INFLUENCE OF COVER CROP AND TILLAGE MANAGEMENT PRACTICES ON SOIL PHYSICAL AND HYDRAULIC PROPERTIES

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by

SAMUEL IDOKO HARUNA

Dr. Stephen H. Anderson

Dissertation supervisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the dissertation entitled,

INFLUENCE OF COVER CROP AND TILLAGE MANAGEMENT PRACTICES ON SOIL PHYSICAL AND HYDRAULIC PROPERTIES

Presented by

SAMUEL IDOKO HARUNA

a candidate for the degree of

DOCTOR OF PHILOSOPHY

and hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Stephen H. Anderson, Professor (Chair)

Dr. Nsalambi V. Nkongolo, Adjunct Professor

Dr. Ranjith P. Udawatta, Associate Professor

Dr. Frieda Eivazi, Adjunct Associate Professor

Dr. Allen L. Thompson, Professor

Unto the king eternal, immortal, invisible, the only wise God, be honor and glory forever and ever. Amen. (1 Timothy 1:17)

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Dr. S. H. Anderson, Dissertation Supervisor

ABSTRACT

Several agricultural land management practices, such as cover crops and tillage, can influence soil physical and hydraulic properties, soil health indicators and crop productivity. This study evaluated the influence of cover crops, tillage and perennial biofuel crops on soil physical and hydraulic properties. The objectives of this study included: (i) evaluate hydraulic properties for soils managed by cover crops and tillage, (ii) assess the influence of cover crops and tillage management on *in situ* water infiltration parameters, and (iii) evaluate thermal conductivity (λ), volumetric heat capacity (C_V) and thermal diffusivity (D) for soils managed by perennial biofuel and cover crops. Two field sites were used for the study; the first and second objectives were conducted at Lincoln University's Freeman Research Center while the third objective was conducted at University of Missouri Bradford Research Center. The cover crop grown at Freeman Research Center was Cereal rye (*Secale cereal* L.), while Cereal rye, Hairy vetch (*Vicia villosa subsp. villosa*) and Austrian winter pea (*Pisum sativum subsp. arvense*) were grown at Bradford Research Center. The perennial biofuel crops at Bradford Research Center included giant miscanthus (*Miscanthus x gigantus* J.M. Geef & Deuter ex Hodkinson & Renvoize) and switchgrass (*Panicum vergatum* L.). The tillage treatments at Freeman

Research Center included tillage using a moldboard plow to a depth of 15 cm and no-till. The soil at Bradford Research Center was managed with no-till. Intact soil samples (76 by 76 mm) were collected for objectives one and three with samples taken in 2014 and 2015, respectively. Infiltrometers were used to measure infiltration rates for objective two during 2014 and 2015. The physically-based Parlange and Green-Ampt infiltration models were fit to estimate saturated hydraulic conductivity (K_S) and sorptivity (S) parameters. Results showed that bulk density values for tillage were 13% lower compared with no-till management right after tillage. At the 0-10 cm soil depth, water content was significantly higher at the 0.0 and -0.4 kPa pressures for tillage compared with no-till management, right after spring tillage. However, this effect did not persist over time probably due to soil consolidation after some rainfall events. Tillage improved coarse mesopores by 32% compared with no-till; and this effect resulted in 87% higher saturated hydraulic conductivity values in tillage compared with no-till management, right after spring tillage. Cover crops improved macropores by 24% compared with no cover crop; this can potentially increase water infiltration and reduce runoff. As a result of higher macroporosity, saturated hydraulic conductivity was higher in the cover crop compared with no cover crop management. This study demonstrated that the effects of tillage in improving some soil hydraulic properties may not persist over time. The Parlange and Green-Ampt model appeared to fit measured infiltration data well with coefficient of variation (r^2) ranging from 0.92 to 0.99. The K_S parameter value estimated from the Parlange and Green-Ampt models in 2014 were 42% and 54% higher in no-till compared with tillage management, respectively. In 2015, the S parameter values estimated from the Parlange and Green-Ampt models were 82% and 90% higher in cover crop management compared to no cover crop management, respectively. This study showed that cover crops can improve water infiltration and may reduce water and nutrient runoff which can lead to enhanced agricultural productivity. Results of the third objective showed that perennial biofuel crops (giant miscanthus and switchgrass) had 11% higher C_V at saturation compared to row crops (cover crops and no cover crops). Cover crops compared to no cover crop had 18% higher volumetric water content at saturation and 26% higher soil organic carbon; this led to 13% higher C_V compared to no cover crops. Row crops had significantly higher λ and D compared to perennial biofuel crops. This study showed that perennial biofuel and cover crops can change soil thermal properties by reducing λ and D and increasing C_V; this indicates that these management systems can improve the ability of the soil to buffer against rapid heat change and better handle a more variable climate. Results from these studies showed that tillage may influence some soil properties temporarily; however, these influences may diminish over time. Cover crops can improve soil physical and hydraulic properties and soil health indicators and this can lead to improved productivity. However, longer-term studies are needed to evaluate these effects over time, especially with an increasingly changing climate.

CHAPTER 1

INTRODUCTION

Soils are one of humankind's most important assets. Soils are mainly used for food and fiber production as well as biofuel production. It is therefore important that the soil be preserved from erosion and the quality of soil be maintained in order to produce optimal benefits. The physical and hydraulic properties of the soil have long been used as indicators of soil quality, especially with regards to water and nutrient holding capacity. For example, water and nutrient holding capacity of the soil can be estimated by measuring soil physical properties such as soil water characteristics, pore size distributions, soil structure and texture (Jabro et al., 2009, Raczkowski et al., 2012).

Soil quality can be affected by natural causes such as erosion, which can wash away soil materials. The management activities in agriculture (e.g perennial biofuel and cover crops, tillage, etc.) also have a profound effect on soil quality (Hamza et al., 2005). Tillage has been used in agriculture to prepare the seedbed; to incorporate fertilizers, manures, and residues into the soil; to relieve compaction; and to control weeds (Conant et al., 2006; Bhattacharyya et al., 2012). However, tilling the soil is disruptive and can promote soil structure degradation, dissipation of organic carbon as well as soil water and nutrient losses.

Conventional tillage is often classified into two types; primary and secondary. There is no strict boundary between them except for a loose distinction between tillage that is deep and more thorough (primary) and tillage that is shallower and more selective of location (secondary) (Flowers and Lal, 1998). Primary tillage, such as plowing, tends to produce a rough surface finish, whereas secondary tillage tends to produce a smoother surface finish, such as that required to make a good seedbed for many crops (Flowers and Lal, 1998; Reicosky, 2002).

Conventional tillage can temporarily alleviate soil compaction, increase availability of SOM and improve the soil temperature and moisture environment for seed germination in early spring (Stone et al., 1990; Doumbia et al., 2009; He et al., 2010). However, these benefits may be reversed over time. Conversely, no-till have been reported to help maintain SOM and aggregate stability (Rhoton, 2000), conserve soil moisture, maintain constant soil temperatures (Benegas et al., 1998) and improve water infiltration rates (Bhattacharyya et al., 2008). No-till also leads to better soil structure and an extensive system of macropores (Martino and Shaykewich, 1994), which benefits root growth (Lampurlanes et al., 2001).

Cropping systems include a community of plants that are managed by a farm unit to achieve various goals. These describe how a producer might grow crops. Cropping systems (which include cover cropping, crop rotation, and mixed cropping) may improve or decrease soil quality depending on the specific crop rotation, nutrient amendments and tillage practices employed (Sharma et al., 2009; Raczkowski et al., 2012). Concerns over global fossil fuel consumption and the possibility of increased global climate change has led to the inclusion of perennial warm season crops such giant miscanthus (*Miscanthus x gigantus* J.M. Geef & Deuter ex Hodkinson & Renvoize) and switchgrass (*Panicum vergatum* L.) into cropping systems on the landscape as a means of alternative energy production (Gressel, 2008). Advantages of these perennial energy crops over annual energy crops such as cereals, sugar beet (*Beta vulgaris subsp. vulgaris convar. vulgaris var.*

altissima) and rapeseed (*Brassica napus* L.) are the relatively high net fossil energy and greenhouse gas emission savings per unit of biomass and per unit of agricultural land (Boehmel et al., 2007). Besides their high energy output, these crops can also improve soil quality by increasing porosity, reducing bulk density, improving soil aggregation and increasing infiltration (Tufekcioglu et al., 1998; Ma et al., 2000; Mann et al., 2012).

Conventional crop production methods developed in the last few decades have been linked to negative effects on the environment, human health and safety, and long term soil fertility. Nitrate leaching and groundwater pollution, degradation of soil structure, and decreased surface infiltration of water are some of the common problems associated with conventional cropping systems (Sharma et al., 2009). However, the inclusion of cover crops into crop production cycles can ameliorate some of these problems and help improve soil quality (Dabney, 2001).

Cover crops provide soil conservation benefits by producing protective vegetative cover between the harvest of a previous year's crop, and the growing of a following year's crop. Cover crops have benefits of fixing atmospheric nitrogen, sequestering carbon into the soil, suppressing weeds and taking up excess soil nitrogen, thus reducing nitrogen loss (Moller et al., 2008).

The leaves of cover crops can also intercept rainfall and reduce splash detachment. It has been estimated (USDA-ARS Agriculture Handbook, 1997) that cotton (*Gossipium hirsutum* L.) and sunflower (*Helianthus annuus* L.) residue weighing 1,012 kg ha^{-1} at harvest provides about 40% surface cover, while corn (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) weighing the same at harvest provides about 59% surface cover. However, cover crops like alfalfa (*Medicago sativa* L.) and rye (*Secale cereal* L.), with the same residue weight at harvest, provide about 76% surface cover. Haramoto and Gallandt, (2004) reported that Brassicas (*Brassica juncea L*.) can provide more than 80% soil coverage when used as a winter cover crop. Cover crops have also been reported to increase soil organic matter by between 7-12% compared to no cover crop management (Kuo et al., 1997; Sainju et al., 2002; Villamil et al., 2006) and this can lead to improved soil aggregate formation and increased water infiltration (Folorunso et al., 1992; Joyce et al., 2002). This better soil cover and aggregation can be the difference in agricultural sustainability after a few decades.

Although several studies have evaluated the effects of tillage on soil physical properties and the effects of cover crops on these properties, few studies have evaluated their combined effects. In addition, no studies evaluated the effects of cover crops on soil thermal properties, an important group of physical properties. Therefore, this study evaluated how cover crop and tillage management practices influences soil physical and hydraulic properties.

