.10	0.81	0.35	0.98

Note: CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

†GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop

††Means with different letters within a column are significantly different at $P < 0.05$ within the treatment for each site

Table 3.3. Labile soil carbon and nitrogen fractions for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites in 2018.

Treatment	CWEC (μg C g soil^{-1})		CWEN (μg N g soil^{-1})		HWEC (μg C g soil^{-1})		HWEN (μg N g soil^{-1})	
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
Northern Brookings								
GZ†	290.8	218.2	30.1	26.1	1469.2	766.7	163.2	83.3
UG	297.7	251.8	32.9	30.7	1471.5	752.8	170.2	86.7
NC	284.2	221.0	31.3	24.5	1392.8	708.1	138.4	76.0
ANOVA (*P*>*F*)								
UG vs. NC	0.45	0.21	0.68	0.28	0.21	0.49	0.05	0.36
GZ vs. UG	0.53	0.04	0.32	0.32	0.96	0.71	0.53	0.61
GZ vs. NC	0.46	0.87	0.71	0.59	0.39	0.28	0.14	0.41
Northwestern Brookings								
GZ	238.6	279.8	27.4	36.9	891.4	558.8	105.0	56.5
UG	234.5	256.9	33.6	41.1	941.1	596.2	103.6	57.4
NC	203.5	262.6	23.9	34.0	865.5	613.7	100.1	56.4
ANOVA (*P*>*F*)								
UG vs. NC	0.02	0.80	<0.01	0.41	0.30	0.65	0.55	0.77
GZ vs. UG	0.71	0.20	<0.01	0.65	0.34	0.41	0.81	0.85
GZ vs. NC	0.01	0.42	0.04	0.77	0.69	0.30	0.56	0.98

Note: CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

†GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

Table 3.4. Labile soil carbon and nitrogen fractions for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites in 2019.

Treatment	CWEC (µg C g soil^{-1})		CWEN (µg N g soil^{-1})		HWEC (µg C g soil^{-1})		HWEN (µg N g soil^{-1})	
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
				Northern Brookings				
GdC[†]	250.5a[††]	267.7a	25.2a	32.4a	1599.3a	679.3a	172.1a	60.2cd
GdC+G	271.7a	238.5ab	28.4a	36.0a	1460.0b	632.6ab	154.7a	72.8b
LdC	264.8a	228.3bc	31.2a	35.3a	1478.5b	679.6a	148.7a	85.0a
LdC+G	289.2a	241.3ab	35.1a	30.9a	1513.3ab	558.3bc	171.0a	64.6bc
NC	285.0a	199.0c	33.6a	26.3a	1288.0c	503.5c	148.4a	50.5d
P-value	0.22	0.01	0.32	0.32	<0.01	<0.01	0.10	<0.01
				Northwestern Brookings				
GdC	304.5	251.8	28.6	23.9	910.3	547.8	103.6	52.9
GdC+G	325.1	242.4	29.7	26.9	918.5	585.6	105.6	50.1
LdC	302.7	253.9	26.5	29.3	886.6	619.7	100.7	55.4
LdC+G	303.5	226.5	26.3	22.0	896.8	634.6	102.2	57.1
NC	303.3	238.4	28.5	26.8	875.5	561.4	105.4	48.8
P-value	0.86	0.16	0.83	0.09	0.67	0.48	0.96	0.25

Note: CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

[†]GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop

[††]Means with different letters within a column are significantly different at $P < 0.05$ within the treatment for each site

Table 3.5. Labile soil carbon and nitrogen fractions for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites in 2019.

Treatment	CWEC (μg C g soil^{-1})		CWEN (μg N g soil^{-1})		HWEC (μg C g soil^{-1})		HWEN (μg N g soil^{-1})	
	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm	0-10 cm	10-20 cm
				Northern Brookings				
GZ[†]	280.5	239.9	31.8	33.4	1486.7	595.5	162.8	68.7
UG	257.7	248.0	28.2	33.9	1538.9	679.4	160.4	72.6
NC	285.0	199.0	33.6	26.3	1288.0	503.5	148.4	50.5
				ANOVA (*P*>*F*)				
UG vs. NC	0.03	0.01	0.31	0.15	<0.01	<0.01	0.24	0.04
GZ vs. UG	0.09	0.37	0.39	0.91	0.13	0.03	0.74	0.10
GZ vs. NC	0.80	0.03	0.54	0.02	0.01	0.02	0.15	0.01
				Northwestern Brookings				
GZ	314.3	234.5	28.0	24.4	907.6	610.1	103.9	53.6
UG	303.6	252.8	27.5	26.6	898.4	583.8	102.2	54.2
NC	303.3	238.4	28.5	26.8	875.5	561.4	105.4	48.8
				ANOVA (*P*>*F*)				
UG vs. NC	0.98	0.11	0.65	0.95	0.50	0.69	0.60	0.17
GZ vs. UG	0.58	0.02	0.87	0.27	0.63	0.46	0.77	0.84
GZ vs. NC	0.47	0.73	0.88	0.36	0.23	0.32	0.82	0.22

Note: CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

[†]GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

Table 3.6. Soil bulk density and penetration resistance as influenced by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites for 2018 and 2019.

Treatment	ρ_b (Mg m^{-3})				SPR (MPa)			
	2018	2019	2018	2019	2018	2019	2018	2019
	0-10 cm		10-20 cm		0-10 cm		10-20 cm	
				Northern Brookings				
GZ†	1.36	1.23	1.47	1.40	0.88	1.26	1.19	1.73
UG	1.30	1.23	1.43	1.33	0.58	1.10	0.98	1.55
NC	1.42	1.27	1.56	1.33	0.96	1.71	1.22	1.86
				ANOVA (*P*>*F*)				
Treatment	<0.01	<0.01	<0.01	0.12	<0.01	<0.01	0.07	0.19
UG vs. NC	<0.01	0.04	<0.01	0.99	<0.01	<0.01	0.02	0.02
GZ vs. UG	0.02	0.98	0.06	0.03	<0.01	<0.01	0.04	0.15
GZ vs. NC	0.08	0.12	<0.01	0.06	0.26	<0.01	0.82	0.23
				Northwestern Brookings				
GZ	1.43	1.47	1.57	1.51	1.17	1.24	1.88	1.47
UG	1.39	1.33	1.55	1.45	0.87	1.10	1.56	1.36
NC	1.51	1.48	1.54	1.52	2.07	1.34	2.37	1.78
				ANOVA (*P*>*F*)				
Treatment	0.05	<0.01	0.61	0.03	<0.01	0.09	0.01	<0.01
UG vs. NC	0.01	<0.01	0.63	<0.01	<0.01	0.01	0.01	<0.01
GZ vs. UG	0.21	<0.01	0.43	0.02	<0.01	0.04	0.03	0.14
GZ vs. NC	0.08	0.62	0.07	0.69	<0.01	0.26	0.01	<0.01

†GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

Table 3.7. Soil water retention characteristics for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites for 2018.

Treatment	Soil water pressure (kPa)							
	0	-0.4	-1.0	-2.5	-5.0	-10.0	-20.0	-30.0
	---------------------------------------m^3m^{-3}---							
	Northern Brookings							
GZ†	0.546	0.544	0.530	0.494	0.492	0.465	0.456	0.449
UG	0.608	0.601	0.586	0.548	0.545	0.507	0.495	0.484
NC	0.536	0.533	0.520	0.482	0.482	0.456	0.445	0.437
	ANOVA ($P>F$)							
Treatment	<0.01	0.01	0.02	<0.01	<0.01	0.03	0.05	0.08
UG vs. NC	0.03	0.04	0.05	0.02	0.02	0.08	0.11	0.13
GZ vs. UG	<0.01	0.01	0.02	0.01	0.01	0.06	0.11	0.14
GZ vs. NC	0.65	0.62	0.62	0.58	0.65	0.71	0.62	0.59
	Northwestern Brookings							
GZ	0.515	0.506	0.487	0.470	0.469	0.453	0.443	0.435
UG	0.548	0.538	0.516	0.479	0.479	0.456	0.444	0.435
NC	0.528	0.517	0.497	0.474	0.473	0.462	0.452	0.443
	ANOVA ($P>F$)							
Treatment	0.21	0.21	0.26	0.74	0.69	0.69	0.65	0.65
UG vs. NC	0.50	0.48	0.56	0.96	0.98	0.60	0.53	0.52
GZ vs. UG	0.32	0.34	0.59	0.65	0.68	0.43	0.29	0.24
GZ vs. NC	0.92	0.97	0.80	0.66	0.67	0.98	0.90	0.85

†GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

Table 3.8. Soil water retention characteristics for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites for 2019.

Treatment	Soil water pressure (kPa)							
	0	-0.4	-1.0	-2.5	-5.0	-10.0	-20.0	-30.0
	---------------------------------------m^3m^{-3}---							
	Northern Brookings							
GZ[†]	0.420	0.416	0.386	0.336	0.334	0.306	0.290	0.282
UG	0.471	0.461	0.436	0.376	0.374	0.348	0.333	0.325
NC	0.398	0.397	0.377	0.335	0.334	0.300	0.292	0.284
	ANOVA (*P*>*F*)							
Treatment	0.01	0.02	0.01	0.06	0.06	0.02	0.03	0.03
UG vs. NC	0.01	0.01	0.01	0.03	0.03	0.01	0.02	0.02
GZ vs. UG	0.02	0.03	0.01	0.02	0.02	0.01	0.01	0.01
GZ vs. NC	0.25	0.29	0.43	0.89	0.96	0.54	0.88	0.90
	Northwestern Brookings							
GZ	0.508	0.502	0.489	0.475	0.466	0.445	0.442	0.432
UG	0.577	0.567	0.546	0.523	0.511	0.494	0.489	0.476
NC	0.507	0.494	0.474	0.463	0.456	0.436	0.429	0.416
	ANOVA (*P*>*F*)							
Treatment	<0.01	<0.01	<0.01	0.01	0.01	<0.01	<0.01	<0.01
UG vs. NC	0.01	0.01	0.02	0.06	0.06	0.04	0.04	0.05
GZ vs. UG	<0.01	<0.01	<0.01	0.02	0.02	<0.01	0.01	0.02
GZ vs. NC	0.95	0.42	0.20	0.36	0.35	0.44	0.36	0.25

[†]GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

Table 3.9. Soil pore size distribution for different treatments of cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites for 2018.

Treatment	Macropores (>1000µm)	Coarse mesopores (60-1000 µm)	Fine mesopores (10-60 µm)	Micropores (<10 µm)	Total pores
			Northern Brookings		
GdC†	0.004a††	0.046a	0.049a	0.491a	0.589ab
GdC+G	0.002a	0.058a	0.044a	0.415a	0.519b
LdC	0.010a	0.066a	0.074a	0.477a	0.626a
LdC+G	0.003a	0.046a	0.043a	0.482a	0.574ab
NC	0.003a	0.052a	0.045a	0.437a	0.536b
P-value	0.09	0.72	0.28	0.08	<0.01
			Northwestern Brookings		
GdC	0.011	0.058ab	0.048	0.417	0.533
GdC+G	0.009	0.033c	0.031	0.445	0.518
LdC	0.009	0.061a	0.039	0.453	0.563
LdC+G	0.009	0.040c	0.038	0.425	0.512
NC	0.011	0.043bc	0.030	0.443	0.528
P-value	0.91	<0.01	0.35	0.65	0.21

†GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop

††Means with different letters within a column are significantly different at $P < 0.05$ within the treatment for each site

Table 3.10. Soil pore size distribution for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites for 2018.

Treatment	Macropores (>1000μm)	Coarse mesopores (60-1000 μm)	Fine mesopores (10-60 μm)	Micropores (<10 μm)	Total pores
			Northern Brookings		
GZ†	0.002	0.052	0.043	0.449	0.546
UG	0.007	0.056	0.061	0.484	0.608
NC	0.003	0.052	0.045	0.437	0.536
			ANOVA (*P>F*)		
UG vs. NC	0.27	0.81	0.37	0.13	0.03
GZ vs. UG	0.06	0.79	0.16	0.14	<0.01
GZ vs. NC	0.54	0.97	0.78	0.59	0.65
			Northwestern Brookings		
GZ	0.009	0.037	0.034	0.435	0.515
UG	0.010	0.059	0.044	0.435	0.548
NC	0.011	0.043	0.030	0.443	0.528
			ANOVA (*P>F*)		
UG vs. NC	0.81	<0.01	0.15	0.52	0.50
GZ vs. UG	0.48	<0.01	0.24	0.24	0.32
GZ vs. NC	0.38	0.30	0.68	0.85	0.92

†GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

Table 3.11. Soil pore size distribution for different treatments of cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites for 2019.

Treatment	Macropores (>1000µm)	Coarse mesopores (60-1000 µm)	Fine mesopores (10-60 µm)	Micropores (<10 µm)	Total pores
			Northern Brookings		
GdC†	0.011a††	0.077a	0.048ab	0.321ab	0.456ab
GdC+G	0.003a	0.067a	0.041b	0.288bc	0.400b
LdC	0.009a	0.097a	0.051ab	0.328a	0.486a
LdC+G	0.006a	0.096a	0.062a	0.276c	0.440ab
NC	0.001a	0.063a	0.050ab	0.284c	0.398b
P-value	0.18	0.15	0.04	0.03	0.01
			Northwestern Brookings		
GdC	0.014	0.056a	0.042	0.448ab	0.560ab
GdC+G	0.007	0.039ab	0.035	0.417b	0.497c
LdC	0.007	0.055ab	0.028	0.504a	0.594a
LdC+G	0.006	0.034b	0.033	0.447ab	0.519bc
NC	0.014	0.038ab	0.040	0.416b	0.507bc
P-value	0.64	0.02	0.75	<0.01	<0.01

†GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop

††Means with different letters within a column are significantly different at $P < 0.05$ within the treatment for each site

Table 3.12. Soil pore size distribution for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites for 2019.

Treatment	Macropores (>1000µm)	Coarse mesopores (60-1000 µm)	Fine mesopores (10-60 µm)	Micropores (<10 µm)	Total pores
			Northern Brookings		
GZ[†]	0.004	0.082	0.052	0.282	0.420
UG	0.010	0.087	0.050	0.325	0.471
NC	0.001	0.063	0.050	0.284	0.398
			ANOVA (*P*>*F*)		
UG vs. NC	0.03	0.09	0.98	0.02	0.01
GZ vs. UG	0.11	0.64	0.62	0.01	0.02
GZ vs. NC	0.03	0.26	0.81	0.90	0.25
			Northwestern Brookings		
GZ	0.006	0.036	0.034	0.432	0.508
UG	0.010	0.056	0.035	0.476	0.577
NC	0.014	0.038	0.040	0.416	0.507
			ANOVA (*P*>*F*)		
UG vs. NC	0.64	0.04	0.63	0.05	0.01
GZ vs. UG	0.43	<0.01	0.87	0.02	<0.01
GZ vs. NC	0.19	0.63	0.53	0.25	0.95

[†]GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

Table 3.13. Soil water infiltration rate (q_s) and Green-Ampt model estimated sorptivity (S) and saturated hydraulic conductivity (K_s) for different treatments of cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites in 2018.

Treatment	q_s (mm hr^{-1})	S (mm hr$^{-0.5}$)	K_s (mm hr^{-1})
	Northern Brookings		
GdC[†]	478.6a[††]	149.1a	457.4a
GdC+G	493.6a	392.2a	360.3a
LdC	448.2a	181.2a	370.4a
LdC+G	315.9a	154.7a	207.8a
NC	123.5a	94.4a	97.7a
P-value	0.12	0.10	0.12
	Northwestern Brookings		
GdC	39.4a	25.4a	12.8
GdC+G	13.3ab	9.5ab	13.9
LdC	17.9ab	12.6ab	11.7
LdC+G	7.6b	9.6ab	6.1
NC	4.3b	6.9b	5.0
P-value	0.01	0.04	0.64

[†]GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop

[††]Means with different letters within a column are significantly different at $P < 0.05$ within the treatment for each site

Table 3.14. Soil water infiltration rate (q_s) and Green-Ampt model estimated sorptivity (S) and saturated hydraulic conductivity (K_s) for different treatments of by cover crops and grazing under integrated crop-livestock system at Northern and Northwestern Brookings sites in 2018.

Treatment	q_s (mm/hr)	S (mm/hr$^{0.5}$)	K_s (mm/hr)
	Northern Brookings		
GZ†	404.7	273.5	284.0
UG	463.4	165.1	413.9
NC	123.5	94.4	97.7
	ANOVA (P>F)		
UG vs. NC	0.03	0.28	0.03
GZ vs. UG	0.60	0.41	0.23
GZ vs. NC	0.05	0.19	0.07
	Northwestern Brookings		
GZ	10.5	9.5	10.0
UG	28.6	19.0	12.3
NC	4.3	6.9	5.0
	ANOVA (P>F)		
UG vs. NC	0.08	0.09	0.29
GZ vs. UG	0.03	0.05	0.75
GZ vs. NC	0.11	0.37	0.34

†GZ, grazed cover crop (average of grazed legume and grazed grass cover crop); UG, ungrazed cover crop (average of ungrazed legume and ungrazed grass cover crop); NC, no cover crop

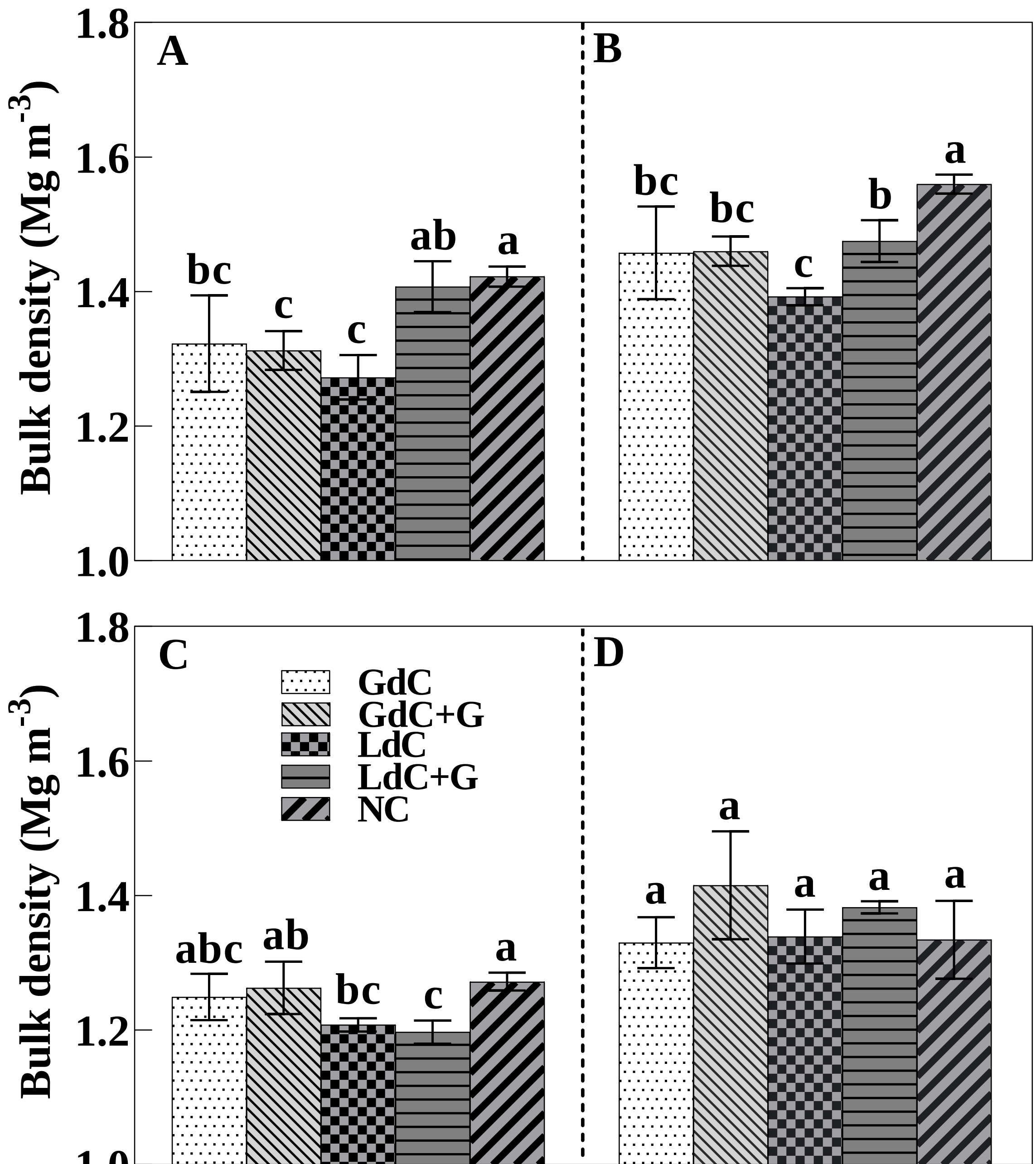

Fig. 3.1. Soil bulk density for grass dominated cover crop (GdC), cattle -grazed GdC (GdC+G), legume dominated cover cop (LdC), cattle -grazed LdC (LdC+G), and no cover crop (NC) treatments for (A) 0 to 10 cm, (B) 10 to 20 cm depths, in 2018 and (C) 0 to 10 cm, (D) 10 to 20 cm depths in 2019 at Northern Brookings site.

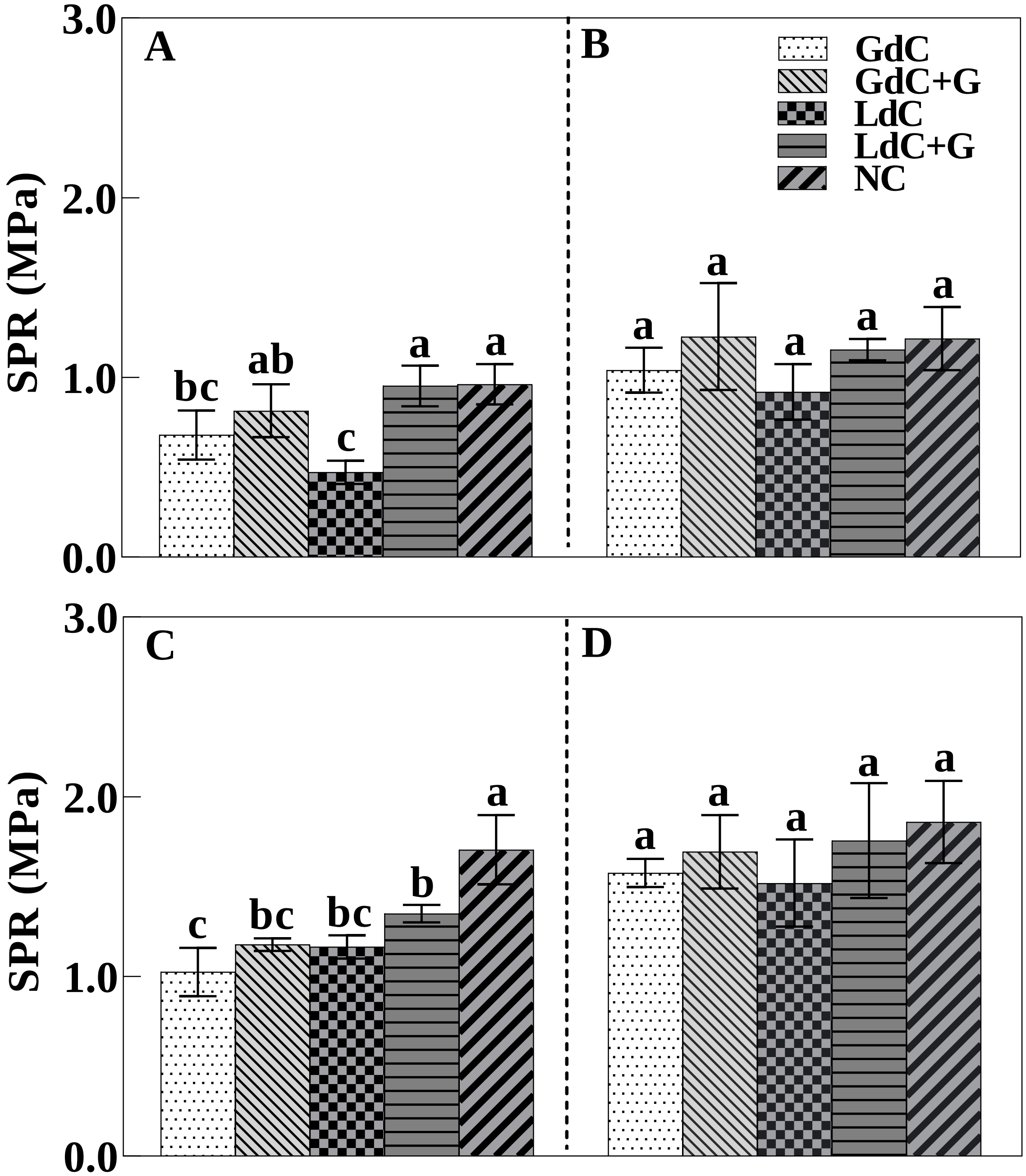

Fig. 3.2. Soil penetration resistance for grass dominated cover crop (GdC), cattle -grazed GdC (GdC+G), legume dominated cover cop (LdC), cattle -grazed LdC (LdC+G), and no cover crop (NC) treatments for (A) 0 to 10 cm, (B) 10 to 20 cm depths, in 2018 and (C) 0 to 10 cm, (D) 10 to 20 cm depths in 2019 at Northern Brookings site.

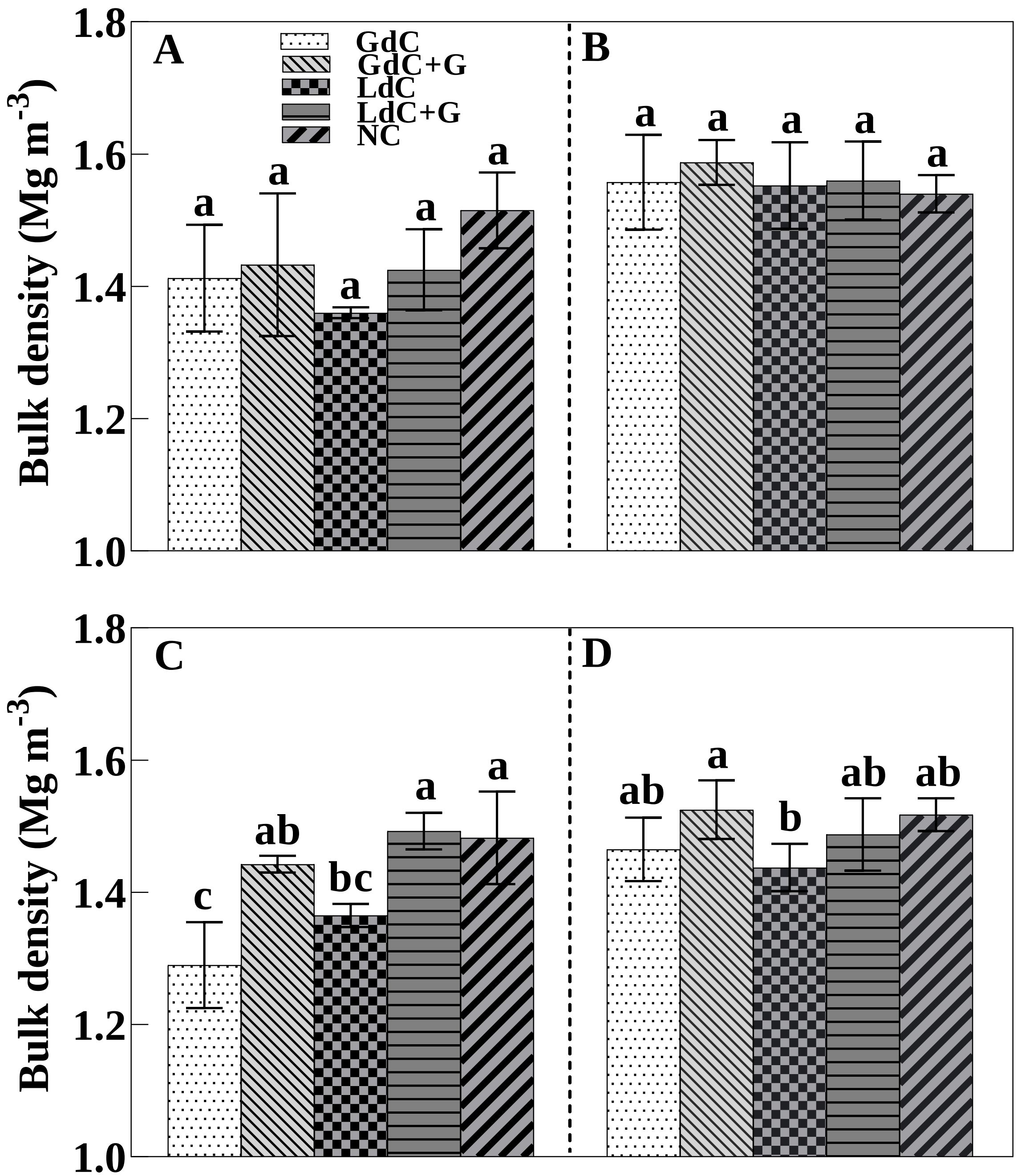

Fig. 3.3. Soil bulk density for grass dominated cover crop (GdC), cattle -grazed GdC (GdC+G), legume dominated cover cop (LdC), cattle -grazed LdC (LdC+G), and no cover crop (NC) treatments for (A) 0 to 10 cm, (B) 10 to 20 cm depths, in 2018 and (C) 0 to 10 cm, (D) 10 to 20 cm depths in 2019 at Northwestern Brookings site.

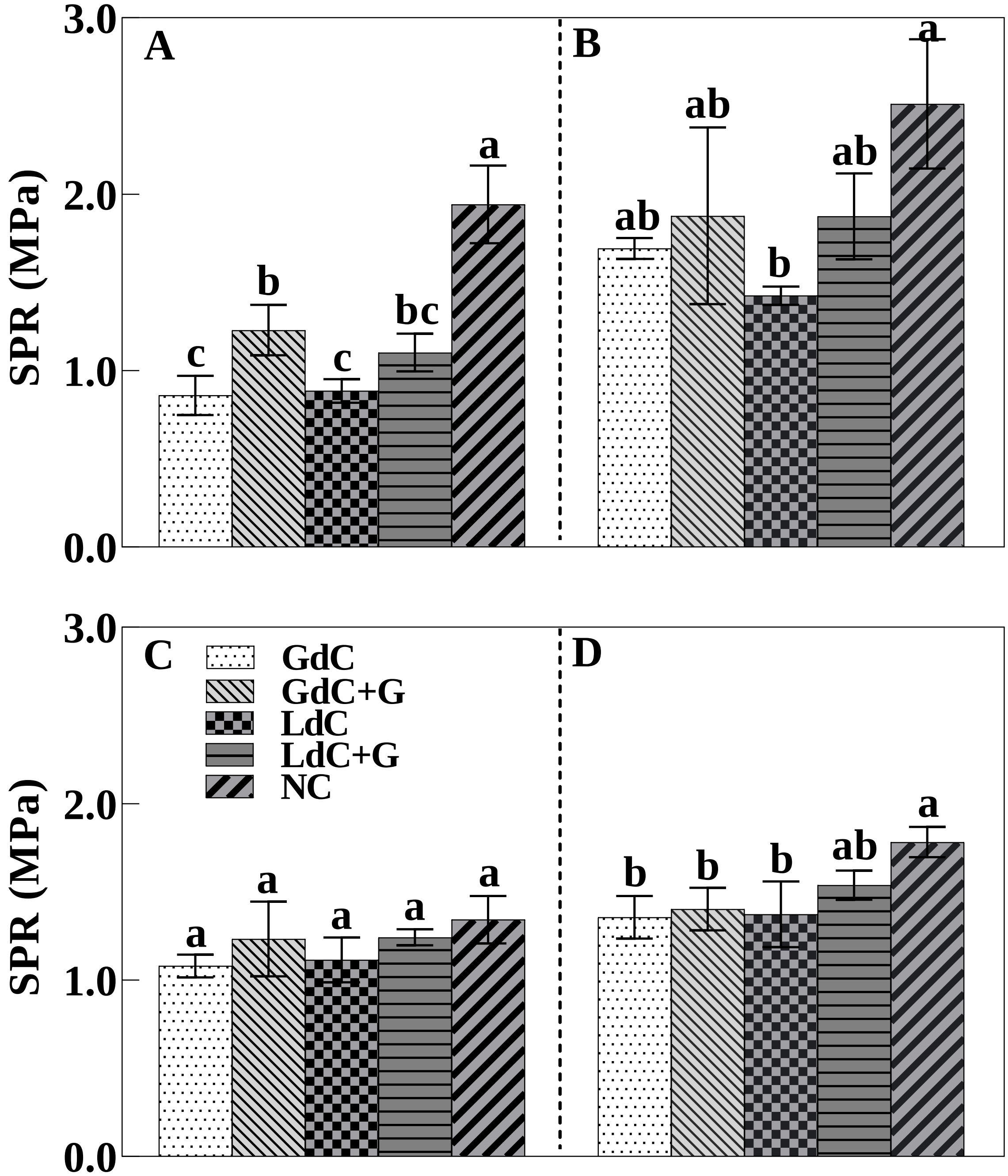

Fig. 3.4. Soil penetration resistance for grass dominated cover crop (GdC), cattle -grazed GdC (GdC+G), legume dominated cover cop (LdC), cattle -grazed LdC (LdC+G), and no cover crop (NC) treatments for (A) 0 to 10 cm, (B) 10 to 20 cm depths, in 2018 and (C) 0 to 10 cm, (D) 10 to 20 cm depths in 2019 at Northwestern Brookings site.

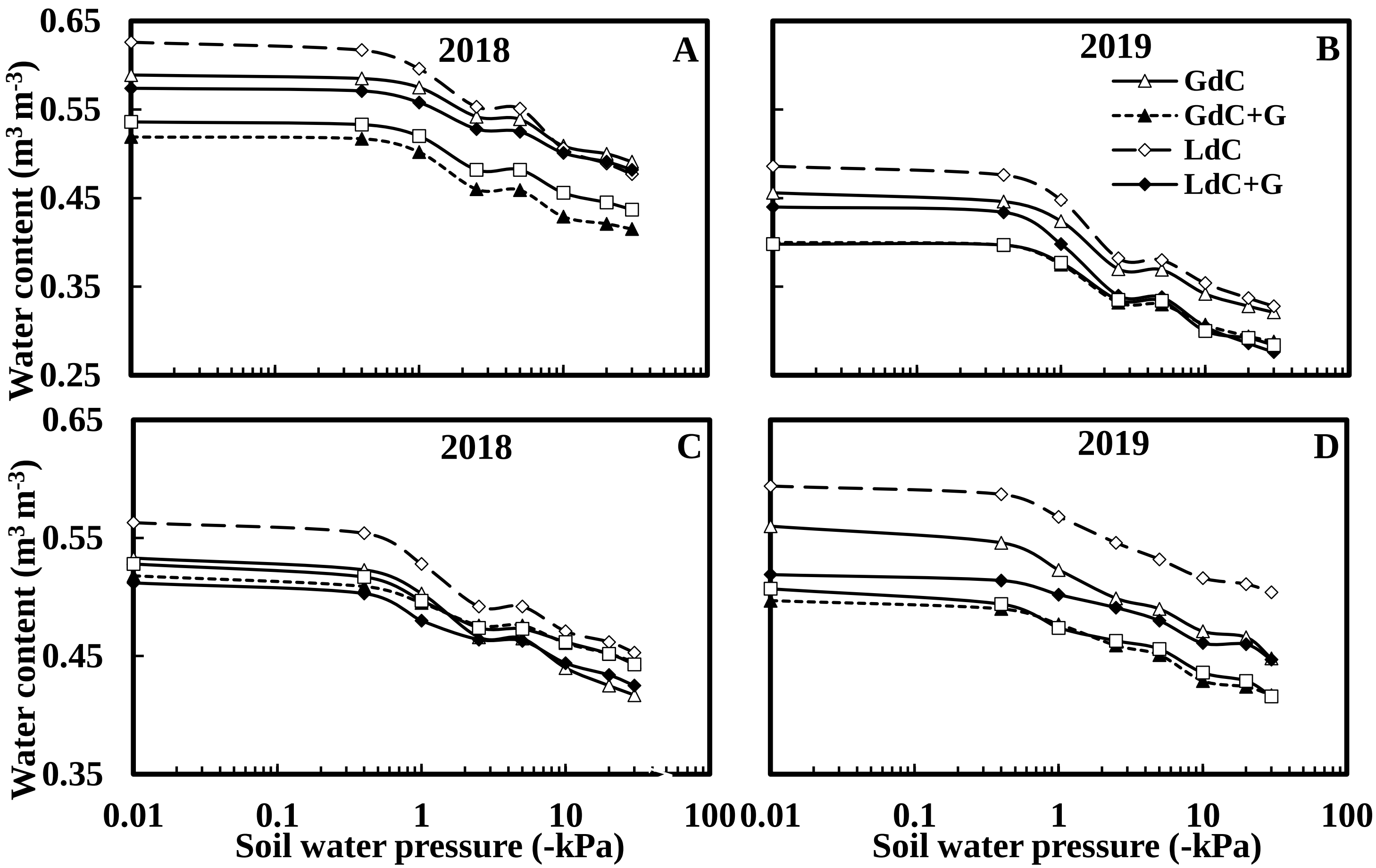

Fig. 3.5. Soil water retention curves for grass dominated cover crop (GdC), cattle -grazed GdC (GdC+G), legume dominated cover cop (LdC), cattle -grazed LdC (LdC+G), and no cover crop (NC) treatments for Northern Brookings (A, B) and Northwestern Brookings sites (C, D).

CHAPTER 4

CROP-LIVESTOCK INTEGRATION IMPACTED X-RAY-COMPUTED-TOMOGRAPHY-MEASURED NEAR-SURFACE SOIL PORE PARAMETERS

ABSTRACT

Soil porosity estimated by conventional methods is unable to provide spatial distribution and geometrical properties of pore network. Computed tomography (CT) techniques are non-destructive and provide spatial and geometrical characteristics of soil pores. This on-farm study was conducted near Salem, South Dakota with the specific objective to quantify CT-measured soil pore properties as influenced by crop-livestock integration and correlate these with soil hydro-physical properties. Study treatments included: (i) native grazed pasture (NGP), (ii) integrated crop livestock system (ICLS), and (iii) corn-soybean cropping system (CNT). Results showed that the CT-measured macroporosity was significantly higher in ICLS (0.084 mm^3 mm^{-3}) and NGP (0.093 mm^3 mm^{-3}) compared to the CNT (0.012 mm^3 mm^{-3}). Higher connected porosity, connection probability and macroporosity in ICLS and NGP significantly enhanced saturated hydraulic conductivity compared to CNT. The CNT increased bulk density (1.51 Mg m^{-3}) compared to ICLS (1.18 Mg m^{-3}) and NGP (0.99 Mg m^{-3}). In comparison with conventional methods, CT scanning can provide information about number of pores, pore radius, surface area, pore network connectivity and tortuosity. This study illustrates that long-term integration of crops and livestock significantly improved soil pore architecture quantified with CT scanning technique, which is critical for soil water conduction and storage.