Objectives

The objectives of this study were evaluated in three sub-studies as outlined below. Specific objectives were developed for each study.

Study 1. Study was entitled "soil hydraulic properties: influence of tillage and cover crops" with the specific objective of assessing the influence of cover crops and tillage management on soil hydraulic properties including; bulk density, water retention, pore size distributions and saturated hydraulic conductivity.

Study 2. This study was referred to as "in situ infiltration as influenced by cover crop and tillage management" with the specific objective of evaluating the influence of cover crop and tillage management on water infiltration parameters (sorptivity, saturated hydraulic conductivity, quasi-steady infiltration rate and field saturated hydraulic conductivity).

Study 3. This study was entitled "soil thermal properties influenced by perennial biofuel and cover crop management" with the specific objective of evaluating the effects of perennial biofuel and cover crops on volumetric water content, soil organic carbon, thermal conductivity, volumetric heat capacity and thermal diffusivity.

All three studies were written independently in the format of journal manuscripts for publication purposes. Study 1 has been accepted by *Pedosphere* for publication. Study 2 has been accepted for publication by *Journal of Soil and Water Conservation*. Study 3 has been accepted for publication by *Soil Science Society of America Journal*.

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CHAPTER 2

LITERATURE REVIEW

Agriculture provides food, fiber, and fuel for man and animals. As the world's population has and continues to increase, it has become very imperative to increase production to meet these demands. In order to do this, proper agricultural land management practices should be in place. These practices must, among other things, improve soil quality, improve crop yield, and reduce the environmental impact of agricultural practices. For many decades, tillage and various cropping systems, such as cover cropping, have been used as a means of improving soil quality and crop yield (Pieters, 1927; Periera, 1975). However, recent studies, in the past few decades, suggest that tillage practices may be more harmful to the soil than initially thought (Balesdent et al., 1990; Lal, 1997; Franzleubber et al., 2004; Alvarez and Steinbach, 2009; Zhang et al., 2012). Long-term tillage practices have been linked to reduction in crop yield and soil quality, as well as increasing the susceptibility of farmland to environmental impacts such as erosion (Mahli et al., 2006). Cropping systems may affect soil quality depending on the specific crop rotation practice employed. This chapter describes and reviews previous results on the influence of cover crops and tillage management practices on soil physical and hydraulic properties.

TILLAGE AND COVER CROPS

Tillage

Tillage is the agricultural preparation of the soil by mechanical agitation of various types such as digging, stirring and overturning. Throughout the history of human civilization, soil tillage has been integral to crop production. Tillage was initially practiced as a means of relieving soil compaction, enhancing seedbed preparation, improving soil aeration, homogenizing topsoil and mixing organic matter (Periera, 1975). With recent research, however, it has been discovered that long-term tillage practices may reduce soil quality by destroying soil structure (Franzeleubbers et al., 2004; Alvarez and Steinbach, 2009). Some tillage practices include conservation tillage, intensive tillage, ridge tillage, alternate tillage, and no-till.

Conservation tillage systems are methods of tillage which leave a minimum of 30% of crop residues on the soil surface or at least 1,100 kg ha^{-1} of small grain residues on the surface during the critical soil erosion period (Angers et al., 2009). This reduces the kinetic energy of raindrops, and may lead to reduced soil and nutrient loss. Conservation tillage systems also benefit farmers by reducing fuel consumption and soil compaction. This was used on about 38%, the equivalent of 440,000 km^2, of all US cropland, planted as of 2007 according to the United States Department of Agriculture (USDA) (Chatskikh et al., 2009). Conservation tillage reduces some of the negative impacts of tillage, preserves soil resources and can lead to accrual of much of the soil carbon lost during conventional tillage (Conant et al., 2006; Bollero et al., 2006; Chatskikh et al., 2009).

Intensive tillage systems leave less than 15% crop residue cover or less than 560 kg ha^{-1} of small grain residue (Angers et al., 2009). This type of tillage system is often referred to as conventional tillage; however, as reduced and conservation tillage systems have been more widely adopted, it is often not as appropriate to refer to this type of system as conventional (Angers et al., 2009). This tillage system (intensive tillage) often involves multiple operations with implements such as a moldboard plow, disk, and/or chisel plow. Then a finishing operation with a harrow, rolling basket, and cutter can be used to prepare the seedbed. Moldboard plowing involves the inversion of soil with implements attached to animals or tractors for tilling the ground. A chisel plow uses metal shanks, for tilling and loosening the soil (Jokela et al., 2011).

Ridge-till, a tillage system involving scalping and planting on ridges built during cultivation of the previous year's crop, usually involves spring-planted row crops grown with a combination of herbicides and at least one cultivation (Conant et al., 2007). Intensive land cultivation has often caused soil degradation, for whole regions in some cases; and has decreased the quality of groundwater and surface water; and contributed to air pollution, including emissions of greenhouse gases (Chatskikh et al., 2009).

Long-term tillage practices can lead to a decline in soil quality. It has been reported that following long-term tillage, soil carbon stocks can be reduced by as much as 20%-50% (Simon et al., 2009; Christopher et al., 2009; Ochsner et al., 2011). The type and frequency of tillage and associated residue management in a cropping system can affect the accumulation of soil organic matter and other factors related to soil quality (Hamza et al., 2005).

No-till systems are generally recommended as effective management systems for maintaining and even improving soil productivity and quality (Raper and Bergtold, 2007; Shi et al., 2012). Reduced mechanical disturbance associated with no-till often leads to improved soil structure, as indicated by more macro-aggregation, and more total and mineralizable carbon, but these effects tend to be limited to the top soil (Jokela et al., 2011). No-till systems also have the advantage of reducing soil erosion and surface runoff (Nyakatawa et al., 2000; Zhang et al., 2009), decreasing time and cost (fuel and labor) requirements for land preparation (Raper and Bergtold, 2007; McLaughlin et al., 2008), and slowing soil organic matter loss (Koch and Stockfisch, 2006).

Cropping Systems

A cropping system is an integration of various agricultural practices including shifting cultivation, crop rotations, cover cropping, mixed farming, etc. Midwestern United States cropping systems include a variety of crops and crop rotations; continuous corn (*Zea mays*), short rotations of corn with soybean (*Glycine max*) or other annual grains, or longer rotations that include multiple years of perennial forages/bio-energy crops (Jokela et al., 2011). The aim of the various cropping systems in agriculture is to optimize economic returns and possibly enhance soil quality.

The implementation of different cropping systems in agriculture has been around since planting and harvesting itself. Much attention was not given to cropping systems until the early 1900's, when there was a need to increase food production and maximize land use (Sharma et al., 2009). In the past few decades, a move towards sustainability in agriculture has also developed, integrating ideas of socio-economic justice and conservation of resources and the environment within a farming system. This has led to the development of many responses to the conventional agriculture approach, including organic agriculture, urban agriculture, community supported agriculture, ecological or biological agriculture, integrated farming and holistic management, as well as an increased trends toward agricultural diversification (Umiker et al., 2008).

Cropping systems have the potential to provide several benefits to farmers and have been studied both in the context of forage production for cattle and bioenergy feed stock production (Ochsner et al., 2011). Experiments have shown that a double-cropping system can result in 6-10% increase in total biomass production relative to corn silage alone (Jokela et al., 2011; Ochsner et al., 2011).

Perennial biofuel crops like switchgrass and miscanthus, due to their year-round surface cover, may protect soil from erosion, improve soil properties, soil productivity, and wildlife habitat and diversity (Blanco-Canqui, 2010). Roots and earthworm burrows under perennial biofuel crops can penetrate compacted soil layers and change the pore structure, increasing water infiltration and storage at lower depths (Katsvairo et al., 2007). Bharati et al. (2002) reported that cumulative water infiltration after 1 hr was five times greater in switchgrass than in row crops and pasture after 6 yrs of management. Perennial biofuel crops can also influence soil water retention and unsaturated water flow. Rachman et al. (2004) reported that saturated hydraulic conductivity and volumetric water content (at 0 kPa) were significantly higher in switchgrass hedges compared to row crops. In addition to their potential as biofuel, these crops may also serve as a valuable animal feedstock, which is particularly important in years of drought (Craine et al., 2010). The practice of various cropping systems has been shown to improve the physical and hydraulic properties of the soil.

Cover Crops

Cover crops have been referred to as crops planted primarily to manage soil health, weeds, water quality, biodiversity, control pests and diseases (Lu et al., 2000). Most cover crops are not grown solely for economic benefits, but for the ecosystem benefits they provide. Yunusa and Newton (2003) referred to cover crops as ‘primer plants’; crops grown to condition the soil for the subsequent crops.

Growing cover crops has been a popular practice in crop production throughout history (Reeves, 1994). They were originally grown as green manures, serving as a mulch and soil amendment, and were later incorporated into soil to improve fertility (Kasper and Singer, 2011). Utilizing green manures as a source of nitrogen was a standard practice in the US until the mid-twentieth century, when synthetic nitrogen fertilizers became widely available (MacRae and Mehuys, 1985). Currently, the use of synthetic nitrogen fertilizers dominates grain crop production, limiting the use of green manure cover crops.

Cover crops have benefits of fixing atmospheric nitrogen, sequestering carbon into the soil, and suppressing weeds. Moller et al. (2008) estimated that leguminous cover crops could fix between 60-80 kg ha^{-1} of nitrogen into the soil compared with non-leguminous cover crops. Non-leguminous cover crops can also immobilize excess soil nitrogen, thus reducing nitrogen loss (Umiker et al., 2009). Cover crops can also reduce weeds by maintaining cover at critical times. Fisk et al., (2001) reported that using an annual medic or a clover (*Medicago Spp*.) cover crop in no-till corn reduced winter annual weeds by between 41-81% compared with no cover crop. Cover crops can enhance soil quality through addition of organic matter when incorporated into the soil, helping to reduce compaction and increase infiltration; thus reducing runoff and immobilizing soil nitrogen, and reducing non-point source pollution (Dabney et al., 2001). Wyland et al., (1996) reported a 65-70% reduction in nitrate leaching when cover crops replaced winter fallow. Cover crops can also increase nutrient uptake (Umiker et al., 2009) and reduce soil erosion from splash detachment by reducing the kinetic energy of raindrops.