***Keywords*:** CT scanning, Integrated crop livestock system, pore-size distribution, saturated hydraulic conductivity, soil pore structure

4.1. Introduction

Soil porosity plays a major role in the transmission and retention of fluids and gases (Eynard *et al.*, 2004). The soil pore space arrangement and the pore connectivity control vital physical and hydrological processes at the soil-plant and soil-atmosphere interfaces such as diffusion, mass flow of water and nutrient uptake by roots (Young and Crawford, 2004). The importance of soil pores in transfer of fluids and solutes lies directly in their geometrical and topological characteristics, of which pore-size distribution and pore connectivity are of major relevance (Vogel, 2000). Therefore, more detailed quantification of soil porosity is very critical. Soil porosity and pore-size distribution are usually simply estimated by traditional water retention methods. However, these methods do not provide information of unconnected pores (Rab *et al.*, 2014) and pore morphology (Gantzer and Anderson, 2002). Conversely, the use of computed tomography (CT) imaging techniques to study soil porosity has increased markedly during the last decade (Vaz *et al.*, 2014). These techniques are fast, robust and non-invasive and provide a unique opportunity to quantify detailed pore morphological parameters and permit three-dimensional visualization of soil structural properties (Carlson *et al.*, 2003) on a micrometer scale (Hapca *et al.*, 2015). In addition, they also provide information on spatial distribution of soil pores and their characteristics as well as connected and unconnected pores which can be easily visualized and quantified (Rab *et al.*, 2014).

Management practices such as integrated crop-livestock systems (ICLS) can greatly influence soil porosity and other soil physical and hydrological properties. Integrated crop-livestock systems can provide various benefits in terms of increased nutrient cycling (Franzluebbers, 2007), improved soil aggregation (de Moraes *et al.*, 2014), providing ecosystem services, environmental sustainability and farm profitability (Russelle *et al.*, 2007; Lemaire *et al.*, 2014). However, the improvement in soil properties in ICLS depends, particularly, on the adequate management of the livestock (Kumar *et al.*, 2019). Properly managed grazing under ICLS can increase soil aggregate stability (Loss *et al.*, 2012), total porosity, soil macroporosity (Bonetti *et al.*, 2018), and biodiversity (Franzluebbers and Stuedemann, 2015). Despite the increased usage of CT scanning in quantification of soil porosity in different management practices (Luo *et al.*, 2010; Cercioglu *et al.*, 2018), the studies showing impacts of ICLS on detailed soil pore characteristics in general, and using CT scanning in particular, are limited. The quantitative evaluation of different management interventions through advanced imaging techniques is required to understand their effects on the distribution and characteristics of soil pores and their impact on soil functions related to storage and transport of water through soils. In this study, we hypothesized that the ICLS improve soil porosity by altering pore features within the soil profile. The objectives of this study were to (1) quantify the architecture of soil pores using X-ray CT for soils under integrated crop-livestock, native grazed pasture and corn-soybean cropping system (control) NGP and CNT, and (2) determine the correlation between CT-measured pore parameters and soil hydro-physical properties.

4.2. Materials and Methods

4.2.1. Study Site

The current on-farm study was conducted near the city of Salem located in South Dakota, USA. Soils at the study location were classified as Davision soil series (fine-loamy, mixed, superactive, mesic Aeric Calciaquolls). The study site has warm, humid summers and snowy winters. The treatments included three management systems *viz.* long-term grazing of crop residues (60-62 years) and cover crops (CC) which include radish (*Raphanus raphanistrum* L.), turnip (*Brassica rapa* L.), cowpea (*Vigna unguiculata* L.), and oat (*Avena sativa* L.)), also known as integrated crop-livestock system (ICLS); 76 years old native grazed pasture (NGP); and control (CNT), having corn-soybean cropping system without grazing (38 years). The CNT and ICLS treatments were located within the 100-m distance to each other, while the NGP was about 500 m distance from the CNT and ICLS treatments. The grazing was done with a group of Aberdeen Angus cattle and was based on the forage availability.

4.2.2. Soil Sampling and Sample Preparation

Soil samples from random spots were collected from each treatment during July-August 2018 at 0-10 cm depth and were kept fresh and stored in cold room at 4^{o}C pending analysis. Undisturbed soil samples in plexiglass cores (76.2 mm long and 76.2 mm inner diameter, with a 3.2-mm-thick wall) from each treatment were also collected from 0-10 cm depth. The cores were sampled by driving the plexiglass cores vertically in the soil using a core sampler and excavating them manually. A total of 9 cores (3 treatments × 3 replicates) were collected. The soils were near field capacity (θ = 0.31-

0.34 cm^3 cm^{-3}) at the time of sampling. Soil cores were trimmed, sealed with plastic caps at each end, labeled, kept in plastic bags and transferred to the laboratory and stored at 4°C pending analysis. Soil cores were slowly saturated, and then drained at -4.0 kPa using a tension table only for the scanning purpose. This process discharged the water from macropores to improve image contrast between air-filled pores and soil matrix. The cores were then transported to University of Missouri Veterinary Health Center at Columbia, Missouri, USA for computed tomography (CT) scanning.

4.2.3. X-ray Computed Tomography Scanning and Image Analysis

A Toshiba Aquilion 64 X-ray CT scanner was used to acquire CT scan images. The soil cores were placed horizontally on the scanner bench and spiral scanning was performed using a voltage of 120 kVp, an exposure time of 500 mAs and an X-ray tube current of 250 mA. The pixel resolution of the scans was 0.226 × 0.226 mm, with a slice thickness of 0.5 mm, thus producing a voxel size of 0.026 mm^3.The images were processed using the public domain software program ImageJ ver. 1.52n (Schindelin *et al.*, 2012). First, the 3-D image was cropped to obtain a region of interest (ROI) of 71.19 mm in diameter and 66 mm in height to avoid artifacts due to core walls and on both ends of soil column to remove uneven soil surfaces.A median 3D filter with a radius of 2 voxels was used to eliminate noise (Luo *et al.*, 2010). The contrast between the soil matrix and pores was enhanced by normalizing the image using “enhance contrast” algorithm. Choosing manual thresholds for the images can lead to inconsistent results due to operator subjectivity (Anovitz and Cole, 2015). Therefore, a local adaptive thresholding method of Phansalkar *et al.* (2011) was performed in which the threshold value of each pixel in the image is calculated on the basis of mean and standard deviation of the grey values of the neighboring pixels. The pixels having grey values lower than the threshold value were identified as pores. The images were also visually inspected to check the quality of the segmented images. This procedure resulted in a binary image, in which pores and soil matrix were represented by white and black pixels, respectively. The scattered features with one-pixel width were removed by applying erosion operation. The *Particle Analyser* plugin within the *BoneJ* plugin in ImageJ (Doube *et al.*, 2010) was used to measure the statistics of individual pores. Total porosity (macroporosity plus coarse mesoporosity), macroporosity (>1,000 μm diam.) and coarse mesoporosity (60 to 1,000 μm diam.) were obtained as the ratio of total volume of all pores, macropores and coarse mesopores, respectively, to the volume of ROI. Macropore number density (number m^{-3}) was calculated as the ratio of number of macropores to the volume of ROI. The pore circularity (Cir) was calculated using the following equation:

$$Cir = \frac{4\pi A}{P^2}$$

where, A is the surface area of the pore and P is the pore perimeter. In addition, some pore structural parameters like equivalent cylindrical diameter (ECD), macropore number density, calculated as the number of macropores per unit volume of soil (m^{-3}); degree of anisotropy (DA), an indicator of 3D pore symmetry (Harrigan and Mann, 1984); 3D fractal dimension (FD), an indicator of self-similarity and surface detail; estimated through a box-counting algorithm (Perret *et al.*, 2003); average tortuosity (τ) were obtained from skeletons of macropores generated using *Skeletonize 3D* plugin (Doube *et al.*, 2010) in ImageJ software. A skeleton is the central line of a pore with a thickness of one voxel. The skeletons were analyzed using *Analyse Skeleton* plugin (Doube *et al.*,

2010) in ImageJ. The average τ was calculated as the ratio of the total actual lengths of all macropores to the sum of the shortest distance between two ends of the macropores (Katuwal *et al.*, 2015). In addition, three measures of pore connectivity were derived from the CT scanned data: i) the presence of a pore cluster that is connected from the soil surface to the bottom of the sample, called as connected porosity (CP, $mm^3\ mm^{-3}$), ii) fraction of porosity in the largest cluster (F_L), and iii) connection probability (Γ), i.e. probability that two randomly chosen pore voxels in the ROI are connected (Renard and Allard, 2013), and is calculated as:

$$\Gamma = \frac{V_L^2}{(\sum_{i=1}^{n} V_i)^2}$$

where, V_L is the volume of the largest pore cluster, V_i is the volume of i^{th} pore cluster, *n* is the number of pore clusters

4.2.4. Saturated Hydraulic Conductivity and Bulk Density

After scanning, saturated hydraulic conductivity (K_{sat}) and dry bulk density (ρ_b) were determined for all the sampled cores. The K_{sat} was measured with constant-head method (Klute and Dirksen, 1986) by employing Darcy's equation:

$$K\text{sat} = \left(\frac{Q}{At}\right)\left(\frac{L}{L+H}\right)$$

where, Q is the outflow volume (cm^3), A is the cross-sectional area of soil column (cm^2), t is the time (h), L is the length of soil column (cm), H is the height of pounded water at the top of soil column (cm). Soil bulk density was determined on oven-dried soils (105°C) until a constant weight was observed.

4.2.5. Soil Water Retention

Soil cores were saturated with water by capillarity and the soil water retention (SWR) characteristics were measured at eight (0, -0.4, -1.0, -2.5, -5.0, -10.0, -20.0 and -30.0 kPa) matric potentials (ψ_m) by using tension table and pressure plate extractors (Soil moisture Equipment Corp., Santa Barbara, CA, USA) (Klute and Dirksen, 1986).

4.2.6. Soil Wet Aggregate Stability

The wet aggregate stability was measured using the method described by Kemper and Rosenau (1986). Briefly, 3 g of 1-2 mm air-dry soil aggregates were placed on a 0.25 mm screen and pre-moistened to saturation in a vaporization chamber. The samples were first subjected to an oscillating movement in water for 5 minutes in a wet sieving equipment (Kemper and Rosenau, 1986) to separate unstable aggregates, and then to the sonicator (Sonic dismembrator model 550, Fisher Scientific Co.) to obtain the stable aggregates. Soil suspension was oven-dried at 105 ºC until a constant weight. The percentage of water stable aggregates was calculated as the ratio of oven dried stable aggregates to the initial soil weight.

4.2.7. Soil Organic Carbon

Soil samples were ground to pass through a 0.5 mm sieve to determine the total C by dry combustion method using a TruSpec carbon/hydrogen/nitrogen (CHN) analyzer (LECO Corporation, St. Joseph, MI, USA). Inorganic C at 0-5 cm depth was below detection limits; therefore, total C was considered to be SOC in this study (Stetson *et al.*, 2012). Soil pH and EC values were ranged from 6.03 to 7.60, and 0.24 to 0.26 dS m^{-1}, respectively. Soil total nitrogen ranged from 3.75 to 5.03 g kg^{-1}.

4.2.8. Statistical Analysis

Differences among the parameters between the treatments were analyzed using one-way analysis of variance and Fisher's protected least significant difference. Significance was determined at $\alpha = 0.05$ level for all statistical analysis in this study. Pearson correlation analysis was used to determine the relationships between K_{sat} and the soil pore characteristics. All statistical analyses used SAS version 9.4 (SAS, 2013).

4.3. Results and Discussion

4.3.1. Soil Organic Carbon, Aggregate Stability and Bulk Density

Data on soil organic carbon (SOC), wet soil aggregate stability (WSA), and bulk density (ρ_b) as affected by different treatments are shown in Table 4.1. Soil organic carbon was significantly higher in NGP and ICLS than that in the CNT ($P < 0.01$; Table 4.1). Similarly, WSA was significantly higher in NGP (87.4%) and ICLS (85%) than that of the CNT (64.3%). Soil ρ_b was significantly reduced under the NGP (0.99 Mg m^{-3}) and ICLS (1.18 Mg m^{-3}) as compared to that under the CNT (1.51 Mg m^{-3}). The organic matter accumulation in soils is a consequence of complex interaction among soil properties, topography, climate, cultivation and fauna-flora diversity (Ghani *et al.*, 2003). Soil organic carbon accumulation occurs when amount of C added from fine root exudates, aboveground plant biomass and manure is greater than that of decomposition (Rees *et al.*, 2005). Grazing can stimulate aboveground biomass and can enhance incorporation of aboveground plant C and N components into the soil (Schuman *et al.*, 1999). Properly managed grazing under ICLS can stimulate root litter deposition which improves nutrient cycling and promotes SOC accumulation in the soil (Wilson *et al.*, 2018). Previous studies have demonstrated the increase in fine root C exudation in response to defoliation via grazing (Hamilton *et al.*, 2008), which stimulates the growth of the microbial community. In addition, animal traffic increases physical breakdown and incorporation of litter into the soil, which can enhance the transfer of C and nutrients into the soil (Schuman *et al.*, 2002). In the present study, all these factors may have contributed to the increase in SOC in grazing under ICLS than that of the CNT (Hafner *et al.*, 2012). Soil organic carbon acts as a binding agent that protects the aggregates from physical disruption and slaking due to raindrop impact (Blanco-Canqui & Lal, 2009). On the other hand, stable aggregates protect the SOC from microbial decomposition by forming a physical barrier between the substrates and microbes (Tisdall and Oades, 1982). A significantly positive correlation of SOC with WSA found in the current study also support these results. Gajic *et al.* (2013) also reported higher percentages of WSA under natural grassland (50%) than the arable fields (41%). Further, higher SOC and aggregate stability under NGP and ICLS lowered the soil ρ_b in NGP and ICLS as compared to the CNT. Additionally, lower ρ_b may be attributed to the increased porosity (Singh *et al.*, 2019) due to the decayed roots of permanent plants (Mele *et al.*, 2003) (NGP) and cover crops (ICLS), lesser disturbance and compaction compared to the cropland (Abu, 2013).

4.3.2. CT-Measured Pore Characteristics

The results of CT-measured soil pore characteristics under different treatments are shown in Table 4.2. The native grazed pasture had significantly higher number of pores (28266) as compared to the ICLS (21965) and CNT (6828) treatments. Similarly, the NGP and ICLS increased macropores by six and five times, respectively, than the CNT treatment. Macropores represented 43, 45, and 29% of the total CT-measured pore count in the NGP, ICLS, and CNT treatments, respectively. A similar trend in the number of coarse mesopores was also observed (Table 4.2) where NGP and ICLS had 3 and 2.5 times higher coarse mesopores than the CNT treatment. Coarse mesopores represented 57, 55, and 71% of the total number of CT-measured pores in the NGP, ICLS, and CNT treatments, respectively. Native grazed pasture had higher porosity (0.104 mm^3 mm^{-3}), macroporosity (0.093 mm^3 mm^{-3}) and coarse mesoporosity (0.011 mm^3 mm^{-3}) than the CNT treatment (0.015, 0.012, and 0.003 mm^3 mm^{-3}, respectively). Total porosity, macroporosity and coarse mesoporosity for the ICLS was about 6, 7, and 2.6 times higher than the CNT treatment, respectively (Table 4.2). However, the NGP and the ICLS treatments were at par in terms of the total porosity and macroporosity. The total porosity, macroporosity and coarse mesoporosity varied with sample depth (Fig. 4.1) and the highest total porosity and macroporosity was observed in the top 20–25 mm for NGP and ICLS. The pores in all the treatments were visualized and typical replicates for the NGP, ICLS and CNT are shown in Fig. 4.2. Data on CT-measured pore connectivity parameters and various pore characteristics under different treatments are shown in Table 4.3. Connected porosity (CP), proportion of pore volume contained in the largest pore cluster (F_L) and connection probability (Γ) were significantly higher in NGP and ICLS compared to that of the CNT. Significantly higher CT-measured porosity and pore connectivity in the NGP and ICLS than that of the CNT can be attributed to the combined effect of reduced soil disturbance and accumulation of SOC and enhanced biological (earthworm) activities which may lead to the formation and stability of aggregates (Daynes *et al.*, 2013). As a consequence, the abundance and inter-connectivity of the pore networks was enhanced in these treatments as evident from strong positive correlation of WSA with CT-measured pore characteristics and connectivity parameters.

Livestock grazing under ICLS may trigger a significant burst in the root production to increase nutrient acquisition in order to compensate for the lost foliage (Ziter and MacDougall, 2013). Furthermore, the planting of diverse cover crop mixture under ICLS can also increase the number of CT-measured porosity compared to that of the CNT. Previous studies also suggested that the tap roots of the cover crops can create macropores after their decay, which enhance water and air flow through the soils (Chen and Weil, 2010). Our results are consistent with the previous studies. For instance, Abu (2013) reported that the fields under perennial pasture grasses with controlled grazing had significantly higher total porosity (attributing to greater SOC and lesser disturbance and compaction) compared to that of fields under >50 yrs of continuous cultivation of cereals–legumes, which had the poorest soil physical quality among different land uses. Bonetti *et al.* (2018) also observed an increase in the macroporosity in the ICLS compared to the non-grazed areas due to the greater root development under ICL system. Our study showed that properly managed grazing of cover crops and crop residue under long-term ICLS enhanced the CT-measured soil porosity.

Equivalent cylindrical diameter (ECD) was significantly different among the treatments ($P < 0.01$; Table 4.3). Native grazed pasture (1.18 mm) and ICLS (1.25 mm) had significantly higher ECD as compared to that of the CNT (0.94 mm), however, the ICLS and NGP treatments had statistically similar ECDs. The CT-measured pore circularity (Cir) and degree of anisotropy (DA) was not affected by the treatments ($P > 0.05$; Table 4.3). Fractal dimension (D) of pores was higher for NGP (2.47) and ICLS (2.44) as compared to that for the CNT (2.09). Conversely, the tortuosity (τ) of pores in the CNT (1.42) was significantly higher than that of the NGP (1.37) and ICLS (1.38), however, the latter two treatments were at par. Fractal dimension is a measure of space filling characteristics of a pore and it depends upon the number of pores and their size distribution (Rachman *et al.*, 2005). The higher fractal dimension for the NGP and ICLS indicates that the pores in these treatments were more space filling, which is attributed to the long (higher mean macropore length; data not shown), large (higher ECD) and more elongated pores compared to the CNT (Rachman *et al.*, 2005). Xia *et al.* (2018) also reported that the average ECD of soil pores for the *Kobresia* meadow was significantly higher than that of the cropland. The pore paths of the NGP and ICLS were less tortuous compared to the CNT owing to the reduced bulk density values, thus the fluid movement can be more effective through the aggregates because of less tortuous, continuous and wider flow paths of the these treatments (Peth *et al.*, 2008). Reduction in the stability of aggregates and increase in ρ_b may be the possible reasons behind lower D, ECD and higher τ of the pore paths under CNT (Rezanezhad *et al.*, 2009).

4.3.3. Soil Water Retention

Data on average soil water retention (SWR) at different matric potentials (Ψ_m) as influenced by the treatments are illustrated in Table 4.4. Native grazed pasture and ICLS retained significantly higher amount of water at Ψ_m of 0, -0.4, -1.0, -2.5 and -5.0 kPa compared to that under the CNT, however, at Ψ_m of -100 kPa, water retained under the CNT (0.37 m^3m^{-3}) was significantly higher than that of the NGP (0.33 m^3m^{-3}) and the ICLS (0.30 m^3m^{-3}). Soil water retention at Ψ_m of -10, -20 and -30 kPa was not impacted by either of the treatments.

The soils under ICLS and NGP retained more water between saturation and -5 kPa compared to that of the CNT due to the higher SOC and lower bulk density values in these treatments. Yang *et al.* (2014) reported that at high matric potentials, SWR is greatly influenced by SOC as it alters the soil structure and enhances the soil porosity. Similar results were reported by other researchers (Wall and Heiskanen, 2003; Haghighi *et al.*, 2010). In this study, CNT retained less water at higher Ψ_m (0 to -5 kPa), which was due to the reduced porosity, especially macropores, those were filled with gravitational water at these Ψ_m, which was the outcome of lower SOC in this treatment. Soils under CNT exhibited typical characteristics of a compacted (high ρ_b) soil (Reeve and Carter, 1991) and showed an increase in water retention at Ψ_m of -30 and -100 kPa, which was mainly due to the increased micropores (numerically) (Table 4.5), that were filled with capillary water at these Ψ_m. This increase in water retention at lower Ψ_m may be due to the reason that the residual soil water forms a thin film, which is primarily retained by adsorption (with high energy) around the soil colloids (Cavalieri *et al.*, 2006). Conversely, the ICLS and NGP retained less water at lower Ψ_m compared to that of the

CNT, or in other words, these treatments (ICLS and NGP) reduced the water retained in micropores. Similar results were reported in the previous studies (Cavalieri *et al.*, 2006; Hebb *et al.*, 2017).

4.3.4. Saturated Hydraulic Conductivity

Native grazed pasture (209.2 mm h^{-1}) and ICLS (119.3 mm h^{-1}) recorded significantly higher saturated hydraulic conductivity (K_{sat}) than that of the CNT (19.7 mm h^{-1}). The present study showed that the management significantly affected the saturated hydraulic conductivity. Significantly higher K_{sat} in NGP and ICLS than the CNT may be explained by higher pore connectivity, macroporosity and total porosity. Highly continuous pores that are connected from the surface to the bottom of the soil column are mainly responsible for water and air movement in the soils (Allaire-Leung *et al.*, 2000). Further, significantly high correlation of K_{sat} with connectivity parameters such as CP, F_L and Γ indicated that the water transport in the soils is mainly governed by pore connectivity (Fig. 4.3). The results also showed that the parameters that are responsible for increasing porosity were positively correlated with the K_{sat}. In contrast, soils under CNT lacked the connectivity in pores and exhibited significantly lower soil porosity, that resulted in significant reduction of K_{sat} in this treatment. This may be due to the compaction of the soils under CNT, as it is well documented that compaction reduces water, heat and gas flow through the soils (Lipiec and Hatano, 2003).

4.4. Conclusions

The current study examined the changes in CT-measured pore parameters and other soil hydro-physical properties in response to different treatments that included: integrated crop-livestock system, annual corn-soybean cropping system and native grazed pasture. Treatments had a significant impact on soil water conduction and retention. Intense agricultural use, such as annual corn-soybean cropping system reduced soil organic carbon, saturated hydraulic conductivity, CT-measured total number of pores, number of macropores, number of coarse mesopores, total porosity, macroporosity, coarse mesoporosity, and fractal dimension and other macropore characteristics and increased bulk density. In contrast, native grazed pasture soils showed highest CT-measured pore parameters and hydraulic conductivities, while the soils under integrated crop-livestock system behaved in-between native grazed pasture soils and cropland soils showing the signs of improvement in the hydro-physical properties. This study showed that the long-term application of integrated crop-livestock system that involve mixed cover crops, no-till system and diverse rotation can be beneficial in enhancing the soil hydrological and physical environment as compared to the conventional corn-system cropping system.

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Table 4.1. Soil organic carbon (SOC), wet soil aggregate stability (WSA), bulk density (ρ_b) and saturated hydraulic conductivity (K_{sat}) as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth.

Treatment	SOC (g kg^{-1})	WSA (%)	ρ_b (Mg m^{-3})	K_{sat} (mm h^{-1})
NGP	41.8[a†]	87.4[a]	0.99[c†]	209.15[a]
ICLS	33.4[b]	85.0[a]	1.18[b]	119.30[b]
CNT	29.4[c]	64.3[b]	1.51[a]	19.70[c]
p-value	<0.01	<0.01	<0.01	<0.01

†Means with different letters within a column are significantly different at $P<0.05$.

Table 4.2. Computed tomography- measured average total number of pores (pores, macropores, and coarse mesopores) and porosity (total porosity, macroporosity, and coarse mesoporosity) as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth.

Treatment	Total pores	Macro pores	Coarse meso pores	Porosity		
				Total porosity	Macroporosity	Coarse mesoporosity
				------------- $mm^3\ mm^{-3}$ ----------------		
NGP	28266[a†]	12250[a]	16017[a]	0.104[a]	0.093[a]	0.011[a]
ICLS	21965[b]	9858[b]	12107[b]	0.092[a]	0.084[a]	0.008[b]
CNT	6828[c]	1972[c]	4856[c]	0.015[b]	0.012[b]	0.003[c]
p-value	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

†Means with different letters within a column are significantly different at $P<0.05$.

Table 4.3. Computed tomography derived connectivity parameters and various pore characteristics as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth.

Treatment	CP $mm^3\ mm^{-3}$	F_L	Γ	ECD mm	Cir	DA	D	τ
NGP	0.079[a†]	0.76[a]	0.58[a]	1.18[a]	0.81[a]	0.34[a]	2.47[a]	1.37[b]
ICLS	0.056[a]	0.61[a]	0.38[a]	1.25[a]	0.82[a]	0.32[a]	2.44[a]	1.38[b]
CNT	0.000[b]	0.00[b]	0.00[b]	0.94[b]	0.84[a]	0.26[a]	2.09[b]	1.42[a]
p-value	<0.01	<0.01	<0.01	<0.01	0.08	0.40	<0.01	0.01

[†]Means with different letters within a column are significantly different at $P<0.05$.
CP, Connected porosity; F_L, proportion of pore volume contained in the largest pore cluster; Γ, connection probability, ECD, Equivalent cylindrical diameter; Cir, Pore circularity; DA, Degree of anisotropy; D, fractal dimension; τ, Tortuosity

Table 4.4. Average soil water content ($m^3\ m^{-3}$) at different soil water pressures (-kPa) as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth.

	Soil water pressure (kPa)								
Treatments	0	-0.4	-1.0	-2.5	-5.0	-10.0	-20.0	-30.0	-100
	m^3m^{-3}								
NGP	0.67[a†]	0.65[a]	0.59[a]	0.53[a]	0.53[a]	0.43[a]	0.41[a]	0.37[a]	0.33[b]
ICLS	0.57[b]	0.55[b]	0.50[b]	0.45[b]	0.45[b]	0.39[a]	0.37[a]	0.33[a]	0.30[c]
CNT	0.49[c]	0.48[c]	0.45[c]	0.43[c]	0.43[c]	0.40[a]	0.39[a]	0.38[a]	0.37[a]
p-value	<0.01	<0.01	0.01	0.03	0.03	0.43	0.35	0.10	<0.01

[†]Means with different letters within a column are significantly different at $P<0.05$.

Table 4.5. Pore size distribution measured by water retention method as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth.

Treatments	Macropores (>1000 µm)	Coarse me sopores (60-1000 µm)	Fine mesopores (10-60 µm)	Micropores (<10 µm)	Total pores
	----------------------------------	----------------------------------	m^3m^{-3}	----------------------------------	----------------------------------
NGP	0.021[a†]	0.117[a]	0.164[a]	0.369[a]	0.672[a]
ICLS	0.017[ab]	0.097[b]	0.120[a]	0.331[a]	0.565[b]
CNT	0.013[b]	0.048[c]	0.051[b]	0.378[a]	0.490[c]
p-value	0.03	<0.01	<0.01	0.10	<0.01

[†]Means with different letters within a column are significantly different at $P<0.05$.

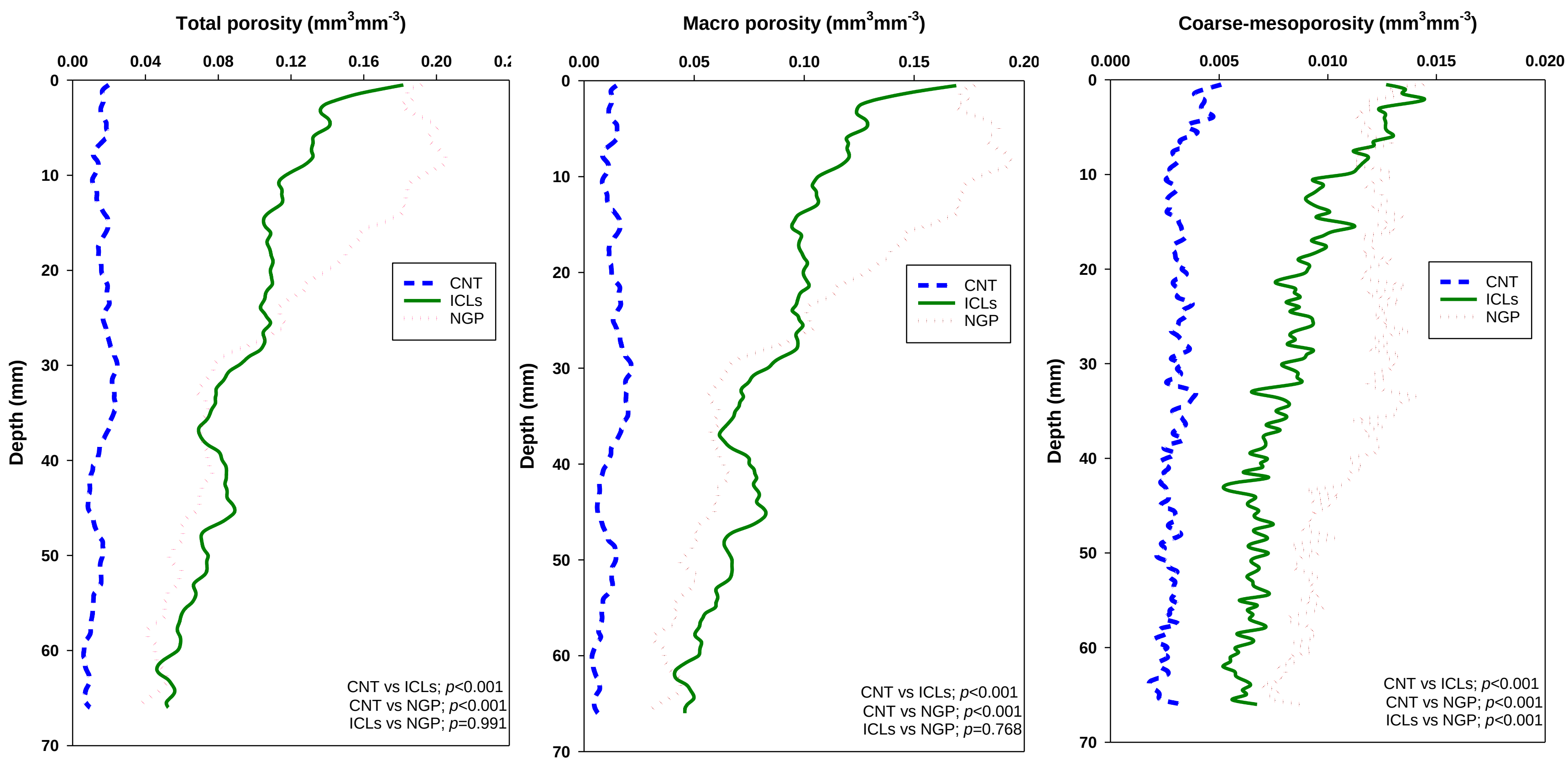

Fig. 4.1. Computed tomography measured total porosity, macroporosity, and coarse mesoporosity as influenced by soil depth under native grazed pasture (NGP), integrated crop- livestock system (ICLS) corn-soybean cropping system (CNT) for the surface (0-10 cm) depth.

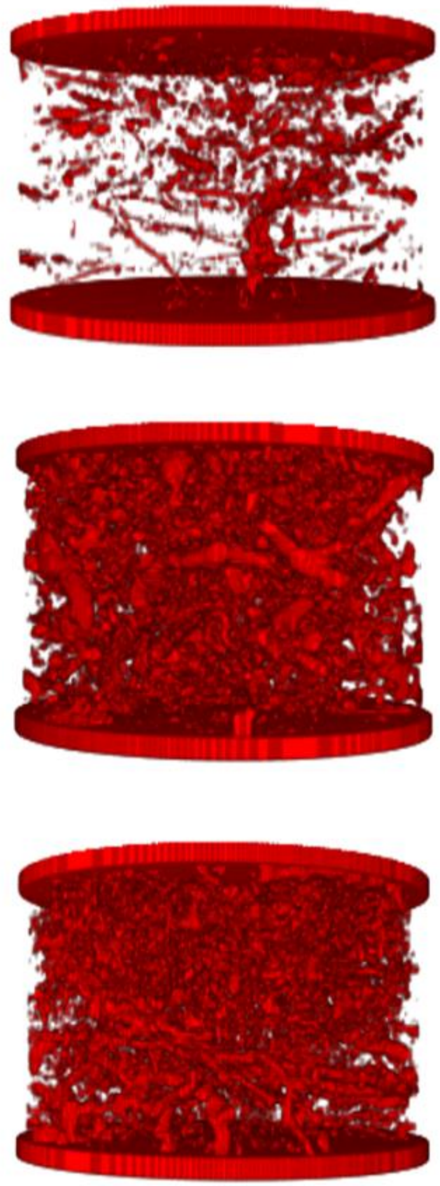

Fig. 4.2. Computed tomography measured pore geometry as affected by corn-soybean cropping system (top), integrated crop livestock system (middle), and native grazed pasture (bottom) for the surface (0-10 cm) depth. Soil pore spaces are shown in red color.

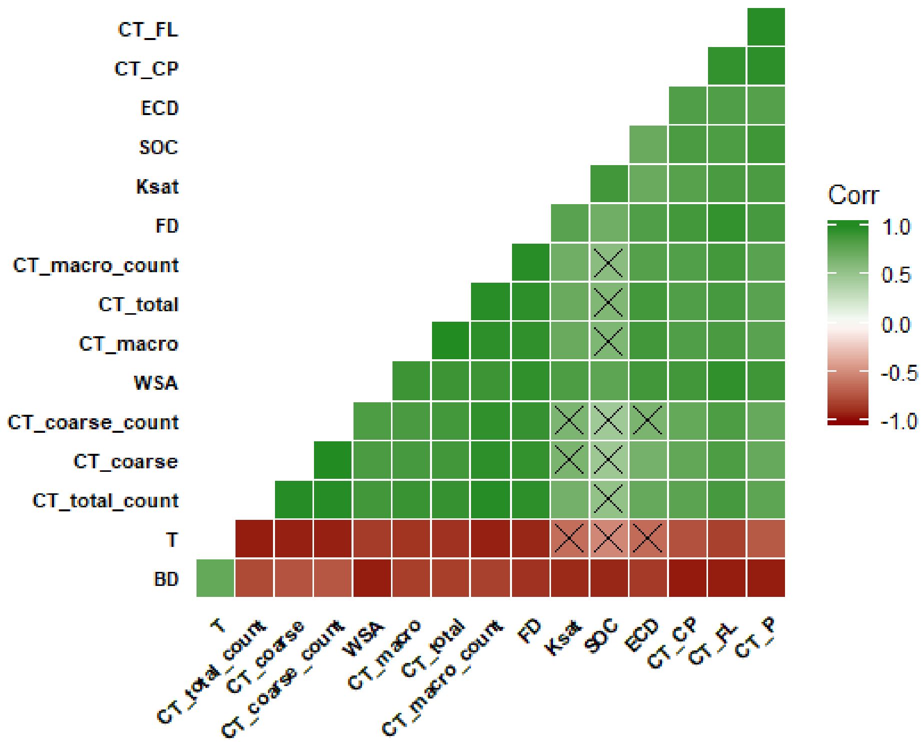

Fig. 4.3**.** Pearson correlation coefficients among different variables monitored from soils under native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) at the surface (0-10 cm) depth. BD, soil bulk density; ECD, equivalent cylindrical diameter; SOC, soil organic carbon; Ksat, saturated hydraulic conductivity; WSA, water stable aggregates; CT_coarse_count, CT measured number of coarse mesopores; CT_coarse, CT measured coarse mesoporosity; CT_total_count, CT measured total number of pores; FD, fractal dimension; CT_macro_count, CT measured number of macropores; CT_macro, CT measured macroporosity; CT_total, CT measured total porosity; CT_P, connection probability; CT_FL, proportion of pore volume contained in the largest pore cluster; CT_CP, connected porosity; T, tortuosity

CHAPTER 5

SHORT-TERM GRAZING OF COVER CROPS AND MAIZE RESIDUE IMPACTS ON SOIL GREENHOUSE GAS FLUXES IN TWO MOLLISOLS

ABSTRACT

Integrated crop-livestock system (ICLS), when managed properly, can help in mitigating soil surface greenhouse gas (GHG) fluxes (especially carbon dioxide, CO_2; methane, CH_4; and nitrous oxide, N_2O). However, the impacts of ICLS on GHG fluxes are poorly understood. Thus, the present study was conducted at two sites [north (N) Brookings and northwest (NW) Brookings] established in 2016 and 2017, respectively, under loamy soils in South Dakota. Specific objective was to evaluate the impact of cover crops (CC) and grazed CC under oats (*Avena sativa* L.)/cover crops-maize (*Zea mays* L.) rotation on GHG fluxes. Study treatments included: (i) legume dominated CC (LdC), (ii) cattle grazed LdC (LdC+G), (iii) grass dominated CC (GdC), (iv) cattle grazed GdC (GdC+G), and (v) control (without CC or grazing). Greenhouse gas monitoring occurred weekly during the growing crop seasons in 2016 and 2017 for N-Brookings, and 2017 and 2018 for NW-Brookings. Data showed that cumulative CO_2 and N_2O fluxes in N-Brookings were lower for GdC+G (4042 kg C ha^{-1} for CO_2 and 1499 g N ha^{-1} for N_2O) than for LdC+G (4819 kg C $ha^{-1}$for CO_2 and 2017 g N ha^{-1} for N_2O), indicating the superiority of GdC+G over the LdC+G in reducing the GHG fluxes. However, no effect from grazed CC on cumulative CO_2 and N_2O fluxes were observed at NW-Brookings site. Cumulative CH_4 flux was not affected by ICLS at either site. This short-term investigation showed that, in general, CC and grazing of CC and maize residue did not impact GHG fluxes.

***Keywords*:** Grazing, cover crops, integrated crop-livestock system, GHG fluxes

5.1. Introduction

Integrated crop-livestock system (ICLS) is a practice of utilizing crops and livestock on a single farm (Hilimire, 2011) in a way that they complement each other spatio-temporally, concurrently or separately and in rotation or in succession (de Moraes *et al.*, 2014). Adoption of ICLS offers some major benefits in certain areas that include greater outputs and relatively fewer inputs, expense reduction and increased ecosystem services (Gil *et al.*, 2016). The recoupling of crops and livestock (the ICLS) can also play a prominent role in mitigating greenhouse gas (GHG) emissions (Salton *et al.*, 2014; Buller *et al.*, 2015). However, ICLS can also increase GHG emissions because livestock production also contributes to atmospheric CH_4 mainly by enteric fermentation and through addition of manure in the soils, accounting for about 20 to 25% of the global rise of atmospheric CH_4 (Lassey, 2007; Hargreaves *et al.*, 2015).

Integrated crop-livestock system can be beneficial in mitigating soil GHG emissions, such as carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The CO_2emissions are directly influenced by the quantity of carbon (C) sequestered in the soil (Alluvione *et al.*, 2010; Abagandura *et al.*, 2019a). The equilibrium of soil C inputs and losses is regulated by addition of cover crop (CC) residues in the soil and decomposition of soil organic matter (SOM). The plant derived C sources (root respiration, rhizo-microbial respiration and microbial decomposition of dead plant residues) contribute to approximately more than half of the total soil CO_2 emissions (Kuzyakov, 2006). Previous studies reported a hike in CO_2 emissions due to plant root respiration and enhanced microbial activity in the rhizosphere (Sanz-Cobena *et al.*, 2014; Negassa *et al.*, 2015). The addition of CC to conventional cropping systems can help in enhancing soil organic carbon (SOC) and nitrogen (N) sequestration potentials to mitigate climate changes (Liebig *et al.*, 2012a). Cover crops can reduce N_2O emissions by depleting NO_3^- pool, which is the principal substrate for denitrification (Beauchamp, 1997). However, CC can also enhance N_2O emissions by releasing labile C and N through root exudates and rhizodeposition during their growth period which can stimulate microbial activity (Mitchell *et al.*, 2013). The CH_4 flux can be influenced by various factors such as soil aeration, alternative electron acceptor presence, SOM abundance, vegetation type and methanogenic population (Chiavegato, 2014). Sanz-Cobena *et al.* (2014) reported similar CH_4 emissions among the studied CC types and noticed that one legume CC acted both as a source as well as a sink in different seasons.

Grazing is an integral component of ICLS and strongly impacts GHG emissions (Cai *et al.*, 2017). Grazing can result in the reduction of C translocation to the roots, restriction of microbial activity and reduction in soil respiration (Bahn *et al.*, 2008). Greenhouse gas emissions could also increase after grazing due to the increased CH_4 emissions from enteric fermentation (i.e., produced during digestion and exhaled through the nose and mouth of livestock) and deposition of cattle dung and urine over the soil, which may dissolute SOC and N, and enhance microbial respiration (Lambie *et al.*, 2013).

Since, the application of ICLS as a GHG mitigation strategy is poorly understood, thus, understanding the influences of different cover crops, and grazing cover crops and row crops under ICLS on GHG emissions is potentially important. Thus, we hypothesize that multispecies cover crops and grazing under integrated crop-livestock system can enhance soil properties and reduce soil surface greenhouse gas fluxes. Specific objective of this study was to evaluate the impact of cover crops (CC) and grazed CC and maize (*Zea mays* L.) residue under oats (*Avena sativa* L.)/cover crops-maize rotation on GHG fluxes.

5.2. Materials and Methods

5.2.1. Experimental Site, Treatments, and Study Design

A field experiment to assess the impacts of ICLS on soil surface GHG fluxes at two sites, N-Brookings and NW-Brookings was conducted at the research farm of South Dakota State University, Brookings, SD, USA. The study was conducted for two years at each site; 2016 and 2017 for N-Brookings and 2017 and 2018 for NW-Brookings. The N-Brookings site (44°20'34.8"N, 96°48'14.8"W) had Fordville soil series (fine-loamy over sandy or sandy-skeletal, mixed, superactive, frigid Pachic Hapludolls), and NW-Brookings (44°20'14.5"N 96°48'28.8"W) had Barnes soil series (fine-loamy, mixed, frigid Udic Haploborolls). The study sites are characterized by continental temperature with warm, humid summers and snowy winters. Mean annual precipitation for the experimental site is 637 mm and the mean temperature is –15.8 °C in the winter and 27.8 °C in the summer. Before the initiation of the experiment, the average SOC and total N (TN) at N-Brookings were 30.3 g kg^{-1} and 2.7 g kg^{-1}, and 31.2 g kg^{-1} and 3.9 g kg^{-1}, respectively, at NW-Brookings for 0-5 cm depth. Study treatments included: (i) legume dominated CC (LdC), (ii) cattle grazed LdC (LdC+G), (iii) grass dominated CC (GdC), (iv) cattle grazed GdC (GdC+G), and (v) without CC and grazing (NC). The study was divided into two periods: Period I included cover crops before grazing, thus treatments of this period included LdC, GdC and NC, whereas, period II included grazing of cover crops and maize residue, thus treatments of this phase are LdC, GdC, NC, LdC+G and GdC+G. These treatments at either site were laid out in a randomized complete block design with four replications under oat/cover-crops-maize rotation, with CC planted after oats harvest in 19-cm wide rows using a grain drill (John Deere 750; Deere and Co., Moline, Illinois, USA). The individual plot sizes at the N-Brookings and NW-Brookings were 18.3m × 27.4m, and 18.3m × 30.5m, respectively. The details of CC blend for each site are given in Table 5.1. The details and timeline of agronomic and grazing management and GHG sampling are shown in Table 5.2 and Fig.5.1. The grazing treatment (based on the forage availability) at each site consisted of grazing CC and maize crop residue with a group of Aberdeen Angus cattle, those are commonly used for beef production in South Dakota. Following the best grazing management practices, the goal of cattle grazing was to utilize approximately one-half of the available forage and leave one-half over the soil to protect it from erosion. The plots to be grazed were electrically fenced in order to prevent grazing in the non-grazed plots. The cattle did not take rest during the grazing and were present all the time in the field during their stay. The stocking rate was decided based on the amount of biomass available in the field for grazing assuming 12.7 kg of dry matter consumed per animal per day (Uresk, 2010).

5.2.2. Soil Sampling and Analysis

Four soil samples from random spots in each plot were collected at the 0–5 cm depth using a push probe auger (3.2-cm diam.) from either site at the end of experiment.

These samples were composited, air-dried at room temperature and ground to pass through a 0.5 mm sieve after removing all visible residues. Soil total C and N were determined by dry combustion using a TruSpec carbon/hydrogen/nitrogen (CHN) analyzer (LECO Corporation, St. Joseph, MI, USA). Inorganic C at 0-5 cm depth was below detection limits; therefore, total C was considered to be SOC (Stetson *et al.*, 2012). Additionally, undisturbed intact soil cores (5 cm diameter and 5 cm height) were also extracted to a depth of 5 cm to determine the bulk density (ρ_b) from all the plots using the core method (Grossman and Reinsch, 2002).

5.2.3. GHG Monitoring and Analysis

Measurements of soil surface GHG fluxes were conducted from August to November in 2016 and May to December in 2017 at N-Brookings, and August to November in 2017 and April to November in 2018 at NW-Brookings (Fig. 5.1). GHG fluxes were not measured during the grazing of CC (November 17-21, 2016) at N-Brookings due to heavy snow accumulation. Sampling and analysis for GHG fluxes were based on the method described by Parkin and Venterea (2010). Two vented static collars (25 cm diameter × 15 cm high) manufactured from nonreactive polyvinyl chloride (PVC) pipe were installed between plant rows in each plot which remained undisturbed during the whole monitoring period. A PVC cap with a vent tube and sampling port (sealed with a septum) was placed on the collars before taking gas samples. The cap was fixed securely over the collar to ensure no leakage of gas from the collar during sampling. The gas samples from the collar were collected using a 10 ml syringe at 0, 20 and 40 minutes via sampling port and then transferred into pre-vacuumed 10 mL glass vials sealed with butyl rubber septa. The vials were filled with argon gas which was released by needle puncture before transferring the collected gas samples from the static collars into them. The gas samples were collected at weekly interval. However, when there was any heavy rainfall event, the gas samples were collected within 2-3 days depending upon the amount of rainfall. During and after the cattle grazing, GHG sampling was conducted daily to capture the impacts of grazing on GHG fluxes. However, GHG sampling was not conducted during grazing phase in 2016 due to the adverse weather conditions at N-Brookings site in 2016. In total, GHG was monitored for 29 days at N-Brookings during 2016-17 and for 44 days at NW-Brookings during 2017-18. Gas samples were collected between 8:00 am to noon during all the sampling events and were analyzed using a gas chromatograph [(Model-GC2014, with a CombiPal AOC-5000 Plus autosampler (Shimadzu Corporation, Kyoto, Japan)], having a flame ionization detector (FID) equipped with a methanizer (at 380°C) and an electron capture detector (ECD) (at 325°C). Helium was the carrier gas with air and hydrogen for the FID. The CO_2 was measured by FID in the system equipped with a methanizer and N_2O was measured by ECD. All carrier gases were of highest grade and prefiltered. Calibration was routinely performed using dilutions of a certified gas standard mix (Scott Specialty Gases, Plumsteadville, PA, USA). Daily gas flux was calculated from the concentration vs. time data using linear regression or the algorithm of Hutchinson and Mosier (1981) when the concentration vs. time data were curvilinear. Cumulative flux for each site was calculated using linear interpolation. During each gas-sampling event, the air temperature inside each collar and soil temperature near the collar at 0-5 cm depth were measured with a thermometer (Taylor 14769 Digital 0.7" Lcd Folding Thermometer). Soil water content (θ) at

0-5 cm was determined near every collar at the time of gas sampling using a HH2 moisture sensor (Delta-T-Devices, Cambridge, England). Daily weather data for 2016 - 2018 were collected from a weather station located approximately 2.4 km from the study site.

5.2.4. Statistical Analysis

Daily GHG flux data were analyzed using the repeated measures analysis PROC MIXED in SAS 9.4 (SAS, 2013). Sampling date was considered as a repeated measure variable. The treatments were considered as fixed effects and the replication as random effects. Cumulative GHG fluxes were statistically compared using the pairwise differences method (adjusted by Tukey) by a mixed model, where treatments were defined as fixed effects and the replication as random effects. Multiple linear regression analysis was conducted to examine the relationship between soil temperature and θ with CO_2 and N_2O fluxes using SIGMA PLOT 14.0. The normal distribution of the data was tested by Kolmogorov–Smirnov test. Significance was determined at $\alpha = 0.05$ level for all statistical analysis in this study.

5.3. Results

5.3.1. Soil Properties

At N-Brookings, the SOC, TN and ρ_b values ranged from 33.2 to 36.8 g kg^{-1}, 4.2 to 4.6 g kg^{-1}, and 1.33 to 1.43 Mg m^{-3}, respectively (Table 5.3). However, no significant differences in these parameters were observed among treatments. At NW-Brookings, the SOC, TN and ρ_b were also not influenced by the treatments, and the values ranged from

29.5 to 32.5 g kg^{-1}, 3.8 to 4.9 g kg^{-1}, and 1.38 to 1.49 Mg m^{-3}, respectively (Table 5.3). Cover crop biomass at either site was not affected by the treatments (data not shown).

5.3.2. Weather, Soil Temperature and Water Content

Daily mean air temperature (maximum and minimum) and precipitation for 2016, 2017 and 2018 are shown in Fig. 5.2. The average total precipitation for the three study years was 733 mm. The long-term (1986-2015) annual mean precipitation was 649 mm. Soil water content reflected the trend of precipitation during the monitoring days.
Air temperature at the beginning of growing season at each site was higher and gradually decreased towards the end during 2016, 2017 and 2018. Soil temperature increased at the initiation of growing seasons and declined thereafter in all the years (Fig. 5.3-5.4) and followed the trend of air temperature. Both θ and soil temperature were not affected by the treatments at either site before or after grazing CC ($p > 0.05$). The CO_2 and N_2O fluxes plotted against θ and soil temperature over the study period for N-Brookings and NW-Brookings are shown in Fig. 5.5-5.6. Multiple regression analysis showed significant positive correlations between the combination of θ and soil temperature with CO_2 and N_2O fluxes ($p < 0.001$ for both CO_2 and N_2O fluxes at N-Brookings; $p < 0.001$ for CO_2 flux and $p = 0.0106$ for N_2O flux at NW-Brookings). At N-Brookings, the combination of θ and soil temperature explained up to 68% of the variations in CO_2 flux and 18% in N_2O flux. At NW-Brookings, the corresponding values were 57% and 1%, respectively. In general, the highest CO_2 and N_2O flux was observed at θ >28% and soil temperature >21˚C.

5.3.3. Daily and Cumulative CO_2, CH_4 and N_2O flux

5.3.3.1. CO_2 Flux

Trend of daily GHG flux during period I and II at N-Brookings is shown in Fig. 5.7. Daily flux of CO_2 during period I (August 11, 2016 to November 16, 2016) was higher at the beginning and declined at the end of this period under all CC treatments (Fig. 5.7). Soil surface GHG flux was not measured during the grazing of CC (November 17-21, 2016) at this site due to heavy snow accumulation. Daily CO_2 flux during period II (May 6, 2017 to December 10, 2017) was higher in July and gradually decreased towards the end of this period (Fig. 5.7). However, no significant differences were observed in daily CO_2 flux. Cumulative CO_2 flux during period I and II at this site is shown in Table 5.4. During period I, the CC did not impact cumulative CO_2 flux (Table 5.4). Comparing grazed CC with ungrazed CC (GdC+G vs. GdC, and LdC+G vs. LdC) indicated that grazing CC resulted in cumulative CO_2 flux similar to those under ungrazed CC during period II (Table 5.4). Cumulative CO_2 flux was significantly lower in GdC+G than the LdC+G, however, it was similar to that of NC (Table 5.4). Trend of daily GHG flux during period I and II at NW-Brookings is shown in Fig. 5.8. Daily flux of CO_2 during period I (August 2, 2017 to October 17, 2017) was higher in August and declined at the end of this period under all CC treatments. Unlike N-Brookings, GHG flux was measured during and after the grazing of CC (November 21-29, 2017) at this site. The CO_2 flux gradually lowered during this period. Daily CO_2 flux during period II (April 11, 2018 to November 27, 2018) was higher during June-July and gradually decreased towards the end of this period (Fig. 5.8). However, no significant differences were observed in daily CO_2 flux. At this site, the cumulative CO_2 flux during period I was not impacted by CC

(Table 5.4). Cumulative CO_2 flux during and after grazing of CC is listed in Table 5.5. When comparing grazed CC with ungrazed CC (GdC+G vs. GdC, and LdC+G vs. LdC), the data indicated that grazing CC resulted in cumulative CO_2 flux similar to those under ungrazed CC during period II at this site (Table 5.4). Cumulative CO_2 flux in grazed CC was similar to that of the NC (Table 5.4).

5.3.3.2. CH_4 Flux

The flux pattern of the CH_4 flux during period I and II under all the treatments varied on the sampling dates at N-Brookings (Fig. 5.7) and NW-Brookings (Fig. 5.8). Daily and cumulative CH_4 flux was not influenced by CC and grazing at either site (Table 5.4).

5.3.3.3. N_2O Flux

At N-Brookings, daily N_2O flux during period I showed a general downward trend under all CC treatments (Fig. 5.7). The flux of daily N_2O during period II was higher during May-June and gradually decreased towards the end of this period (Fig. 5.7). However, no significant differences were observed in daily N_2O flux. Cumulative N_2O flux was not affected by CC during period I at N-Brookings (Table 5.4). During period II, GdC+G and LdC+G resulted in similar cumulative N_2O flux compared to those in GdC and LdC, respectively, (Table 5.4).

However, cumulative N_2O flux was significantly lower in GdC+G than in LdC+G. Also, significantly lower cumulative N_2O flux was recorded in GdC compared to the LdC (Table 5.4). Significantly lower cumulative N_2O flux was recorded in NC than in the LdC+G and LdC.

At NW-Brookings, daily flux of N_2O remained almost similar under all CC treatments during period I (Fig. 5.8). Daily N_2O flux during period II showed a huge peak in May and had a decreasing trend until August, after which the trend was variable. However, no significant difference was observed in daily N_2O flux at this site. At this site, the cumulative N_2O flux during period I was not impacted by CC (Table 5.4). While comparing grazed CC with ungrazed CC (GdC+G vs. GdC, and LdC+G vs. LdC), the data indicated that grazing CC resulted in similar cumulative N_2O flux compared to ungrazed CC during period II at this site. Cumulative N_2O flux in grazed CC were similar to that of the NC (Table 5.4).

5.4. Discussion

5.4.1. Soil Properties

Soil properties (SOC, TN and ρ_b) were similar among all the study treatments probably due to the short period of this study. For example, the detectable changes in SOC influenced by ICLS are very difficult to observe in a relatively shorter duration (<10 yr); however, they may be noticed under the conditions of extremely high stocking density or prolonged drought (Liebig *et al.*, 2008). In a study under similar soil (Mollisols) and climate conditions (semi-arid continental), Liebig *et al.* (2012b) found that the change in soil properties (including SOC, TN and ρ_b) due to ICLS occurs slowly, most likely on a decadal timescale. Furthermore, small changes in SOC are difficult to measure in soils with high buffering capacity and inherent resistance to change (Liebig *et al.*, 2012b), as we have observed in our study. Similar ρ_b values observed under all treatments at either site were attributed to the lack of changes in SOC. In this study, the grazing duration and trampling were minimal, and hence can also be the reason behind similar SOC and ρ_b values in the study treatments. In addition, grazing was done at the time when soil was frozen at NW-Brookings, which might have negated any impacts of ICLS on soil ρ_b. This may be due to the fact that medium-textured soils froze at relatively low water content and the elasticity provided by SOM may enable the aggregates to bear the pressure before fracturing (Flerchinger *et al.*, 2005). Clark *et al.* (2004) conducted a study on similar soil and reported that ICLS (winter grazed maize stalks) did not impact soil ρ_b even after longer grazing period (28 days) when soil was frozen.

5.4.2. Soil Temperature and Water Content

Biomass yield of cover crop affects the shade intensity, which can further influence the θ and soil temperature (Sainju *et al.*, 2008). However, θ and soil temperature were not affected by the treatments probably due to the reason that biomass produced by different CC was similar in this study. Similarly, in a study conducted on Mollisols in Wyoming, the θ and soil temperature in ICLS areas did not differ from the ungrazed grass areas owing to similar plant biomass among the treatments (Risch *et al.*, 2007). Moreover, properly managed grazing under ICLS in the present study, which was intended to leave approximately one-half of the available forage over the soil to protect it from erosion, may be the cause of non-significant differences in θ and soil temperature. Another reason behind this may be that the SOC was similar among all treatments and change in SOC can further impact the θ and soil temperature (King and Blesh, 2018).

5.4.3. Daily and Cumulative GHG Flux

5.4.3.1. CO_2 Flux

Higher daily CO_2 flux in June-July at each site was probably due to high soil temperature prevalent during these months, which was in response to higher air temperature. Increased decomposition of SOC, along with higher temperature values could account for the increase in CO_2 flux (Barsotti *et al.*, 2013). The gradual decline in daily flux of CO_2 from September until November at each site (Fig. 5.7-5.8) may be due to the decrease in soil temperature, which can lower the microbial activity (Wegner *et al.*, 2018).

The non-significant difference in cumulative CO_2 flux among CC treatments before grazing (period I) at each site was probably due to the fact that CC might not have produced enough biomass (average CC biomass was 1.96 tons per acre). It was expected that CC might increase CO_2 flux through root respiration during CC growth; however, low CC biomass in this study resulted in minimal changes in CO_2 flux during this period. It has been reported that the CC biomass of 0.10 to 2.23 tons per acre may not affect CO_2 emissions while CC biomass yields of more than 2.23 tons per acre may increase CO_2 emissions (Ruis *et al.*, 2018). Also, there was unwanted growth of weeds in the control (no CC) plots as compared to the CC plots in our study which may have contributed to the CO_2 flux. Furthermore, the decomposition of previous aboveground and belowground crop residue of oats after harvest in control plots might emit considerable CO_2 which might be the reason behind no difference in CO_2 flux among CC and no CC. Guardia *et al.* (2016) found that CO_2 flux did not differ among vetch CC, barley CC and fallow (no cover crop) treatments. At N-Brookings, similar cumulative CO_2 flux from grazed CC compared to the ungrazed CC (period II) was probably due to the short duration of grazing (4 d) in the winter, which was not sufficient to change the SOC. Risch and Frank (2006) stated that grassland C flows were not influenced by ICLS, and observed no differences on CO_2 flux between ICLS and ungrazed grassland. Furthermore, θ and soil temperature also did not differ among the treatments (Köster *et al.*, 2015), and hence did not impact the soil CO_2 flux. However, higher cumulative flux of CO_2 in LdC+G than those in the GdC+G were attributed to the enhanced decomposition of legume residues due to lower C/N ratio compared to the grasses. At NW-Brookings, similar cumulative CO_2 flux among the treatments was likely due to the non-significant effect of CC and grazing on soil temperature over the study period. Another soil attribute that could influence soil respiration is the SOC; however, no significant effect of treatments on SOC was observed.

5.4.3.2. CH4 Flux

No significant effect of CC and grazing CC on daily and cumulative CH_4 flux was observed because short duration of grazing probably resulted in minimal accumulation of manure and urine. Additionally, the non-significant effect of CC and grazing CC on θ and the low magnitude of CH_4 flux could also be the possible reason behind similar CH_4 flux in the treatments. Tang *et al.* (2013) found that light grazing (24-30% forage utilization) had no significant impact on CH_4 uptake as compared to that of un-grazed sites. The activity of CH_4-releasing microbes is enhanced under anaerobic conditions and the activity of CH_4-uptaking microbes under aerobic conditions, which decides whether a soil will act as a source or a sink for CH_4 (Lee *et al.*, 2014). Upland agricultural soils generally emit minimal CH_4, therefore, agricultural management practices usually have little effect on CH_4 flux in these systems (Abagandura *et al.*, 2019a).

5.4.3.3. N_2O Flux

The decreasing trend of daily N_2O flux over the study period at either site may be due to the gradual decrease in air temperature and soil temperature, thereby reducing microbial activity and N_2O flux (Dobbie and Smith, 2001). Before CC grazing (period I), the non-significant impact of CC on cumulative N_2O flux at each site may be attributed to the similar θ and soil temperature among the treatments, those are the two important precursors of N_2O losses from soils via nitrification and denitrification. Mitchell *et al.* (2013) reported that cumulative N_2O flux for the entire growing season of CC did not differ between winter rye CC and control in a CC-maize cropping system when no N fertilizer was applied.

At N-Brookings, non-significant difference in cumulative N_2O flux in grazed CC compared to the ungrazed CC during (period II) may be due to the shorter duration of the site. Our previous study (e.g., Abagandura *et al.*, 2019b) also reported that grazing CC for about a month did not affect cumulative N_2O flux compared to the CC. However, significantly higher cumulative N_2O flux in LdC+G than in the GdC+G at this site may be due to higher N concentration of legume residue that decompose rapidly and release N_2O. Mineralization of crop residues and flux of N_2O is dependent on C:N ratio of the residues (Wu *et al.*, 2016). The legume-based plant residues having a narrow C:N ratio and high N-content generally result in rapid N mineralization and particularly higher

N_2O flux as compared to the residues having high C:N ratio (Li *et al.*, 2016). Thus, in the current study, the mineralization of N fixing legume residue and stimulation of microbial activity (Gomes *et al.*, 2009) might be possible reasons behind higher cumulative N_2O flux in the LdC+G than in the GdC+G during grazing of CC.

At NW-Brookings, the non-significant difference in cumulative N_2O flux among treatments during grazing of CC may be due to similar TN in all the treatments. It was expected that urine and fecal matter additions in the soils from livestock might enhance microbial activity and N mineralization, which might result in increased N_2O flux from the grazed plots (Hartmann *et al.*, 2013; Boon *et al.*, 2014). However, the flux of cumulative N_2O in grazed CC was similar to ungrazed CC, which could be attributed to the short-term and well-managed grazing pursued in this study. This less intense grazing was not sufficient to produce any changes in microbial activities which could further influence the N_2O flux (Fuchs *et al.*, 2018). Cover crops and grazing treatments behaved differently within the sites due to differences in various factors that include crop of oats/cover crops-maize rotation present in each year was different (both sites established one year apart), soil moisture (occasional high moisture observed at one site), biomass growth, and weather.

5.5. Limitations of the Study and Future Directions

This study had some limitations those need to be considered for future studies. The first limitation is related to the grazing management. Although properly managed, the duration of grazing in this study was short; therefore, a longer grazing period may be required to capture significant treatment effects on GHG fluxes. Second, the measurement of GHG fluxes was done only during the growing season due to the cold weather; therefore, the effect of ICLS on GHG fluxes might be incomplete. The monitoring of GHG fluxes over the entire year may be required to evaluate the overall effect of ICLS on GHG fluxes. Third, the data collected in this study was for a short period (only 2 years). Management practices such as ICLS may need a longer time to manifest a noticeable change in the measured GHG fluxes. In order to measure the impact of treatment on net GHG emissions, CO_2 emissions due to farm operations, N fertilization, C sequestration, and CO_2 equivalent of CH_4 emissions due to enteric fermentation should be accounted.

5.6. Conclusions

A study was conducted to investigate the influence of cover crops and grazing under integrated crop-livestock system on soil surface greenhouse gas fluxes at two sites. Grazing of grass dominated cover crops significantly reduced CO_2 and N_2O fluxes compared to the grazing of legume dominated cover crops only at one site (N-Brookings) probably due to the favorable conditions for rapid decomposition of low C:N ratio legume cover crops residue. Cover crops and grazing treatments behaved differently within the sites due to differences in various factors that include crop of oats/cover crops-maize rotation present in each year was different (both sites established one year apart), soil moisture (occasional high moisture observed at one site), biomass growth, and weather. Regardless of cover crop type, grazed cover crops recorded similar CO_2 and N_2O fluxes compared to the ungrazed cover crops at either site. Grazing of grass dominated cover crops recorded CO_2 and N_2O fluxes similar to the no cover crops and no grazing probably due to the similar cover crop biomass. Data from this study showed that, in general, cover crops and grazing of cover crop and maize residue did not impact CO_2 and N_2O emissions. It can be concluded that a long-term study is needed which can account for CO_2 equivalents of farm operations, N fertilization, C sequestration, N_2O and CH_4 emissions, and CH_4 emissions due to enteric fermentation from the cattle to measure the net GHG emissions under ICL systems.

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Table 5.1. Details of cover crop blend used at North Brookings and North West Brookings sites.

Crop	Scientific name	LdC†	GdC‡	LdC	GdC
		(% makeup of the seed mixtures by seed weight)		seed rate of individual cover crop (kg ha^{-1})	
Radish	*Raphanus sativus* L.	15	20	11.21	11.21
Turnip	*Brassica rapa* L. var. *rapa*	10	-	3.36	-
Kale	*Brassica oleracea* L.	10	-	4.48	-
Pea	*Pisum sativum* L.	10	5	67.26	67.26
Lentil	*Lens culinaris* Medik.	15	-	33.63	-
Cowpea	*Vigna unguiculata* (L.) Walp.	15	-	33.63	-
Proso millet	*Panicum miliaceum* L.	10	18.75	22.42	22.42
Oats	*Avena sativa* L.	15	18.75	78.47	78.47
Pearl millet	*Pennisetum glaucum* (L.)	-	18.75	-	28.03
Barley	*Hordeum vulgare* L.	-	18.75	-	84.08

†LdC, legume dominated cover crop blend; GdC, grass dominated cover crop blend
‡ The mixture of CC was used with the purpose of enhancing species diversity in the cropping system.

Table 5.2. Details of agronomic management during the cropping season at North Brookings and North West Brookings sites.

Crops	Planting time†	Seed rate	Fertilizer application (kg N ha^{-1})	Harvest time
		North Brookings		
Oats	May 2016	3.5 million seeds ha^{-1}	-	June 2016
Cover crop	July 2016	33.6 kg ha^{-1} (LdC) ‡	-	-
		45.9 kg ha^{-1} (GdC)		
Maize	June 6, 2017	75,000 seeds ha^{-1}	140	Nov 10, 2017
		North West Brookings		
Oats	May 2017	3.5 million seeds ha^{-1}	-	June 2017
Cover crop	July 25, 2017	33.6 kg ha^{-1} (LdC)	-	-
		45.9 kg ha^{-1} (GdC)		
Maize	May 17, 2018	75,000 seeds ha^{-1}	145	Oct 23, 2018

†Each site was managed with minimum tillage. No pesticide was applied to the experimental plots at each site during the study period.
‡LdC, legume dominated cover crop blend; GdC, grass dominated cover crop blend.

Table 5.3. Soil properties as influenced by cover crops and grazing under integrated crop-livestock system at North Brookings and North West Brookings sites.

Treatment	ρ_b (Mg m^{-3})	SOC (g kg^{-1})	TN (g kg^{-1})
	North Brookings		
GdC†	1.33‡	36.8	4.61
GdC+G	1.41	35.2	4.46
LdC	1.34	34.0	4.18
LdC+G	1.43	36.7	4.65
NC	1.42	33.2	4.27
p-value	0.63	0.20	0.13
	North West Brookings		
GdC	1.44	29.5	3.81
GdC+G	1.45	32.5	4.11
LdC	1.38	30.9	3.94
LdC+G	1.43	30.6	3.93
NC	1.49	31.2	3.95
p-value	0.09	0.55	0.53

†GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop.
‡No letters are shown if there is no significant difference within a column for each site at $p < 0.05$.

Table 5.4. Cumulative soil surface CO_2, CH_4, and N_2O fluxes as influenced by cover crops (before grazing) and grazing of cover crops and maize residue under integrated crop-livestock system at North Brookings and North West Brookings sites.

Treatments	North Brookings			North West Brookings		
	CO_2 kg C ha^{-1}	N_2O g N ha^{-1}	CH_4 g C ha^{-1}	CO_2 kg C ha^{-1}	N_2O g N ha^{-1}	CH_4 g C ha^{-1}
	Period I: Cover crops (before grazing)					
GdC†	1885a‡ (±126)	912a (±71)	488a (±35)	1769a (±79)	389a (±35)	268a (±30)
LdC	2178a (±86)	951a (±59)	431a (±34)	1908a (±55)	408a (±31)	135a (±21)
NC	1904a (±77)	919a (±41)	501a (±119)	1886a (±145)	437a (±36)	57a (±102)
p-value	0.0681	0.6067	0.7931	0.5091	0.6887	0.1496
	Period II: Grazing of cover crops and maize residue					
GdC	4186ab (±87)	1595bc (±81)	732a (±200)	4072a (±482)	2198a (±33)	560a (±207)
GdC+G	4042b (±138)	1499c (±111)	832a (±60)	3687a (±37)	1701a (±16)	1202a (±57)
LdC	4864a (±111)	2199a (±61)	874a (±50)	3210a (±462)	2179a (±36)	1072a (±34)
LdC+G	4819a (±200)	2017ab (±111)	654a (±197)	2958a (±175)	2113a (±47)	1149a (±163)
NC	4278 ab (±159)	1329c (±118)	423a (±55)	3101a (±463)	2356a (±292)	781a (±40)
p-value	0.010	0.001	0.330	0.278	0.069	0.054

†GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop.

‡Values followed by the same letter within a column for each period are not significantly different at $p < 0.05$. Standard error values (±) are shown in the parentheses.

Table 5.5. Cumulative soil surface CO_2, CH_4, and N_2O fluxes during and after grazing of cover crops at North West Brookings site.

Treatments	CO_2 kg C ha^{-1}	N_2O g N ha^{-1}	CH_4 g C ha^{-1}
GdC†	37(±4)	50(±5)	35(±18)
GdC+G	48(±3)	73(±7)	12(±15)
LdC	37(±2)	55(±3)	4(±7)
LdC+G	54(±4)	80(±8)	21(±17)
NC	39(±3)	47(±3)	10(±9)

†GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; NC, no cover crop.

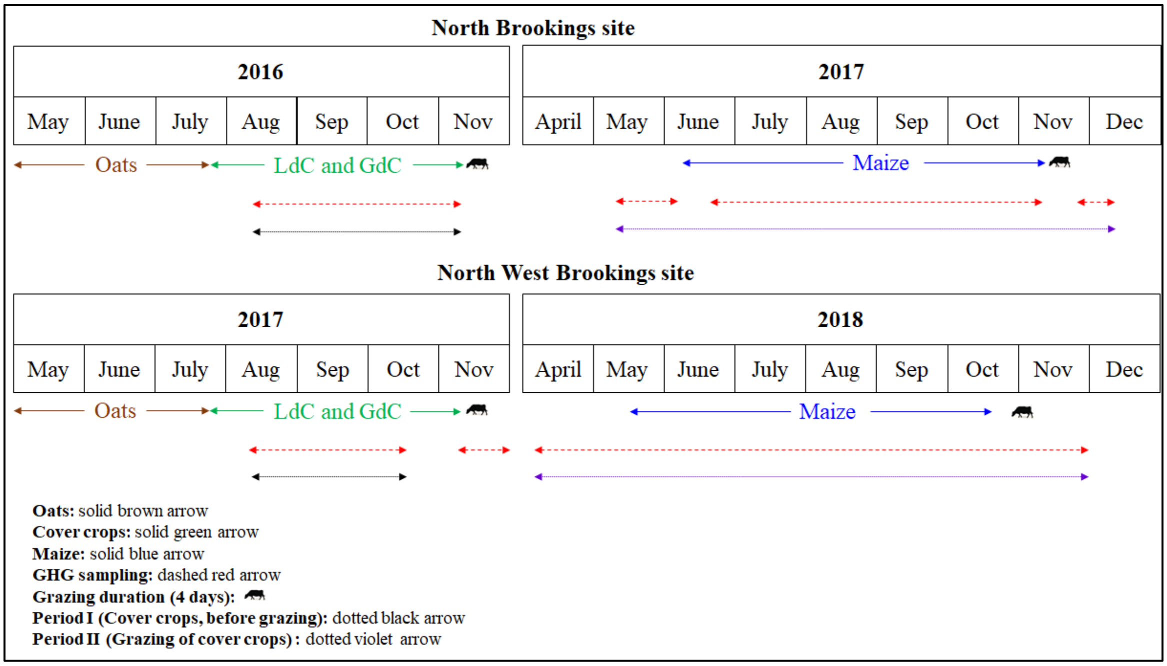

Fig. 5.1. Timeline of agronomic and grazing management at North Brookings and North West Brookings sites performed during 2016, 2017 and 2018.

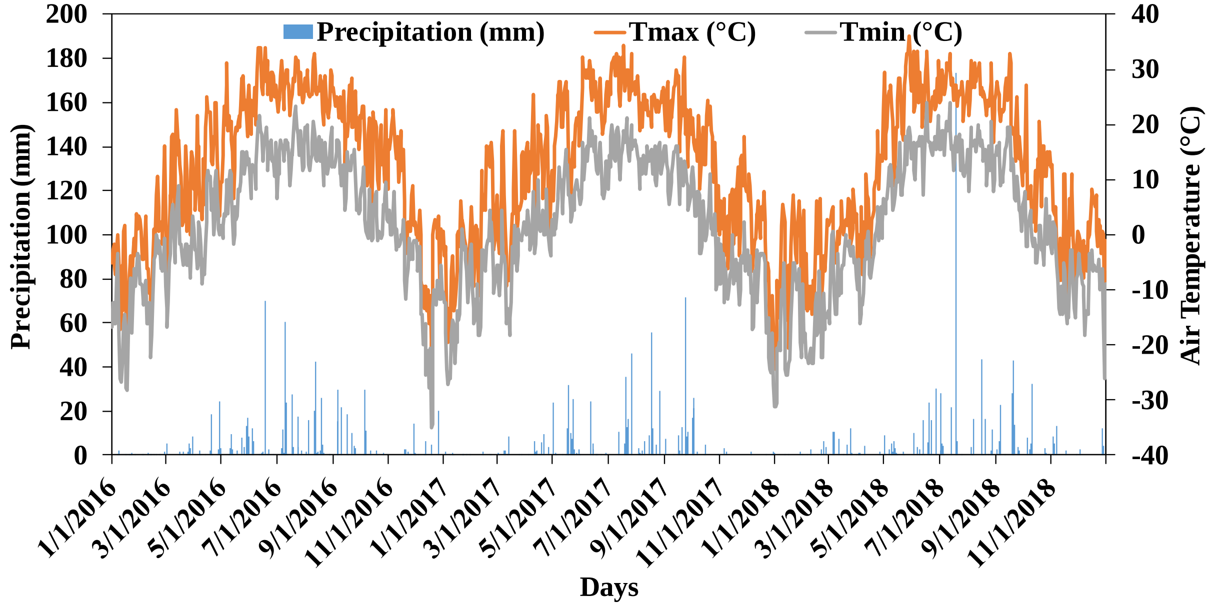

Fig. 5.2. Daily air maximum and minimum temperature and precipitation from 2016 to 2018 at Brookings, South Dakota. Tmax, maximum temperature; Tmin, minimum temperature

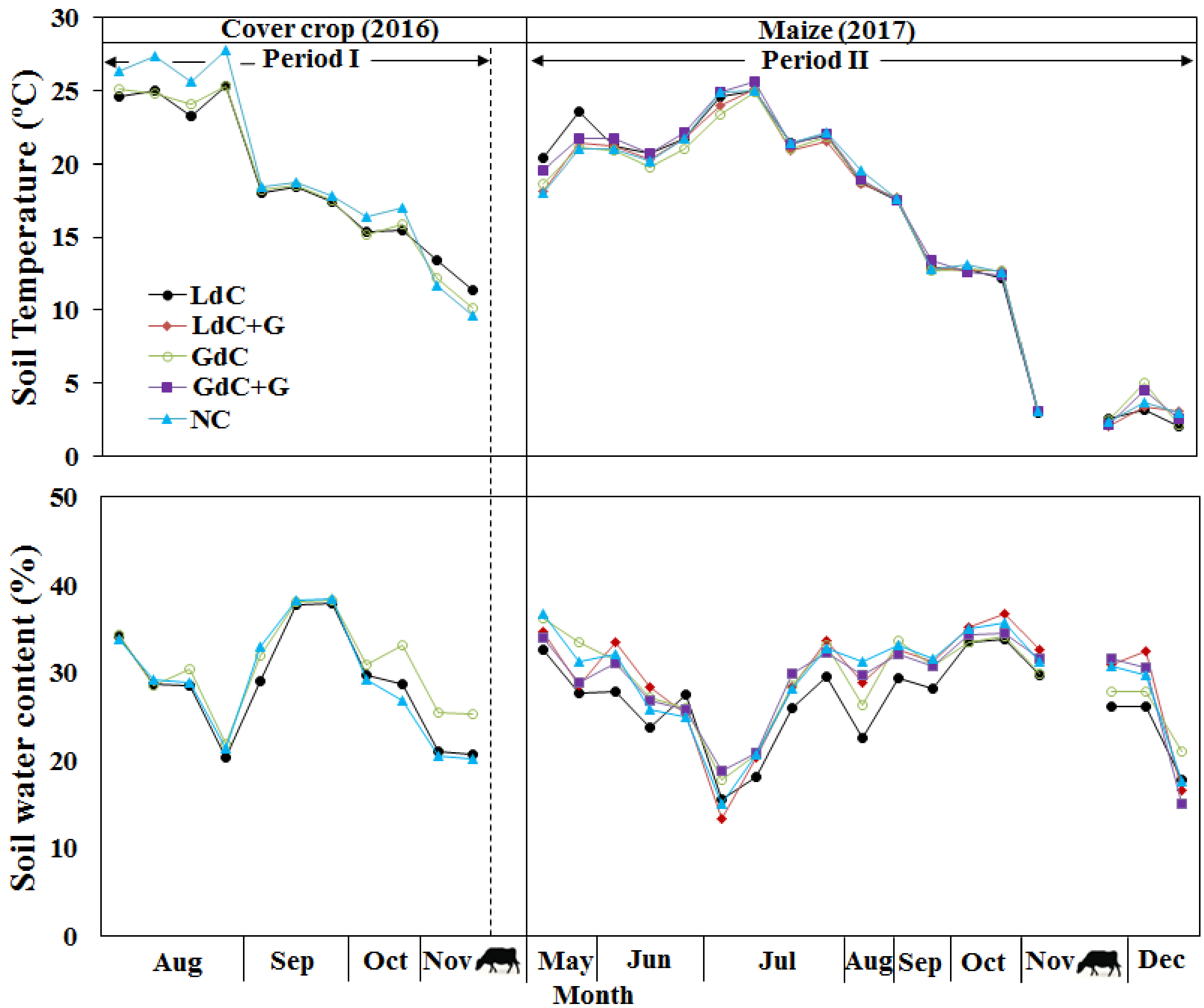

Fig. 5.3. Trends of soil temperature and water content as influenced by cover crops (before grazing) (period I) and grazing of cover crops and maize residue (period II) under integrated crop livestock system at North Brookings site. LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend NC, no cover crop; , cattle grazing.