Despite its importance, only about 3% of farmers incorporate cover crops into their farming practices mostly because of the cost of seeds, labor, planting, and terminating equipment and probable competition for available water (personal communication, Lara Bryant, Agriculture Program Coordinator, National Wildlife Federation). Recent reports suggest, however, that current cover crop usage is increasing (North Central Sustainable Agriculture Research & Education, 2015).

SOIL PHYSICAL AND HYDRAULIC PROPERTIES

Soil physical and hydraulic properties are important factors that can determine agricultural productivity and environmental sustainability. These properties influence the water and nutrient holding capacity of the soil and they serve as indicators of soil quality. Some of these properties include bulk density, pore size distributions, soil water retention, saturated hydraulic conductivity, water infiltration and thermal properties.

Soil Bulk Density and Compaction

Bulk density is a basic parameter usually used to describe soil compactness and for estimates of permeability. Bulk density determination, just like most soil chemical properties analysis, usually excludes the coarser stone and gravel fractions (Heuscher et al., 2005). The bulk density of *in situ* developed mineral soils, except for compaction effects, is assumed to increase with soil depth (Nemes et al., 2010).

If a soil is compacted, bulk density increases and porosity decreases correspondingly. However, absolute values of bulk density are unsuitable for characterizing soil compactness with respect to crop yield when comparing different soils, as optimum and critical limits of bulk density for crop growth strongly depend upon soil type (Keller and Håkansson, 2008), i.e. different values of bulk density are optimum for different soils, as demonstrated by Reichert et al. (2009). A bulk density that indicates a compact state in one soil may imply a loose state in another (Håkansson, 1990). Therefore, relative bulk density has been suggested to describe the compactness of soil. The relative bulk density is generally obtained as the ratio of actual field bulk density (i.e. bulk density measured either directly in the field or on undisturbed soil samples collected in the field) to a reference bulk density (Håkansson, 1990).

One of the major negative consequences of modern agricultural production is soil physical degradation resulting in soil compaction and erosion, which is attributed to deep and intensive tillage practices (Poesse, 1992; Bronick and Lal, 2005; Hamza and Anderson, 2005). Soil compaction is defined as: ‘‘the process by which the soil grains are rearranged to decrease void space and bring them into closer contact with one another, thereby increasing the bulk density’’ (Soil Science Society of America, 2008). It is related to soil aggregation because compaction alters the spatial arrangement, size and shape of clods and aggregates and consequently the pore spaces both inside and between these units (Defossez and Richard, 2002).

Soil compaction seriously threatens agricultural production in some areas. Soil compaction at the soil surface can be remediated by soil tillage, plant root growth and biological activity. However, deep soil compaction under the plow layer can decrease the growth of plants by reducing rooting depth and plant available soil water, which often results in a decrease of crop yield (Ide and Hofman, 1990) and is extremely difficult to remediate. The extent of compacted soil worldwide is estimated at 68 million hectares of land from vehicular traffic alone (Flowers and Lal, 1998). Although farming systems have improved significantly to cope with the new pressures associated with intensive agriculture, the structure of many otherwise healthy soils has deteriorated to the extent that crop yields have been reduced.

Pore Size Distributions

Soil pores can be characterized, depending upon their effective diameters, as macropores (> 1,000 μm effective diameter), coarse mesopores (60-1,000 μm effective diameter), fine mesopores (10-60 μm effective diameter) and micropores (< 10 μm effective diameter) (Anderson et al., 1990). Macroporosity represents inter-aggregate porosity, characterized by a large degree of structural continuity. Mesopore systems consist of inter-aggregate pores with less continuity and higher tortuosity (Messing and Jarvis, 1993). The choice of an effective size to delimit macropores is often more related to details of experimental technique than to considerations of flow processes (Luxemore, 1981; Beven and Germann, 1982).

Soil Water Retention

Soil water controls plant growth and influences a variety of soil processes including erosion, chemical exchange, microbial activity, transport of solutes and water, energy balance of the soil–plant system, and pedo-genesis (Western et al., 2003). The relationship between water content and water potential determines, in part, the nature of these effects. Soil water represents a small portion of the water in the hydrologic cycle. However, due to its vital role in the ecosystem, the temporal and spatial variability of soil water has a controlling influence on ecosystem processes at a variety of scales (Western et al., 2003).

Water retention is a hydro-physical property of soil that can be described by the dependence between soil water content and soil water potential (Walczak et al., 2006). Soil water retention denotes the ability of the soil to retain water at a specific pressure and it is often represented in the form of a graph. Soil water retention is important as it highlights the ability of the soil to retain water for plant use between periods of infiltration. The fact that two soils have the same matric potential does not mean that they possess the same amount of water; therefore, not all of this soil water is available for crops (Walczak et al., 2006). Agronomically, the most important factor on soil water content is the water available for crop use; the plant available water content. A common requirement is to know plant available water in non-saturated soil through the water retention curve (Perez-de-los-Reyes et al., 2011). The water retention curve can be constructed from experimental measurements or from empirical equations known as pedo-transfer functions (Wosten et al., 2001).

The main properties of the soil that influence the water retention curves are texture and structure (Nimmo, 1997). At high potential values, the amount of water retained depends on the capillary effect and on the distribution of pore size; which is greatly affected by the structure of the soil (Kironchi et al., 1995; Pachepski and Rawls, 2003; Juarez et al., 2006; Juhasz et al., 2007). Conversely, at low potential values, retention is due to the increase in absorption, more influenced by texture and specific soil surface materials (Kironchi et al., 1995; Nimmo, 1997; Juarez et al., 2006). Williams et al. (1983) showed that the factors influencing water retention properties are the distribution of the particle size, the clay mineralogy, the content of organic matter and the bulk density of the soil; which are properties related to the texture and structure. Kironchi et al. (1995) also highlighted the type of clay as an important factor in water retention.

Saturated Hydraulic Conductivity (K_{sat})

Hydraulic conductivity of saturated soil is an important soil property that controls water infiltration and surface runoff, leaching of pesticides from agricultural lands, and migration of pollutants from contaminated sites to the ground water (Gimenez et al., 1997).

Saturated hydraulic conductivity depends strongly on soil texture and structure and therefore can vary widely spatially (Logsdon and Jaynes, 1996).

Hydraulic conductivity also shows a temporal variability that depends on different interrelated factors, including soil nature and stability, climate, land use, dynamics of plant canopy and roots, and tillage operations (Prieksat et al., 1994). In a study by Seobi et al. (2005) on the influence of grass and agroforestry buffer strips on soil hydraulic properties of an Albaqualf, they reported that saturated hydraulic conductivity (K_{sat}) was higher for agroforestry buffer treatment compared with grass buffer and row crop treatments for all depths except in the 10-20cm depth where it was only higher than the grass buffer treatment. Kumar et al (2008) reported 15.4 and 19.7 times higher K_{sat} values in fields with agroforestry buffers than continuously and rotationally grazed pastures, respectively. This was attributed to lower soil bulk density and higher macroporosity in the agroforestry buffers.

Infiltration

Water infiltration refers to the movement of water into the soil and it is an important factor in water conservation strategy, runoff and erosion control (Shukla, 2003) and crop productivity. Infiltration is governed by two factors; capillarity and gravity. Smaller pores can move water with or against gravity and influence the infiltration rate of the soil (Shukla, 2014). Larger pores move water under gravity and control a significant amount of the infiltration. Lin et al. (1996) reported that 10% of macropores (> 1,000 µm diameter) and mesopores (10 - 1,000 µm diameter) contributed about 89% of total water flux.

Infiltration rate is affected by both natural and anthropogenic factors. The duration of the infiltration event is an important factor affecting infiltration. The infiltration rate is usually higher initially, unless the soil is wet, and decreases with time until it becomes nearly constant. This may be because of the decrease in the soil water potential gradient as the soil becomes wet. Thus, antecedent soil water content plays an important role in infiltration by significantly influencing the sorptivity of the soil; the soil's ability to absorb and desorb water under capillarity (Shukla, 2014).

Soil texture also has an important influence on water infiltration rate. Infiltration rates generally reduce with a higher proportion of fine particles (clays and silts). Surface conditions are also important for infiltration. Good soil structure promotes infiltration, while bad structure diminishes it. The presence of an impeding soil layer with a different texture than the above layer can also greatly affect the infiltration rate. If the impeding layer is predominantly clayey, the lower hydraulic conductivity associated with clays slows down the flow of water.

Land use and management systems greatly influence water infiltration into the soil. Generally, management practices that increase pore continuity, connectivity, size and distribution also tend to improve water infiltration. Due to the initial increase in porosity and lower water content, tillage has been reported to increase infiltration compared with no-till management (Alegre et al., 1991; Logsdon et al., 1993). However, lower infiltration has been noticed under tillage management compared with no-till after long-term management due to increased potential for surface crusting, loss of soil organic matter and structure, and breakdown of soil aggregates (Shipitalo and Edwards, 1996). Conversely, no-till can increase soil organic matter and aggregation and increase infiltration into the soil compared with tillage (Shukla, 2003; Shukla and Lal, 2005). Management practices like perennial biofuel and cover crops can improve porosity, increase soil organic matter and aggregation, transpire water and increase infiltration (Joyce et al., 2002).

Soil Thermal Properties

Heat transport through the soil is an important factor for ecosystems (Shukla, 2014). The primary source of energy in an ecosystem is from the sun. The radiation coming to the earth's surface raises the temperature of the air and soil. Depending on abiotic factors, such as water content, texture, structure, density and thermal properties of the soil, changes in soil temperature may take place at different soil depths and time (de Vries, 1975). The type of vegetation growing on the soil can also have a major effect on heat transport through the soil. An open canopy has an important influence in modifying the microclimate and soil surface conditions, characterized by localized conditions of soil water and thermal regimes within canopies, thus influencing the soil water dynamics in unsaturated soils (Deb et al., 2011).

Heat transfer through a soil profile essentially denotes movement of heat from the soil surface to deeper layers or heat loss from subsoil layers to the surface. Heat transfer normally occurs from warmer soil layers to cooler soil layers. Thus, heat transfer through the soil is affected by season and time of day. For example, during the summer, heat transfer is from upper soil layers to deeper soil layers, and during winter periods, this process is reversed (Kiehl and Trenberth, 1997). Heat transfer also changes direction during the day and night, depending on the air-soil surface temperature. Heat transfer is a very dynamic process.