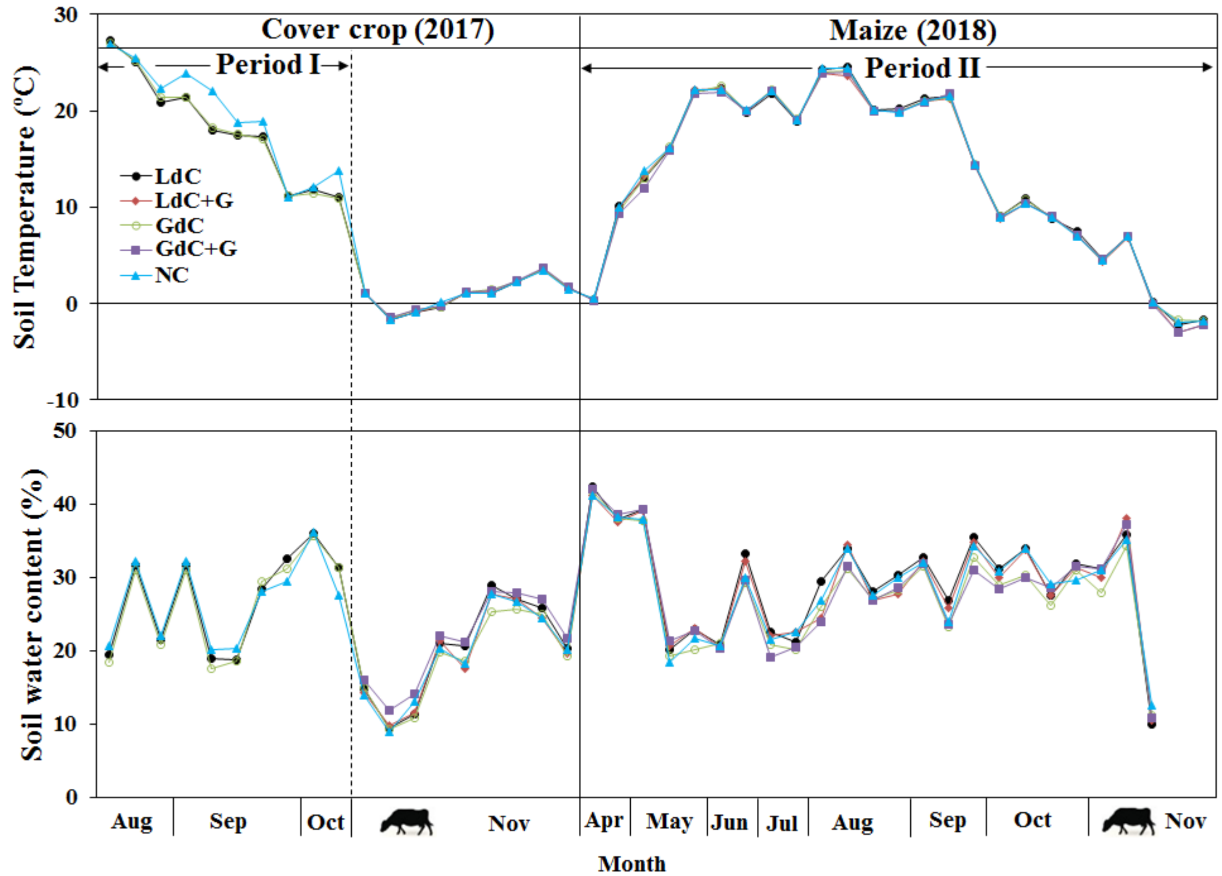

Fig. 5.4. Trends of soil temperature and water content as influenced by cover crops (before grazing) (period I) and grazing of cover crops and maize residue (period II) under integrated crop livestock system at North West Brookings site. LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend NC, no cover crop; [cattle icon], cattle grazing.

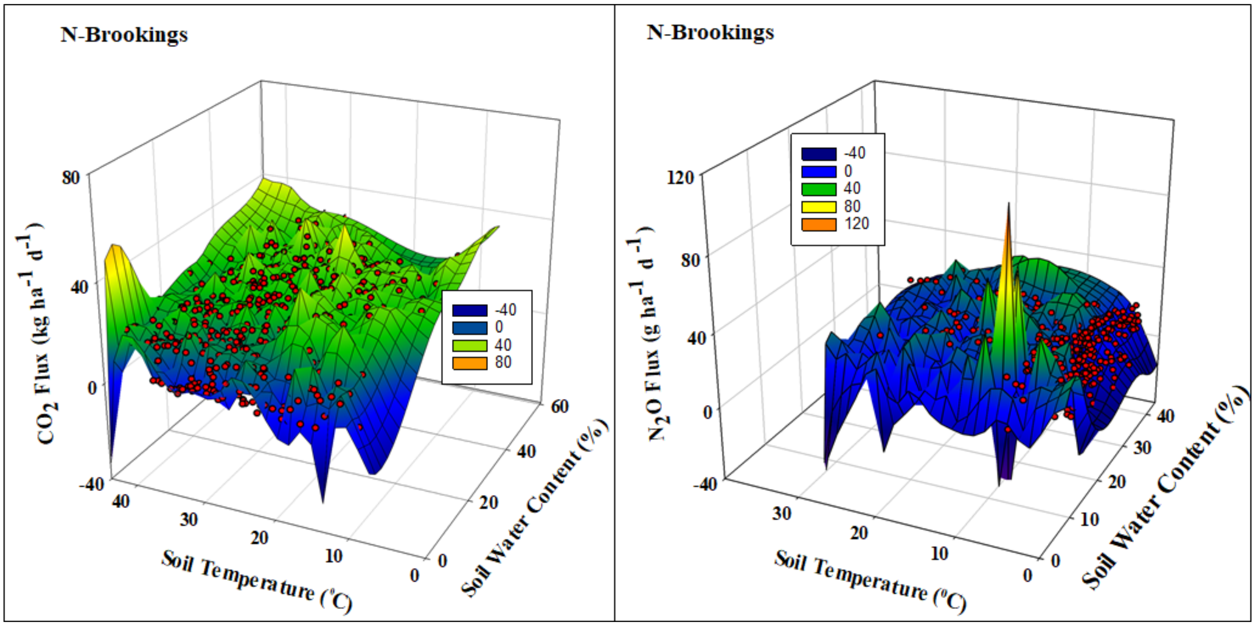

Fig. 5.5. Influence of soil water content (%) and temperature (˚C) on CO_2 and N_2O fluxes over the study period at N-Brookings.

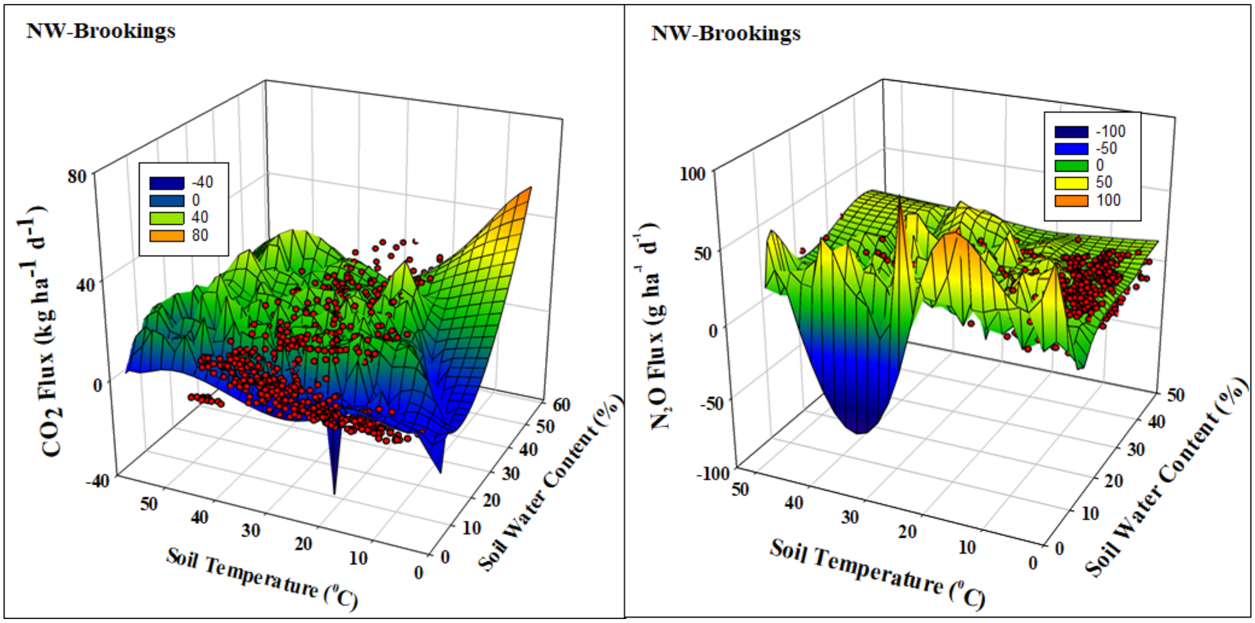

Fig. 5.6. Influence of soil water content (%) and temperature (˚C) on CO_2 and N_2O fluxes over the study period at NW-Brookings.

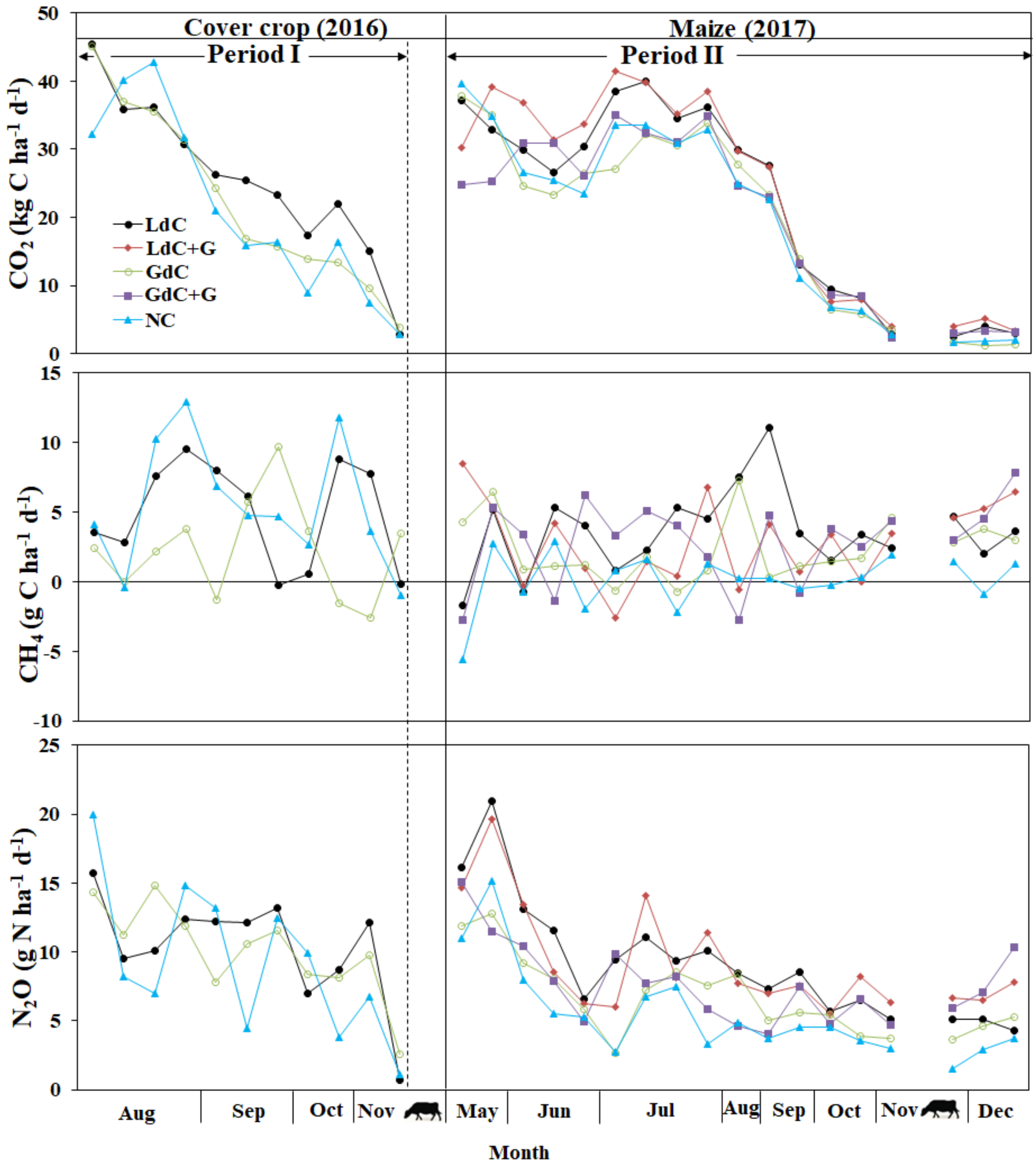

Fig. 5.7. Trends of daily greenhouse gas flux as influenced by cover crops (before grazing) (period I) and grazing of cover crops and maize residue (period II) under integrated crop-livestock system at North Brookings site. LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; NC, no cover crop; , cattle grazing.

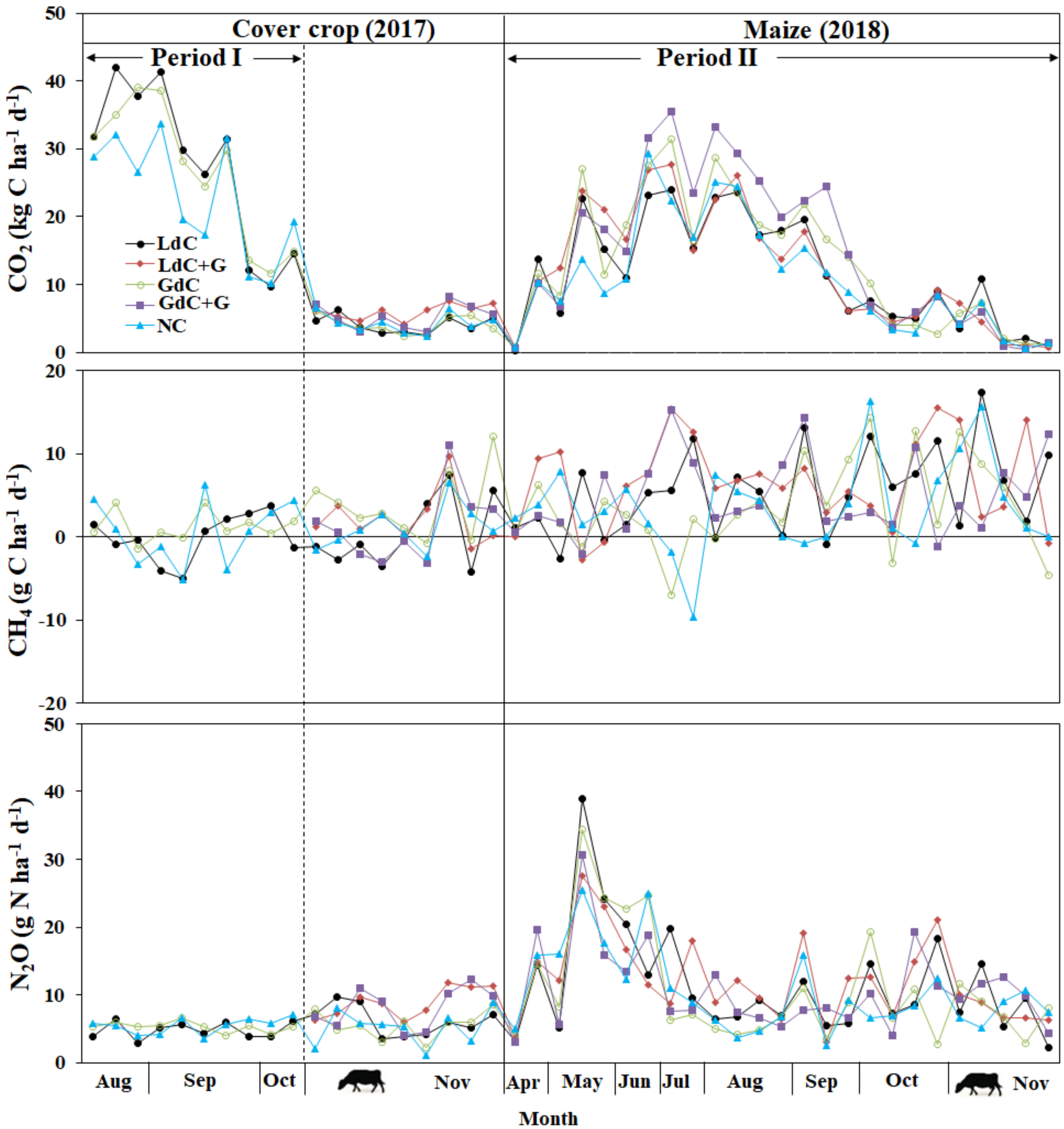

Fig. 5.8. Trends of daily greenhouse gas flux as influenced by cover crops (before grazing) (period I) and grazing of cover crops and maize residue (period II) under integrated crop-livestock system at North West Brookings site. LdC, legume dominated cover crop blend; LdC+G, grazing of legume dominated cover crop blend; GdC, grass dominated cover crop blend; GdC+G, grazing of grass dominated cover crop blend; NC, no cover crop; [cattle symbol], cattle grazing.

CHAPTER 6

MODELING SOIL WATER AND THERMAL REGIME UNDER INTEGRATED CROP-LIVESTOCK SYSTEM WITH HYDRUS

ABSTRACT

Predicting soil water and thermal regimes of the soils under integrated crop-livestock systems through numerical modeling is crucial for effective soil water management under changing weather scenarios. The objective of this study was to calibrate and validate the HYDRUS model, with measured soil water content and temperature from cover cropped (CC), grazed CC, and bare soils (control) under integrated crop-livestock systems. Study treatments included grass-dominated CC (GdC), cattle-grazed GdC (GdC+G), and control (NC), that were laid down in randomized complete block design with four replications in 2017. Soil water content and temperature were monitored using soil moisture sensors at 15, 30 and 45 cm and external soil temperature sensors at 15 and 30 cm depths during the growing crop season. HYDRUS was calibrated using the daily average volumetric soil water content and temperature for growing season of 2017 and validated for the growing season of 2018. Among different treatments, the simulated soil water content matched closely with the measured soil water at different depths for validation (R^2 = 0.26–0.78, d = 0.52–0.89, NSE = -0.02–0.71 and RMSE = 0.08–0.15). Simulations of soil temperature across different treatments were well agreed with that of the measured data (R^2 = 0.48–0.99, d = 0.80–0.99, NSE = 0.28–0.99 and RMSE = 0.49–4.12). HYDRUS performed better in simulating soil temperature compared to that of the soil water content over the study period. Overall, HYDRUS performed reasonably well in predicting the soil hydro-thermal regimes under integrated crop-livestock systems. The modeling outcomes can assist in modifying the conservation management practices according to the future climate change scenarios for maintaining or improving sustainability of agroecosystems. A future study can be beneficial in calibrating the HYDRUS model for longer durations and deeper soil depths in simulating various conservation practices that involve multispecies cover crops and grazing cover crops under integrated crop-livestock systems for enhancing soil moisture conservation.

***Keywords*:** HYDRUS, water flow, soil water content, soil temperature, numerical modeling

6.1. Introduction

Soil water is a limiting factor for crop production, especially where precipitation is the only source to recharge the soil moisture. Moisture in the soils plays a vital role in controlling water and energy fluxes in the soil profile (Vereecken *et al.*, 2007) and influencing the planting of crops, soil processes, nutrient dynamics among others. Deficient or excess water in the soil profile at various stages of crop growth can adversely affect physiological processes such as root respiration and plant water uptake. The increasing weather extremities that cause droughts and flooding disturb the soil moisture regime and hence impact the maximum yield potential of the row crops. Soil moisture conditions influence soil water infiltration, evaporation, plant transpiration, runoff, percolation and deep drainage and thus control the distribution of water inputs and their availability to the crops. Similarly, soil temperature is one of the most essential variables of the soil that can significantly impact seed germination (Nabi and Mullins, 2008), nutrient uptake (Ropokis *et al.*, 2019), soil evaporation (Kader *et al.*, 2017), greenhouse gas emissions (Dowhower *et al.*, 2020), crop growth (Iwasaki *et al.*, 2019) and microbial processes (Yu *et al.*, 2019) in the soil. Water and heat transport through the soil profile under different management systems are primarily regulated by soil properties, surface cover characteristics, and microclimatic conditions in the field. Thus, understanding soil water and heat transport dynamics is critical in gaining knowledge regarding eco-physiological processes that govern water and energy exchange between soil and the atmosphere. The collection of field data pertaining to soil moisture status and soil temperature for designing soil water conservation systems is tedious and can take long time periods. Although several methods for soil water content measurement are available that include gravimetric, neutron scattering, time domain reflectometry, capacitance methods etc. (Hillel, 1998), these techniques are limited spatio-temporally and are expensive for measurement at multiple locations. Soil water modeling coupled with the field research plays a crucial role in overcoming these difficulties in studying soil water and thermal conditions under changing weather scenarios. Hydrological models are the robust tools for studying the soil moisture and thermal regimes in the agroecosystems and to evaluate the long-term impacts of some agricultural practices on the soil system. Several one-dimensional models are available to study the soil water and temperature dynamics include DRAINMOD (Skaggs *et al.*, 2012), RZWQM (Ma *et al.*, 2006) and HYDRUS-1D (Šimůnek *et al.*, 2008). Numerical models such as HYDRUS have the ability to analyze and predict water flow, storage and water movement processes in vadose zone very accurately due to the flexibility of selecting boundary conditions and soil hydraulic functions (Saito *et al.*, 2006). HYDRUS is a Windows-based modeling software that simulates water, heat and multiple solute transport in one-dimensional variably saturated porous media by solving the Richards equation (Šimůnek *et al.*, 2008). It has been applied successfully in various studies for predicting soil moisture content and water and heat transport under diverse conditions (Li *et al.*, 2017; Wang *et al.*, 2018; Baek *et al.*, 2020). Detailed description of the model is available in Šimůnek *et al.* (2008).

A good understanding of soil water processes during the crop growing season and their influencing factors is important for efficient water management, especially under rainfed agroecosystems. Therefore, the objective of this study was to calibrate and validate the HYDRUS model, with measured soil water content and temperature from cover cropped (CC), grazed CC, and bare soils under integrated crop-livestock systems.

6.2. Materials and Methods

6.2.1. Experimental Site, Treatments and Experimental Design

The experiment was conducted for two years (2017-2018) at the Brookings-northwest (NW) research farm of South Dakota State University, Brookings, SD (44°20'14.5"N 96°48'28.8"W). The study site is characterized by continental temperature with warm, humid summers and snowy winters. Mean annual precipitation for the experimental site is 637 mm and the mean temperature is −15.8 °C in the winter and 27.8 °C in the summer. Soils at the experimental site were classified as Barnes (fine-loamy, mixed, frigid Udic Haploborolls). The experimental design was a randomized complete block design having three treatments viz., (i) grass dominated CC (GdC), (ii) cattle grazed GdC (GdC+G), and (iii) without CC and grazing (NC) with 3 replications. The individual plots were 18.3 m wide and 30.5 m long. The cropping system at the experimental site was oat (*Avena sativa* L.)-corn (*Zea mays* L.). Grass dominated cover crop (CC) blend included 18.75% Proso millet (*Panicum miliaceum* L.), 18.75% Oats (*Avena sativa* L.), 18.75% Pearl millet (*Pennisetum glaucum* L.), 18.75% Barley (*Hordeum vulgare* L.), 20% Radish (*Raphanus sativus* L.) and 5% Pea (*Pisum sativum* L.). The CC blend was planted in 19-cm wide rows using a grain drill [John Deere 750 series grain drill (Deere and Co., Moline, Illinois, USA)] after the harvest of oats. Further details of agronomic management practices are shown in Table 6.1. Aberdeen Angus (*Bos taurus*), a cattle breed commonly used for beef production in South Dakota, were used for grazing the CC and corn crop residue. The grazed plots were electrically fenced to prevent grazing in the ungrazed plots and animals were present all the time in the grazed plots during grazing. The stocking rate of cattle was determined on the basis of quantity of above-ground crop biomass available in the field for grazing assuming 12.7 kg of dry matter consumed per animal per day (Uresk, 2010). Approximately one-half of the available biomass was grazed and the other half was left on the soil to prevent soil erosion. Additional information about the study sites can be obtained from Singh *et al.* (2020).

6.2.2. Soil Sampling and Field Instrumentation

Soil sampling was carried out in the experimental area in 2017 before planting the cover crop. Bulk soil samples from 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths were taken with hydraulic push probe and were sealed in Ziploc bags and transferred to the lab for analysis. After removing all visible residues, the samples were air-dried at room temperature and sieved to 2-mm for soil texture analysis using hydrometer method (Gee and Or, 2002). Soil total C and N contents were determined on the samples (0.5 mm-sieved) by dry combustion using a TruSpec carbon/hydrogen/nitrogen (CHN) analyzer (LECO Corporation, St. Joseph, MI, USA). Inorganic C in the samples was found to be below detection limits; hence, total C was considered to be SOC (Stetson *et al.*, 2012). Immediately after planting, the plots were instrumented with soil moisture and temperature sensors. Soil water content and temperature were monitored using WaterScout SM 100 soil moisture sensors (Spectrum Technologies Inc., Aurora, IL) were installed at 15, 30 and 45 cm and external soil temperature sensors installed at 15 and 30 cm depths. The sensor access holes were made at the desired depths near the effective root zones using push probe auger. Soil moisture and temperature sensors were fit inside the PVC pipes and installed at the specific depths. The access holes were then carefully backfilled and tamped down to eliminate air pockets. Sensors were connected to battery powered WatchDog 1000 series micro stations to record hourly volumetric soil water content and soil temperature during the entire growing season.

6.2.3. Hydrological Modeling

6.2.3.1. Model Description

The numerical model package HYDRUS was used to simulate the unsaturated water flow and heat movement in one-dimensional variably saturated media. The program numerically solves the Richard’s equation for saturated and unsaturated soil water flow:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} + 1\right)\right] - S$$

where θ is volumetric water content (m^3m^{-3}), t is time (d), z is vertical coordinate (m) positive downward, K is the unsaturated hydraulic conductivity ($m\ d^{-1}$), h is the water pressure head (m), and S is the source/sink term accounting for water uptake by plant roots ($m^3m^{-3}d^{-1}$). The unsaturated hydraulic conductivity K, as a function of h, is given in the van Genuchten's equation (Van Genuchten, 1980):

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases}$$

$$K(h) = \begin{cases} K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 & h < 0 \\ K_s & h \geq 0 \end{cases}$$

$$\text{with } m = 1 - \frac{1}{n}, n > 1 \text{ and } S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

where θ_r is the residual water content (m^3m^{-3}), θ_s is the saturated water content (m^3m^{-3}), h is the water pressure head (m), α (m^{-1}), m and n are fitting parameters of soil water characteristic curve, l is the pore connectivity parameter (=0.5) (Mualem, 1976), K_s is saturated hydraulic conductivity ($m\ d^{-1}$) and S_e is the effective saturation.

6.2.3.2. Time Variable Boundary and Initial Conditions

The water flow boundary at the soil surface was specified as atmospheric boundary condition, using the daily potential evaporation from the soil (E_p), transpiration from the plants (T_p), and precipitation data. HYDRUS requires E_p, T_p, and daily rainfall values as time variable inputs for specified atmospheric boundary conditions. A free-drainage condition was imposed as the bottom boundary condition. The variable boundary conditions of this study are illustrated in Fig. 6.4. HYDRUS can simulate water content at any specific soil depth. The observation nodes were set at 15, 30 and 45 cm representing the location of the soil moisture and temperature sensors. For the heat transport boundary conditions, a boundary condition with specified time-variable temperatures was assigned along the soil surface (atmospheric boundary condition). A boundary condition representing free drainage boundary conditions at the bottom of the flow domain was imposed for heat transport. Initial conditions in the model were represented by the direct measurements of soil water content and soil temperature along the vertical dimension at initial time step of model simulation. For water flow simulation, initial conditions were provided by specifying the top (15 cm) and bottom (45 cm) Watermark sensor data and assuming a linear distribution of these data with the soil depth for the 45-cm flow domain. For heat transport, the initial conditions were provided by specifying the 15 cm and 30 cm soil temperature data. The initial values of soil hydraulic parameters (θ_r, θ_s, α, n, K_s and l) were derived from soil's texture using a neural network prediction (Rosetta Lite version 1.1, (Schaap *et al.*, 2001)) function in HYDRUS, based on pedotransfer functions. The default values for heat transport parameters were used from the HYDRUS database (Chung and Horton, 1987). The root water uptake model of Feddes *et al.* (1978) without any osmotic stress was used to describe the water stress response functions in the HYDRUS simulations.

6.2.4. Statistical Evaluation

During the HYDRUS calibration and validation, model predictions of daily average volumetric water content values at depths of 15, 30 and 45 cm and soil temperature values at 15 and 30 cm were compared to the measured values by using statistical measures such as index of agreement (d) (Willmott, 1981), root mean square error (RMSE), coefficient of determination (R^2) and Nash-Sutcliffe modelling efficiency (NSE) (Nash and Sutcliffe, 1970). The d, RMSE and NSE are defined as follows:

$$d = 1 - \frac{\sum_{i=1}^{n} (p_i - o_i)^2}{\sum_{i=1}^{n} \left(|p_i'| + |o_i'| \right)^2}$$

where $p_i' = p_i - \bar{o}$ and $o_i' = o_i - \bar{o}$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (p_i - o_i)^2}{n}}$$

$$NSE = 1 - \frac{\sum_{i=1}^{n} (o_i - p_i)^2}{\sum_{i=1}^{n} (o_i - \bar{o})^2}$$

where n is the number of paired observed and predicted values; p_i is the i^{th} predicted value; o_i is the i^{th} measured value and $\bar{o}$ is the mean of observed values.

The index of agreement (*d*) is a measure of the degree to which the predicted variation precisely estimates the observed variation. The value of *d* varies between 0 (no agreement) and 1 (perfect agreement between measured and simulated values). The value of RMSE gives a measure of the relative difference of simulated versus observed data. The lower RMSE value indicates better model performance. RMSE is capable of expressing the error with the same units as that of the variable, that can provide more information about model efficiency than R^2. Nash–Sutcliffe modeling efficiencies can range from $-\infty$ to 1. The simulation results are considered to be acceptable if $0 < NSE < 1.0$ and a negative NSE indicates unacceptable performance (Ket *et al.*, 2018). An efficiency of 1 (NSE = 1) corresponds to a perfect match between modeled values and observed data. An efficiency of 0 (NSE = 0) indicates that the model predictions are as accurate as the mean of the observed data, whereas an efficiency less than zero ($-\infty <$ NSE < 0) occurs when the observed mean is a better predictor than the model.

6.3. Results and Discussion

6.3.1. Soil Properties and Weather Conditions

Based on the particle size analysis of soil samples at various depths, we found that the upper soil layer (0-5 cm) was dominated by sandy loam soil, while the bottom soil layer (45-60 cm) was dominated by sandy clay loam soil type. Soil organic carbon content was the highest at the surface soil layer (31.2 g kg^{-1}) and decreased with the depth. A similar trend in total nitrogen content was also observed. The detailed results for particle size analysis, SOC and TN for various soil depths are presented in Table 6.2. Daily mean air temperature (maximum and minimum) and precipitation for 2017 and 2018 are shown in Fig. 6.1. The total annual precipitation received in 2017 and 2018 was 671.1 and 787.4 mm, respectively. Total annual precipitation was 17% higher in 2018 than that in 2017.

6.3.2. Measured Soil Water Content

Soil water content under all the treatments for 2017 and 2018 has been presented in Fig. 6.2 and 6.3. In 2017, measured average soil water content values ranged from 0.11 to 0.51 cm^3 cm^{-3} among different treatments at 15 cm depth. The corresponding values for 30 and 45 cm depth were 0.03 to 0.55 and 0.05 to 0.56 cm^3 cm^{-3}. Soil water content, in general, remained higher under GdC than that of the GdC+G and NC during the growing season at 15 cm depth, however the differences were not always significant. The GdC and GdC+G treatments exhibited greater soil water as compared to that of the NC at 30 cm depth. A similar pattern was observed at 45 cm depth. Consecutive precipitation events of 72, 9, and 11 mm on 267, 268 and 269 day of year (DOY) and 17, 21 and 26 mm on 274, 275 and 276 DOY, respectively, recharged soil water in the 45 cm profile among different treatments (Fig. 6.2). In 2018, measured average soil water readings ranged from 0.02 to 0.67 $cm^3\ cm^{-3}$ among different treatments through the soil profile. The trend of soil water content varied among different treatments during the growing season in 2018. Two major recharging events occurred total precipitation of 89 mm from 261 to 264 DOY and 40 mm from 281 to 283 DOY (Fig. 6.3).

6.3.3. Model Calibration and Validation With Soil Water Content

HYDRUS was calibrated using the daily average volumetric soil water content for growing season of 2017 and validated for the growing season of 2018. Details of input parameters used for HYDRUS modeling are shown in Table 6.3. The differences in the measured and simulated soil water contents in the different soil layers for different treatments are shown in Table 6.4. HYDRUS performed reasonably well in simulating soil water content for 0-15 cm among different treatments as indicated by high index of agreement (0.66-0.81) and low RMSE (0.04-0.06 $cm^3\ cm^{-3}$) values during calibration (Fig. 6.5). The positive values of NSE indicated acceptable simulated soil water content values for CNT and GdC+G for the upper soil layer. The model performance during validation was similar to that of the calibration for 0-15 cm soil layer. The values of d

ranged from 0.52 to 0.89 and RMSE ranged from 0.08 to 0.12 cm^3 cm^{-3} and R^2 ranged from 0.26 to 0.78, which indicated that the model performed equally well during the validation period. For, 15-30 cm soil layer, the values of *d* were lowered for the GdC and NC treatments, however, the model showed good agreement between observed and predicted soil water content for GdC+G during calibration (*d*=0.59; Table 6.4). The RMSE values were also found to be lower for this depth and ranged from 0.06-0.16 cm^3 cm^{-3}. During the validation period, the model showed an improved performance in predicting the soil water content at 15-30 cm soil layer under different treatments as evident from the increase in the *d*, NSE and R^2 values compared to the calibration period (Table 6.4). For 30-45 cm soil layer, the model showed a good agreement between the measured and simulated soil water content during calibration. The values of *d* for GdC, GdC+G and NC were 0.85, 0.64 and 0.50, respectively. The corresponding values of NSE were 0.35, 0.14 and 0.14 and RMSE were 0.02, 0.05 and 0.13 cm^3 cm^{-3} for this depth. The model statistics (*d*, NSE and R^2) suggests that simulations were better during the validation period as compared to the calibration for GdC+G and NC treatments, however an opposite trend was observed for GdC treatment at this depth (Table 6.4). The differences between the measured and simulated water contents at different soil depths under different treatments might be ascribed to the errors related to the measured data acquisition those are likely due to the potential inaccuracy in sensor responses. The measurement errors in the capacitance type sensors may be expected under field conditions. The deviations between measured and simulated data could also be due to the inherent variability in soils. A comparable model statistics have also been reported in previous HYDRUS modeling studies (Caiqiong and Jun, 2016; Graham *et al.*, 2019).

6.3.4. *Measured Soil Temperature*

In 2017, measured average soil temperature values ranged from 2.8 to 22.1°C among different treatments at 15 cm depth. The corresponding values for 30 cm depth were from 2.8 to 22°C. Soil water content, in general, remained higher under NC than other treatments, however the differences were not always significant (data not shown). In 2018, measured average soil temperature values ranged from 3.5 to 37.6°C and from 5.1 to 19.9°C among different treatments at 15 and 30 cm depths, respectively.

6.3.5. *Model Calibration and Validation With Soil Temperature*

Calibration of HYDRUS was performed using the daily average soil temperature for growing season of 2017 and the model was validated for the growing season of 2018. Soil temperature measured at 15 and 30 cm soil depths in all the treatments during the growing seasons in 2017 and 2018 by using temperature sensors were compared with the HYDRUS simulated soil temperature (Table 6.5). The magnitudes of the measured soil temperatures at these soil depths under different treatments during both growing seasons reliably corresponded to soil temperatures predicted by HYDRUS, which was implied by the results of statistical evaluation of measured versus simulated soil temperature. For 0-15 cm layer, the values of NSE varied from 0.94 to 0.99 and R^2 varied from 0.95 to 0.99 under the treatments of GdC, GdC+G and CNT during calibration. The high values of *d* also suggested a good agreement between measured and simulated soil temperature at this depth. A satisfactory model performance was observed during the validation period with fairly large values of *d*, NSE and R^2 (Table 6.5). The RMSE values varied from 0.37 to 0.60 °C during model calibration. Similar model statistics were also observed during the model calibration and validation for soil temperature under different treatments at 15-30 cm soil layer. A comparable model statistic was also reported by Kader *et al.* (2019) for the simulations of soil temperature with HYDRUS under straw mulched and bare soils. They attributed the deviations among the observed and simulated soil temperatures to the effects of the specified surface and bottom heat-transport boundary conditions for the numerical flow domain.

6.4. Conclusions

Integrated crop-livestock system has potential for enhancing soil health and moisture conservation. However, these data need to be collected for longer duration which quite often is expensive. Hence, modeling tools are very beneficial in simulating various conservation practices in enhancing the soil moisture conservation. The present study was conducted to use the HYDRUS model in simulating soil moisture and temperature under integrated crop-livestock system that involved cover crops, grazed cover crops and control (no cover crops and grazing). In this study, HYDRUS model was confronted with the field measurement of soil water content (at 15, 30 and 45 cm soil depths) and temperature (at 15 and 30 cm soil depths) collected using WaterScout soil moisture and temperature sensors in three treatments viz. grass dominated cover crops, cattle grazed grass dominated cover crops and a control having bare soil. Data showed that HYDRUS simulated soil water content and temperature agreed with the measured data at different soil depths for all treatments to a reasonable accuracy, as suggested by values of statistical indices d, NSE, RMSE, and R^2.

Overall, the HYDRUS model performed better in simulating soil temperature compared to that of the soil water content at the studied depths under different treatments. We postulate that the predictions for the soil water contents can be improved by optimizing the soil hydraulic parameters that govern the water flow through the soil profile. The results show that soil water flow models can act as a powerful tool to understand the hydro-thermal regimes of the soils subjected to different management practices. A future study needs to be extended further that can use the calibrated and validated HYDRUS model and explore various cover crops and grazing management strategies under integrated crop-livestock systems in enhancing the soil moisture conservation.

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Table 6.1. Details of agronomic management information during the cropping season at the study site.

Crops	Planting time	Seed rate	Fertilizer application (kg N ha^{-1})	Harvest time
Oats	May 2017	3.5 million seeds ha^{-1}	-	June 2017
Cover crop	July 25, 2017	45.9 kg ha^{-1}	-	-
Corn	May 17, 2018	75,000 seeds ha^{-1}	145	Oct 23, 2018

Table 6.2. Basic soil properties for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths of the study site.

Depth	Sand	Silt	Clay	Texture
cm	---------g kg^{-1}---------			
0-5	64.0	19.7	16.3	Sandy loam
5-15	45.1	28.5	26.4	Loam
15-30	61.0	18.4	20.6	Sandy clay loam
30-45	65.7	16.8	17.5	Sandy loam
45-60	53.4	23.9	22.7	Sandy clay loam

Table 6.3. Input parameters used for HYDRUS model set up.

Parameters	Values			
Geometry information				
Depth (cm)				
For water flow	45			
For heat transport	30			
No. of soil materials				
For water flow	4			
For heat transport	3			
No. of observational nodes				
For water flow	3			
For heat transport	2			
Time step	Daily			
Soil hydraulic model	Van-Genuchten-Mualem			
Hysteresis	No hysteresis			
Hydraulic parameters				
Layer (cm)	0-5	5-15	15-30	30-45
θ_r (cm^3 cm^{-3})	0.053	0.072	0.060	0.055
θ_s (cm^3 cm^{-3})	0.384	0.500	0.500	0.490
α (cm^{-1})	0.028	0.017	0.026	0.029
n	1.373	1.382	1.348	1.365
K_s (cm d^{-1})	26.49	7.93	18.52	25.37
l	0.5	0.5	0.5	0.5
Boundary conditions				
Upper boundary condition				
For water flow	Atmospheric BC with surface layer			
For heat transport	Temperature BC			
Lower boundary condition				
For water flow	Free drainage			
For heat transport	Zero gradient			

Table 6.4. Performance of HYDRUS in simulating soil moisture content of grass dominated cover cropped (GdC) soil, cattle grazed GdC soil (GdC+G) and the bare soil (NC) treatments in terms of coefficient of determination (R^2), index of agreement (d), Nash-Sutcliffe modelling efficiency (NSE) and Root Mean Square Error (RMSE, $cm^3\ cm^{-3}$) during the periods of calibration (2017) and validation (2018).

Treatment		Calibration				Validation			
	Depth (cm)	R^2	*d*	NSE	RMSE	R^2	*d*	NSE	RMSE
GdC	0-15	0.68	0.66	-0.84	0.04	0.78	0.84	0.52	0.08
	15-30	0.51	0.21	-28.4	0.06	0.58	0.69	0.40	0.15
	30-45	0.56	0.85	0.35	0.02	0.36	0.74	0.34	0.14
GdC+G	0-15	0.35	0.74	0.26	0.04	0.26	0.52	-0.02	0.12
	15-30	0.30	0.59	-0.20	0.06	0.71	0.90	0.50	0.08
	30-45	0.23	0.64	0.14	0.05	0.52	0.79	0.49	0.14
NC	0-15	0.52	0.81	0.09	0.06	0.75	0.89	0.71	0.09
	15-30	0.15	0.27	-0.82	0.16	0.31	0.70	0.07	0.14
	30-45	0.22	0.50	0.14	0.13	0.62	0.87	0.54	0.10

Table 6.5. Performance of HYDRUS in simulating soil temperature of grass dominated cover cropped (GdC) soil, cattle grazed GdC soil (GdC+G) and the bare soil (NC) treatments in terms of coefficient of determination (R^2), index of agreement (d), Nash-Sutcliffe modelling efficiency (NSE) and Root Mean Square Error (RMSE, $cm^3\ cm^{-3}$) during the periods of calibration (2017) and validation (2018).

Treatment		Calibration				Validation			
	Depth (cm)	R^2	*d*	NSE	RMSE	R^2	*d*	NSE	RMSE
GdC	0-15	0.95	0.98	0.94	0.37	0.98	0.99	0.98	0.57
	15-30	0.98	0.95	0.79	0.60	0.99	0.99	0.98	0.68
GdC+G	0-15	0.99	0.99	0.99	0.39	0.82	0.95	0.82	2.49
	15-30	0.99	0.99	0.99	0.38	0.48	0.80	0.28	4.12
NC	0-15	0.99	0.99	0.99	0.48	0.99	0.99	0.99	0.49
	15-30	0.99	0.99	0.99	0.48	0.99	0.99	0.98	0.67

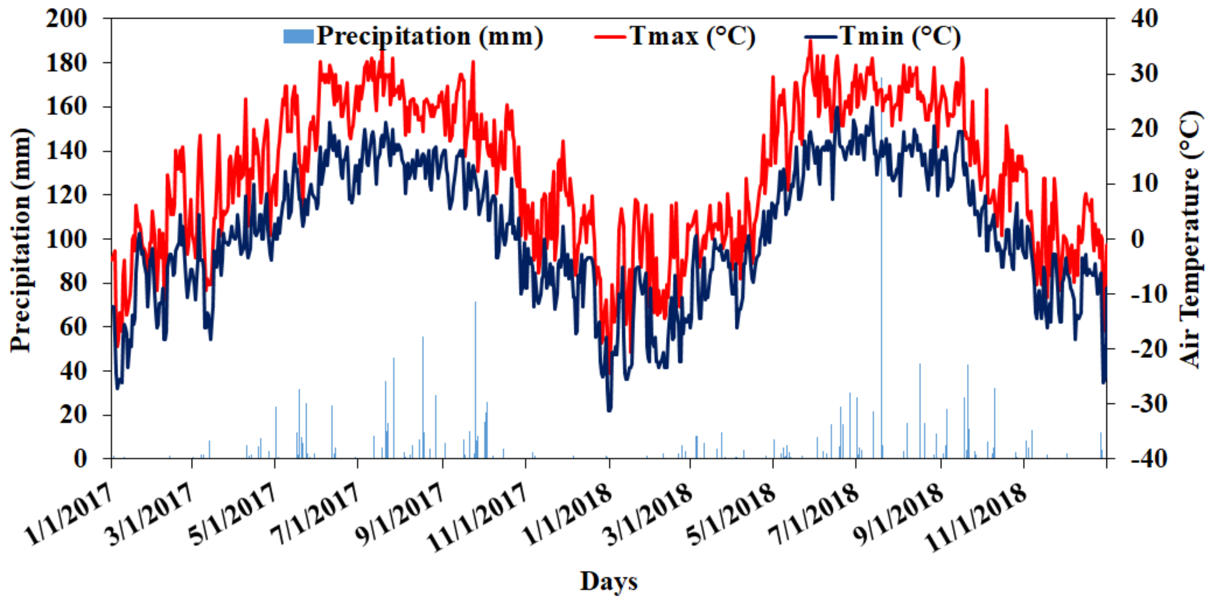


Fig. 6.1. Daily air maximum and minimum temperature and precipitation during 2017 and 2018 at Brookings, South Dakota. Tmax, maximum temperature; Tmin, minimum temperature

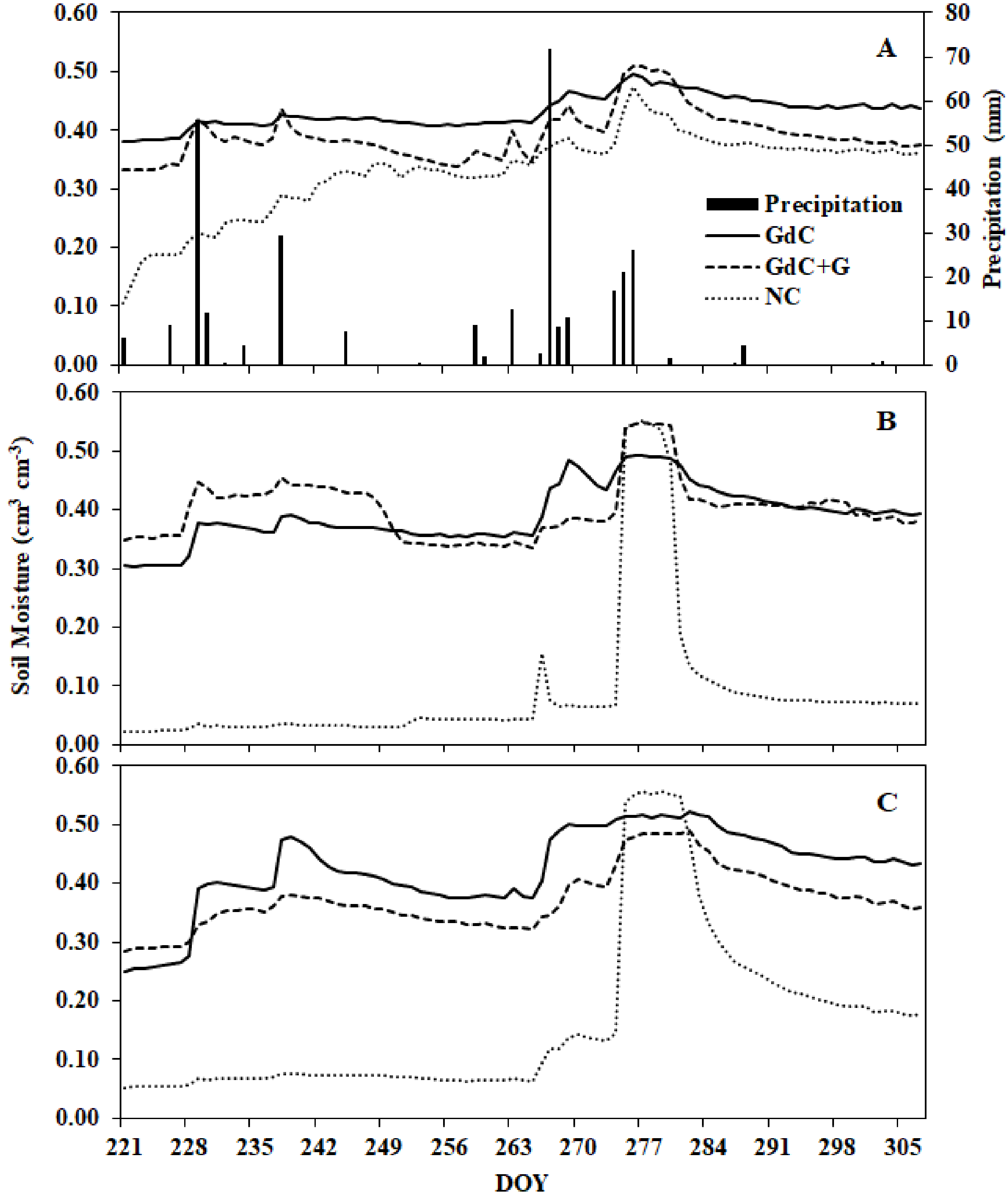


Fig. 6.2. Precipitation distribution (during study period) and measured volumetric water content for the treatments of grass dominated cover crops (GdC), cattle grazed GdC (GdC+G) and control (NC) at depths of (A) 15 cm, (B) 30 cm, and (C) 45 cm in 2017. DOY, Day of Year.

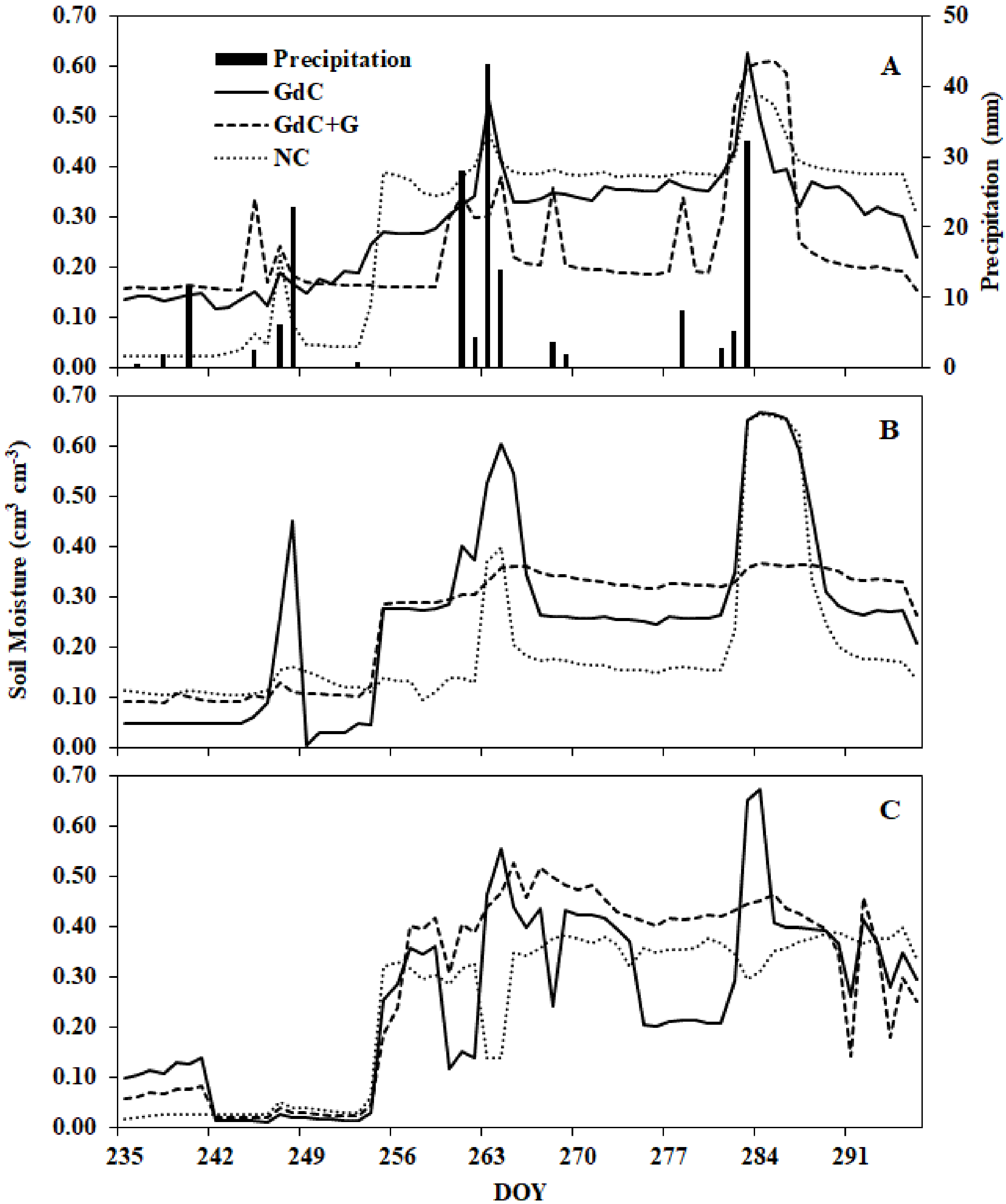


Fig. 6.3. Precipitation distribution (during study period) and measured volumetric water content for the treatments of grass dominated cover crops (GdC), cattle grazed GdC (GdC+G) and control (NC) at depths of (A) 15 cm, (B) 30 cm, and (C) 45 cm in 2018. DOY, Day of Year.

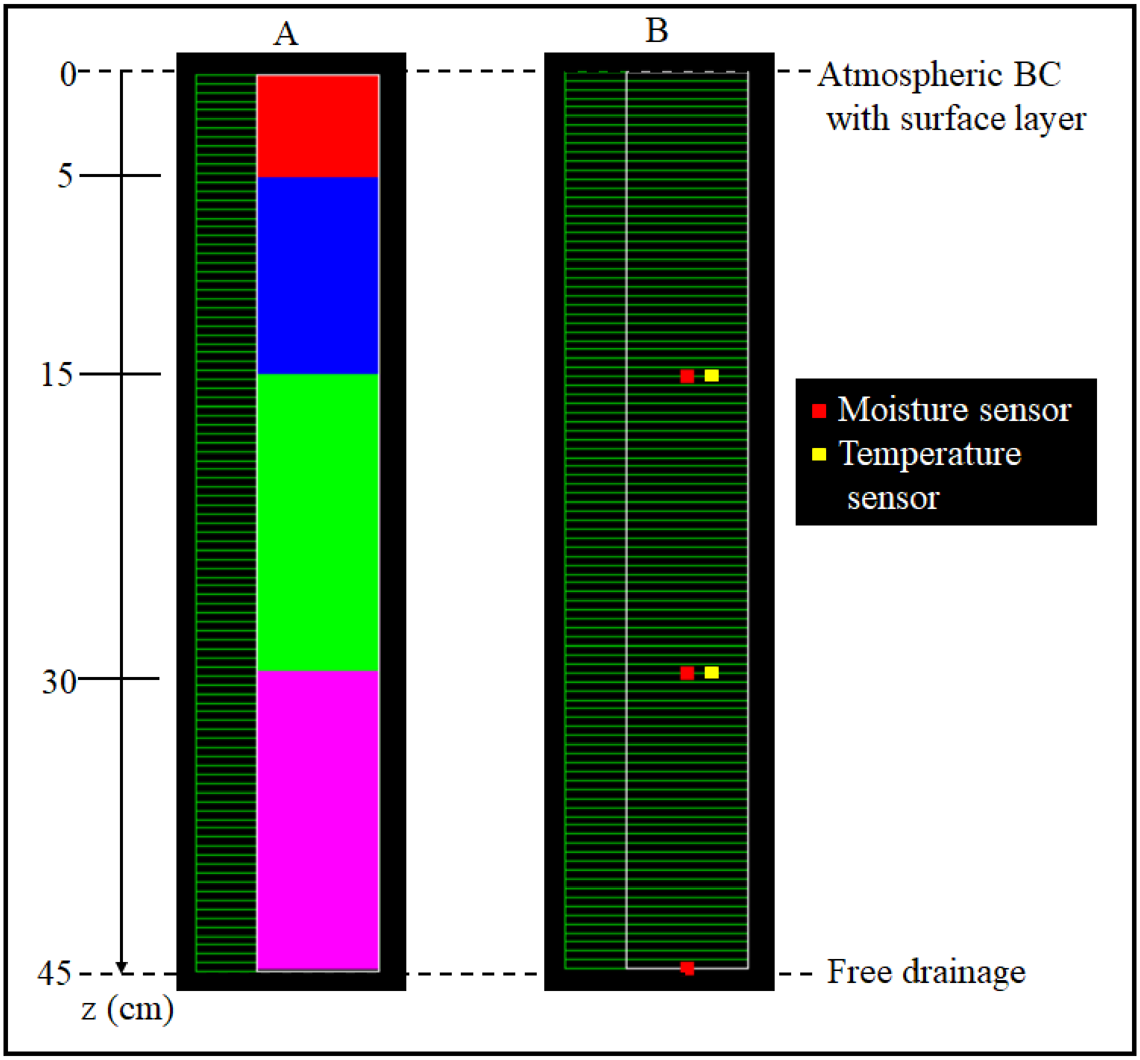


Fig. 6.4. Flow domain and boundary conditions used in HYDRUS simulations. A) distribution of soil profile for 2017 through 2019, and B) location of soil moisture and temperature sensors.

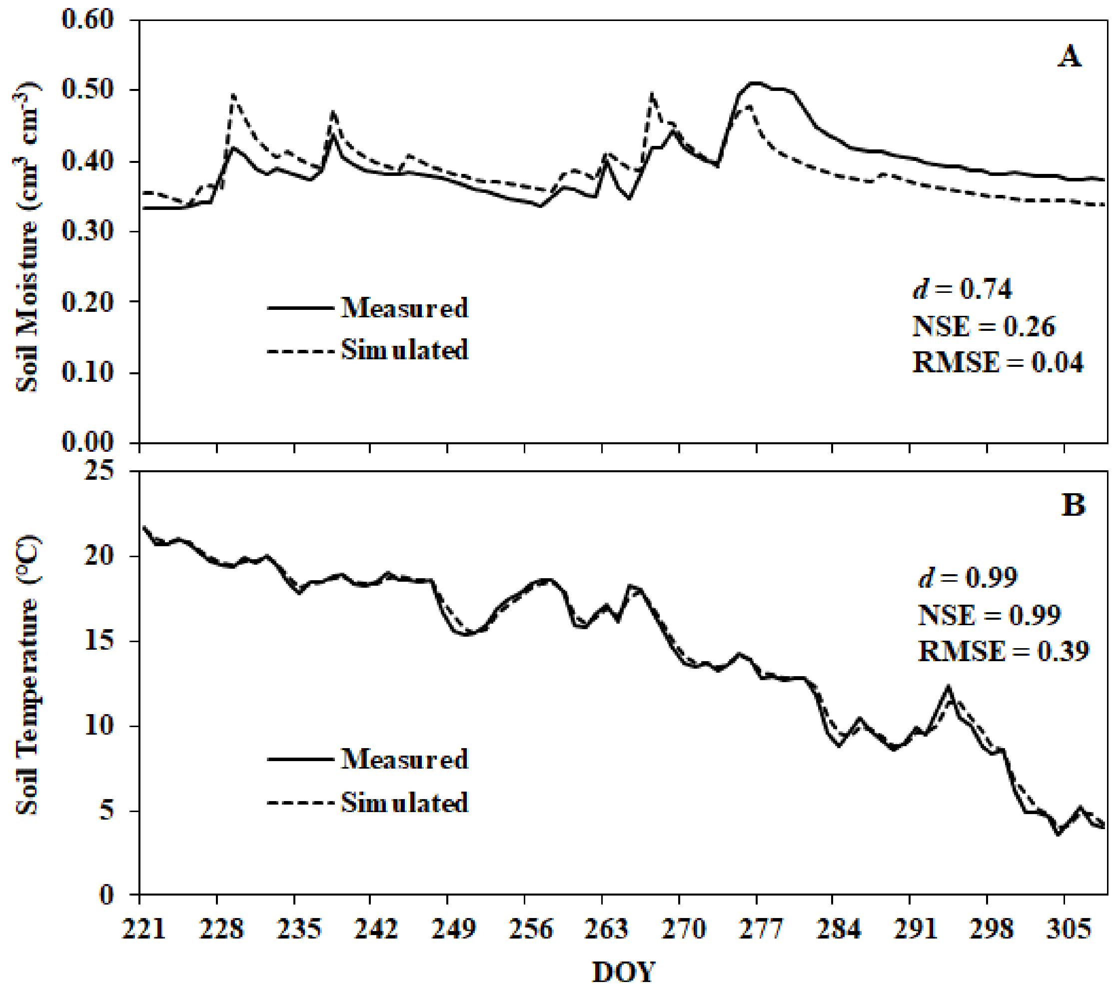


Fig. 6.5. Comparisons between measured and simulated (A) volumetric water content and (B) soil temperature in the treatment GdC+G at 15 cm soil depth during the crop growing season in 2017. DOY, Day of Year.

CHAPTER 7

CONCLUSIONS

Soil physical and hydrological properties, greenhouse gas emissions, soil water and thermal regime from the soils managed under grass dominated cover crops (GdC), cattle grazed GdC (GdC+G), legume dominated cover crops (LdC), cattle grazed LdC (LdC+G) and no cover crops (NC) were studied from 2016 through 2019 at two study sites. These sites viz., northern Brookings (44°20′34.8″ N, 96°48′14.8″ W) and northwestern Brookings (44°20′14.5″ N, 96°48′28.8″ W) are located at the research farms of South Dakota State University, Brookings, SD, USA. The experiment was a randomized complete block design with four replications and the individual plot sizes at the Brookings-N and Brookings-NW sites were 18.3 by 27.4 m, and 18.3 by 30.5 m, respectively. Soils at Brookings-N and Brookings-NW sites were dominated by sandy clay loam and sandy loam soils, respectively.

The following conclusions were determined from the four experimental studies:

Study 1 – Soil Physical and Hydrological Properties

1. Cover crops had lower soil bulk density (ρ_b) and soil penetration resistance (SPR) at 0-10 and 10-20 cm depths and, in general, higher soil water retention (SWR) and total porosity compared to the no cover crop and grazing (NC) at either site.
2. Cattle grazing generally increased the ρ_b and SPR at both depths, however, the SPR did not surpass the critical values for root proliferation at either depth. Soil water retention and total porosity were decreased in response to the grazing.

Study 2 – Computed Tomography-Measured Soil Porosity

1. Long-term integrated crop-livestock system (ICLS) had greater CT-measured macroporosity compared to the corn-soybean cropping system (CNT).
2. Higher connected porosity, connection probability and macroporosity in ICLS significantly enhanced saturated hydraulic conductivity (K_{sat}) compared to CNT.
3. All CT-measured pore parameters except tortuosity were positively correlated with K_{sat}.
4. The ICLS enhanced soil pore parameters; and the CT scanning approach is an useful tool in providing the information about number of pores, pore thickness, surface area, pore network connectivity and tortuosity in soils, which cannot be acquired with the conventional methods of studying soil porosity.

Study 3 – Greenhouse Gas Emissions

1. Cumulative carbon dioxide (CO_2) and nitrous oxide (N_2O) fluxes at Brookings-N were lower for GdC+G (4042 kg C ha^{-1} for CO_2 and 1499 g N ha^{-1} for N_2O) than for LdC+G (4819 kg C $ha^{-1}$for CO_2 and 2017 g N ha^{-1} for N_2O), indicating the superiority of GdC+G over the LdC+G in reducing the greenhouse gas (GHG) fluxes.
2. No effect from grazed CC on cumulative CO_2 and N_2O fluxes were observed at the Brookings-NW site.
3. Cumulative methane (CH_4) flux was not affected by ICLS at either site.

Study 4 – Simulated Soil Water Content and Temperature

1. Soil water content and soil temperature from the GdC, GdC+G and NC treatments were measured during the growing season at Brookings-NW site. The HYDRUS model was used to simulate soil water content and soil temperature by using measured soils data. The model was calibrated using soils data from 2017 and then validated with data from 2018.
2. Simulated soil water content matched closely with the measured soil water at different depths during validation (R^2 = 0.26–0.78, d = 0.52–0.89, NSE = -0.02–0.71 and RMSE = 0.08–0.15).
3. Simulations of soil temperature across different treatments was well agreed with that of the measured data (R^2 = 0.48–0.99, d = 0.80–0.99, NSE = 0.28–0.99 and RMSE = 0.49–4.12).
4. HYDRUS performed better in simulating soil temperature compared to that of the soil water content over the study period.

SUMMARY

A study was conducted to investigate the influence of CCs and grazing under an ICLS on soil physical and hydrological properties, CT-measured soil pore parameters, soil surface GHG fluxes and simulated soil water content and temperature. This study showed that CCs, in general, reduced the soil compaction indicators (bulk density and penetration resistance) and enhanced the soil water retention and total porosity at the 0-10 and 10-20 cm depths. The positive effects of CCs on soil physical and hydrological attributes suggest that CCs can improve the water flow in the soils and can reduce the risks of water erosion. Cattle grazing of CCs and crop residue slightly densified the soil at both the depths, however, these values did not pass the critical limits for root growth. Intense agricultural use, such as corn-soybean cropping system reduced soil organic carbon, CT-measured total number of pores, number of macropores, number of coarse mesopores, total porosity, macroporosity, coarse mesoporosity, and fractal dimension and other macropore characteristics and increased bulk density. However, integration of crops and livestock for long-term (60- to 62-yr) in our study increased organic matter to the soil that improved the soil porosity and thus enhanced saturated hydraulic conductivity. However, short-term ICLS did not influence SOC and TN content of soils, which can directly affect the soil surface CO_2 and N_2O fluxes. Short-term grazing of grass dominated CCs significantly reduced CO_2 and N_2O fluxes compared to the grazing of legume dominated CCs probably due to the favorable conditions for rapid decomposition of low C:N ratio legume CCs residue. In general, CCs and grazing of CC and corn residue did not impact CO_2 and N_2O emissions likely due to the shorter duration of the study period. Management practices such as an ICLS may need a longer time to manifest a noticeable change in the measured GHG fluxes. The GHG fluxes are also controlled by soil water content and soil temperature. In order to study the soil water and temperature regime of the soils under ICLS, field measurement of these parameters was coupled with hydrological modeling with HYDRUS. Simulated soil water content and temperature agreed with measured data at different soil depths for all treatments to a reasonable accuracy that was indicated by values of statistical indices such as *d*, NSE, RMSE, and R^2. Overall, the HYDRUS model performed better in simulating soil temperature compared to that of the soil water content at the studied depths under different treatments. The results showed that soil water flow models, once calibrated with the field measured data, can act as a robust tool to understand the hydro-thermal regimes of the soils subjected to different management practices.

APPENDICES

APPENDIX 1

A1.1. Labile carbon and nitrogen fractions as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2018 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop; CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

TRT	REP	CWEC 0-10 cm	CWEC 10-20 cm	CWEN 0-10 cm	CWEN 10-20 cm	HWEC 0-10 cm	HWEC 10-20 cm	HWEN 0-10 cm	HWEN 10-20 cm
LdC	1	230.8	165.1	39.9	36.8	1539.0	829.8	212.6	133.7
LdC	2	291.7	293.0	23.9	19.2	1343.0	873.7	131.9	98.6
LdC	3	300.1	265.1	28.1	48.4	1362.0	884.4	141.1	98.6
LdC	4	275.0	237.6	30.6	21.4	1414.7	648.3	161.9	63.2
LdC+G	1	298.8	216.6	28.8	23.3	1318.0	868.0	147.0	116.7
LdC+G	2	261.5	199.2	29.1	28.3	1308.0	990.4	160.0	113.1
LdC+G	3	316.0	248.3	31.4	29.1	1484.0	731.5	129.2	70.3
LdC+G	4	262.9	203.0	26.0	22.8	1370.0	628.7	151.9	61.6
NC	1	277.8	241.8	22.8	16.1	1327.0	665.0	133.4	103.5
NC	2	284.3	196.8	39.9	28.5	1468.0	827.4	145.7	83.0
NC	3	294.8	244.0	31.2	24.1	1302.0	624.6	136.0	51.6
NC	4	280.0	201.3	31.3	29.5	1474.0	715.3	138.4	65.8
GdC	1	309.8	223.5	37.8	28.6	1521.0	777.5	181.5	87.7
GdC	2	321.0	276.8	33.3	32.3	1519.0	756.3	179.6	90.1
GdC	3	319.5	278.7	39.7	34.2	1621.0	585.1	174.2	55.5
GdC	4	333.7	275.0	30.1	24.8	1452.0	666.9	178.4	66.2
GdC+G	1	296.7	174.0	31.3	30.1	1735.0	767.7	212.8	96.6
GdC+G	2	282.4	256.0	39.9	26.6	1577.0	856.3	194.5	72.9
GdC+G	3	311.0	256.9	22.8	20.1	1393.0	729.8	131.0	75.9
GdC+G	4	296.7	191.7	31.3	28.5	1568.3	561.4	179.4	59.3

A1.2. Labile carbon and nitrogen fractions as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2019 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop; CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

TRT	REP	CWEC 0-10 cm	CWEC 10-20 cm	CWEN 0-10 cm	CWEN 10-20 cm	HWEC 0-10 cm	HWEC 10-20 cm	HWEN 0-10 cm	HWEN 10-20 cm
LdC	1	263.3	227.7	35.7	42.8	1406.0	486.2	177.5	82.3
LdC	2	267.7	206.5	20.5	29.0	1472.0	756.5	132.2	88.4
LdC	3	272.2	252.5	20.2	47.1	1539.0	797.7	154.4	92.0
LdC	4	256.0	226.6	48.6	22.4	1497.0	677.8	130.7	77.3
LdC+G	1	283.4	241.9	39.9	41.5	1353.0	528.4	152.7	63.9
LdC+G	2	257.3	235.0	30.2	29.3	1654.0	539.3	192.3	67.5
LdC+G	3	326.8	247.0	35.1	21.9	1533.0	607.2	168.0	62.4
LdC+G	4	289.2	241.3	35.1	30.9	1513.3	558.3	171.0	64.6
NC	1	294.4	201.2	31.6	31.5	1347.0	447.7	169.9	30.3
NC	2	297.2	226.7	33.3	25.8	1203.0	508.6	129.4	68.4
NC	3	263.4	169.1	36.1	21.5	1314.0	554.3	145.8	52.7
NC	4	285.0	199.0	33.6	26.3	1288.0	503.5	148.4	50.5
GdC	1	221.9	283.0	29.4	36.0	1558.0	689.8	177.9	56.2
GdC	2	275.6	262.2	23.8	38.4	1595.0	664.2	160.3	56.9
GdC	3	254.1	258.0	22.5	22.9	1645.0	683.8	178.0	67.6
GdC	4	250.5	267.7	25.2	32.4	1599.3	679.3	172.1	60.2
GdC+G	1	223.7	254.0	23.1	44.8	1456.0	531.2	156.3	67.8
GdC+G	2	312.9	188.6	35.3	30.8	1415.0	615.1	154.2	69.8
GdC+G	3	278.6	273.0	26.9	32.3	1509.0	751.6	153.5	80.7
GdC+G	4	271.7	238.5	28.4	36.0	1460.0	632.6	154.7	72.8

A1.3. Soil bulk density (ρ_b), penetration resistance (SPR) and pore size distribution as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2018 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	ρ_b 0-10 cm	ρ_b 10-20 cm	SPR 0-10 cm	SPR 10-20 cm	Macro pores	Coarse-mesopores	Fine-mesopores	Micro pores	Total pores
LdC	1	1.31	1.39	0.44	0.91	0.006	0.114	0.134	0.408	0.663
LdC	2	1.29	1.39	0.44	1.13	0.019	0.047	0.055	0.439	0.561
LdC	3	1.25	1.41	0.44	0.88	0.001	0.071	0.062	0.542	0.676
LdC	4	1.24	1.38	0.57	0.76	0.012	0.030	0.044	0.520	0.607
LdC+G	1	1.44	1.46	1.10	1.09	0.001	0.039	0.048	0.501	0.590
LdC+G	2	1.38	1.49	0.91	1.13	0.005	0.028	0.043	0.485	0.561
LdC+G	3	1.37	1.51	0.97	1.17	0.001	0.077	0.039	0.480	0.598
LdC+G	4	1.44	1.44	0.83	1.23	0.003	0.039	0.039	0.464	0.545
NC	1	1.44	1.54	1.12	1.22	0.002	0.054	0.060	0.438	0.554
NC	2	1.41	1.57	0.96	1.46	0.003	0.038	0.041	0.447	0.528
NC	3	1.41	1.57	0.90	1.13	0.001	0.045	0.031	0.421	0.498
NC	4	1.43	1.56	0.87	1.05	0.007	0.070	0.048	0.441	0.566
GdC	1	1.31	1.41	0.88	1.08	0.005	0.056	0.031	0.561	0.652
GdC	2	1.23	1.4	0.64	1.07	0.002	0.048	0.069	0.462	0.581
GdC	3	1.35	1.47	0.63	0.86	0.007	0.022	0.040	0.493	0.563
GdC	4	1.4	1.55	0.57	1.15	0.003	0.057	0.056	0.446	0.561
GdC+G	1	1.35	1.46	0.90	1.48	0.003	0.056	0.036	0.438	0.533
GdC+G	2	1.31	1.43	0.69	1.48	0.001	0.062	0.050	0.422	0.535
GdC+G	3	1.28	1.47	0.98	1.05	0.003	0.084	0.062	0.374	0.522
GdC+G	4	1.31	1.48	0.69	0.90	0.003	0.032	0.026	0.426	0.487

A1.4. Soil bulk density (ρ_b), penetration resistance (SPR) and pore size distribution as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2019 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	ρ_b 0-10 cm	ρ_b 10-20 cm	SPR 0-10 cm	SPR 10-20 cm	Macro pores	Coarse-mesopores	Fine-mesopores	Micro pores	Total pores
LdC	1	1.20	1.39	1.20	1.31	0.007	0.125	0.045	0.372	0.549
LdC	2	1.21	1.29	1.24	1.78	0.023	0.082	0.046	0.304	0.455
LdC	3	1.21	1.35	1.11	1.67	0.003	0.106	0.044	0.293	0.446
LdC	4	1.22	1.33	1.12	1.31	0.004	0.074	0.070	0.344	0.492
LdC+G	1	1.17	1.38	1.39	1.72	0.008	0.129	0.067	0.228	0.432
LdC+G	2	1.21	1.39	1.39	1.32	0.003	0.056	0.048	0.292	0.399
LdC+G	3	1.20	1.37	1.33	1.94	0.006	0.103	0.072	0.308	0.489
LdC+G	4	1.20	1.39	1.29	2.04	0.006	0.096	0.062	0.276	0.440
NC	1	1.25	1.42	1.96	1.72	0.001	0.052	0.054	0.283	0.390
NC	2	1.28	1.31	1.64	1.70	0.001	0.079	0.036	0.284	0.401
NC	3	1.27	1.29	1.51	2.19	0.002	0.059	0.059	0.284	0.403
NC	4	1.28	1.32	1.71	1.83	0.001	0.063	0.050	0.284	0.398
GdC	1	1.24	1.31	0.98	1.49	0.012	0.105	0.044	0.319	0.480
GdC	2	1.28	1.32	1.16	1.68	0.025	0.075	0.045	0.308	0.453
GdC	3	1.21	1.39	0.86	1.59	0.004	0.067	0.048	0.337	0.456
GdC	4	1.27	1.30	1.10	1.56	0.002	0.060	0.056	0.319	0.437
GdC+G	1	1.27	1.45	1.17	1.50	0.001	0.046	0.035	0.287	0.368
GdC+G	2	1.21	1.36	1.17	1.68	0.003	0.063	0.042	0.279	0.387
GdC+G	3	1.29	1.34	1.23	1.98	0.005	0.094	0.048	0.298	0.445
GdC+G	4	1.29	1.51	1.15	1.62	0.003	0.067	0.041	0.288	0.400

A1.5. Soil water content (m^3/m^3) at different soil water pressures (kPa), steady state infiltration rate (qs), the Green–Ampt model estimated sorptivity (S) and saturated hydraulic conductivity (Ks) parameters as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2018 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	0	-0.4	-1.0	-2.5	-5	-10	-20	-30	q_s	S	K_s
		---------------------------------				kPa			------------------------------------	(mm/hr)	($mm/hr^{0.5}$)	(mm/hr)
LdC	1	0.663	0.656	0.634	0.544	0.542	0.449	0.422	0.408	592.3	207.8	474.5
LdC	2	0.561	0.542	0.507	0.499	0.494	0.474	0.452	0.439	589.3	270.0	523.3
LdC	3	0.676	0.675	0.665	0.599	0.604	0.561	0.552	0.542	162.9	65.7	113.4
LdC	4	0.607	0.594	0.578	0.571	0.564	0.538	0.530	0.520	-	-	-
LdC+G	1	0.590	0.589	0.577	0.550	0.550	0.516	0.508	0.501	414.6	168.5	399.4
LdC+G	2	0.561	0.556	0.540	0.532	0.528	0.510	0.496	0.485	414.6	253.8	167.1
LdC+G	3	0.598	0.597	0.587	0.524	0.519	0.502	0.490	0.480	118.5	41.9	56.8
LdC+G	4	0.545	0.542	0.530	0.506	0.503	0.477	0.471	0.464	-	-	-
NC	1	0.554	0.552	0.540	0.500	0.498	0.471	0.451	0.438	201.4	217.3	153.7
NC	2	0.528	0.526	0.518	0.488	0.488	0.462	0.453	0.447	43.4	12.6	39.1
NC	3	0.498	0.497	0.485	0.452	0.451	0.434	0.427	0.421	125.6	53.4	100.3
NC	4	0.566	0.559	0.536	0.486	0.489	0.457	0.448	0.441	-	-	-
GdC	1	0.652	0.648	0.637	0.594	0.592	0.572	0.568	0.561	331.7	122.6	313.8
GdC	2	0.581	0.579	0.574	0.536	0.531	0.481	0.472	0.462	592.3	210.0	543.1
GdC	3	0.563	0.556	0.541	0.535	0.533	0.520	0.508	0.493	511.8	114.6	515.3
GdC	4	0.561	0.558	0.548	0.501	0.501	0.463	0.453	0.446	-	-	-
GdC+G	1	0.533	0.530	0.518	0.480	0.474	0.450	0.444	0.438	592.3	451.3	489.2
GdC+G	2	0.535	0.534	0.516	0.474	0.472	0.436	0.427	0.422	296.2	185.4	210.9
GdC+G	3	0.522	0.520	0.496	0.435	0.435	0.391	0.381	0.374	592.3	539.8	380.8
GdC+G	4	0.487	0.485	0.481	0.453	0.453	0.438	0.433	0.426	-	-	-