Heat transfer through the soil is dependent on the heat capacity and conductivity of different soil layers and constituents (Bristow, 2002). Since both heat capacity and conductivity of soil is dependent on soil water content, heat transfer is strongly influenced by soil water content (Scanlon et al., 2005). In addition, this process is also influenced by soil organic carbon content and density; this process is also affected the amount of energy arriving at the soil surface which is influenced by type of vegetation, and topography. Heat transfer usually increases with an increase in soil bulk density or compaction due to the increased contact between soil minerals (Bristow, 2002). Wet soils with higher organic carbon content have higher heat capacity and are more buffered relative to changes in temperature compared to dry soils with lower organic carbon content due to their lower heat capacity. Knowledge of heat transport through soils is important and this process may affect crop productivity in a changing global climate.

TILLAGE EFFECTS ON SOIL PHYSICAL AND HYDRAULIC PROPERTIES

Two of the most commonly measured soil properties affecting hydraulic properties and processes are soil bulk density and porosity. Soil bulk density and porosity are also fundamental to soil compaction and related agricultural management issues. Thus, the importance of these properties is readily apparent to soil scientists. An understanding of soil pore geometry and structure is fundamental to identifying the effects of tillage on soil physical and hydraulic properties.

Soil Bulk Density

Some tillage operations can disrupt soil structure and affect soil bulk density. Jokela et al. (2011) conducted an 18-year experiment in the Midwest on cropping system effects on soil properties and on a soil quality index in Wisconsin. They found a significantly higher bulk density in tilled compared to no-till plots. They attributed this difference to multiple trips with harvesting equipment for the tilled treatment and infrequent tillage for the no-till treatment. They also found lower soil water content in tillage management compared to no-till. They attributed this difference to the extended evaporation of soil water because of tillage practices and aerating the soil. Similarly, Oschner et al. (2011) reported higher bulk density under chisel tillage management compared to no-till.

Conversely, in a study on the effects of tillage on the physical properties of agricultural organic soils of north central Ohio conducted by Elder and Lal (2008), soil bulk density of no-till and fallow treatments were higher compared to moldboard plow treatments at the 0–10 cm depth, right after tillage. Hamza et al. (2005), D'Haene et al. (2008) and Eltaif et al. (2011) reported similar trends in bulk density for mineral soils. One of the reasons for the differences in bulk density results reported by these researchers could be due to the time of sampling; bulk density immediately after tillage is lower while it may increase over time due to the disturbance of soil structure. Soil crusting develops faster under tillage management compared to no-till and this can increase bulk density (Shipitalo and Edwards, 1996).

Pore Size Distributions

Tillage management can lead to a redistribution of soil pore sizes. From their experiment, Raczkowski et al. (2012) reported that macroporosity was greater in conventional tillage compared to a no-till system, but no significant differences existed in microporosity. They also reported higher total porosity in tillage compared to no-till systems. Hill et al. (1985) and Kay and VandenBygaart (2002) reported similar findings. Kay and VandenBygart (2002) attributed this higher porosity to soil mixing through tillage.

In their experiment, Schwen et al. (2011) found that total porosity was very similar between conventional tillage and reduced tillage, but significantly higher than a no-till treatment, with overall means of 0.50, 0.50, and 0.46 cm^3 cm^{-3}, respectively. These researchers also reported lower bulk density under tillage compared to no-till management right after tillage. They suggested that the greater soil bulk density and smaller total porosity under no-till was likely due to natural compaction, as soil in this treatment was not artificially loosened by tillage for 12 years. Strudley et al. (2008) and Alvarez et al. (2009) reported similar findings.

Soil Water Retention and Saturated Hydraulic Conductivity

Water storage can change in conjunction with water flux parameters as affected by tillage, and the response to tillage may be equally uncertain as compared to bulk density. Chang and Lindwall (1989, 1990, 1992), in their studies over 10 years on the effect of no-till management on a loam soil in Canada with continuous winter wheat (*Triticum aestivum* L.), observed lower water-holding capacity in tilled compared with no-till management at the 3 to 6 cm depth interval despite no discernible tillage effects above and below this zone. Brandt (1992) investigated 12 years of conventional till (CT) versus no-till (NT), and found that NT resulted in greater soil water content compared to CT in 9 of 36 cases and no significant differences in the rest. Likewise, Mahboubi et al. (1993) detected greater water holding capacity in NT compared to CT management on two Ohio silt loam soils during a 28-year study. Azooz and Arshad (2001) measured water retention at six water pressures from -5 to -160 kPa. The rate of soil drying in the top 30 cm was significantly greater in CT than NT, while the rate of wetting (based on a recharge coefficient) was significantly greater in NT.

No-till systems exhibit variations in saturated hydraulic conductivity (K_{sat}) response. Horne et al. (1992) extended a tillage study (Ross and Hughes, 1985) for 10 years under NT, minimum till (MT), and CT (using moldboard plow) on a silt loam soil in New Zealand and discovered that K_{sat} values in soil cores taken from the top 10 cm immediately before seedbed preparation did not differ significantly between the tillage treatments. This result was obtained despite declines in total porosity and infiltration rates, and increased bulk density and aggregate size under NT compared with MT and CT right after tillage. Long-term (28-year) studies on two Ohio silt loam soils by Mahboubi et al. (1993) showed significantly greater mean hydraulic conductivity in NT compared to chisel and moldboard plowing. Azooz and Arshad (1996, 2001) studied the long-term effects of CT and NT practices on two soils (silt loam and sandy loam gray Luvisols) of the northwestern Canadian prairies and concluded that long-term NT practices can maintain soil pore structure and continuity, which can contribute to significantly greater hydraulic conductivity in NT than in CT management.

Infiltration

A number of researchers in various parts of the world has documented No-till effects on infiltration capacity and sorptivity. In southeastern Australia, NT resulted in higher sorptivity in duplex soils compared to CT (Carter and Steed, 1992), while in New Zealand, NT resulted in the lowest infiltration rates compared with MT and CT on a silt loam during a 10-year study (Horne et al. (1992). Azooz and Arshad (1996, 2001) measured significantly lower ponded infiltration rates under CT compared to NT on a silt and sandy loam gray luvisols of the northwestern Canadian prairies, which contrasts with the results of Alegre et al. (1991) who summarized results of multiple studies in Latin America documenting reduced infiltration rates for NT compared with conventional disk tillage.

Soil Thermal Properties

Soil thermal properties can also be affected by tillage practices. Abu-Hamdeh and Reeder (2000) reported that tillage could increase soil bulk density, reduce the spaces between soil particles, reduce volumetric water content and alter soil thermal properties. Ochsner et al. (2001) also reported similar findings. Abu-Hamdeh (2000) reported that for clay loam soils, thermal conductivity ranged from 0.33 to 0.72 W m^{-1} K^{-1} in chisel plowed treatments, from 0.30 to 0.48 W m^{-1} K^{-1} in rotary plowed treatments, and from 0.45 to 0.78 W m^{-1} K^{-1} in no-till treatments. Ghauman and Lal (1985) reported similar results. In general, tillage may reduce thermal conductivity by reducing contact between soil minerals, and decrease heat capacity by reducing soil organic carbon over time with tillage and soil water content right after tillage. However, this result of changes in thermal conductivity may be reversed over time due to the probability of increased crusting encouraged by tillage after a few rainfall events.

COVER CROP EFFECTS ON SOIL PHYSICAL AND HYDRAULIC PROPERTIES

The introduction of cover crops within the crop rotation cycle is a widely used measure to improve soil quality and fertility. Most cover crops are grown in periods when the field is left bare and they can help prime the soil for the corresponding cash crops (Yunusa and Newon, 2003) by influencing soil physical and hydraulic properties.

Soil Bulk Density and Pore Size Distributions

The influence of cover crops on changes in bulk density and pore size distributions usually results from the roots of the crops. Blanco-Canqui et al. (2011) carried out a 15-year study on the effects of including cover crops for enhancing the potential of no-till for improving soil physical properties; they found that cover crops had no effect on penetrometer resistance but affected other soil physical properties. Sunn hemp (*Crotalaria juncea* L.) reduced bulk density by about 4% compared to no cover crop within the 0-7.5 cm depth.

Bollero et al. (2006) noticed that bulk density significantly increased with depth for all crop sequences, which was in agreement with Blanco-Canqui et al. (2011). However, these increases were more pronounced with the use of winter cover crops than with winter fallowing. While the average increment of bulk density with depth for the fallow treatment was 8.5%, winter cover crop increases in bulk density with depth averaged 15% (Bollero et al., 2006). This was due to the lower bulk density at the soil surface with cover crops and normal increase in density with depth.

In the study conducted by Bollero et al. (2006), they found that the introduction of winter cover crops decreased bulk density and therefore significantly increased total soil porosity at the soil surface. Changes in pore-size distribution were reflected in significant increases in the volume of transmission pores with the use of the corn-rye/soybean-rye sequence, and the volume of storage pores with the use of any winter cover crop sequences as compared with the corn/soybean sequence. In addition, they (Bollero et al., 2006) reported that a winter cover crop showed a significant reduction of occluded porosity compared with corn/soybean rotation. Bodner et al., (2013), in a study conducted on an arable field in Austria found that the only parameter that was significantly influenced by the soil cover treatment was the pore radius, with cereal rye (*Secale cereal L.*) having a significantly higher average pore radius compared to no cover crop. They attributed this to the root system of rye being more intense in the top soil compared to mustard roots.

Bodner et al. (2013) also reported that the only parameter that significantly influenced the pore radius was the soil cover treatment, with rye having a significantly higher average pore radius compared to other treatments. Several researchers (Lal et al., 1991; Villamil et al.; 2006; Haruna and Nkongolo, 2015) have reported higher porosity in cover crop compared to no cover crop management. Williams and Weil (2004) considered cover crops as an effective way to alleviate soil compaction due to root-induced biopores being used by the following crop to penetrate the soil.

Water Content

The overall effects of cover crops on soil water availability depends largely on the amount of precipitation, water infiltration, evaporation, and transpiration by the cover crops (Unger and Vigil, 1998). Previous studies have shown that cover crops can reduce soil water content, thereby reducing the yield of the subsequent cash crops (Campbell at al., 1984a&b, Ewing et al., 1991, Keisling et al., 1994). In contrast, Daigh et al. (2014) reported that a cover crop did not significantly affect soil water content even in a dry growing season. In fact, they (Daigh et al., 2014) reported that a cover crop either maintained, or in some cases improved, soil water conservation compared with no cover crop management.