A1.6. Soil water content (m^3/m^3) at different soil water pressures (kPa) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2019 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**0**	**-0.4**	**-1.0**	**-2.5**	**-5**	**-10**	**-20**	**-30**
		kPa							
LdC	1	0.549	0.542	0.503	0.421	0.417	0.399	0.378	0.372
LdC	2	0.455	0.433	0.410	0.351	0.350	0.333	0.313	0.304
LdC	3	0.446	0.443	0.409	0.339	0.337	0.318	0.300	0.293
LdC	4	0.492	0.488	0.470	0.417	0.414	0.365	0.356	0.344
LdC+G	1	0.432	0.424	0.383	0.298	0.295	0.268	0.237	0.228
LdC+G	2	0.399	0.396	0.370	0.340	0.340	0.305	0.298	0.292
LdC+G	3	0.489	0.483	0.442	0.383	0.380	0.341	0.323	0.308
LdC+G	4	0.440	0.434	0.398	0.340	0.338	0.305	0.286	0.276
NC	1	0.390	0.389	0.374	0.337	0.337	0.298	0.290	0.283
NC	2	0.401	0.400	0.372	0.323	0.320	0.294	0.288	0.284
NC	3	0.403	0.402	0.385	0.344	0.343	0.309	0.298	0.284
NC	4	0.398	0.397	0.377	0.335	0.334	0.300	0.292	0.284
GdC	1	0.480	0.468	0.432	0.365	0.363	0.343	0.326	0.319
GdC	2	0.453	0.428	0.413	0.352	0.353	0.335	0.316	0.308
GdC	3	0.456	0.452	0.434	0.386	0.385	0.353	0.344	0.337
GdC	4	0.437	0.435	0.418	0.377	0.375	0.335	0.328	0.319
GdC+G	1	0.368	0.368	0.352	0.323	0.322	0.303	0.295	0.287
GdC+G	2	0.387	0.384	0.358	0.322	0.321	0.288	0.282	0.279
GdC+G	3	0.445	0.440	0.413	0.350	0.346	0.329	0.306	0.298
GdC+G	4	0.400	0.397	0.375	0.332	0.330	0.307	0.294	0.288

A1.7. Labile carbon and nitrogen fractions as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop; CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

TRT	**REP**	**CWEC 0-10 cm**	**CWEC 10-20 cm**	**CWEN 0-10 cm**	**CWEN 10-20 cm**	**HWEC 0-10 cm**	**HWEC 10-20 cm**	**HWEN 0-10 cm**	**HWEN 10-20 cm**
LdC	1	238.9	201.3	34.6	41.5	844.0	523.7	93.5	58.2
LdC	2	239.0	199.3	28.2	29.8	853.6	704.2	97.1	68.0
LdC	3	260.8	287.0	31.6	34.3	858.7	603.9	117.6	53.1
LdC	4	196.7	277.3	38.6	40.6	878.6	494.1	102.2	46.8
LdC+G	1	245.0	223.9	28.1	25.9	944.3	481.4	107.3	44.0
LdC+G	2	222.1	240.4	26.3	30.2	702.3	582.9	80.1	57.4
LdC+G	3	212.6	293.3	26.8	36.0	904.2	467.9	92.4	47.3
LdC+G	4	271.8	367.6	31.2	82.6	910.8	709.4	104.4	73.2
NC	1	201.9	262.3	30.2	32.5	735.8	613.5	82.3	56.0
NC	2	215.7	260.6	32.6	38.1	865.5	594.1	114.3	56.8
NC	3	192.1	231.1	35.2	36.7	947.3	667.1	102.3	60.5
NC	4	204.3	296.5	37.7	28.6	913.5	579.9	101.5	52.3
GdC	1	232.8	299.0	31.4	78.1	875.4	606.4	94.5	60.2
GdC	2	217.2	224.7	34.3	26.1	921.1	590.6	101.3	57.9
GdC	3	240.7	287.1	34.0	43.1	1161.0	578.6	127.4	54.8
GdC	4	250.0	279.7	36.3	35.0	1136.0	667.7	95.1	60.1
GdC+G	1	246.2	243.6	27.3	25.9	715.4	523.1	113.9	50.6
GdC+G	2	253.0	276.1	28.1	27.9	937.2	556.2	109.5	55.2
GdC+G	3	226.9	303.7	24.8	30.8	972.1	432.4	110.0	56.0
GdC+G	4	231.0	289.7	26.7	35.8	1045.0	717.0	122.1	68.7

A1.8. Labile carbon and nitrogen fractions as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2019 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop; CWEC, Cold water extractable carbon; CWEN, Cold water extractable nitrogen; HWEC, Hot water extractable carbon; HWEN, Hot water extractable nitrogen

TRT	REP	CWEC 0-10 cm	CWEC 10-20 cm	CWEN 0-10 cm	CWEN 10-20 cm	HWEC 0-10 cm	HWEC 10-20 cm	HWEN 0-10 cm	HWEN 10-20 cm
LdC	1	382.7	233.1	30.8	34.7	904.0	594.4	87.3	58.7
LdC	2	259.0	256.3	22.4	26.8	821.0	659.5	95.3	56.7
LdC	3	306.1	264.7	30.6	24.7	918.0	596.8	107.4	53.4
LdC	4	263.0	261.4	22.3	31.2	903.2	628.0	112.9	52.9
LdC+G	1	340.6	207.1	31.5	23.9	964.0	571.2	88.5	57.1
LdC+G	2	289.4	216.2	25.8	28.1	815.0	660.6	83.5	63.5
LdC+G	3	279.0	259.7	21.5	18.0	873.0	577.5	104.7	52.8
LdC+G	4	305.0	223.0	26.3	17.9	935.0	729.0	132.2	55.1
NC	1	304.5	249.4	32.3	25.3	976.7	591.9	112.9	54.1
NC	2	297.2	237.8	25.8	27.7	856.0	613.7	80.6	43.3
NC	3	324.3	216.8	33.9	26.3	815.2	537.1	115.6	52.8
NC	4	287.0	249.6	21.9	27.9	854.0	503.0	112.5	44.8
GdC	1	267.1	257.0	26.8	23.9	995.6	425.0	115.6	46.7
GdC	2	326.8	238.6	29.3	28.6	776.7	513.5	86.1	50.9
GdC	3	333.0	249.9	30.1	20.6	956.0	514.8	102.9	48.7
GdC	4	291.0	261.7	28.1	22.6	913.0	738.0	109.8	65.3
GdC+G	1	368.5	228.2	38.4	25.9	1015.0	634.2	112.5	56.3
GdC+G	2	287.7	245.3	29.0	32.5	793.0	521.1	76.2	47.1
GdC+G	3	316.0	239.1	20.1	28.0	895.0	492.1	104.3	43.9
GdC+G	4	328.0	257.0	31.1	21.1	971.0	695.0	129.4	52.9

A1.9. Soil bulk density (ρ_b), penetration resistance (SPR) and pore size distribution as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	ρ_b 0-10 cm	ρ_b 10-20 cm	SPR 0-10 cm	SPR 10-20 cm	Macro pores	Coarse-mesopores	Fine-mesopores	Micro pores	Total pores
LdC	1	1.37	1.56	0.82	1.39	0.004	0.065	0.063	0.399	0.530
LdC	2	1.36	1.63	0.98	1.39	0.014	0.066	0.034	0.509	0.623
LdC	3	1.35	1.47	0.87	1.42	0.014	0.058	0.028	0.407	0.506
LdC	4	1.36	1.55	0.87	1.50	0.007	0.056	0.033	0.498	0.593
LdC+G	1	1.48	1.58	1.23	2.10	0.009	0.033	0.031	0.402	0.474
LdC+G	2	1.40	1.62	1.12	1.94	0.007	0.032	0.027	0.462	0.528
LdC+G	3	1.47	1.48	1.09	1.93	0.012	0.055	0.056	0.411	0.533
LdC+G	4	1.35	1.56	0.97	1.53	0.009	0.040	0.038	0.425	0.512
NC	1	1.52	1.52	2.73	2.65	0.014	0.041	0.034	0.423	0.512
NC	2	1.58	1.58	2.04	2.54	0.014	0.048	0.026	0.451	0.540
NC	3	1.52	1.52	1.82	2.86	0.004	0.041	0.029	0.457	0.531
NC	4	1.44	1.54	1.71	1.43	0.011	0.043	0.030	0.443	0.528
GdC	1	1.48	1.59	0.95	1.66	0.010	0.052	0.028	0.474	0.564
GdC	2	1.46	1.60	0.95	1.68	0.012	0.069	0.072	0.364	0.518
GdC	3	1.30	1.59	0.82	1.78	0.012	0.048	0.045	0.422	0.529
GdC	4	1.41	1.45	0.72	1.65	0.007	0.060	0.049	0.406	0.522
GdC+G	1	1.55	1.60	1.29	2.19	0.009	0.030	0.039	0.460	0.538
GdC+G	2	1.46	1.62	1.36	2.19	0.008	0.029	0.013	0.471	0.521
GdC+G	3	1.29	1.54	1.03	1.99	0.009	0.041	0.041	0.403	0.494
GdC+G	4	1.43	1.59	1.24	1.14	0.009	0.033	0.031	0.445	0.518

A1.10. Soil bulk density (ρ_b), penetration resistance (SPR) and pore size distribution as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2019 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**ρ_b 0-10 cm**	**ρ_b 10-20 cm**	**SPR 0-10 cm**	**SPR 10-20 cm**	**Macro pores**	**Coarse-mesopores**	**Fine-mesopores**	**Micro pores**	**Total pores**
LdC	1	1.38	1.41	1.17	1.42	0.009	0.054	0.030	0.498	0.591
LdC	2	1.37	1.49	1.06	1.55	0.005	0.064	0.021	0.479	0.568
LdC	3	1.34	1.42	1.26	1.41	0.002	0.050	0.030	0.489	0.571
LdC	4	1.37	1.43	0.97	1.11	0.010	0.053	0.033	0.548	0.645
LdC+G	1	1.52	1.44	1.25	1.52	0.018	0.029	0.049	0.421	0.516
LdC+G	2	1.46	1.54	1.30	1.65	0.001	0.026	0.028	0.454	0.509
LdC+G	3	1.51	1.44	1.19	1.45	0.002	0.034	0.041	0.443	0.520
LdC+G	4	1.48	1.53	1.23	1.53	0.003	0.044	0.016	0.469	0.532
NC	1	1.52	1.48	1.17	1.86	0.001	0.036	0.025	0.427	0.489
NC	2	1.47	1.53	1.35	1.76	0.014	0.053	0.030	0.421	0.519
NC	3	1.55	1.53	1.35	1.84	0.023	0.037	0.046	0.397	0.503
NC	4	1.39	1.53	1.50	1.67	0.016	0.028	0.058	0.418	0.520
GdC	1	1.31	1.42	1.04	1.19	0.014	0.058	0.034	0.398	0.504
GdC	2	1.22	1.52	1.17	1.48	0.003	0.033	0.036	0.519	0.590
GdC	3	1.26	1.49	1.03	1.38	0.002	0.063	0.023	0.438	0.526
GdC	4	1.37	1.43	1.08	1.37	0.037	0.071	0.077	0.435	0.620
GdC+G	1	1.44	1.54	1.17	1.45	0.019	0.038	0.055	0.394	0.507
GdC+G	2	1.44	1.54	1.40	1.36	0.004	0.043	0.032	0.429	0.509
GdC+G	3	1.43	1.56	1.40	1.26	0.004	0.032	0.032	0.422	0.490
GdC+G	4	1.46	1.46	0.96	1.54	0.001	0.042	0.020	0.420	0.484

A1.11. Soil water content (m^3/m^3) at different soil water pressures (kPa), steady state infiltration rate (*q*s), the Green–Ampt model estimated sorptivity (*S*) and saturated hydraulic conductivity (*K*s) parameters as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**0**	**-0.4**	**-1.0**	**-2.5**	**-5**	**-10**	**-20**	**-30**	q_s	*S*	K_s
		----------------------------------kPa----------------------------------								**(mm/hr)**	**(mm/hr$^{0.5}$)**	**(mm/hr)**
LdC	1	0.530	0.526	0.507	0.459	0.462	0.421	0.409	0.399	15.4	20.0	10.0
LdC	2	0.623	0.610	0.567	0.541	0.543	0.528	0.519	0.509	7.5	10.0	4.0
LdC	3	0.506	0.493	0.477	0.434	0.434	0.421	0.413	0.407	30.8	7.7	21.2
LdC	4	0.593	0.587	0.562	0.532	0.530	0.515	0.506	0.498	-	-	-
LdC+G	1	0.474	0.465	0.447	0.433	0.433	0.414	0.406	0.402	5.9	7.9	7.1
LdC+G	2	0.528	0.521	0.503	0.490	0.489	0.476	0.472	0.462	9.1	12.0	8.0
LdC+G	3	0.533	0.521	0.489	0.468	0.466	0.441	0.424	0.411	7.9	8.8	3.2
LdC+G	4	0.512	0.503	0.480	0.464	0.463	0.444	0.434	0.425	-	-	-
NC	1	0.512	0.497	0.477	0.457	0.457	0.444	0.433	0.423	3.8	13.0	8.0
NC	2	0.540	0.526	0.502	0.479	0.477	0.469	0.458	0.451	4.2	2.7	3.2
NC	3	0.531	0.527	0.511	0.486	0.486	0.472	0.465	0.457	4.7	5.1	3.9
NC	4	0.528	0.517	0.497	0.474	0.473	0.462	0.452	0.443	-	-	-
GdC	1	0.564	0.554	0.546	0.502	0.502	0.484	0.479	0.474	57.7	40.0	5.0
GdC	2	0.518	0.506	0.470	0.436	0.436	0.397	0.376	0.364	40.3	21.2	28.5
GdC	3	0.529	0.516	0.494	0.468	0.468	0.450	0.432	0.422	20.1	15.0	5.0
GdC	4	0.522	0.515	0.502	0.459	0.455	0.429	0.415	0.406	-	-	-
GdC+G	1	0.538	0.529	0.512	0.501	0.499	0.479	0.468	0.460	14.6	12.0	25.0
GdC+G	2	0.521	0.513	0.509	0.485	0.484	0.478	0.475	0.471	5.9	5.0	4.0
GdC+G	3	0.494	0.484	0.464	0.443	0.444	0.425	0.412	0.403	19.3	11.6	12.8
GdC+G	4	0.518	0.509	0.495	0.476	0.476	0.461	0.452	0.445	-	-	-

A1.12. Soil water content (m^3/m^3) at different soil water pressures (kPa) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2019 and used in Chapter 3. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**0**	**-0.4**	**-1.0**	**-2.5**	**-5**	**-10**	**-20**	**-30**
		------kPa------							
LdC	1	0.591	0.582	0.570	0.548	0.528	0.503	0.500	0.498
LdC	2	0.568	0.564	0.543	0.517	0.500	0.495	0.488	0.479
LdC	3	0.571	0.569	0.544	0.523	0.519	0.501	0.496	0.489
LdC	4	0.645	0.634	0.617	0.598	0.581	0.567	0.562	0.548
LdC+G	1	0.516	0.499	0.479	0.472	0.469	0.442	0.435	0.421
LdC+G	2	0.509	0.508	0.503	0.495	0.482	0.459	0.457	0.454
LdC+G	3	0.520	0.519	0.511	0.499	0.484	0.461	0.470	0.443
LdC+G	4	0.532	0.529	0.514	0.499	0.485	0.483	0.478	0.469
NC	1	0.489	0.488	0.474	0.459	0.452	0.442	0.436	0.427
NC	2	0.519	0.504	0.480	0.463	0.451	0.444	0.439	0.421
NC	3	0.503	0.480	0.455	0.451	0.443	0.417	0.411	0.397
NC	4	0.520	0.503	0.486	0.478	0.476	0.440	0.432	0.418
GdC	1	0.504	0.490	0.470	0.435	0.432	0.430	0.425	0.398
GdC	2	0.590	0.588	0.583	0.570	0.555	0.540	0.539	0.519
GdC	3	0.526	0.524	0.499	0.471	0.461	0.449	0.445	0.438
GdC	4	0.620	0.583	0.538	0.521	0.512	0.465	0.455	0.435
GdC+G	1	0.507	0.487	0.460	0.439	0.449	0.420	0.414	0.394
GdC+G	2	0.509	0.505	0.497	0.478	0.462	0.436	0.430	0.429
GdC+G	3	0.490	0.486	0.483	0.469	0.454	0.429	0.425	0.422
GdC+G	4	0.484	0.482	0.468	0.448	0.440	0.432	0.427	0.420

APPENDIX 2

A2.1. Soil organic carbon (SOC), wet soil aggregate stability (WSA), bulk density (ρ_b) and saturated hydraulic conductivity (K_{sat}) as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth and used in Chapter 4.

Treatment	Replication	SOC ($g\ kg^{-1}$)	WSA (%)	ρ_b ($Mg\ m^{-3}$)	K_{sat} ($mm\ h^{-1}$)
NGP	1	41.1	88.7	1.02	264.4
NGP	2	42.6	87.5	0.96	153.9
NGP	3	41.4	85.9	0.99	209.15
ICLS	1	33.8	84.6	1.12	128.1
ICLS	2	33.3	84.9	1.15	110.5
ICLS	3	33.1	84.7	1.26	119.3
CNT	1	29.1	63.2	1.60	8.21
CNT	2	29.8	67.3	1.45	15.5
CNT	3	29.3	62.3	1.47	35.4

A2.2. Computed tomography- measured total number of pores (pores, macropores, and coarse mesopores) and porosity (total porosity, macroporosity, and coarse mesoporosity) as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth and used in Chapter 4.

Treatment	**Replication**	**Total pores**	**Macropores**	**Coarse mesopores**	**Porosity**		
					Total porosity	**Macroporosity**	**Coarse mesoporosity**
					------------- mm^3 mm^{-3} ----------------		
NGP	1	29283	11919	17364	0.099	0.087	0.012
NGP	2	28751	13495	15256	0.124	0.113	0.011
NGP	3	26765	11335	15430	0.091	0.080	0.011
ICLS	1	22765	10377	12388	0.111	0.103	0.009
ICLS	2	21789	10418	11371	0.100	0.092	0.008
ICLS	3	21341	8778	12563	0.064	0.056	0.009
CNT	1	7165	1913	5252	0.014	0.011	0.003
CNT	2	5956	2121	3835	0.018	0.016	0.002
CNT	3	7363	1883	5480	0.013	0.009	0.003

A2.3. Computed tomography derived connectivity parameters and various pore characteristics as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth and used in Chapter 4. CP, Connected porosity; F_L, proportion of pore volume contained in the largest pore cluster; Γ, connection probability, ECD, Equivalent cylindrical diameter; Cir, Pore circularity; DA, Degree of anisotropy; D, fractal dimension; τ, Tortuosity

Treatment	**Replication**	**CP** $mm^3\ mm^{-3}$	F_L	**Γ**	**ECD** mm	**Cir**	**DA**	**D**	**τ**
NGP	1	0.072	0.73	0.53	1.14	0.82	0.32	2.47	1.37
NGP	2	0.103	0.83	0.69	1.26	0.8	0.35	2.48	1.36
NGP	3	0.065	0.72	0.51	1.16	0.82	0.35	2.46	1.37
ICLS	1	0.075	0.67	0.45	1.30	0.82	0.38	2.47	1.39
ICLS	2	0.053	0.52	0.28	1.32	0.82	0.33	2.45	1.38
ICLS	3	0.042	0.65	0.43	1.11	0.81	0.25	2.39	1.38
CNT	1	0.000	0.00	0.00	0.89	0.85	0.18	2.09	1.43
CNT	2	0.000	0.00	0.00	1.07	0.82	0.35	2.08	1.43
CNT	3	0.000	0.00	0.00	0.86	0.86	0.26	2.10	1.40

A2.4. Soil water content ($m^3 m^{-3}$) at different soil water pressures (-kPa) as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth and used in Chapter 4.

		Soil water pressure (kPa)								
Treatment	**Replication**	**0**	**-0.4**	**-1.0**	**-2.5**	**-5.0**	**-10.0**	**-20.0**	**-30.0**	**-100**
		------------------ m^3m^{-3} ------------------								
NGP	1	0.67	0.65	0.59	0.53	0.53	0.44	0.43	0.39	0.34
NGP	2	0.67	0.65	0.58	0.53	0.53	0.42	0.38	0.36	0.33
NGP	3	0.67	0.65	0.59	0.54	0.54	0.44	0.42	0.36	0.33
ICLS	1	0.61	0.60	0.56	0.51	0.51	0.46	0.42	0.37	0.32
ICLS	2	0.57	0.55	0.51	0.46	0.46	0.38	0.36	0.32	0.28
ICLS	3	0.52	0.49	0.43	0.38	0.38	0.32	0.32	0.30	0.30
CNT	1	0.50	0.49	0.46	0.44	0.44	0.41	0.38	0.38	0.37
CNT	2	0.48	0.47	0.44	0.42	0.42	0.40	0.40	0.38	0.38
CNT	3	0.49	0.47	0.44	0.42	0.42	0.40	0.39	0.37	0.37

A2.5. Pore size distribution measured by water retention method as affected by native grazed pasture (NGP), integrated crop livestock system (ICLS) and corn-soybean cropping system (CNT) for the surface (0-10 cm) depth and used in Chapter 4.

Treatment	**Replication**	**Macropores (>1000 µm)**	**Coarse mesopores (60-1000 µm)**	**Fine mesopores (10-60 µm)**	**Micropores (<10 µm)**	**Total pores**
		------------------------------- **m^3m^{-3}**			--------------------------------------	
NGP	1	0.023	0.114	0.147	0.388	0.671
NGP	2	0.022	0.123	0.167	0.359	0.671
NGP	3	0.019	0.114	0.180	0.360	0.673
ICLS	1	0.013	0.091	0.138	0.372	0.614
ICLS	2	0.017	0.087	0.146	0.316	0.567
ICLS	3	0.022	0.113	0.075	0.305	0.515
CNT	1	0.012	0.045	0.066	0.377	0.500
CNT	2	0.013	0.048	0.039	0.384	0.484
CNT	3	0.013	0.049	0.049	0.374	0.485

APPENDIX 3

A3.1. Daily soil surface carbon dioxide (CO_2, kg ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2016 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	8/11/16	8/18/16	8/23/16	8/30/16	9/12/16	9/23/16	9/27/16	10/10/16	10/17/16	11/1/16	11/16/16
LdC	1	27.65	41.26	50.71	39.66	36.04	32.23	26.40	24.03	20.45	39.88	5.62
LdC	2	38.40	27.11	41.19	37.88	36.09	18.80	18.64	8.02	12.19	11.13	2.45
LdC	3	32.60	32.93	30.37	15.56	23.68	19.63	29.20	18.52	32.57	9.75	3.52
LdC	4	60.67	46.50	25.47	21.24	25.23	31.09	24.10	18.80	26.04	19.01	3.07
LdC+G	1	53.72	20.57	30.68	38.18	16.25	28.11	18.54	32.65	9.60	5.29	2.01
LdC+G	2	39.72	41.60	42.16	31.74	28.76	19.60	22.04	8.99	10.00	16.62	1.23
LdC+G	3	49.78	38.98	18.49	36.68	20.95	16.61	28.68	11.29	25.32	3.83	2.53
LdC+G	4	60.73	37.57	49.89	25.13	23.55	38.21	18.97	16.77	39.29	14.55	2.02
NC	1	18.71	39.60	41.98	39.25	21.50	18.33	13.75	4.16	8.31	8.27	3.96
NC	2	25.74	47.83	40.46	42.35	19.60	4.74	14.96	11.50	16.58	11.21	1.77
NC	3	40.22	22.68	47.07	30.21	28.74	8.50	24.19	7.63	26.88	8.32	3.60
NC	4	44.32	50.55	41.88	15.06	14.39	31.71	12.78	12.88	13.70	2.15	2.36
GdC	1	34.23	39.75	45.31	28.66	39.58	12.31	21.12	12.93	14.20	13.84	1.88
GdC	2	41.28	35.73	43.10	38.22	22.60	26.36	28.18	1.94	13.94	12.29	2.17
GdC	3	46.96	30.01	29.01	27.26	22.98	19.17	11.14	13.05	29.69	21.40	3.94
GdC	4	43.90	35.15	32.23	46.90	16.68	15.95	13.56	22.18	9.15	4.95	3.31
GdC+G	1	42.58	46.26	40.96	35.92	29.80	18.02	18.59	21.90	15.36	11.08	11.99
GdC+G	2	41.15	29.81	23.94	25.24	10.93	6.43	7.48	8.12	6.12	6.26	5.27
GdC+G	3	56.15	44.04	29.85	30.19	18.86	16.73	8.85	9.30	4.30	4.76	0.22
GdC+G	4	54.20	35.38	39.82	19.30	32.52	19.92	17.48	21.76	14.56	2.75	1.73

A3.2. Daily soil surface carbon dioxide (CO_2, kg ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**5/6/17**	**5/8/17**	**6/19/17**	**6/25/17**	**6/30/17**	**7/8/17**	**7/15/17**	**7/24/17**	**7/30/17**	**8/11/17**	**9/4/17**
LdC	1	13.86	29.71	32.2	24.3	29.3	41.3	35.4	32.8	29.5	21.9	26.8
LdC	2	51.90	39.20	30.7	25.7	34.7	35.0	40.4	30.8	39.1	37.6	33.4
LdC	3	42.91	29.40	35.7	32.2	25.6	40.9	42.0	32.0	35.9	28.3	29.7
LdC	4	40.01	33.32	21.5	24.4	32.0	37.0	42.0	42.2	40.5	32.0	20.4
LdC+G	1	25.37	33.81	29.0	15.8	27.2	33.7	32.8	35.5	44.4	24.9	28.8
LdC+G	2	29.45	43.13	35.4	31.0	35.9	45.2	45.1	33.2	31.7	41.4	21.6
LdC+G	3	29.20	46.77	38.0	40.1	32.0	33.9	40.9	34.9	40.6	26.0	33.3
LdC+G	4	36.83	32.99	44.9	38.3	39.5	52.8	40.3	37.0	37.3	26.7	25.8
NC	1	48.31	49.20	29.8	23.0	24.2	28.8	29.0	28.0	27.3	25.2	23.5
NC	2	35.50	46.85	30.7	23.6	17.6	33.9	42.2	34.3	32.2	24.4	22.3
NC	3	34.98	12.91	27.1	17.3	22.0	31.2	26.1	29.4	40.0	27.5	24.2
NC	4	39.51	30.61	19.0	37.8	30.4	40.2	37.0	31.5	32.1	22.8	20.5
GdC	1	42.78	43.05	20.7	17.2	27.6	25.5	31.0	32.0	28.0	27.1	24.8
GdC	2	32.70	41.92	23.2	16.6	19.2	19.8	24.8	30.1	34.4	31.3	16.2
GdC	3	40.65	37.38	24.0	34.0	28.8	24.5	31.3	39.0	39.1	24.5	28.0
GdC	4	35.10	17.55	30.7	25.2	30.1	38.7	41.9	21.4	33.8	27.9	24.4
GdC+G	1	11.33	14.28	28.8	29.7	30.1	34.2	30.2	26.5	37.9	21.2	24.1
GdC+G	2	22.54	19.47	30.9	22.7	21.9	25.9	37.2	29.3	34.4	32.8	22.0
GdC+G	3	29.14	32.75	30.0	37.3	25.6	35.4	34.1	28.0	35.7	17.9	26.9
GdC+G	4	36.28	34.45	33.9	33.6	26.7	44.5	28.2	40.3	31.7	27.0	19.2

A3.2. Cont'd

TRT	REP	9/17/17	9/30/17	10/12/17	11/4/17	11/30/17	12/1/17	12/10/17
LdC	1	16.3	9.8	9.3	2.6	2.0	3.0	3.3
LdC	2	12.8	7.5	8.6	2.7	2.1	5.5	3.0
LdC	3	13.0	9.0	5.5	1.3	2.4	5.6	5.5
LdC	4	10.1	11.6	9.0	4.8	3.7	2.3	0.4
LdC+G	1	13.7	10.1	6.6	3.3	3.5	3.2	1.1
LdC+G	2	12.5	6.0	8.5	5.0	3.7	5.5	3.3
LdC+G	3	17.8	7.2	10.8	3.7	4.6	6.3	3.1
LdC+G	4	9.6	7.7	6.4	4.3	4.0	5.7	6.1
NC	1	12.4	8.8	5.2	1.4	2.9	2.6	2.2
NC	2	9.7	6.2	7.5	2.0	0.4	1.9	2.8
NC	3	13.1	7.4	5.9	3.6	1.3	1.8	2.5
NC	4	9.3	5.3	6.8	4.6	2.2	1.1	0.6
GdC	1	15.2	5.8	5.6	3.3	2.5	1.1	1.1
GdC	2	10.8	7.4	7.7	2.9	1.0	2.3	1.9
GdC	3	15.4	4.4	3.5	4.9	2.3	0.6	1.0
GdC	4	14.2	8.1	6.4	2.9	1.4	0.7	1.2
GdC+G	1	13.2	12.1	7.4	2.3	2.7	2.6	2.7
GdC+G	2	11.9	7.3	8.3	2.0	3.0	3.9	4.9
GdC+G	3	15.3	6.9	8.5	2.4	2.7	3.5	1.2
GdC+G	4	12.7	8.5	10.0	3.0	3.6	3.4	3.9

A3.3. Daily soil surface nitrous oxide (N_2O, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2016 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	8/11/16	8/18/16	8/23/16	8/30/16	9/12/16	9/23/16	9/27/16	10/10/16	10/17/16	11/1/16	11/16/16
LdC	1	11.90	2.66	7.92	7.70	16.43	9.34	13.16	14.35	2.89	24.70	0.92
LdC	2	17.10	4.22	22.27	18.89	16.80	17.21	9.47	4.81	4.30	13.67	0.60
LdC	3	15.67	16.45	9.17	18.82	4.19	11.28	8.80	11.53	13.74	10.41	2.08
LdC	4	18.82	11.09	6.64	7.02	16.26	17.06	16.37	5.98	8.92	2.30	1.56
LdC+G	1	10.80	4.79	16.86	13.52	12.20	15.20	13.22	2.50	5.35	4.40	0.00
LdC+G	2	11.03	8.44	6.57	1.28	12.44	7.16	8.10	5.20	9.74	9.08	0.00
LdC+G	3	27.01	11.05	4.70	5.39	7.34	3.67	12.44	4.50	11.79	15.59	0.31
LdC+G	4	13.40	17.51	6.40	26.50	11.93	16.25	24.22	7.10	13.16	16.62	0.00
NC	1	15.90	9.77	3.28	17.78	10.10	6.33	9.82	3.93	2.10	5.56	0.00
NC	2	15.99	6.46	12.78	14.62	15.39	2.87	11.86	4.99	8.70	7.67	0.00
NC	3	19.93	9.77	6.98	16.65	14.82	2.70	15.80	13.49	0.99	10.00	2.94
NC	4	27.90	6.90	4.87	10.24	12.33	5.85	12.28	17.32	3.54	3.85	1.61
GdC	1	6.79	11.98	4.11	0.90	6.60	2.40	21.28	4.16	13.86	12.97	2.20
GdC	2	10.21	4.89	25.95	12.25	3.97	7.90	9.28	12.40	10.49	8.95	0.00
GdC	3	24.95	11.29	11.66	11.58	16.19	19.35	14.82	4.40	6.14	5.91	12.00
GdC	4	19.85	4.68	25.95	11.81	7.08	22.04	7.69	16.04	6.13	12.02	1.85
GdC+G	1	5.58	16.40	21.09	10.10	3.60	4.84	8.29	1.29	11.39	18.45	0.00
GdC+G	2	6.34	9.62	8.37	3.84	7.81	6.44	6.40	3.63	1.91	9.35	0.00
GdC+G	3	22.47	11.24	1.87	25.01	4.92	4.64	19.85	7.13	10.70	2.41	4.71
GdC+G	4	18.20	19.85	19.83	19.35	12.29	17.25	4.92	18.20	4.69	7.76	0.09

A3.4. Daily soil surface nitrous oxide (N_2O, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**5/6/17**	**5/8/17**	**6/19/17**	**6/25/17**	**6/30/17**	**7/8/17**	**7/15/17**	**7/24/17**	**7/30/17**	**8/11/17**	**9/4/17**
LdC	1	11.15	7.80	10.97	3.12	5.58	7.30	7.77	12.42	11.08	2.65	11.91
LdC	2	16.15	27.20	17.43	12.67	11.44	9.46	7.89	9.24	6.63	9.78	4.87
LdC	3	19.30	29.00	11.09	7.90	5.22	12.06	13.93	10.63	13.19	9.06	5.75
LdC	4	17.80	19.66	12.82	22.70	4.03	9.03	14.83	5.25	9.40	12.27	6.88
LdC+G	1	9.97	14.29	11.31	7.28	6.48	6.44	6.82	9.92	12.06	5.10	7.74
LdC+G	2	7.98	17.73	12.73	10.35	5.28	2.10	13.26	3.55	10.86	3.77	5.90
LdC+G	3	20.60	31.20	13.37	9.33	8.54	7.17	16.79	8.79	9.58	6.27	6.89
LdC+G	4	20.13	15.42	16.27	7.23	4.89	8.47	19.49	10.23	12.97	15.64	7.50
NC	1	6.45	3.58	8.96	3.02	3.47	1.30	3.57	6.79	4.88	4.69	5.00
NC	2	13.61	24.01	8.23	7.81	3.26	4.46	6.52	3.55	0.56	5.18	6.70
NC	3	17.96	11.50	4.33	2.92	7.64	2.36	9.06	14.19	3.45	2.44	2.31
NC	4	5.83	21.56	10.36	8.26	6.70	2.75	7.79	5.44	4.43	7.04	0.98
GdC	1	5.20	3.49	3.38	7.12	4.99	3.05	7.93	8.90	5.09	5.58	6.74
GdC	2	11.44	18.15	11.80	7.66	4.54	0.84	4.89	9.69	7.11	14.68	5.37
GdC	3	19.13	16.65	10.04	8.59	9.39	5.00	7.88	13.00	10.82	2.93	2.47
GdC	4	11.92	12.76	11.57	8.74	4.62	1.67	8.38	2.61	7.11	10.22	5.47
GdC+G	1	4.35	8.39	9.45	7.05	1.81	5.05	4.39	9.30	5.11	3.21	4.95
GdC+G	2	19.46	10.12	10.94	6.25	7.45	12.40	9.31	5.33	5.03	4.95	2.76
GdC+G	3	22.22	13.60	6.51	11.64	5.38	9.83	12.24	8.49	4.41	4.87	6.52
GdC+G	4	14.31	13.87	14.75	6.67	5.22	11.97	5.10	9.74	8.87	5.59	2.13

A3.4. Cont'd

TRT	REP	9/17/17	9/30/17	10/12/17	11/4/17	11/30/17	12/1/17	12/10/17
LdC	1	5.70	6.53	6.68	5.11	6.84	3.62	3.07
LdC	2	8.03	6.59	7.17	7.09	5.17	6.35	4.00
LdC	3	12.61	2.18	5.55	1.79	4.78	6.08	5.34
LdC	4	7.73	7.39	6.54	6.57	3.78	4.53	4.65
LdC+G	1	7.52	4.72	6.31	8.17	7.03	6.17	4.80
LdC+G	2	9.29	7.99	10.90	8.59	8.75	5.47	7.09
LdC+G	3	8.37	3.75	6.11	4.73	7.08	2.93	11.47
LdC+G	4	5.02	5.64	9.51	3.72	3.94	11.30	7.73
NC	1	4.88	4.66	2.94	2.62	0.19	4.11	3.55
NC	2	4.13	6.72	1.49	5.07	2.15	5.05	1.68
NC	3	3.98	3.59	3.98	4.06	2.08	1.77	6.83
NC	4	5.11	3.12	5.93	0.40	1.81	0.73	2.96
GdC	1	4.25	4.53	3.08	3.50	3.70	9.63	4.04
GdC	2	5.57	8.86	4.35	3.16	3.66	3.23	3.30
GdC	3	5.59	2.56	6.10	5.52	4.68	2.37	6.82
GdC	4	7.16	5.69	1.94	2.71	2.72	3.31	6.88
GdC+G	1	7.93	4.70	6.37	3.64	3.95	6.61	6.90
GdC+G	2	7.10	6.95	5.32	4.02	5.85	3.31	16.54
GdC+G	3	7.45	3.11	9.03	6.41	4.01	8.01	10.14
GdC+G	4	7.48	4.55	5.53	4.65	9.77	10.26	7.73

A3.5. Daily soil surface methane (CH_4, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2016 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**8/11/16**	**8/18/16**	**8/23/16**	**8/30/16**	**9/12/16**	**9/23/16**	**9/27/16**	**10/10/16**	**10/17/16**	**11/1/16**	**11/16/16**
LdC	1	10.50	6.67	-2.42	0.90	-8.60	2.20	-7.16	10.00	-1.13	27.50	-2.60
LdC	2	1.20	12.19	25.55	21.31	23.25	19.80	2.98	-1.04	12.68	25.89	-2.24
LdC	3	3.84	-2.91	3.70	0.45	-15.03	10.82	7.15	4.82	15.93	4.82	4.03
LdC	4	8.47	17.86	13.01	12.00	21.13	-8.22	16.50	7.05	9.71	1.80	4.17
LdC+G	1	15.10	-0.50	6.12	0.50	-6.45	11.59	-9.98	-1.50	-3.48	3.55	-3.13
LdC+G	2	-12.91	9.15	10.99	20.15	12.15	14.26	-17.65	-4.63	14.68	3.70	0.05
LdC+G	3	0.45	-4.95	-4.76	9.14	24.55	-5.23	7.59	-0.35	18.79	-6.10	-1.38
LdC+G	4	1.84	-14.80	8.63	11.39	12.85	3.68	-1.65	-9.80	2.87	0.85	-0.50
NC	1	-2.11	2.74	2.28	15.80	20.85	4.56	9.73	-11.55	9.60	5.70	2.65
NC	2	19.59	-7.20	12.32	21.89	-1.92	-8.60	2.06	8.42	26.34	4.87	-8.91
NC	3	0.74	-3.55	21.07	4.10	3.76	9.21	-7.90	17.16	1.75	-13.10	4.50
NC	4	-1.82	6.44	5.17	9.92	4.75	13.81	14.74	-3.31	9.47	16.89	-2.30
GdC	1	1.56	7.60	0.03	-0.14	1.50	-23.74	2.25	16.95	1.35	-5.25	-0.52
GdC	2	-6.45	-15.30	-7.25	-9.12	-8.72	12.68	11.70	-18.84	4.73	-5.73	4.55
GdC	3	8.74	6.23	1.71	4.06	-2.35	5.30	10.59	-1.77	-13.69	-9.05	-3.13
GdC	4	-0.90	-2.05	10.42	15.25	-4.37	22.70	22.00	4.10	-9.29	10.79	3.16
GdC+G	1	-6.57	-22.55	1.34	7.38	1.18	-7.86	18.25	6.78	16.66	2.25	10.43
GdC+G	2	-7.82	5.56	1.51	-6.26	-1.32	9.86	-22.66	9.19	3.83	-6.84	6.85
GdC+G	3	3.11	20.77	1.83	10.81	11.73	2.55	18.66	10.80	-12.00	-6.28	2.57
GdC+G	4	27.45	-0.21	7.85	8.02	-8.20	24.28	16.40	1.46	-4.22	-0.67	3.52