Blanco-Canqui et al., (2011) showed that a cover crop conserved more soil water compared with a no cover crop treatment. These researchers found that cover crops improved the field volumetric water content and buffered soil temperature by acting as a cover, reducing sunlight penetration and water evaporation. Soil water content was greater under cover crops compared to no cover crops by an average of 35% at the 0-20 cm depth (Blanco-Canqui et al., 2011). Soil temperature during the day was also consistently lower under cover crops than in plots without cover crops. On the average, they (Blanco-Canqui et al., 2011) reported that cover crops reduced the soil temperature during their field measurements in early spring by 4°C at the 5 cm depth, 2°C at 15 cm, and 1°C lower at 30 cm. As expected, the volumetric water content was highly correlated with soil temperature. Differences in soil temperature explained about 62% of the variability in water content at the 0-15 cm soil depth (Blanco-Canqui et al., 2011). This result is similar to the findings of Ward et al. (2012) and Blanco-Canqui et al. (2014).

In the same study carried out by Blanco-Canqui et al., (2011), they reported that the addition of cover crops enhanced no-till performance by improving near surface soil physical and hydraulic properties. They also noted that cover crops might ameliorate some risks of excessive near-surface soil compaction and improve soil structure in no-till systems. They (Blanco-Canqui et al., 2011) suggested that cover crops, particularly sunn hemp, might reduce runoff and soil loss by increasing water infiltration. This is consistent with several researchers' findings on the effect cover crops has on soil physical properties (Jokela et al., 2011; Ward et al., 2012; Haruna and Nkongolo, 2015).

Water Infiltration and Saturated Hydraulic Conductivity

Cover crops can transpire excess water from the field and this can have infiltration benefits. Folorunso et al. (1992) and Joyce et al. (2002) reported improved rainfall infiltration in cover crop plots compared to a fallow rotation. Sunn hemp cover crop has been reported to increase water infiltration rates and cumulative infiltration by three times relative to no-cover crop plots (Blanco-Canqui et al., 2011). These researchers attributed this increase in water infiltration to high earthworm populations enhanced by no-till and cover crops. Kemper and Derpsch (1981) reported that cover crops increased infiltration by 416% on Oxisols and by 629% on Alfisols compared to no cover crops. They attributed this increase in infiltration rate to the bio-pores formed by the cover crop roots.

Wilson et al. (1982) reported an increase in macro-pores and infiltration with the use of cover crops on an eroded Alfisol in southern Nigeria. McVay et al. (1989) measured infiltration rate on a Coastal plain soil in Georgia using a sprinkler infiltrometer after 3 years of cropping. They reported that the infiltration rate in no-till grain sorghum planted after hairy vetch cover crop averaged about 5.8 cm hr^{-1}, following a wheat cover crop the infiltration rate was about 4.2 cm hr^{-1}, and was 3.8 cm hr^{-1} following a winter fallow. They also reported that hairy vetch increased infiltration compared with winter fallow in the no-till corn system on a Limestone valley soil. Bruce et al., (1992) reported similar findings.

There have been conflicting reports on the effects of cover crops on saturated hydraulic conductivity (K_{sat}). For example, Keisling et al., (1990) reported that rye-hairy vetch cover crop sequence increased K_{sat} by 166% in the upper 5 cm of the soil, 194% in the 5-10 cm depth and 359% in the 10-15 cm depth compared with no cover crop treatment. However, Wagger and Denton (1989) found no differences in soil porosity and K_{sat} as a result of wheat and hairy vetch cover crop compared to fallow in a strip tillage system. Carof et al. (2007) and Bodner et al. (2008) did not find a significantly higher hydraulic conductivity under cover crops, but showed a stabilization of near saturated hydraulic properties over time in cover crop compared to no cover crop management.

Soil Thermal Properties

Because of their potential ability to reduce water evaporation (Blanco-Canqui et al., 2011), increase infiltration (Folorunso et al., 1992; Joyce et al., 2002), increase soil organic matter and aggregation (Dabney et al., 2001) and increase porosity (Williams and Weil, 2004), cover cops may have an important benefit on thermal properties within the vadoze zone. However, there are currently no studies available to provide valuable information on the effects of cover crops on soil thermal properties. The fifth chapter of this dissertation shows the influence of perennial biofuel and cover crops on soil thermal properties.

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CHAPTER 3

SOIL HYDRAULIC PROPERTIES: INFLUENCE OF TILLAGE AND COVER CROPS

ABSTRACT

Understanding the effects of cover crops and tillage on soil physical properties is important for determining soil productivity. This study was conducted at Lincoln University's Freeman Center to evaluate the effects of tillage and cover crop management on soil hydraulic properties. The field site included three replicate blocks in a randomized complete block design with each plot measuring 21.3 m length and 12.2 m width. Treatment factors were tillage at two levels (moldboard plow tillage vs. no till) and cover crop at two levels (cereal rye [*Secale cereal* L.] cover crop vs. no cover crop). Soil samples were collected in late spring/early summer from each treatment in 10 cm depth increments from the soil surface to a depth of 40 cm using 76.2 mm diameter x 76.2 mm long cores. Soil bulk density values for tillage were 13% lower compared with no-till management. Water content was significantly higher at the 0.0 and -0.4 kPa pressures for the tillage compared with no-till management. Tillage improved coarse mesopores by 32% compared with no-till and this resulted in 87% higher saturated hydraulic conductivity values. Cover crops improved macropores by 24% compared with no cover crop; this can potentially increase water infiltration and reduce runoff. As a result of higher macroporosity, saturated hydraulic conductivity was higher in the cover crop compared with no cover crop management. This study demonstrated that tillage can benefit soil hydraulic properties in the short term but these effects may not persist over time. Cover crops may slightly improve soil hydraulic properties but longer term studies are needed to evaluate its long term effects.

Key Words: pore size distribution, saturated hydraulic conductivity, soil bulk density, soil water retention.

INTRODUCTION

Increased water infiltration and retention in the soil, especially within the vadoze zone, are important factors that determine crop productivity and soil loss. These processes are especially important in less developed regions of the world where most producers have little or no access to irrigation. Soil water is important for nutrient availability and transport (Sparling and West, 1989) and microbial activity (Sylvia *et al.,* 2005). Agricultural land management practices can influence soil structure and they may have a direct or indirect effect on soil hydraulic properties. One of those management practices is tillage.

Tillage involves seedbed preparation through mechanical agitation by digging, stirring and overturning the soil (Conant *et al.,* 2007). Tillage has been used to prepare seedbeds, incorporate fertilizers, manures and residues into the soil, and to control weeds (Leij *et al.,* 2002). However, tillage can be destructive and lead to soil and nutrient loss, soil moisture loss and overall degradation of soils (Ogle *et al*., 2003). One way to assess the effects of tillage on soil structure is to evaluate hydraulic properties. Hydraulic properties that are agronomically important include, but are not limited to, soil bulk density, soil water retention, pore size distribution (Haverkamp *et al*., 2005; Walczak *et al*., 2006; Shukla, 2014) and saturated hydraulic conductivity (K_{sat}) (Logsdon and Jaynes, 1996; Prieksat *et al*., 1994). These properties may show a temporal variability that depends on different interrelated factors, including soil stability, climate, land use, dynamics of plant canopy and roots, and various soil management operations (Prieksat *et al*., 1994).

In their 10 year study of no-till with winter wheat on a silt loam soil in Canada, Chang and Lindwall (1992) observed lower water holding capacity in the 3-6 cm depth interval due to tillage despite no noticeable tillage effects above or below this zone.

However, in a 12 year study of no-till (NT) vs conventional tillage (CT), Brandt (1992), found that no-till resulted in greater soil water content in 9 out of the 36 sites studied and no significant differences in the rest. This was due to biopores developed by soil microorganisms due to less soil disturbance. Water retention at 6 matric potentials, from -5 to -160 kPa, was measured by Azooz and Arshad (2001). They found higher water retention in no-till compared with conventional tillage. They also reported that the rate of soil drying in the top 30 cm was greater for CT compared with NT, while the rate of wetting was greater in the NT. Because tillage can increase soil pore tortuosity, Benjamin (1993) reported that NT improved saturated hydraulic conductivity by 30 to 180% compared with moldboard plow and chisel plow. Other researchers (e.g Azooz and Arshad, 1996; Osunbitan *et al*., 2005) have reported similar findings. However, Heard *et al*. (1988) reported contrasting results with saturated hydraulic conductivities of their treatments in the following order: moldboard plow > chisel plow > ridge till > no-till.

Besides tillage management, producers and farm managers also implement cover crops under favorable climatic and financial conditions for various reasons. Cover crops are crops grown for their ability to condition the soil and protect it from erosion, especially during periods when the soil is left bare (Troeh *et al*., 2004). Cover crops have been reported to reduce soil bulk density (Blanco-Canqui *et al*., 2011) and increase soil macroporosity (Villamil *et al*., 2006).

Auler *et al*. (2014) reported that annual ryegrass (*Lolium multflorum* L.) used as a cover crop reduced soil bulk density and microporosity and increased macroporosity and total porosity which can lead to better water flow in the soil. They also reported that water retention was higher in the top 10 cm of the soil when ryegrass was planted in combination with CT, minimum tillage (MT) and chisel tillage. In their study of the effects of tillage systems and cover crops on soil quality, Abdollahi *et al*. (2014) reported that the use of a cover crop increased air-filled porosity at -10 kPa, air permeability, and pore organization and reduced the value of blocked air porosity at all depths for all tillage treatments.

In Arkansas, Keisling *et al*. (1990) reported that ryegrass - hairy vetch (*Vicia villosa* L.) cover crop sequence improved the K_{sat} of the top 5 cm of the soil by 166%, by 194% in the 5-10 cm depth and by 359% in the 10-15 cm depth compared with no cover crop treatment. However, Wagger and Denton (1989) found no differences in soil porosity and K_{sat} as a result of wheat (*Triticum* L.) and hairy vetch cover crop compared to fallow in a strip tillage system.

The ambiguities in these findings suggests that more studies need to be conducted to improve our understanding on how tillage, cover crops and the interactions between these management practices affect soil hydraulic properties. Such studies would be very beneficial in agriculturally important regions such as the Midwestern United States. We hypothesize that tillage and cover crop may significantly affect soil hydraulic properties in the short term. The specific objective of this study was to assess the influence of tillage and cover crops on soil hydraulic properties. These properties included soil bulk density, soil water retention, pore size distribution and saturated hydraulic conductivity.

MATERIALS AND METHODS

Site description

The study area, Lincoln University's Freeman Center, is located about 8 km northeast of Jefferson City, Missouri, USA. The soil is classified by the United States

Department of Agriculture (USDA) as a Waldron silt-loam (fine, smectitic, calcareous, mesic Aeric Fluvaquents). Table 3.1 shows selected soil physical and chemical properties of the soil. The study site lies at an elevation of about 166 m above sea level with a 2% slope. It was in a 50 yr corn *(Zea mays* L.) and soybean (*Glycine max* L.) rotation with moldboard plow prior to the establishment of this research in 2010. This study was carried out four years after the establishment of this research. For this study, the field was set up using a randomized complete block design with treatments that included tillage (moldboard plow) at two levels (tillage vs no tillage) and cereal rye cover crop (*Secale cereal* L.) at two levels (cover crop vs no cover crop), with three replicates. The main crop grown on the field site was corn planted in late April or early May, depending on weather variability, and harvested in September or October of each growing season. The cover crop was planted after harvesting the main crop each year. The cover crop was allowed to grow during winter and spring months and terminated in April using glyphosate (*N*-[phosphonomethyl] glycine) prior to tillage and planting of the main crop. The soil was tilled to a depth of 15 cm. This was done in late April or early May of each growing season. Further details about the site and the experimental design are given in Haruna and Nkongolo (2015).

Soil sampling

Soil samples were collected using a sampler with a cylindrical core measuring 76.2 mm diameter by 76.2 mm long (Uhland, 1942). The samples were collected two weeks after cover crop termination (just after tillage), in the third week of May, 2014, at four depths of 10 cm increments from the soil surface to a depth of 40 cm (Kladivko *et al*., 2014). During soil sample collection, the cores were taken at the middle of each depth. For example, at the 10-20 cm depth, the soil samples were collected from 11 to 18.6 cm depth.

Thus, the plow pan transition zone lies between 15 to 17.5 cm within the sample cylinder (before and after plowing). The specific treatments included cover crop with tillage (CC-Till), cover crop with no till (CC-NT), no cover crop with tillage (NC-Till) and no cover crop with no till (NC-NT). Two samples (sub-samples) were collected at each depth in all treatments (4 treatments x 4 depths x 2 sub-samples x 3 replicates = 96 cores).

Soil samples were also collected one week before the cover crop termination from each of the aforementioned treatments and replicates from two depths only, 0-10 and 10-20 cm (4 treatments x 2 depths x 3 replicates = 24 cores). This additional sampling was done to better demonstrate and understand the immediate influence of tillage and the annual benefits of cover crops on soil hydraulic properties. These samples also represent field conditions approximately one growing season after the previous tillage and was done for a temporal comparison of tillage effects on soil properties. Each plot measured 21.3 m length and 12.2 m width. All soil samples were stored in a cold storage room at $4^{o}C$ until analysis was done.

Sample preparation and analysis

For saturated hydraulic conductivity measurements, cheesecloth was attached to the bottom of the soil core using rubber bands and another empty core was attached to the top of the core. Soils were saturated for about 48 hours in a tub by gently raising the water level. The electrical conductivity of the water was 0.68 dS m^{-1} and the sodium absorption ratio was 2.34. To reduce preferential flow along the core wall, a mixture of bentonite and water in a ratio of 1:8 was added to the core edge. The constant head method was used to evaluate saturated hydraulic conductivity (K_{sat}) (Reynolds and Elrick, 2002). For soils with K_{sat} values less than 0.1 cm hr^{-1}, the falling head method was used.

Using the same cores, water retention was then measured immediately after K_{sat} measurement at 0.0, -0.4, -1.0, -2.5, -5.0, -10, and -20 kPa pressures using compressed air and ceramic plates. The samples were air dried at 35ºC for 120 hrs, removed from the sampling cylinder and split into two halves: one half was used for obtaining soil aggregates while the other half was ground and passed through a 2 mm sieve. The aggregate sample was used with pressure plates for -33 and -100 kPa pressures. The < 2 mm samples were used with pressure plates at -1500 kPa pressure (Dane and Hopmans, 2002). The soil bulk density was determined using the air-dried weight adjusted for oven dry weight with a measured water content.

Pore size distributions were calculated using the capillary rise equation to estimate effective pore size classes (Jury *et al*., 1991) from the water retention data. Four classes of pore sizes were used: macropores (>1,000 µm effective diameter), coarse mesopores (60 to 1,000 µm effective diameter), fine mesopores (10 to 60 µm effective diameter) and micropores (<10 µm effective diameter) (Anderson *et al*., 1990).

Statistical analysis

A test of variance homogeneity within the different treatments was conducted to evaluate the variability in the measurements. Analysis of variance (ANOVA) was conducted using SAS statistical software (SAS institute 2013) using the general linear model (GLM) procedure. Single degree of freedom contrasts for the treatment (tillage and cover crop) effects were divided into 'tillage vs. no-till', 'cover crop vs. no cover crop' and 'tillage x cover crop' interaction. Statistical differences are declared to exist at $\alpha \leq 0.05$ level.

RESULTS AND DISCUSSION

Bulk density

Bulk density results for the main sampling (two weeks after spring tillage and cover crop termination; four depths, 0-10, 10-20, 20-30 and 30-40 cm) are shown in Table 3.2 and Figure 3.1a. Results show a significant treatment by depth (treatment x depth) interaction for soil bulk density ($p < 0.01$). Bulk density was 13% lower when the soil was tilled compared with no tillage in the 0-10 cm depth (Fig. 3.1a). As expected, bulk density was lowest in the 0-10 cm depth of the tilled treatments compared to the no-till treatments but no differences occurred at the 10-20 cm depth (Fig. 3.1a). Since soil samples were collected right after tillage, it is presumed that this lower bulk density results from the fact that tillage can temporarily relieve soil compaction. This may be beneficial in soils compacted by equipment, human and animal traffic like new farms converted from previous forests and the edges of some farms. Several researchers (e.g Lampurlanes and Cantero-Martinez, 2003; Osunbitan *et al.*, 2005; Dam *et al.*, 2005) have reported similar findings.

Averaged across soil depth, soil bulk density was not significantly affected by cover crop or tillage. However, tillage had numerically lower soil bulk density values compared to no-till (Table 3.2). Bulk density was significantly lower in the 0-10 cm depth and highest in the 10-20 cm depth (Table 3.2). One possible reason for this high bulk density in the 10-20 cm depth is that tillage can result in a compacted 'plow pan' layer directly below the tilled depth. This study is only 4 years old with the field being under 50 yrs of prior moldboard plow. This time may not be sufficient for the soil to recover from the previous management effects, especially at this depth. There was a significant treatment by depth interaction at the 30-40 cm depth. The NC-NT had the lowest soil bulk density values at this depth (Fig. 3.1a). Bulk density was numerically lower in the NC-Till management compared with the CC-Till management (Fig. 3.1a).

Results of bulk density for the sampling one week before cover crop termination and tillage (two depths, 0-10 and 10-20 cm) are shown in Table 3.2 and Figure 3.1b. Soil bulk density was not significantly affected by tillage or cover crop at the top 20 cm depth of soil just before cover crops were terminated. Bulk density was 8.4% lower in the 0-10 cm depth compared to the 10-20 cm depth. Among other things, weather can affect the growth of winter cover crops (Dabney *et al*., 2001). Late cover crop planting on this site in the fall of 2013 did not allow the cover crops enough time to establish strong roots before going dormant during the winter. Low cover crop stands in our field during soil sampling (average cover crop biomass = 587 kg ha^{-1}) resulted in less cover crop effects on soil properties.

In order to understand the temporal variability in soil properties due to management, results from the 0-10 cm and 10-20 cm depths of soil samples collected two weeks after spring tillage and cover crop termination were used for comparison with results from the sampling one week before cover crop termination and tillage (two depths, 0-10 and 10-20 cm). Therefore, the soil samples collected one week before cover crop termination and tillage also represented one-year post tillage. Averaged over the first two depths right after tillage (0-10 cm and 10-20 cm depths of soil samples collected two weeks after spring tillage and cover crop termination), the significant treatment effects were the same as those averaged over four depths, with slight contrasts in the magnitude of the differences between the treatments (Table 3.2). Approximately one year after the previous tillage (one week before cover crops were terminated), the effect of tillage on soil bulk density decreased (Fig. 3.1a & b). In fact, there was a higher increase in bulk density in tilled plots after one year compared with other treatments, especially in the 0-10 cm depth. This suggests that the benefit of tillage on bulk density does not persist over time.

Soil water retention

Soil water retention results for the main sampling (two weeks after spring tillage and cover crop termination; four depths, 0-10, 10-20, 20-30 and 30-40 cm) are shown in Table 3.3 and Figure 3.2. Depth had a significant effect on volumetric water content at all water pressures between 0.0 and -33.0 kPa (Table 3.3). Volumetric water content was higher at soil water pressures between saturation and -5.0 kPa in the 0-10 cm depth. This is consistent with lower bulk density at this depth. Below -5.0 kPa pressure, however, the relationship between water content and bulk density was not consistent. Water content at the 10-20 and 20-30 cm depths were similar due, in part, to the similarity in bulk density and texture at these depths (Tables 3.2 & 3.3).

Averaged over the four depths, there was no significant treatment effects on volumetric water content at all soil water pressures (Table 3.3). Apart from the first depth, no significant differences occurred in the other depths due to management (Fig. 3.2). Water content was higher at 0.0 and -0.4 kPa pressures for the tilled treatments compared with no-till treatments in the 0-10 cm depth (Fig. 3.2a). This mirrors the results from bulk density and it suggests that tillage can immediately improve the proportion of larger diameter pores that drain water at these pressures. This corresponds to the fact that the changes in soil water content resulting from tillage occurs only in the larger pore size range (Ahuja *et al*., 1998). Cameron (1978) related the shape of the water retention curve to bulk density and he found that the slope of the water retention curve decreased with an increase in bulk density. This was similar to our results. We found the lowest slope for water retention curve in the NC-NT management at the 10-20 cm depth (Fig. 3.2b) which also had the highest bulk density at this depth (Fig. 3.1a). The slope of the water retention curve also decreased with increasing soil depth from 0-10 cm to 10-20 cm depths (Fig. 3.2a & b), which also corresponds with increasing soil bulk density (Fig. 3.1a). Treatment by depth interactions between the various treatments only occurred at pressures between saturation and -2.5 kPa pressures at depths below 10 cm (data not shown). For example, NC-NT had significantly lower water content at saturation in 10-20 cm depth while CC-Till management had the lowest water content at saturation in the 30-40 cm depth. A comparison of both tillage managements at -33.0 kPa pressure in the 0-10 cm depth indicated that water content was numerically higher in CC-Till management compared to NC-Till management. It is presumed that the roots of the previous cover crops are responsible for the slightly higher water content. In the 10-20 cm depth, however, the result was reversed.