A3.6. Daily soil surface methane (CH_4, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**5/6/17**	**5/8/17**	**6/19/17**	**6/25/17**	**6/30/17**	**7/8/17**	**7/15/17**	**7/24/17**	**7/30/17**	**8/11/17**	**9/4/17**
LdC	1	10.40	3.67	0.09	14.16	-3.63	-1.50	0.09	5.32	-0.07	15.38	13.93
LdC	2	-3.31	-8.28	8.26	10.48	6.21	5.79	-2.23	6.63	10.23	-	6.10
LdC	3	-17.51	14.60	-6.20	1.24	11.65	1.40	5.04	6.94	1.33	4.65	11.38
LdC	4	3.48	10.54	-5.03	-4.57	1.97	-2.55	6.04	2.47	6.60	2.52	12.69
LdC+G	1	2.47	8.66	-1.29	-5.40	10.78	-6.66	3.51	-2.93	6.29	0.03	7.85
LdC+G	2	19.78	0.69	-2.91	14.53	-7.30	-2.50	8.39	-2.58	7.22	-3.24	-5.26
LdC+G	3	6.19	-3.35	-5.36	6.52	-3.19	-3.37	5.20	5.40	11.18	0.47	-4.40
LdC+G	4	5.28	15.13	8.32	1.01	3.56	2.19	-11.42	1.54	2.37	0.57	18.20
NC	1	-11.04	1.44	1.67	5.78	-2.22	-2.97	3.02	-8.22	5.34	0.91	2.99
NC	2	-13.46	1.47	3.52	1.66	2.26	2.95	3.84	4.64	-0.19	2.67	0.19
NC	3	-9.77	13.37	-4.14	0.31	-2.95	3.69	0.86	0.93	1.82	-0.88	1.73
NC	4	11.87	-5.38	-4.07	3.81	-4.78	-0.64	-1.40	-6.22	-1.78	-1.83	-4.01
GdC	1	2.15	5.93	6.04	0.57	-10.32	-2.20	5.09	6.21	-0.79	-5.38	-0.75
GdC	2	7.18	7.95	-3.22	2.69	7.26	-3.30	2.12	-1.12	-2.99	-	-0.93
GdC	3	2.23	-0.22	-3.19	-6.01	-2.61	0.13	-3.98	0.20	5.15	4.30	-12.24
GdC	4	5.39	12.25	3.78	7.25	10.40	2.62	3.89	-8.39	1.91	22.72	15.29
GdC+G	1	-1.61	12.36	9.29	7.49	15.39	-4.56	6.30	9.33	-5.31	-5.66	0.16
GdC+G	2	-7.44	5.48	6.10	-2.24	8.29	-3.54	8.12	-1.61	-1.41	-3.37	0.41
GdC+G	3	-0.55	-0.65	0.35	-10.77	0.22	6.46	7.76	1.64	9.23	3.91	13.84
GdC+G	4	-1.35	4.15	-2.34	0.11	0.99	14.88	-2.02	6.85	4.58	-5.86	4.46

A3.6. Cont'd

TRT	REP	9/17/17	9/30/17	10/12/17	11/4/17	11/30/17	12/1/17	12/10/17
LdC	1	9.26	2.66	6.75	8.77	3.29	1.54	1.60
LdC	2	-0.30	-0.91	1.29	-8.32	0.42	-1.06	10.53
LdC	3	4.55	2.07	0.05	3.19	10.97	7.07	0.61
LdC	4	0.26	2.23	5.55	5.99	3.91	0.56	1.76
LdC+G	1	-0.33	0.68	-1.23	2.48	4.38	3.97	1.90
LdC+G	2	0.17	4.61	4.37	7.95	6.14	-1.66	2.84
LdC+G	3	-1.74	3.22	-5.95	8.94	3.23	8.13	5.56
LdC+G	4	4.64	4.88	2.66	-5.43	4.70	10.66	15.44
NC	1	0.67	-1.02	2.89	3.56	3.57	-3.74	3.50
NC	2	3.65	1.91	3.84	2.95	4.36	-2.48	3.49
NC	3	-1.85	-0.26	-2.95	-0.17	-5.90	-2.58	-5.02
NC	4	-4.30	-1.66	-2.69	1.31	3.65	5.07	3.11
GdC	1	-6.02	-0.31	3.04	1.29	11.71	5.61	-4.92
GdC	2	8.82	2.75	3.51	8.93	-5.50	0.54	6.35
GdC	3	2.34	2.53	0.39	3.96	8.67	2.56	0.80
GdC	4	-0.60	0.68	-0.27	4.19	-3.48	6.29	9.79
GdC+G	1	-3.55	3.08	4.02	6.14	2.25	7.59	9.98
GdC+G	2	-5.88	-0.59	5.29	-6.18	-0.08	-4.33	13.24
GdC+G	3	-2.03	7.77	1.52	10.95	6.37	7.26	-11.62
GdC+G	4	8.20	4.94	-0.96	6.42	3.24	7.58	19.58

A3.7. Daily soil surface carbon dioxide (CO_2, kg ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**8/2/17**	**8/18/17**	**8/24/17**	**9/02/17**	**9/07/17**	**9/10/17**	**9/21/17**	**9/29/17**	**10/8/17**	**10/17/17**
LdC	1	23.80	34.55	27.97	34.12	22.26	20.31	27.61	11.55	6.20	15.59
LdC	2	32.64	37.83	38.44	30.48	16.07	25.33	21.21	15.46	10.82	6.89
LdC	3	31.57	45.40	44.17	40.02	34.82	28.41	32.89	14.42	13.13	16.59
LdC	4	30.97	32.90	40.78	45.25	33.62	25.46	29.55	3.73	2.91	16.74
LdC+G	1	38.34	39.50	48.00	52.28	31.45	34.75	37.92	16.54	11.33	18.78
LdC+G	2	29.12	40.30	36.96	31.76	20.97	30.82	24.19	12.44	10.28	14.97
LdC+G	3	34.28	51.60	35.68	43.92	31.72	21.37	36.55	12.39	10.25	11.75
LdC+G	4	33.59	53.84	30.18	52.12	47.10	23.78	40.84	9.77	12.04	15.55
NC	1	39.28	35.02	37.64	39.60	18.95	19.23	33.09	17.24	12.08	17.15
NC	2	26.15	32.14	22.87	31.33	15.96	19.34	22.77	12.54	9.28	13.99
NC	3	20.68	37.37	23.25	39.26	20.67	11.35	34.00	10.95	16.58	21.54
NC	4	29.26	23.47	22.68	24.82	22.77	19.47	36.46	3.79	2.76	24.15
GdC	1	31.33	33.10	54.20	27.82	31.69	28.10	29.18	14.99	10.94	12.89
GdC	2	25.71	33.20	30.16	32.84	14.01	22.85	16.62	11.73	10.27	9.35
GdC	3	37.32	52.60	48.41	42.60	38.73	27.66	39.20	15.87	13.12	10.30
GdC	4	27.41	20.90	29.58	30.64	23.98	20.14	27.68	7.21	6.86	18.38
GdC+G	1	48.88	34.00	48.00	61.31	37.97	35.36	41.33	27.39	15.49	22.40
GdC+G	2	33.57	31.50	40.29	31.97	23.35	27.22	21.40	10.70	13.29	12.46
GdC+G	3	23.96	36.72	26.48	35.78	32.13	16.78	32.38	10.22	13.92	13.56
GdC+G	4	25.79	37.50	35.36	45.63	24.00	17.39	30.15	10.01	8.51	19.35

A3.7. Cont'd

TRT	REP	11/21/17	11/22/17	11/23/17	11/24/17	11/25/17	11/26/17	11/27/17	11/28/17	11/29/17
LdC	1	7.35	6.31	3.87	2.58	4.18	3.52	3.62	1.80	4.07
LdC	2	4.00	7.97	2.84	3.06	1.63	3.30	7.82	5.43	6.58
LdC	3	3.45	7.21	4.33	3.72	3.00	1.38	2.49	3.44	5.85
LdC	4	3.76	3.65	3.96	1.80	3.15	1.69	6.78	3.05	3.91
LdC+G	1	10.48	9.14	5.20	8.31	4.58	6.54	8.70	7.10	2.17
LdC+G	2	4.77	4.73	4.63	3.76	4.06	6.07	5.06	7.67	9.80
LdC+G	3	4.45	3.15	2.96	5.80	5.24	4.10	7.50	3.02	7.17
LdC+G	4	5.50	3.90	5.64	7.47	2.56	8.64	9.30	7.98	9.95
NC	1	4.39	6.64	1.90	6.52	1.94	2.11	5.63	5.04	4.60
NC	2	7.84	3.20	6.70	2.34	3.52	0.98	5.08	4.70	6.47
NC	3	4.52	3.51	2.52	4.53	3.91	3.83	3.44	1.53	2.38
NC	4	9.45	4.20	2.35	4.56	2.15	2.46	11.44	3.76	5.71
GdC	1	9.51	4.97	4.89	5.17	2.88	2.65	5.46	5.10	2.47
GdC	2	4.24	3.50	1.49	1.81	1.00	1.93	3.31	8.01	1.87
GdC	3	5.86	5.62	4.38	4.38	4.70	3.15	3.70	6.10	6.31
GdC	4	4.59	3.66	3.26	3.34	1.10	2.88	8.63	2.82	3.68
GdC+G	1	7.90	7.30	4.54	8.07	5.22	3.82	9.29	4.60	4.63
GdC+G	2	12.78	5.05	3.61	3.22	3.09	1.38	5.89	6.74	3.35
GdC+G	3	4.04	3.55	1.82	7.27	2.71	2.99	8.47	8.92	9.12
GdC+G	4	3.75	3.02	2.42	2.58	3.75	3.73	9.50	6.63	5.41

A3.8. Daily soil surface carbon dioxide (CO_2, kg ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	4/11/2018	4/30/18	5/1/2018	5/21/2018	5/29/2018	6/10/2018	7/2/2018	7/10/2018	7/31/2018
LdC	1	0.40	23.20	11.49	31.67	19.98	11.01	22.19	14.84	13.89
LdC	2	0.37	11.85	4.02	30.64	17.89	9.30	39.76	37.14	22.68
LdC	3	0.00	11.21	5.95	18.97	7.00	11.34	18.17	23.35	14.42
LdC	4	0.53	8.46	1.88	9.55	15.89	12.39	12.56	20.20	10.68
LdC+G	1	0.57	16.24	10.94	23.63	17.14	12.84	20.06	18.11	22.07
LdC+G	2	0.88	4.13	18.65	29.41	20.26	10.51	26.91	17.65	7.63
LdC+G	3	0.43	17.84	10.11	23.19	24.70	24.01	41.56	44.03	12.48
LdC+G	4	0.79	3.71	9.72	18.76	21.97	19.09	19.10	31.07	18.27
NC	1	0.20	14.04	9.71	19.78	9.52	17.39	39.03	24.55	19.87
NC	2	0.49	17.24	8.88	11.60	8.60	5.38	16.81	21.03	13.80
NC	3	1.57	5.83	10.25	15.51	7.56	11.26	32.18	30.19	21.77
NC	4	0.85	4.20	1.40	8.05	8.89	8.99	29.34	13.37	12.18
GdC	1	0.70	15.92	10.00	34.04	10.03	17.58	49.62	53.75	20.09
GdC	2	0.00	13.51	12.56	30.76	20.92	18.77	15.08	20.07	12.23
GdC	3	1.29	9.90	8.56	25.68	8.05	28.62	15.88	19.01	15.68
GdC	4	0.72	7.19	2.61	17.60	6.94	10.13	29.37	32.67	18.26
GdC+G	1	0.55	10.81	8.50	27.25	20.29	14.87	21.87	34.67	23.61
GdC+G	2	0.66	5.38	6.31	13.13	25.93	11.76	42.38	33.35	22.82
GdC+G	3	0.30	14.31	7.01	29.24	15.17	25.92	29.20	28.39	25.80
GdC+G	4	0.59	10.10	4.88	12.46	11.04	6.92	33.03	45.43	21.97

A3.8. Cont'd

TRT	REP	8/10/2018	8/17/2018	8/23/2018	8/30/2018	9/5/2018	9/13/2018	9/27/2018	10/7/2018	10/18/2018
LdC	1	17.48	26.01	9.70	15.89	13.98	7.27	9.42	6.47	5.87
LdC	2	30.67	38.84	25.31	22.38	34.98	15.35	10.13	8.75	7.48
LdC	3	18.87	10.05	11.04	13.10	12.68	11.00	1.97	9.68	5.41
LdC	4	23.95	19.63	22.87	20.65	16.77	11.56	3.06	5.22	2.55
LdC+G	1	27.37	6.76	9.26	8.50	10.48	14.82	8.45	4.49	6.52
LdC+G	2	19.97	16.16	11.42	15.32	12.32	7.96	4.16	9.46	1.44
LdC+G	3	25.72	38.28	23.42	16.03	32.68	11.05	4.44	3.42	4.09
LdC+G	4	17.08	42.81	22.89	15.07	15.44	11.97	7.38	8.09	5.84
NC	1	38.43	31.71	20.05	23.82	22.18	15.00	19.31	6.74	5.15
NC	2	18.84	18.57	14.73	8.62	8.21	11.85	3.99	4.41	1.71
NC	3	27.21	29.88	20.36	6.77	18.42	14.71	9.44	10.43	4.81
NC	4	16.18	17.52	13.98	9.90	12.86	5.44	2.87	3.04	1.43
GdC	1	48.45	24.02	29.15	35.45	25.32	20.94	23.11	11.82	2.18
GdC	2	21.95	21.63	10.31	11.45	19.82	13.51	12.72	14.96	9.11
GdC	3	18.06	24.73	7.70	10.16	16.51	12.38	3.32	4.69	3.03
GdC	4	26.37	23.46	27.87	12.09	25.75	19.67	17.10	9.49	1.40
GdC+G	1	35.80	38.06	26.14	17.00	22.00	23.72	18.40	2.03	2.68
GdC+G	2	38.69	24.30	19.08	21.63	24.78	24.41	12.76	5.40	2.62
GdC+G	3	31.50	29.00	28.91	20.78	21.20	28.14	14.02	9.12	4.18
GdC+G	4	26.86	26.10	26.58	20.22	21.30	21.26	12.12	10.81	5.51

A3.8. Cont’d

TRT	REP	10/30/2018	10/31/2018	11/1/2018	11/2/2018	11/20/2018	11/26/2018	11/27/2018
LdC	1	3.41	7.28	2.00	4.29	0.37	6.16	1.50
LdC	2	4.17	13.15	4.94	8.67	0.85	0.49	0.66
LdC	3	6.55	10.21	3.74	14.08	2.38	1.33	1.45
LdC	4	5.54	5.56	3.14	16.01	2.47	0.50	0.33
LdC+G	1	6.43	7.32	4.30	4.40	1.10	2.01	1.27
LdC+G	2	3.66	11.03	7.15	2.81	0.37	1.15	0.33
LdC+G	3	5.50	6.35	11.33	1.95	1.14	0.77	0.70
LdC+G	4	5.31	11.88	5.96	8.65	1.57	0.63	0.89
NC	1	3.29	10.03	1.92	3.09	1.41	0.96	1.92
NC	2	2.66	12.98	3.47	3.87	0.53	0.38	0.34
NC	3	3.61	3.14	4.26	18.24	2.26	1.00	1.44
NC	4	1.69	7.58	6.90	4.58	2.77	0.23	1.65
GdC	1	3.74	3.30	2.68	4.17	1.07	2.11	0.85
GdC	2	4.05	1.70	2.89	5.38	1.00	0.65	0.93
GdC	3	3.34	2.90	11.79	17.60	3.42	1.62	1.80
GdC	4	4.99	2.63	5.50	1.54	2.41	0.32	1.09
GdC+G	1	8.52	7.05	1.41	5.39	1.05	0.12	0.77
GdC+G	2	2.98	12.34	6.29	2.85	0.13	0.46	1.51
GdC+G	3	3.69	8.81	2.84	8.32	1.33	0.08	0.33
GdC+G	4	8.42	4.39	6.14	7.31	0.84	1.14	3.01

A3.9. Daily soil surface nitrous oxide (N_2O, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**8/2/17**	**8/18/17**	**8/24/17**	**9/02/17**	**9/07/17**	**9/10/17**	**9/21/17**	**9/29/17**	**10/8/17**	**10/17/17**
LdC	1	6.77	3.29	2.00	9.22	8.17	2.16	8.19	1.07	9.72	5.85
LdC	2	2.30	3.50	1.25	2.20	8.46	3.87	9.25	5.29	1.57	5.55
LdC	3	5.45	4.81	1.50	10.32	2.73	1.29	5.20	1.25	1.28	2.62
LdC	4	5.30	11.53	4.21	5.36	2.50	9.60	4.97	10.35	1.19	10.56
LdC+G	1	1.53	2.33	7.79	2.53	4.86	6.29	2.84	2.74	5.74	10.18
LdC+G	2	2.55	4.20	1.65	1.00	8.46	1.06	0.80	2.56	3.43	4.30
LdC+G	3	3.13	8.50	1.38	6.10	1.84	6.53	12.10	6.03	5.06	4.38
LdC+G	4	3.46	13.10	2.75	4.99	8.12	3.62	4.81	1.38	2.96	5.28
NC	1	7.48	4.73	3.23	3.96	7.50	0.28	4.19	5.65	4.80	8.20
NC	2	5.55	5.00	4.00	5.03	11.30	4.22	10.74	4.62	7.40	9.24
NC	3	3.68	10.40	4.46	2.89	5.00	4.70	5.60	6.84	8.03	1.55
NC	4	6.14	1.81	4.32	4.90	2.43	4.89	1.76	8.43	3.23	9.61
GdC	1	6.91	4.50	6.35	2.04	10.71	11.50	4.88	8.72	3.60	4.90
GdC	2	3.14	1.78	5.35	4.30	2.51	2.32	2.66	5.30	4.05	0.38
GdC	3	12.58	3.80	2.54	3.98	6.90	2.84	3.81	6.18	7.20	4.55
GdC	4	5.36	8.71	5.24	11.64	6.66	1.60	1.40	5.99	1.89	3.04
GdC+G	1	1.20	6.18	8.99	3.10	10.19	7.61	5.85	8.50	4.70	9.31
GdC+G	2	1.32	16.80	3.89	3.20	3.72	10.74	2.71	4.41	4.12	7.49
GdC+G	3	2.78	2.19	3.74	9.46	7.59	1.69	6.35	2.95	5.10	6.68
GdC+G	4	9.60	3.28	5.80	5.90	3.95	3.76	4.99	2.08	3.10	5.47

A3.9. Cont'd

TRT	REP	11/21/17	11/22/17	11/23/17	11/24/17	11/25/17	11/26/17	11/27/17	11/28/17	11/29/17
LdC	1	11.90	9.30	9.36	1.22	7.42	3.02	3.22	5.40	5.30
LdC	2	5.97	9.24	8.00	2.97	2.18	6.21	4.64	6.75	8.11
LdC	3	5.62	7.77	9.01	6.46	4.12	2.97	0.91	3.85	7.69
LdC	4	4.80	12.20	9.67	3.55	1.42	4.49	14.88	4.70	7.11
LdC+G	1	6.10	7.18	17.23	9.12	3.05	5.10	6.12	8.89	4.21
LdC+G	2	7.58	9.90	4.70	12.44	3.69	6.04	11.53	20.74	19.33
LdC+G	3	4.71	7.32	0.90	8.80	11.18	9.34	14.02	3.40	4.96
LdC+G	4	6.80	4.89	15.76	4.45	5.74	10.60	15.35	11.77	16.97
NC	1	2.00	9.43	5.45	2.67	4.40	1.13	7.57	4.26	7.30
NC	2	1.26	6.35	7.42	5.51	5.51	1.13	4.69	1.39	22.42
NC	3	2.75	6.40	2.00	12.56	2.48	1.01	11.39	3.18	1.77
NC	4	2.34	9.77	8.34	1.82	8.82	1.25	2.90	3.90	3.77
GdC	1	7.97	2.19	5.21	4.00	7.82	5.65	9.40	6.70	2.60
GdC	2	2.68	4.37	4.00	2.99	6.82	1.45	3.13	9.93	7.04
GdC	3	12.51	10.12	3.08	3.44	5.75	1.82	3.17	4.87	17.56
GdC	4	8.66	2.37	9.29	1.52	4.10	0.20	8.23	2.58	6.93
GdC+G	1	7.78	5.93	3.97	11.21	2.26	4.11	12.31	14.07	12.48
GdC+G	2	2.39	7.68	15.65	8.70	0.50	1.30	3.00	7.71	6.86
GdC+G	3	5.90	4.82	8.02	10.36	4.70	10.89	12.70	13.43	14.40
GdC+G	4	10.75	3.51	16.60	5.92	8.28	1.82	13.00	14.16	5.70

A3.10. Daily soil surface nitrous oxide (N_2O, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	4/11/2018	4/30/18	5/1/2018	5/21/2018	5/29/2018	6/10/2018	7/2/2018	7/10/2018	7/31/2018
LdC	1	2.66	14.15	8.41	39.70	32.51	20.38	8.25	23.15	4.22
LdC	2	0.97	21.39	5.85	41.93	19.66	4.99	18.35	24.12	6.52
LdC	3	3.22	16.26	5.53	32.70	2.40	41.41	21.84	10.11	17.19
LdC	4	6.02	5.62	0.87	41.55	41.90	14.74	3.49	21.53	10.01
LdC+G	1	3.29	20.11	15.10	38.30	28.00	33.49	11.48	8.70	18.65
LdC+G	2	3.15	11.60	19.26	30.41	36.83	10.78	7.89	8.70	26.14
LdC+G	3	4.66	21.32	10.02	15.67	13.27	16.15	17.95	15.81	5.04
LdC+G	4	3.33	6.84	4.01	26.04	13.66	6.12	8.60	1.59	22.34
NC	1	1.22	29.41	20.86	5.68	4.84	3.86	2.93	5.06	0.47
NC	2	7.41	19.80	9.02	29.67	24.07	14.33	37.92	11.95	2.21
NC	3	4.98	5.42	29.28	40.84	14.57	7.26	4.99	15.77	24.28
NC	4	6.33	9.07	4.81	25.40	26.89	23.72	53.70	10.92	8.65
GdC	1	4.97	26.81	6.93	29.40	24.40	11.23	16.40	7.53	0.59
GdC	2	5.31	10.17	9.04	33.53	14.56	22.64	32.92	8.25	4.51
GdC	3	1.65	7.63	10.59	21.50	33.10	38.00	24.68	6.22	11.60
GdC	4	4.03	13.76	6.49	53.40	25.30	18.70	24.72	2.88	11.65
GdC+G	1	5.58	21.04	9.07	16.86	14.64	11.04	7.69	7.50	3.41
GdC+G	2	1.43	16.99	3.83	15.67	35.26	10.71	34.01	9.73	3.02
GdC+G	3	0.54	31.85	6.43	37.15	7.44	23.34	12.03	7.38	10.78
GdC+G	4	4.73	8.33	3.46	52.69	6.16	8.86	21.16	5.39	14.07

A3.10. Cont'd

TRT	REP	8/10/2018	8/17/2018	8/23/2018	8/30/2018	9/5/2018	9/13/2018	9/27/2018	10/7/2018	10/18/2018
LdC	1	2.93	3.67	3.51	4.09	9.72	3.45	10.08	11.62	17.95
LdC	2	11.23	15.62	6.60	5.23	9.74	8.50	6.57	8.14	3.45
LdC	3	7.69	3.19	0.99	8.43	11.85	7.15	4.95	30.85	7.32
LdC	4	3.81	4.90	25.66	10.08	16.81	2.95	1.71	7.75	0.55
LdC+G	1	8.86	21.05	2.16	1.89	10.24	1.96	27.44	9.64	3.93
LdC+G	2	14.98	17.66	21.58	6.88	18.76	5.50	10.96	23.08	9.68
LdC+G	3	5.48	5.87	11.25	14.95	20.43	1.12	7.27	6.25	5.79
LdC+G	4	5.94	3.76	3.12	2.24	27.05	3.61	4.06	11.17	8.10
NC	1	4.74	4.98	3.27	11.32	1.20	1.70	20.62	1.08	9.00
NC	2	13.26	5.95	4.77	4.52	8.85	2.85	3.29	5.00	12.60
NC	3	2.44	2.62	5.90	6.04	38.21	1.86	9.50	15.32	3.75
NC	4	4.65	0.98	4.65	5.31	15.14	3.90	3.62	4.78	2.48
GdC	1	7.97	5.05	3.86	8.46	10.35	3.80	6.32	13.76	6.58
GdC	2	0.23	1.45	3.82	4.60	15.16	0.60	17.36	38.73	13.57
GdC	3	10.55	6.01	3.12	11.67	12.36	4.41	8.20	18.76	2.70
GdC	4	1.30	4.17	8.29	2.31	6.10	5.14	3.87	5.83	3.47
GdC+G	1	2.75	3.97	8.27	4.34	3.80	13.94	6.68	7.90	5.11
GdC+G	2	16.89	13.90	8.19	0.91	9.49	4.41	9.14	0.40	8.70
GdC+G	3	8.04	6.13	5.47	7.86	8.86	10.90	5.44	14.81	0.01
GdC+G	4	24.38	5.48	4.63	8.23	8.92	2.78	5.25	17.34	1.92

A3.10. Cont'd

TRT	REP	10/30/2018	10/31/2018	11/1/2018	11/2/2018	11/20/2018	11/26/2018	11/27/2018
LdC	1	1.00	16.94	14.97	3.65	3.56	11.96	2.10
LdC	2	22.50	16.59	6.88	15.80	1.91	6.79	0.60
LdC	3	3.05	22.40	0.40	11.50	1.51	6.15	2.21
LdC	4	7.60	17.55	7.42	27.29	14.19	12.90	4.24
LdC+G	1	15.11	23.24	5.60	9.71	8.39	6.34	8.15
LdC+G	2	27.00	21.08	9.44	4.45	6.79	5.41	1.97
LdC+G	3	2.84	16.48	17.75	5.45	3.29	1.03	12.05
LdC+G	4	14.68	23.52	7.11	15.79	8.23	13.40	2.62
NC	1	8.34	10.00	12.04	3.25	2.19	12.65	15.75
NC	2	8.56	28.07	3.94	3.63	3.60	6.79	7.36
NC	3	3.76	7.43	1.86	5.11	13.86	18.38	3.55
NC	4	12.73	4.60	8.70	8.45	16.83	4.52	3.00
GdC	1	16.01	2.20	7.24	8.70	1.94	0.64	8.02
GdC	2	16.45	3.30	6.51	9.73	5.55	0.31	14.07
GdC	3	0.85	4.64	24.79	15.14	6.77	3.23	5.85
GdC	4	10.11	0.39	8.33	2.80	13.02	7.49	3.99
GdC+G	1	15.33	2.41	3.25	10.59	17.00	3.72	6.18
GdC+G	2	28.92	3.05	18.24	7.95	6.21	7.77	0.88
GdC+G	3	0.62	21.33	3.99	14.77	6.98	3.58	4.34
GdC+G	4	31.92	18.29	11.76	13.02	19.96	24.25	5.58

A3.11. Daily soil surface methane (CH_4, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**8/2/17**	**8/18/17**	**8/24/17**	**9/02/17**	**9/07/17**	**9/10/17**	**9/21/17**	**9/29/17**	**10/8/17**	**10/17/17**
LdC	1	4.24	5.41	-6.90	-0.23	-9.36	5.04	6.79	-2.82	7.37	-0.60
LdC	2	12.20	-7.84	-5.23	-4.35	2.60	9.77	1.50	9.38	-3.87	-6.88
LdC	3	6.60	-0.37	-3.11	7.71	-10.14	4.96	0.22	9.00	-5.04	-7.58
LdC	4	-8.73	-10.45	-1.62	-9.00	-6.50	9.26	4.09	4.05	5.48	4.45
LdC+G	1	-11.53	6.65	1.46	-3.75	-2.59	7.19	1.81	4.46	12.90	3.34
LdC+G	2	-2.93	-6.14	11.86	-1.62	-3.48	-6.62	-3.08	-1.47	12.47	-0.08
LdC+G	3	2.21	4.80	-0.83	-8.32	-5.91	-11.31	1.56	-0.80	3.28	-4.08
LdC+G	4	9.52	1.20	1.12	-12.80	-5.18	-12.95	4.21	0.63	-3.07	1.56
NC	1	2.11	1.92	-6.37	-0.39	-5.50	14.51	-8.40	-11.13	0.57	3.73
NC	2	3.01	-2.89	-7.50	-2.83	-9.49	-2.60	-4.40	10.98	5.90	-4.28
NC	3	3.50	-6.64	-10.10	-9.28	2.85	15.90	-4.67	-0.42	6.25	12.09
NC	4	9.71	11.70	10.78	8.12	-8.40	-3.00	1.58	3.11	-0.84	6.15
GdC	1	0.13	0.63	-15.02	-3.30	1.80	-0.91	10.06	4.62	-0.73	1.02
GdC	2	0.24	-19.40	3.38	1.01	2.40	-6.75	5.91	-6.64	-5.35	4.80
GdC	3	3.35	18.57	2.55	0.90	-3.30	11.37	-2.04	-3.75	8.09	-0.81
GdC	4	2.10	9.74	-0.71	0.80	1.90	16.27	7.45	-1.86	-3.69	-3.28
GdC+G	1	-5.73	-2.53	-10.67	2.06	4.88	2.96	-21.42	0.43	4.91	0.91
GdC+G	2	-5.43	5.87	13.82	-0.78	-2.10	14.00	-3.32	9.27	3.41	14.56
GdC+G	3	1.29	24.18	-0.81	0.29	-4.00	-0.01	-0.96	0.96	-1.08	-0.88
GdC+G	4	8.03	-3.86	-3.79	4.05	-2.73	-4.29	9.74	11.17	-2.21	-1.18

A3.11. Cont'd

TRT	REP	11/21/17	11/22/17	11/23/17	11/24/17	11/25/17	11/26/17	11/27/17	11/28/17	11/29/17
LdC	1	1.91	-2.18	6.63	-9.60	8.22	9.87	4.38	-4.80	7.81
LdC	2	-2.03	-5.00	-0.96	-3.10	-13.43	1.30	11.19	-4.21	6.73
LdC	3	-5.03	-1.62	5.91	4.92	2.57	4.28	6.72	-7.11	-2.17
LdC	4	0.72	-2.06	-15.20	-6.30	1.17	0.48	7.48	-0.71	9.82
LdC+G	1	4.27	16.03	6.88	-0.66	-1.87	2.50	22.70	10.00	0.15
LdC+G	2	-1.73	-3.08	-9.76	-2.21	4.41	7.96	13.20	-9.96	2.35
LdC+G	3	-0.62	0.50	-1.19	2.08	2.05	2.99	1.32	-16.01	-4.52
LdC+G	4	2.79	1.54	7.80	11.56	-3.36	-0.10	1.62	10.22	2.60
NC	1	2.78	2.41	9.13	5.66	4.12	-19.19	22.62	11.35	-13.22
NC	2	-6.16	1.01	0.00	-4.35	4.60	0.15	-1.25	8.91	19.91
NC	3	-2.24	-6.28	0.78	8.95	-10.11	9.69	1.38	-8.09	-5.51
NC	4	-0.76	1.44	-6.46	0.57	3.00	0.01	3.33	-1.18	1.70
GdC	1	11.15	-4.90	-3.90	12.59	0.58	2.16	17.50	17.68	-2.01
GdC	2	6.15	3.50	7.30	1.74	-11.42	-10.28	-5.76	3.75	6.40
GdC	3	0.29	14.27	8.24	-3.14	-2.80	-4.31	-2.40	-22.40	22.96
GdC	4	4.91	3.84	-2.32	0.34	17.74	9.15	22.66	-0.70	20.79
GdC+G	1	-3.21	-14.67	0.90	-5.21	-4.86	1.63	11.54	-11.23	2.63
GdC+G	2	2.96	21.58	2.95	2.73	1.98	-18.33	12.59	10.57	4.58
GdC+G	3	0.41	-3.09	-10.22	-3.46	2.82	7.30	9.36	21.09	5.69
GdC+G	4	7.60	-1.63	-1.77	-6.15	-1.68	-3.31	10.77	-5.92	0.54

A3.12. Daily soil surface methane (CH_4, g ha^{-1} d^{-1}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	4/11/2018	4/30/18	5/1/2018	5/21/2018	5/29/2018	6/10/2018	7/2/2018	7/10/2018	7/31/2018
LdC	1	1.38	6.89	5.10	-1.56	5.56	1.44	1.99	-16.97	12.97
LdC	2	-3.57	9.85	-12.18	11.21	0.76	-4.49	5.63	13.30	-9.47
LdC	3	5.35	-1.34	-0.57	17.32	-0.33	8.58	14.43	18.33	39.59
LdC	4	1.45	-6.29	-2.60	3.68	-7.29	0.22	-0.56	7.52	4.12
LdC+G	1	-4.72	4.44	12.24	1.49	-7.05	10.84	9.92	13.50	7.85
LdC+G	2	9.16	7.84	22.68	-3.67	1.15	17.83	8.32	11.47	15.54
LdC+G	3	-8.01	14.69	0.55	2.48	3.13	-7.66	11.93	22.15	19.96
LdC+G	4	3.74	10.57	5.60	-11.23	0.32	3.36	0.62	14.59	6.96
NC	1	-1.65	-3.31	4.29	3.33	4.65	9.71	0.35	9.23	-9.00
NC	2	11.21	10.51	19.15	4.41	4.05	4.65	4.88	-7.99	-3.24
NC	3	-2.57	4.13	-1.27	1.56	1.87	9.05	2.03	-1.50	-10.52
NC	4	2.38	4.32	9.14	-3.19	1.87	-0.48	-0.71	-6.90	-15.77
GdC	1	-0.42	5.01	-11.12	0.11	6.58	0.00	5.04	-14.40	-6.40
GdC	2	4.57	4.83	12.18	-2.73	-5.76	2.64	1.91	-11.34	-2.03
GdC	3	8.89	10.92	12.38	3.24	13.96	10.76	-6.18	4.42	9.19
GdC	4	-10.78	4.30	-6.69	-5.37	2.55	-2.84	2.75	-6.63	8.08
GdC+G	1	-0.06	3.39	-1.08	0.42	5.82	-4.86	1.45	19.77	-2.13
GdC+G	2	-1.22	-0.56	3.98	4.97	22.85	5.93	26.49	15.28	13.94
GdC+G	3	8.13	4.04	4.89	-6.62	11.14	1.42	-0.52	15.26	7.06
GdC+G	4	-4.48	3.26	-0.53	-6.91	-9.96	1.61	3.14	10.80	16.66

A3.12. Cont'd

TRT	REP	8/10/2018	8/17/2018	8/23/2018	8/30/2018	9/5/2018	9/13/2018	9/27/2018	10/7/2018	10/18/2018
LdC	1	0.89	11.89	-5.45	-1.91	-1.40	0.98	25.49	23.74	-1.73
LdC	2	3.45	13.13	-1.06	-1.10	-0.81	0.94	-8.31	-0.57	0.44
LdC	3	-4.87	6.90	7.23	-0.89	17.78	4.08	-1.03	20.66	-6.58
LdC	4	0.01	-3.10	21.15	4.55	36.97	-9.32	3.25	4.54	31.89
LdC+G	1	7.27	1.71	6.02	4.55	3.32	-2.44	6.60	8.29	8.01
LdC+G	2	9.73	29.35	11.88	1.63	-13.93	5.21	7.23	14.04	-12.59
LdC+G	3	-5.15	-3.20	22.79	14.86	36.22	6.20	4.17	0.37	2.96
LdC+G	4	11.79	-0.89	-10.33	2.68	7.62	2.56	3.69	-7.85	3.63
NC	1	11.63	10.13	0.16	-0.80	-2.85	-0.35	10.29	12.81	-1.23
NC	2	4.08	2.93	5.58	-3.41	-3.00	-3.31	-1.15	16.83	-3.43
NC	3	2.23	6.57	13.42	-5.24	-0.41	1.59	10.38	10.41	6.70
NC	4	11.91	2.23	-1.73	9.55	3.17	2.32	-3.33	25.09	2.42
GdC	1	-1.50	-11.42	22.75	-0.03	9.49	4.44	15.11	-10.15	-1.02
GdC	2	2.24	17.45	0.56	-5.79	10.51	3.73	18.48	56.05	-12.87
GdC	3	-10.90	2.17	-4.82	32.37	31.73	8.07	-2.36	11.50	9.75
GdC	4	9.35	2.73	-1.62	-19.79	-10.50	-1.14	6.24	-0.05	-8.46
GdC+G	1	-1.00	6.81	-1.39	5.14	4.37	-1.16	10.56	-4.20	-6.70
GdC+G	2	6.23	-2.46	4.36	-2.38	12.44	5.10	3.08	-28.00	3.65
GdC+G	3	-4.51	5.24	2.75	14.54	11.60	-0.24	-0.85	26.85	5.99
GdC+G	4	8.46	2.84	9.29	17.30	29.18	3.75	-2.88	17.01	2.78

A3.12. Cont'd

TRT	REP	10/30/2018	10/31/2018	11/1/2018	11/2/2018	11/20/2018	11/26/2018	11/27/2018
LdC	1	15.11	4.60	-9.01	16.05	-3.77	7.73	16.14
LdC	2	2.61	-1.25	15.45	24.94	6.25	8.97	10.71
LdC	3	5.71	32.24	2.87	11.94	15.25	-5.05	5.13
LdC	4	7.09	10.64	-3.90	16.50	9.63	-4.28	7.31
LdC+G	1	16.43	4.87	-10.10	16.93	4.63	15.47	-4.39
LdC+G	2	6.31	24.95	15.49	2.88	5.51	8.13	-15.44
LdC+G	3	7.74	13.35	21.60	-5.77	1.72	0.62	7.40
LdC+G	4	14.00	18.80	29.33	-4.27	2.56	32.18	9.19
NC	1	3.89	-2.13	-1.43	22.86	0.58	-1.29	-2.84
NC	2	-9.59	7.60	-0.11	18.54	-0.78	-2.97	-6.96
NC	3	-6.93	0.63	11.07	14.30	8.77	6.92	4.25
NC	4	9.81	21.30	32.78	7.13	10.60	1.56	5.59
GdC	1	17.99	10.30	2.63	1.50	-2.84	12.94	-8.47
GdC	2	-2.81	3.41	4.92	9.78	0.63	0.25	-5.56
GdC	3	6.74	-5.90	12.70	17.46	22.52	-2.21	0.36
GdC	4	29.11	-1.66	30.14	6.14	3.83	-5.91	-5.00
GdC+G	1	12.73	-8.55	-5.97	-2.02	8.71	-6.03	-13.71
GdC+G	2	5.84	5.62	17.07	4.53	15.67	2.90	28.14
GdC+G	3	4.05	-5.37	-0.23	3.82	-6.54	3.50	26.49
GdC+G	4	20.60	3.59	3.85	-2.21	13.26	18.93	8.40