Results of soil water retention measurement for the sampling one week before cover crop termination and tillage (two depths, 0-10 and 10-20 cm) are shown in Table 3.3. There was a significant effect of depth on volumetric soil water content at all soil water pressures between 0.0 and -20 kPa (Table 3.3). Volumetric water content was significantly higher in the 0-10 cm depth compared with 10-20 cm depth at pressures between saturation and -10.0 kPa (Table 3.3) and this also corresponds with lower soil bulk density (Table 3.2) and higher macropores at this depth. The highest water content was observed in the 0-10 cm depth that also had the lowest bulk density values at this depth (Tables 3.2 & 3.3).

Significant treatment by depth (treatment x depth) interactions were also noticed at soil water pressures between -5.0 and -10.0 kPa (Table 3.3). At both pressures (-5.0 and -10.0 kPa), a comparison of both tillage management practices demonstrated that water content was numerically higher in the 0-10 cm depth of CC-Till management compared with NC-Till management. In the 10-20 cm depth, the results were reversed.

Averaged over the first two depths right after tillage (0-10 cm and 10-20 cm depths of soil samples collected two weeks after spring tillage and cover crop termination), water retention data indicated a significant till vs no-till contrast on volumetric soil water content at 0.0 and -0.04 kPa pressures. Slopes of the water retention curves were different between the two tillage treatments. There was significantly higher water content with tillage management compared with no-till management (Fig. 3.2a). This may be due to the higher proportion of larger pores due to tillage. Volumetric water content was significantly higher in the 0-10 cm depth compared with 10-20 cm depth at soil water pressures between saturation and -10.0 kPa and this corresponds with lower soil bulk density (Table 3.2) and higher macropores at this depth.

Cover crop did not significantly affect soil water retention probably due to low densities and slow root establishment. Although observed higher water content at pressures is indicative of larger pore diameters in tilled plots right after tillage, this effect did not last over time. Approximately one growing season later (one week prior to cover crop termination), water content was not significantly different for tilled management compared to no-till. This suggests that the benefits of tillage in the context of soil water retention are only immediate and they diminish with time. In agriculturally intensive regions of the world, such as the Midwestern US, lower water retention and the possibility of higher soil water evaporation caused by tillage can lead to lower crop yield. This will be more evident in years with significantly less precipitation. Ghuman and Sur (2001) reported significantly lower corn and wheat (*Triticum aestivum* L.) yields under conventional tillage management compared with no-till due to higher soil moisture loss and they advocated the use of residue mulch and reduced or no-till to curb soil moisture evaporation and to improve yield.

Pore size distributions

Pore size distribution results for the main sampling (two weeks after spring tillage and cover crop termination; four depths) are shown in Table 3.4 and Figure 3.3 (a-d). Macropores and coarse mesopores were significantly affected by treatment. There was a significant depth effect on all pore sizes analyzed except for micropores. Significant interactions included tillage by cover crop (Till x CC) on macropores and treatment by depth (treatment x depth) on coarse and fine mesopores (Table 3.4). There was a significant 'Till vs NT' contrast for coarse mesopores. The Till vs NT contrast for coarse mesopores demonstrated that this pore size was about 32% higher due to tillage management compared with no-till (Table 3.4, Fig. 3.3b). The results suggest that the redistribution of pores by tillage is more evident in coarse mesopores. This may be because moldboard plow is very destructive and it may induce large pores. However, sampling cores can limit the amount of these large, horizontally continuous pores and captures more coarse mesopores, which can transmit more water as evidenced in water retention and K_{sat} results.

The highest macropores were found in the top 10 cm of the soil compared with other depths. The least proportion of macropores were found in the 10-20 cm depth (Table 3.4). This is in concert with the higher bulk density at this depth and the potential of a plow pan development in this layer due to several years of tillage. Coarse and fine mesopores and total pores were also significantly higher in the 0-10 cm depth due to tillage. This can temporarily increase water infiltration at this depth. The tillage by cover crop interaction for macropores showed that NT-NC management had the least macropores as expected, which also corresponds to bulk density and water retention results. Cover crop (0.063) had 24% higher macropores than no cover crop (0.051) (Table 3.4). This suggests that the macropores generated by cover crops can persist for some time. This is important during wet growing seasons as it may help reduce surface water ponding. Treatment by depth interactions indicated that coarse mesopores were significantly higher in the 0-10 cm depth when the soil was tilled compared with no-till (Fig. 3.3b). There was also an interaction between cover crop management at the 20-30 cm and 30-40 cm depths for fine mesopores. Fine mesopores were numerically higher in CC-NT management compared with NC-NT in the 20-30 cm depth. The results were reversed in the 30-40 cm depth.

Results of pore size distributions for the sampling one week before cover crop termination and tillage (two depths), which also represents results after one year of the previous tillage, are shown in Table 3.4 and Figure 3(e-h). There was a significant depth effect on macropores, fine mesopores and total pores. Significant interactions included tillage by cover crop (Till x CC) (Table 3.4). Macropores, fine mesopores and total pores were higher in the 0-10 cm depth compared with the 10-20 cm depth. This is in concert with soil bulk density and water retention results. A combination of tillage and cover crops may improve the proportion of larger pores that can help increase water infiltration and thus reduce runoff. Although not statistically different, macropores were 15% greater numerically due to cover crop compared to no cover crop management (Table 3.4). Although not statistically significant, cover crops had slightly higher total pores compared with no cover crop. This is similar to the findings of Lal *et al*. (1991), Villamil *et al*. (2006) and Haruna and Nkongolo (2015).

Averaged over two depths right after tillage, (0-10 cm and 10-20 cm depths of soil samples collected two weeks after spring tillage and cover crop termination), the significant treatment effects were same as those averaged over four depths, with slight contrast in the magnitude of the differences between the treatments. In addition, there was a 'Till vs NT' contrast for micropores (data not shown). Tillage had slightly (about 8%) more total pores compared with no-till. All pore sizes were higher in the top 0-10 cm depth compared with the 10-20 cm depth (Table 3.4, Fig. 3.3) and this is in concert with results on soil bulk density. Tillage by cover crop interaction indicated that NC-NT management had the least proportion of macropores (Table 3.4, Fig. 3.3a).

The results of pore size distribution were similar to that of Lipiec *et al*. (2006) and Sasal *et al.* (2006) who reported that the differences between tillage treatment was more pronounced in the top 0-10 cm of soil. However, this is contrary to an earlier study by Pagliai *et al.* (1989) who found no differences in the top soil (0-10 cm) due to chisel plow but noticed low porosity in the tilled plots in the 10-15 cm depth. The contrast in results are probably because over time and after a few rainfall events, surface crusts tend to develop faster in tilled plots. A temporal comparison of pore size distributions due to tillage showed a remarkable decrease in the proportion of pore sizes, especially for coarse mesopores, about one year after tillage (Fig. 3.3b & f). This was more evident in the 0-10 cm depth where tillage effects were more pronounced. This means that tillage does not provide long-term porosity benefits.

Pore size distribution is essential for water infiltration into the soil and transport within the soil. Due to the temporary porosity benefits provided by tillage, this management practice may not be suitable for regions with high annual precipitation and regions with relatively high precipitation over a short time. Such regions include the tropical wet (Af), and the tropical wet and dry (Aw and Am) climates on the Köppen Climate Classification System (Peel et al., 2007). Intensive rainfall over short periods may cause the soil to 'settle', thus diminishing the proportion of large pores quickly. This may lead to soil and nutrient loss and possible low yields. In such regions, the inclusion of cover crops may help transpire some water from the soil and their roots can hold the soils in place. This may help mitigate against soil and nutrient loss.

Saturated hydraulic conductivity

Saturated hydraulic conductivity (K_{sat}) is highly dependent upon pore size continuity and arrangement. Saturated hydraulic conductivity results for the main sampling (two weeks after spring tillage and cover crop termination; four depths) are shown in Table 3.2 and Figure 3.1c. Saturated hydraulic conductivity values were significantly affected by treatment, depth and two interactions; tillage by cover crop and treatment by depth (Table 3.2). The 'Till vs NT' contrast revealed that tillage improved K_{sat} values by about 87% compared with no-till. This mirrors the results on soil bulk density and coarse mesopores. The higher K_{sat} values with tillage suggests that tillage was responsible for higher proportions of large pores, especially coarse mesopores. Heard *et al.* (1988) and Carter and Kunelius (1986) also reported higher K_{sat} values with tillage compared with no-till. This is in contrast with the results of Joschko *et al*. (1992) and Bhattachryya *et al.* (2006) who reported higher K_{sat} values in no-till compared with tillage. Bhattachryya *et al.* (2006)

suggested that no-till reduced the volume fraction of the large pores and increased the volume fraction of the smaller pores with higher pore connectivity, while Joschko *et al.* (1992) suggested that the burrows made by endogeic earthworms were responsible for higher K_{sat} values in no-till compared with tilled treatment.

Saturated hydraulic conductivity significantly decreased with soil depth (Table 3.2), with about two times higher K_{sat} values in the 0-10 cm of soil depth compared with the 10-20 cm depth, suggesting more tillage impacts at this depth. Tillage by cover crop interaction results indicated that CC-Till management had significantly higher K_{sat} values compared with other management combinations (Table 3.2). There was also a significant treatment by depth interaction on K_{sat} values and it shows that K_{sat} values were higher in the 0-10 and 10-20 cm soil depth with tillage management compared with no-till management (Fig. 3.1c). Tillage improved K_{sat} values by 87% and 90% in the 0-10 and 10-20 cm depths respectively compared with no-till management. This is consistent with soil bulk density results. The significantly higher difference in K_{sat} values between tillage and no-till managements in the 10-20 cm depth could possibly be due to higher bulk density at this depth; however, tillage relieved some of the compaction in the tilled plots.