A3.13. Soil moisture (cm^3 cm^{-3}) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2016 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	8/11/16	8/18/16	8/23/16	8/30/16	9/12/16	9/23/16	9/27/16	10/10/16	10/17/16	11/1/16	11/16/16
LdC	1	32.9	26.5	25.4	27.4	22.5	34.2	34.4	26.9	25.5	12.2	11.9
LdC	2	37.6	31.2	27.3	22.2	39.7	43.7	43.9	39.9	37.5	19.1	18.8
LdC	3	35.6	33.5	30.1	19.7	27.3	36.3	36.5	36.3	25.6	30.2	30.0
LdC	4	30.6	24.8	24.6	14.3	25.2	36.1	36.3	26.3	20.7	24.6	24.3
LdC+G	1	32.1	28.0	23.7	26.3	27.1	35.7	35.9	23.6	27.7	13.2	13.0
LdC+G	2	36.7	29.5	36.5	17.0	31.1	39.8	40.0	27.0	34.8	15.2	15.0
LdC+G	3	33.9	30.9	30.1	20.8	27.0	39.4	39.6	29.3	30.5	30.0	29.7
LdC+G	4	33.8	25.4	30.1	15.9	32.6	37.1	37.3	29.0	27.6	23.4	23.1
NC	1	33.5	30.7	24.9	16.7	28.5	34.6	34.8	22.8	28.4	16.7	16.5
NC	2	36.8	33.2	33.2	27.0	38.1	42.4	42.6	32.9	35.7	12.0	11.8
NC	3	34.4	29.6	33.5	26.4	38.8	40.1	40.3	34.6	20.2	38.5	38.3
NC	4	31.0	23.7	24.1	15.8	26.4	35.8	36.0	26.5	23.4	14.9	14.6
GdC	1	33.8	29.9	22.8	16.5	29.2	35.7	35.9	25.8	30.4	32.1	31.9
GdC	2	34.6	28.1	36.1	22.2	27.5	38.0	38.2	27.2	31.4	18.4	18.2
GdC	3	37.7	32.8	33.6	21.6	33.4	38.0	38.2	31.4	31.5	37.8	37.6
GdC	4	31.0	29.7	33.3	28.4	33.8	37.1	37.3	32.8	33.8	29.7	29.5
GdC+G	1	33.3	30.6	25.9	15.7	26.7	38.0	38.2	25.3	35.4	18.6	18.4
GdC+G	2	34.1	30.9	30.7	26.0	38.5	42.0	42.2	37.4	38.9	23.5	23.2
GdC+G	3	36.6	22.8	33.9	25.7	36.5	39.2	39.4	38.6	36.2	26.8	26.5
GdC+G	4	33.2	23.7	26.6	19.7	29.8	36.9	37.1	29.3	28.3	17.6	17.3

A3.14. Soil moisture (cm^3 cm^{-3}) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	5/6/17	5/8/17	6/19/17	6/25/17	6/30/17	7/8/17	7/15/17	7/24/17	7/30/17	8/11/17	9/4/17
LdC	1	29.2	23.1	22.43	17.85	43.45	11.10	18.40	25.28	27.53	17.00	25.68
LdC	2	34.8	33.3	33.03	25.98	20.88	16.15	16.05	25.53	29.90	25.73	29.70
LdC	3	36.8	35.6	33.10	30.45	28.53	20.43	19.80	29.35	33.73	23.85	33.68
LdC	4	30.0	19.0	23.13	20.80	17.45	14.40	18.33	23.93	27.10	23.90	28.23
LdC+G	1	27.7	23.6	27.63	20.50	19.75	10.80	19.20	24.25	30.23	18.40	27.08
LdC+G	2	40.0	32.8	34.60	33.40	33.75	16.88	20.70	31.18	37.28	32.55	29.78
LdC+G	3	39.0	35.2	37.95	32.93	26.73	14.15	21.58	30.58	34.85	34.25	36.75
LdC+G	4	32.4	23.0	33.68	26.48	21.28	11.25	19.85	27.40	32.30	30.43	36.78
NC	1	29.4	22.4	25.30	17.25	17.13	9.53	19.73	23.18	25.95	27.90	29.45
NC	2	40.3	37.0	33.28	28.25	31.55	20.58	21.75	27.20	35.68	32.25	30.30
NC	3	42.7	37.4	35.80	31.05	27.90	16.80	23.20	36.10	36.48	34.13	37.85
NC	4	34.8	28.1	33.85	26.78	22.95	13.38	18.18	26.65	33.20	30.50	35.13
GdC	1	30.1	21.9	23.58	16.45	18.13	13.58	18.93	23.15	33.78	17.68	29.45
GdC	2	38.7	34.1	26.80	24.38	24.30	19.28	18.90	25.75	25.60	27.30	29.68
GdC	3	38.9	40.3	39.35	37.93	33.33	19.47	22.53	33.85	38.23	30.38	39.08
GdC	4	37.5	37.5	35.83	30.08	28.20	18.88	22.48	31.28	34.73	29.98	36.48
GdC+G	1	28.7	26.1	23.68	18.05	15.23	7.48	17.70	27.53	29.90	25.20	28.45
GdC+G	2	36.2	31.4	32.68	29.83	30.05	23.63	24.23	30.20	29.85	30.53	31.00
GdC+G	3	38.3	31.5	37.38	33.00	32.30	26.60	23.53	35.15	35.80	34.95	36.13
GdC+G	4	32.9	26.5	30.85	26.40	25.60	17.30	18.03	26.43	33.73	28.40	32.90

A3.14. Cont'd

TRT	REP	9/17/17	9/30/17	10/12/17	11/4/17	11/30/17	12/1/17	12/10/17
LdC	1	25.68	26.28	23.50	20.90	19.58	19.65	17.08
LdC	2	27.53	35.50	37.48	37.20	32.05	33.18	16.80
LdC	3	30.83	39.08	38.38	33.08	27.13	27.38	15.10
LdC	4	28.85	33.03	36.05	27.98	26.18	24.70	22.38
LdC+G	1	26.45	26.03	28.85	23.15	27.70	33.00	18.15
LdC+G	2	31.98	35.80	37.88	38.25	29.18	31.10	15.88
LdC+G	3	33.60	39.88	40.73	37.68	35.80	34.13	14.53
LdC+G	4	33.05	38.80	39.18	31.45	31.15	31.58	18.15
NC	1	29.60	27.58	24.65	20.65	25.25	26.43	13.98
NC	2	29.33	34.50	38.18	37.60	33.40	31.18	20.93
NC	3	34.05	38.38	39.63	34.70	34.20	34.03	19.18
NC	4	33.58	39.60	40.13	32.10	30.08	27.38	16.65
GdC	1	25.60	24.90	23.78	20.95	25.05	22.15	21.60
GdC	2	30.15	30.23	34.30	29.30	27.95	25.43	28.58
GdC	3	34.00	42.23	41.15	36.65	33.90	34.47	14.78
GdC	4	33.13	36.80	37.65	32.58	24.75	29.50	19.33
GdC+G	1	29.20	28.45	29.40	23.68	27.73	27.65	17.08
GdC+G	2	31.58	32.50	34.15	36.38	31.58	32.45	14.80
GdC+G	3	32.63	39.55	37.18	36.48	35.15	29.73	18.48
GdC+G	4	29.48	36.80	37.68	30.05	31.90	32.65	10.03

A3.15. Soil moisture (cm^3 cm^{-3}) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	8/2/17	8/18/17	8/24/17	9/02/17	9/07/17	9/10/17	9/21/17	9/29/17	10/8/17	10/17/17
LdC	1	21.2	33.0	22.3	32.0	18.9	18.5	28.7	32.8	35.8	29.2
LdC	2	17.7	31.2	20.1	30.0	12.7	18.7	27.9	29.4	31.0	27.5
LdC	3	24.4	33.6	23.9	33.3	22.4	18.5	29.2	34.9	37.6	33.4
LdC	4	23.6	38.7	29.4	37.6	30.1	26.1	32.6	40.0	40.8	35.7
LdC+G	1	18.9	32.1	20.7	29.2	16.6	18.2	26.1	30.0	35.9	34.7
LdC+G	2	17.5	30.1	19.2	30.3	16.7	18.3	26.6	26.6	32.3	25.7
LdC+G	3	16.5	27.9	17.6	28.4	17.8	15.0	27.7	29.2	32.9	29.2
LdC+G	4	15.6	27.4	18.9	32.4	16.7	16.8	29.1	36.9	41.1	34.8
NC	1	18.4	30.6	19.8	29.2	15.3	15.5	27.1	25.7	33.4	23.4
NC	2	18.1	31.4	20.1	32.7	19.5	20.6	28.7	26.0	35.6	28.5
NC	3	22.7	30.9	23.5	31.1	19.6	22.2	25.7	27.3	33.9	24.4
NC	4	23.4	35.9	24.9	35.7	26.1	22.6	30.5	39.1	41.6	33.6
GdC	1	17.8	33.6	20.0	30.9	16.7	15.9	30.7	28.3	33.6	28.8
GdC	2	17.6	28.8	19.6	31.0	16.2	20.2	29.0	28.7	32.0	25.1
GdC	3	15.4	31.1	19.4	29.8	18.7	18.1	27.9	33.4	35.1	30.9
GdC	4	25.0	31.8	22.4	32.9	19.1	21.2	29.1	32.6	37.4	35.5
GdC+G	1	13.7	30.2	19.2	27.8	13.7	16.0	27.9	31.0	35.9	31.9
GdC+G	2	16.8	31.4	18.8	31.2	16.4	17.6	29.1	29.6	34.6	30.1
GdC+G	3	20.8	28.5	23.1	30.4	19.6	19.6	28.5	30.6	37.0	32.5
GdC+G	4	20.6	31.8	24.3	33.4	19.9	19.4	32.6	35.4	39.7	35.4

A3.15. Cont'd

TRT	REP	11/21/17	11/22/17	11/23/17	11/24/17	11/25/17	11/26/17	11/27/17	11/28/17	11/29/17
LdC	1	15.0	10.1	11.5	19.8	21.1	24.7	26.1	25.2	20.3
LdC	2	12.5	4.9	7.2	17.2	18.0	27.9	21.6	19.3	15.3
LdC	3	16.6	10.1	11.9	20.9	20.1	29.6	28.4	28.0	20.2
LdC	4	15.1	12.5	14.5	26.0	23.5	33.7	32.0	30.7	25.4
LdC+G	1	13.5	12.0	11.2	19.7	19.7	28.1	27.1	26.7	21.8
LdC+G	2	15.9	6.1	9.1	17.5	17.2	28.0	27.4	23.3	15.0
LdC+G	3	13.0	7.5	11.3	21.8	14.5	22.7	23.8	22.2	17.7
LdC+G	4	14.8	13.8	14.6	26.3	18.6	32.0	29.9	25.3	24.0
NC	1	12.2	5.0	10.0	16.6	13.0	25.3	21.4	21.5	18.5
NC	2	15.9	7.6	12.4	19.4	19.7	27.5	29.7	24.9	17.5
NC	3	14.5	12.5	14.9	21.7	18.7	25.7	24.6	23.5	21.6
NC	4	13.2	10.6	14.7	23.6	21.3	32.6	31.0	28.2	23.0
GdC	1	10.9	7.9	9.2	17.7	18.9	23.1	22.3	21.5	20.3
GdC	2	16.4	7.0	8.5	17.8	18.1	22.4	24.9	25.1	16.5
GdC	3	13.4	11.0	13.3	23.0	15.9	28.1	26.0	27.6	19.0
GdC	4	19.2	11.1	12.6	20.4	21.3	27.4	29.3	25.4	21.5
GdC+G	1	14.4	11.6	10.7	21.9	19.6	24.6	26.3	24.0	21.3
GdC+G	2	16.7	9.3	14.8	18.9	22.2	29.6	26.2	23.7	20.5
GdC+G	3	15.6	10.8	14.9	22.9	20.9	25.9	29.1	29.1	22.1
GdC+G	4	17.3	15.8	15.8	24.8	21.9	31.9	30.2	31.3	22.9

A3.16. Soil moisture (cm^3 cm^{-3}) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	4/11/2018	4/30/18	5/1/2018	5/21/2018	5/29/2018	6/10/2018	7/2/2018	7/10/2018	7/31/2018
LdC	1	44.03	34.25	39.15	18.43	20.93	-	30.43	22.90	19.53
LdC	2	38.25	31.40	37.35	13.58	19.33	16.90	31.45	18.55	13.73
LdC	3	44.00	45.53	39.25	23.03	23.20	21.75	32.45	21.23	25.53
LdC	4	42.98	40.13	41.50	25.78	27.90	24.00	38.45	27.65	25.73
LdC+G	1	41.50	39.93	41.85	25.65	25.13	19.73	33.88	22.33	25.43
LdC+G	2	39.10	35.58	39.40	15.40	20.53	17.80	29.88	23.60	22.13
LdC+G	3	41.93	36.50	35.85	17.53	23.05	17.80	29.60	17.50	19.93
LdC+G	4	41.90	37.83	38.90	23.90	23.80	26.23	35.40	24.95	22.78
NC	1	41.80	35.28	34.50	14.40	14.10	15.35	30.88	19.93	21.28
NC	2	40.90	41.98	38.95	16.85	20.70	19.25	31.98	20.73	21.05
NC	3	41.40	35.95	36.70	17.93	20.98	21.90	22.30	21.73	22.13
NC	4	40.78	40.00	41.05	24.45	30.70	26.35	34.30	23.73	25.50
GdC	1	41.28	34.35	38.20	14.23	15.60	16.98	31.10	19.83	19.25
GdC	2	40.58	35.95	36.25	17.33	20.15	-	29.28	21.30	21.20
GdC	3	42.20	40.00	38.15	24.08	19.68	21.30	28.50	21.63	20.35
GdC	4	42.83	42.00	37.95	21.58	24.73	24.48	27.95	20.23	19.90
GdC+G	1	40.20	37.80	37.60	17.28	18.18	17.73	29.98	18.08	20.18
GdC+G	2	41.80	36.70	38.30	16.68	20.03	17.88	30.15	17.33	16.65
GdC+G	3	42.03	38.20	36.50	23.45	27.05	23.50	25.20	18.88	19.63
GdC+G	4	44.08	41.73	44.40	27.95	25.70	22.00	33.30	21.83	25.40

A3.16. Cont'd

TRT	REP	8/10/2018	8/17/2018	8/23/2018	8/30/2018	9/5/2018	9/13/2018	9/27/2018	10/7/2018	10/18/2018
LdC	1	29.05	31.65	27.40	29.78	32.38	28.23	36.43	33.53	33.55
LdC	2	25.03	30.25	25.85	25.23	28.80	19.88	25.48	24.90	22.00
LdC	3	31.18	36.70	29.80	31.35	33.33	28.35	37.65	33.83	36.95
LdC	4	32.20	36.95	29.33	34.90	36.30	31.20	42.60	32.48	42.85
LdC+G	1	25.53	35.40	28.15	28.05	32.13	28.00	36.30	31.10	35.90
LdC+G	2	25.20	32.10	25.38	26.90	32.80	25.00	34.38	29.53	31.10
LdC+G	3	22.10	33.73	26.03	25.80	29.65	22.43	29.58	27.05	30.10
LdC+G	4	24.88	36.33	27.65	29.83	34.40	27.55	39.05	32.10	37.80
NC	1	23.35	30.10	26.38	25.58	30.18	20.23	29.33	27.03	29.25
NC	2	25.50	32.93	25.85	29.43	30.85	22.50	32.90	31.08	34.55
NC	3	28.40	34.60	27.28	30.13	31.63	23.63	32.70	30.83	32.00
NC	4	29.80	38.33	30.70	34.50	35.40	29.55	41.85	34.48	40.05
GdC	1	23.85	29.20	22.25	25.28	28.85	17.85	27.05	26.08	27.60
GdC	2	26.65	28.43	28.08	29.25	32.08	25.13	33.05	30.08	30.15
GdC	3	25.65	36.10	29.03	30.48	31.45	25.73	36.03	32.08	30.45
GdC	4	27.70	31.23	28.75	28.15	33.53	24.43	34.73	27.58	33.00
GdC+G	1	23.53	28.75	23.30	27.30	28.58	20.23	30.08	28.43	31.10
GdC+G	2	22.23	28.10	25.83	28.10	30.50	22.60	28.28	26.38	25.55
GdC+G	3	23.58	32.58	27.88	29.10	32.93	24.30	29.55	27.73	28.35
GdC+G	4	26.65	36.38	30.08	29.98	35.10	27.15	36.20	30.90	34.55

A3.16. Cont'd

TRT	REP	10/30/2018	10/31/2018	11/1/2018	11/2/2018	11/20/2018
LdC	1	26.28	32.25	33.60	37.38	7.45
LdC	2	18.53	26.53	26.65	32.70	-
LdC	3	32.95	32.75	29.55	36.93	-
LdC	4	32.63	35.95	34.93	36.35	12.55
LdC+G	1	23.05	31.83	30.78	39.78	10.30
LdC+G	2	24.98	30.28	26.35	34.55	9.10
LdC+G	3	30.73	29.48	30.68	35.48	11.85
LdC+G	4	31.25	33.95	32.15	42.50	-
NC	1	24.53	29.53	28.75	31.25	15.45
NC	2	26.25	27.53	32.45	36.20	10.60
NC	3	29.10	27.20	28.75	35.23	13.10
NC	4	36.23	34.45	34.25	37.60	10.90
GdC	1	18.70	29.98	25.78	30.50	11.10
GdC	2	23.35	30.18	27.38	36.28	-
GdC	3	28.58	31.88	26.43	33.38	-
GdC	4	33.73	32.05	31.93	37.00	-
GdC+G	1	24.00	31.35	30.98	36.00	11.20
GdC+G	2	25.65	30.03	27.53	34.63	10.30
GdC+G	3	32.65	31.48	31.83	37.03	-
GdC+G	4	31.63	33.08	34.23	41.20	-

A3.17. Soil temperature (ºC) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2016 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	**REP**	**8/11/16**	**8/18/16**	**8/23/16**	**8/30/16**	**9/12/16**	**9/23/16**	**9/27/16**	**10/10/16**	**10/17/16**	**11/1/16**	**11/16/16**
LdC	1	22.0	24.4	22.5	25.9	18.4	17.8	16.8	16.3	16.6	12.4	10.4
LdC	2	23.3	24.2	23.0	25.1	17.9	17.9	16.9	14.7	14.7	17.7	15.7
LdC	3	25.2	25.1	22.9	26.8	18.1	18.5	17.5	16.0	16.3	11.4	9.4
LdC	4	27.0	28.4	22.8	25.2	18.2	19.8	18.8	15.0	15.8	9.8	7.8
LdC+G	1	22.6	24.2	22.9	24.6	17.9	17.7	16.7	15.6	14.5	14.2	12.2
LdC+G	2	23.1	24.1	25.4	24.1	18.1	17.6	16.6	15.7	15.5	16.5	14.5
LdC+G	3	26.3	25.2	23.1	26.7	18.1	18.8	17.8	15.0	15.3	13.9	11.9
LdC+G	4	27.6	24.8	23.4	24.4	17.9	19.1	18.1	15.2	15.6	11.5	9.5
NC	1	23.0	24.4	23.9	25.6	18.5	17.1	16.1	15.2	15.0	13.4	11.4
NC	2	24.1	30.3	25.9	27.6	18.5	18.3	17.3	17.3	17.0	12.5	10.5
NC	3	27.9	28.7	24.2	31.6	18.5	20.1	19.1	17.6	18.7	9.4	7.4
NC	4	30.4	26.1	28.7	26.3	18.3	19.6	18.6	15.8	17.5	11.4	9.4
GdC	1	23.0	25.2	24.2	25.0	18.5	17.5	16.5	15.4	16.0	15.8	13.8
GdC	2	23.1	24.4	26.3	27.1	18.4	18.4	17.4	15.2	15.9	11.9	9.9
GdC	3	28.5	25.4	22.3	27.0	18.1	19.2	18.2	16.1	16.3	11.3	9.3
GdC	4	26.4	24.2	21.7	23.0	18.1	19.2	18.2	14.3	14.9	10.3	8.3
GdC+G	1	22.8	25.3	24.6	25.5	18.3	17.6	16.6	15.3	15.7	13.3	11.3
GdC+G	2	23.7	24.5	25.3	25.4	18.3	18.2	17.2	15.0	15.6	12.3	10.3
GdC+G	3	26.0	25.5	25.6	25.6	18.3	18.9	17.9	14.8	15.8	12.5	10.5
GdC+G	4	27.5	24.3	23.0	24.1	18.3	19.4	18.4	15.2	17.4	10.2	8.2

A3.18. Soil temperature (ºC) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	5/6/17	5/8/17	6/19/17	6/25/17	6/30/17	7/8/17	7/15/17	7/24/17	7/30/17	8/11/17	9/4/17
LdC	1	17.7	23.7	19.4	19.9	20.3	23.0	22.8	20.8	21.2	17.9	17.6
LdC	2	17.6	21.3	21.1	21.1	21.4	24.2	24.6	20.8	21.8	19.0	17.5
LdC	3	21.3	23.2	20.7	19.8	22.0	25.2	26.0	21.5	22.3	18.7	17.6
LdC	4	25.1	26.2	23.7	22.2	23.4	26.1	26.5	22.7	22.6	19.3	17.7
LdC+G	1	14.2	19.6	18.9	19.5	20.9	23.3	24.9	20.4	21.1	17.5	17.5
LdC+G	2	16.3	20.0	21.1	19.7	21.3	22.6	23.2	20.0	21.1	18.7	17.5
LdC+G	3	20.1	22.0	22.0	20.2	22.0	24.7	26.0	21.1	21.9	18.8	18.0
LdC+G	4	22.0	24.1	22.9	21.8	22.8	25.5	26.4	22.0	21.9	19.4	17.9
NC	1	15.9	20.7	18.3	18.0	19.9	23.2	23.7	21.2	22.0	18.4	17.7
NC	2	16.5	19.8	20.8	19.5	20.5	25.3	24.0	20.5	21.7	20.0	17.6
NC	3	20.4	22.3	22.4	23.0	24.4	25.8	25.1	21.4	22.8	20.1	17.9
NC	4	19.2	21.1	22.6	20.1	21.9	25.2	27.3	22.4	22.3	19.7	17.5
GdC	1	18.1	20.8	19.9	20.0	20.3	22.9	23.7	21.0	21.6	18.7	17.4
GdC	2	16.7	19.5	19.8	18.3	20.2	23.1	24.1	20.5	21.9	18.5	17.4
GdC	3	18.8	21.7	22.2	19.4	21.5	23.2	25.8	20.5	21.5	18.8	17.7
GdC	4	21.2	22.5	21.8	21.3	22.1	24.3	26.0	22.2	22.4	19.6	17.8
GdC+G	1	17.7	20.8	19.1	18.7	20.5	23.3	25.0	20.5	21.3	17.9	17.4
GdC+G	2	17.2	20.7	22.4	20.8	22.4	24.3	25.2	20.6	21.9	19.6	17.4
GdC+G	3	20.2	22.0	23.2	21.1	23.0	25.4	25.4	21.4	22.3	18.4	17.5
GdC+G	4	23.0	23.4	22.1	22.1	22.7	26.5	27.1	22.7	22.6	19.8	17.7

A3.18. Cont'd

TRT	REP	9/17/17	9/30/17	10/12/17	11/4/17	11/30/17	12/1/17	12/10/17
LdC	1	12.9	12.5	10.8	3.0	2.6	3.1	2.2
LdC	2	12.7	12.5	11.9	2.7	2.3	3.5	4.2
LdC	3	13.2	13.2	12.9	3.2	2.3	4.1	0.1
LdC	4	13.0	13.0	13.4	3.2	2.9	1.9	1.5
LdC+G	1	12.9	12.5	10.6	3.0	2.0	2.6	4.9
LdC+G	2	12.5	12.5	13.4	3.2	1.6	4.6	4.8
LdC+G	3	13.3	13.2	13.6	2.9	2.2	4.3	0.2
LdC+G	4	13.1	12.9	13.2	3.1	2.3	2.0	2.3
NC	1	13.0	12.6	11.5	3.3	2.5	4.8	3.9
NC	2	12.4	12.4	12.7	3.2	2.1	4.3	4.6
NC	3	12.9	13.1	13.1	2.8	2.3	2.0	2.6
NC	4	13.1	14.2	12.9	3.0	2.5	3.6	0.7
GdC	1	13.1	12.6	10.8	3.1	2.6	3.8	4.4
GdC	2	12.9	12.7	12.0	3.4	2.6	6.1	3.7
GdC	3	12.2	13.2	15.1	2.6	2.3	3.2	0.1
GdC	4	12.8	12.8	13.1	3.2	2.6	6.9	0.3
GdC+G	1	15.0	12.3	10.2	3.1	2.2	4.0	4.0
GdC+G	2	13.3	12.3	13.3	2.8	1.5	3.3	5.5
GdC+G	3	12.6	12.9	13.1	3.0	2.2	5.1	0.1
GdC+G	4	12.9	13.0	13.2	3.3	2.6	5.6	0.4

A3.19. Soil temperature (ºC) as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2017 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	8/2/17	8/18/17	8/24/17	9/02/17	9/07/17	9/10/17	9/21/17	9/29/17	10/8/17	10/17/17
LdC	1	25.8	24.7	21.4	21.2	17.3	17.2	16.4	10.0	11.7	10.7
LdC	2	26.3	24.4	19.3	20.4	15.3	17.1	16.2	10.4	11.2	9.8
LdC	3	28.2	25.6	21.5	21.9	18.7	18.0	18.5	12.5	12.4	12.7
LdC	4	28.9	25.5	21.8	22.4	21.1	17.9	19.4	11.8	12.8	12.9
LdC+G	1	24.8	24.6	19.8	20.4	17.0	17.3	16.0	10.5	11.4	10.6
LdC+G	2	26.7	24.6	20.3	20.6	16.0	17.1	16.6	10.4	11.2	8.2
LdC+G	3	28.2	25.1	22.0	22.0	19.7	17.6	18.1	11.9	11.4	11.5
LdC+G	4	29.1	25.7	21.4	22.6	18.7	17.8	17.7	12.2	11.9	12.0
NC	1	24.7	25.4	21.1	21.5	17.6	18.3	17.4	9.5	11.4	11.5
NC	2	26.2	24.7	21.2	22.4	20.7	18.1	16.9	10.0	11.4	12.9
NC	3	27.6	26.1	23.6	27.3	26.4	19.1	20.7	12.2	12.8	16.2
NC	4	29.4	25.7	23.1	24.6	23.7	19.4	20.4	12.3	12.6	14.7
GdC	1	24.7	24.8	20.6	20.6	16.2	17.3	16.1	10.3	11.3	10.0
GdC	2	27.1	24.5	21.9	20.5	17.1	17.6	16.2	10.2	11.2	11.0
GdC	3	27.9	25.4	21.1	22.2	19.9	17.8	17.6	12.4	11.6	11.0
GdC	4	28.9	25.0	22.1	22.2	18.6	17.7	18.2	11.9	12.1	12.7
GdC+G	1	25.1	25.1	20.4	20.5	16.4	17.4	16.4	10.9	11.3	10.1
GdC+G	2	26.3	24.7	20.6	20.5	16.8	17.1	15.9	10.4	11.2	10.0
GdC+G	3	27.6	26.1	22.5	23.7	22.2	18.1	18.5	11.4	11.4	12.2
GdC+G	4	28.7	26.1	21.9	20.9	19.1	17.5	17.5	11.6	11.8	10.4

A3.19. Cont'd

TRT	REP	11/21/17	11/22/17	11/23/17	11/24/17	11/25/17	11/26/17	11/27/17	11/28/17	11/29/17
LdC	1	1.1	-1.9	-1.0	-0.4	1.2	0.6	2.0	3.3	1.7
LdC	2	1.0	-2.5	-1.2	-0.5	1.2	0.6	2.2	3.6	1.7
LdC	3	1.1	-1.1	-0.7	-0.2	1.2	1.2	2.1	3.4	1.4
LdC	4	1.2	-1.2	-0.7	-0.3	1.1	1.7	2.4	3.7	1.7
LdC+G	1	0.8	-1.7	-1.2	-0.4	1.1	0.7	2.2	3.5	1.6
LdC+G	2	0.8	-2.2	-1.2	-0.3	1.1	0.6	2.2	3.4	1.5
LdC+G	3	1.2	-1.0	-0.8	-0.1	1.0	1.8	2.2	3.7	1.4
LdC+G	4	1.2	-1.5	-0.7	-0.2	1.0	1.7	2.2	3.6	1.7
NC	1	1.0	-1.9	-1.1	-0.4	1.0	0.6	2.0	3.3	1.6
NC	2	1.0	-2.0	-1.2	-0.3	1.1	0.6	2.1	3.3	1.5
NC	3	1.1	-1.3	-0.6	0.5	1.3	1.9	2.6	3.7	1.5
NC	4	1.2	-1.6	-0.8	0.6	0.8	1.4	2.4	3.6	1.4
GdC	1	1.1	-2.0	-0.8	-0.4	1.2	1.6	2.3	3.7	1.6
GdC	2	0.9	-1.9	-0.9	-0.4	1.0	0.9	2.1	3.3	1.6
GdC	3	1.1	-1.1	-0.7	-0.4	1.1	2.1	2.2	3.5	1.5
GdC	4	1.1	-1.2	-0.5	-0.3	1.3	1.2	2.2	3.7	1.7
GdC+G	1	1.0	-1.6	-0.5	-0.3	1.1	1.0	2.2	3.6	1.7
GdC+G	2	1.1	-1.9	-0.8	-0.3	1.4	0.9	2.2	3.7	1.5
GdC+G	3	1.1	-1.2	-0.7	0.0	1.3	2.7	2.5	3.7	1.6
GdC+G	4	1.2	-1.4	-0.8	-0.4	1.0	0.7	2.2	3.5	1.7

A3.20. Soil temperature (ºC) fluxes as influenced by cover crops and grazing of cover crops and maize residue under an integrated crop–livestock system at the northwestern Brookings site in 2018 and used in Chapter 5. Note: TRT, Treatment; REP, Replication; GdC, grass-dominated cover-crop blend; GdC+G, grazing of grass-dominated cover-crop blend; LdC, legume-dominated cover-crop blend; LdC+G, grazing of legume-dominated cover-crop blend; NC, no cover crop

TRT	REP	4/11/2018	4/30/18	5/1/2018	5/21/2018	5/29/2018	6/10/2018	7/2/2018	7/10/2018	7/31/2018
LdC	1	0.23	8.85	13.40	16.03	21.90		19.65	22.38	18.40
LdC	2	0.35	9.88	13.55	16.03	21.88	21.98	19.35	21.90	18.25
LdC	3	0.18	10.68	12.38	15.65	22.28	22.73	20.23	20.55	19.18
LdC	4	0.85	11.10	12.85	16.15	21.93	22.25	20.13	22.08	19.75
LdC+G	1	0.35	8.90	14.10	16.50	22.48	21.58	19.35	21.88	18.05
LdC+G	2	0.48	9.55	13.93	16.25	22.28	21.75	19.35	21.78	18.33
LdC+G	3	0.23	11.18	13.35	15.93	22.30	22.93	20.53	22.00	19.63
LdC+G	4	0.33	9.90	11.63	15.65	21.85	23.08	20.65	22.55	20.13
NC	1	0.58	9.23	15.18	16.68	22.28	21.35	19.33	21.75	18.05
NC	2	0.40	9.13	13.78	15.98	21.70	21.35	19.55	21.85	18.53
NC	3	0.43	10.90	13.40	15.78	22.23	22.85	20.23	22.05	19.78
NC	4	0.65	10.88	12.95	16.28	22.33	23.30	20.98	22.73	19.93
GdC	1	0.33	8.78	13.18	16.55	21.65	21.45	19.30	22.15	18.60
GdC	2	0.28	8.40	13.20	15.80	21.65		19.63	22.13	18.38
GdC	3	0.35	10.83	13.08	16.68	22.60	23.55	20.20	21.98	19.33
GdC	4	0.35	10.35	12.60	15.83	21.95	22.68	20.55	22.28	20.35
GdC+G	1	0.35	8.65	12.30	16.25	21.80	21.28	19.45	21.93	17.95
GdC+G	2	0.30	8.88	12.78	15.65	21.53	21.38	19.43	22.23	18.40
GdC+G	3	0.20	10.83	12.03	15.70	21.70	22.50	20.33	22.08	19.63
GdC+G	4	0.28	9.00	10.65	15.80	21.93	22.45	20.58	22.10	19.93

A3.20. Cont'd

TRT	REP	8/10/2018	8/17/2018	8/23/2018	8/30/2018	9/5/2018	9/13/2018	9/27/2018	10/7/2018	10/18/2018
LdC	1	24.60	25.53	20.30	19.90	21.78	21.43	14.55	9.00	11.50
LdC	2	24.03	24.43	20.18	20.00	20.73	21.43	14.53	9.00	11.10
LdC	3	23.75	23.75	19.75	20.10	21.00	21.40	14.20	9.13	10.35
LdC	4	24.58	24.43	20.00	20.73	21.78	21.70	14.13	9.10	10.80
LdC+G	1	23.55	23.40	19.95	19.98	20.90	20.88	14.35	8.65	10.15
LdC+G	2	23.50	23.15	20.20	19.93	21.40	21.13	14.28	8.93	11.00
LdC+G	3	24.10	24.30	19.78	19.88	20.78	21.63	14.45	8.75	10.45
LdC+G	4	24.58	23.75	19.68	20.10	20.95	21.65	14.25	8.85	10.00
NC	1	23.90	24.70	20.15	19.43	20.95	21.53	14.10	8.70	10.15
NC	2	23.45	24.03	20.10	19.53	20.73	21.58	14.33	8.90	10.20
NC	3	24.45	24.63	19.80	20.00	21.20	21.58	14.53	9.00	10.45
NC	4	25.80	24.18	20.30	20.33	21.13	21.60	14.58	9.08	10.80
GdC	1	23.73	24.38	20.43	19.90	21.10	21.53	14.48	8.88	10.80
GdC	2	24.03	24.18	20.18	20.10	20.98	21.30	14.13	9.13	10.45
GdC	3	24.53	23.50	19.65	19.70	20.95	21.35	14.38	9.03	10.75
GdC	4	23.85	24.30	19.75	20.03	20.85	21.40	14.53	8.98	11.10
GdC+G	1	23.70	23.88	19.90	19.55	20.83	21.45	14.43	8.70	10.45
GdC+G	2	23.30	23.70	19.98	19.90	20.90	21.90	14.18	8.83	10.80
GdC+G	3	24.10	24.40	20.15	20.50	20.88	21.88	14.35	9.10	10.40
GdC+G	4	24.28	24.05	19.75	19.95	20.70	21.75	14.18	8.85	9.95

A3.20. Cont'd

TRT	REP	10/30/2018	10/31/2018	11/1/2018	11/2/2018	11/20/2018	11/26/18	11/27/18
LdC	1	9.15	6.60	3.88	6.93	0.00	-1.45	-1.85
LdC	2	9.00	7.03	5.00	7.08	0.20	-2.20	-1.75
LdC	3	8.60	8.53	4.80	6.98	0.55	-2.10	-1.50
LdC	4	8.48	7.80	4.73	6.95	-0.05	-3.25	-1.75
LdC+G	1	9.15	6.45	3.98	6.65	0.15	-2.15	-2.50
LdC+G	2	9.23	6.68	3.98	6.78	0.10	-2.95	-2.40
LdC+G	3	8.83	7.68	4.90	6.98	0.05	-3.15	-1.90
LdC+G	4	9.05	7.75	4.48	6.95	0.05	-4.05	-2.40
NC	1	9.15	5.93	3.85	6.75	0.15	-1.65	-2.35
NC	2	9.15	6.78	4.10	6.93	0.20	-1.50	-2.00
NC	3	8.83	7.68	5.03	7.03	0.15	-1.75	-1.30
NC	4	8.63	7.63	4.75	6.90	0.20	-2.85	-1.55
GdC	1	9.05	6.30	3.55	6.70	-1.10	-1.35	-2.70
GdC	2	9.08	6.28	4.58	6.90	-0.15	-2.00	-1.90
GdC	3	8.85	8.03	4.88	7.10	0.35	-1.60	-1.45
GdC	4	8.85	7.95	4.90	7.13	0.10	-2.15	-1.50
GdC+G	1	8.65	6.23	4.30	6.78	-0.35	-2.25	-2.25
GdC+G	2	9.43	6.93	4.53	6.83	-0.30	-2.85	-2.55
GdC+G	3	9.03	7.70	5.03	7.08	0.00	-3.75	-2.15
GdC+G	4	8.98	7.73	4.58	6.93	0.00	-3.10	-2.10

APPENDIX 4

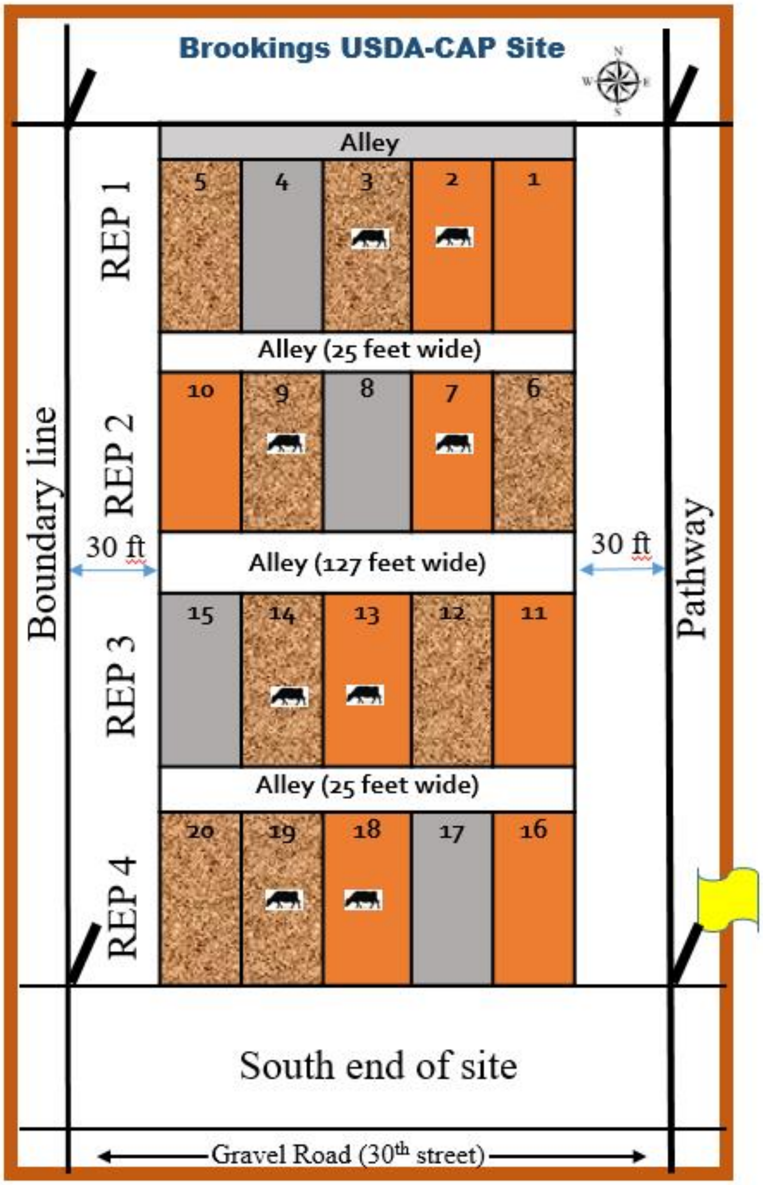
A4.1. Taking core samples from field to analyze soil physical and hydrological properties.

A4.2. Preparing plexiglass cores for computed tomography scanning.

A4.3. Cattle grazing at Northern Brookings site.

A4.4. Taking gas samples from field to analyze CO_2, N_2O and CH_4 emissions.

A4.5. Soil moisture, tension and temperature sensors installed at different depths in the field.



A4.6. Plot layout of the study site.

	NC, Control
	LdC, Legume dominated cover crop
	LdC+G, Grazing of LdC
	GdC, Grass dominated cover crop
	GdC+G, Grazing of GdC

VITA

Navdeep Singh was born at Balachaur, Punjab (India) to Mr. Harbux Singh and Late Mrs. Tejinder Kaur. He received his B.S. (Agriculture) in 2013 and M.S. (Soil Science) in 2016 from Punjab Agricultural University, Punjab, India. For his Ph.D., he joined South Dakota State University-Brookings, SD in 2017 and received the doctorate degree in Soil Physics in 2020 under the supervision of Dr. Sandeep Kumar. He has accepted a Post-Doctoral Researcher position offered by Dr. Gabriel LaHue from Washington State University, Mount Vernon, WA where he will be moving after his graduation.