Results of K_{sat} for the sampling one week before cover crop termination and tillage (two depths), which also represents results after one year of the previous tillage, are shown in Table 3.2 and Figure 3.1d. Results show a significant depth effect on K_{sat} values. Saturated hydraulic conductivity values were 68% greater in the 0-10 cm depth compared with the 10-20 cm depth (Table 3.2). Although not statistically different due to low cover crop density, K_{sat} values (averaged over two depth) were about 32% higher in cover crop plots compared with no cover crop plots (Table 3.2). This is consistent with the slightly higher macropores for this treatment. The slightly higher K_{sat} values are indicative of the ability of cover crops to improve macropores and infiltration due to the activity of their roots. These roots can improve pore connectivity and soil structure (Villamil *et al.,* 2006). This can be very important when dealing with pollutant movement and soil loss.

Averaged over two depths right after tillage, (0-10 cm and 10-20 cm depths of soil samples collected two weeks after spring tillage and cover crop termination), there were significant treatment and depth effects on K_{sat} values (Table 3.2 and Fig. 3.1c). There was about 61% higher K_{sat} values in the 0-10 cm depth compared with the 10-20 cm depth. This is probably because tillage can immediately reduce bulk density and increase the proportion of larger pores that can lead to higher K_{sat} values in this depth.

As with other soil properties analyzed, the benefits of tillage in improving K_{sat} did not last over time. Approximately one year after tillage (one week before cover crop termination), K_{sat} values decreased significantly in tilled plots (Table 3.2). Results also show that the difference in bulk density values does not necessarily translate to K_{sat} values. For example, lower bulk density values do not always translate to higher K_{sat} values for similar soil management practices. Two reasons can be suggested. First, soil bulk density is a coarser (less sensitive) measurement compared with K_{sat}. Second, bulk density does not show pore continuity as evidenced in K_{sat} and soil bulk density values one week prior to cover crop termination and two weeks after cover crop termination (Table 3.2). The first reason is supported by the study conducted by Igbal *et al.* (1997). They reported lower variability in soil bulk density values compared with K_{sat} values. The second reason is supported by Ball *et al.* (1988) and Logsdon *et al.* (1990) who noted that differences in K_{sat} measurements do not translate to bulk density measurements due to pore tortuosity.

The higher bulk density and lower proportion of large pores and K_{sat} noticed in the 10-20 cm depth compared to the 0-10 cm depth under the tillage management suggests that vertical water movement may be hindered by the ‘plow pan’. This may be more evident after several years of tillage. Furthermore, results from the current study suggest that tillage, over time, may not have any beneficial effects on soil hydraulic properties. This may be the reason some farm managers till the soil every growing season; in order to temporarily alleviate the effects of the previous tillage. This may lead to an endless cycle of annual tillage that may increase soil and nutrient loss, farm management cost and reduce crop yield. A viable alternative may be the inclusion of cover crops into crop production systems to stabilize and improve soil hydraulic properties over time. These crops can be planted to help transpire excess water after the harvest of the previous cash crops (in regions of high early season precipitation) or along with the cash crops (in regions with excessive precipitation during the growing season).

SUMMARY AND CONCLUSIONS

This study was conducted to evaluate the influence of tillage and cover crop soil management practices on the hydraulic properties of a silt loam soil. Results showed different effects of these management practices on soil bulk density, water retention, pore size distribution and saturated hydraulic conductivity. For example, soil bulk density was 13% lower when the soil was tilled compared with no-tillage and this effect was more prominent in the top 10 cm of the soil. As a result of lower soil bulk density, we found a significantly higher water content at 0.0 and -0.4 kPa soil water pressures in tillage compared with no-till management. Results of pore size distributions indicated that a combination of tillage and cover crops greatly improved the proportion of macropores (>

1000 μm diameter) compared with any other management combinations. This can possibly increase water infiltration and reduce runoff.

Even though we noticed significantly higher water content at soil water pressures indicative of larger pore diameters in tilled plots right after tillage, this effect did not last over time. Approximately one growing season later, water content was not significantly different. This suggests that the benefits of tillage in the context of soil hydraulic properties are only immediate and they may diminish with time. Results also revealed that some hydraulic properties improve with a combination of both tillage and cover crop management practices. This underscores the need for producers and farm managers to diversify their management portfolio to ensure better soil management and improved productivity.

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Table 3.1 Selected soil physical and chemical properties of the Waldron silt loam at various soil depths and horizons.

Depth (cm)	Horizon	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	OM[a)] (g kg^{-1})	pH (H_2O)
0-10	Ap	201.1	650.6	148.3	16.8	6.71
10-20	Ap	208.5	633.0	158.5	16.6	6.80
20-40	C1	198.5	631.2	170.3	16.6	6.79
40-60	Cg1	209.7	638.4	151.9	16.5	6.85

[a)] OM = Organic matter

Table 3.2 Means and analysis of variance of saturated hydraulic conductivity (Ksat) and soil bulk density for the treatments and soil depths one week before cover crop termination (2 depths) and two weeks after cover crop termination (4 depths for the main sampling and 2 depths for comparison with samples taken one week before cover crop termination). Tillage also occurred two weeks after cover crop termination.

	Post cover crop termination (4 depths)		Prior to cover crop termination (2 depths)		Post cover crop termination (2 depths)	
Treatment	K_{sat} (mm h^{-1})	Bulk Density (g cm^{-3})	K_{sat} (mm h^{-1})	Bulk Density (g cm^{-3})	K_{sat} (mm h^{-1})	Bulk Density (g cm^{-3})
Treatment						
CC-Till[a)]	14.21a[b)]	1.46	3.12	1.48	36.78a	1.37b
CC-NT	2.97b	1.49	9.36	1.55	4.46b	1.47ab
NC-Till	8.84ab	1.42	6.31	1.46	32.46a	1.35b
NC-NT	2.00b	1.50	2.23	1.47	3.10b	1.53a
Depth						
0-10 cm	18.20a	1.32b	8.00a	1.42b	18.20a	1.32b
10-20 cm	7.06b	1.53a	2.53b	1.55a	7.05b	1.53a
20-30 cm	2.93c	1.53a	-	-	-	-
30-40 cm	1.98c	1.48a	-	-	-	-
Analysis of variance *p* > *F*						
Treatment	<0.01	0.64	0.41	0.27	<0.01	0.16
Till vs NT[a)]	<0.01	0.28	0.96	0.25	<0.01	0.04
CC vs NC	0.30	0.80	0.58	0.18	0.32	0.74
Till x CC	0.04	0.60	0.13	0.33	0.62	0.50
Depth	<0.01	<0.01	0.02	0.07	0.01	<0.01
Treatment x Depth	0.05	0.01	0.52	0.66	0.83	0.26

[a)] CC-Till = cover with tillage; CC-NT = cover crop with no till; NC-Till = no cover crop with tillage; NC-NT = no cover crop with no-till; Till = tillage; NT = no till; Till x CC = Tillage by cover crop interaction; Treatment x Depth = Treatment by Depth interaction.

[b)] Mean comparisons were only made when *P values* for the main effects were ≤ 0.05. Means with different letters for a soil property are significantly different at the 0.05 probability level.

Table 3.3 Means and analysis of variance of volumetric water content as a function of soil water pressure for the treatments and soil depths two weeks after cover crop termination and one week prior to cover crop termination. Tillage also occurred two weeks after cover crop termination.

	Soil water pressure (m^3 m^{-3}) two weeks after cover crop termination							
	0.0 kPa	-0.4 kPa	-1.0 kPa	-2.5 kPa	-5.0 kPa	-10.0 kPa	-20.0 kPa	-33.0 kPa
Treatment								
CC-Till[a)]	0.485	0.428	0.395	0.374	0.351	0.344	0.325	0.299
CC-NT	0.481	0.418	0.398	0.382	0.371	0.359	0.345	0.315
NC-Till	0.493	0.438	0.407	0.387	0.369	0.350	0.332	0.309
NC-NT	0.469	0.423	0.403	0.388	0.374	0.366	0.355	0.323
Depth								
0-10 cm	0.526a[b)]	0.460a	0.424a	0.398a	0.375a	0.359ab	0.338b	0.304b
10-20 cm	0.455b	0.410b	0.387b	0.369b	0.363b	0.358ab	0.345ab	0.305b
20-30 cm	0.455b	0.406b	0.383b	0.372b	0.360b	0.349b	0.336b	0.316ab
30-40 cm	0.493ab	0.432ab	0.409ab	0.391a	0.373a	0.364a	0.353a	0.324a
Analysis of variance p > F								
Treatment	0.56	0.13	0.44	0.39	0.36	0.35	0.26	0.66
Till vs NT[a)]	0.27	0.28	0.91	0.63	0.47	0.31	0.15	0.24
CC vs NC	0.87	0.40	0.53	0.44	0.53	0.67	0.49	0.48
Till x CC	0.24	0.56	0.56	0.73	0.69	0.98	0.97	0.91
Depth	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	<0.01	0.02
Treatment x Depth	0.02	<0.01	0.04	0.05	0.01	0.03	0.03	0.01

	Soil water pressure ($m^3\ m^{-3}$) one week prior to cover crop termination							
	0.0 kPa	-0.4 kPa	-1.0 kPa	-2.5 kPa	-5.0 kPa	-10.0 kPa	-20.0 kPa	-33.0 kPa
Treatment								
CC-Till	0.468	0.414	0.398	0.385	0.360	0.368	0.351	0.306
CC-NT	0.464	0.412	0.402	0.392	0.388	0.381	0.368	0.346
NC-Till	0.448	0.410	0.388	0.383	0.376	0.368	0.349	0.302
NC-NT	0.484	0.446	0.432	0.423	0.416	0.408	0.399	0.353
Depth								
0-10 cm	0.526a	0.460a	0.424a	0.398a	0.375a	0.359a	0.338b	0.304
10-20 cm	0.455b	0.410b	0.387b	0.369b	0.363b	0.358b	0.345a	0.305
Analysis of variance p > F								
Treatment	0.99	0.90	0.98	0.98	0.98	0.97	0.94	0.92
Till vs NT	0.96	0.99	0.79	0.80	0.72	0.70	0.61	0.57
CC vs NC	0.90	0.82	0.92	0.88	0.96	0.98	0.99	0.78
Till x CC	0.95	0.51	0.76	0.77	0.82	0.82	0.76	0.84
Depth	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.81
Treatment x Depth	0.59	0.92	0.1	0.07	0.03	0.04	0.09	0.80

[a)] CC-Till = cover with tillage; CC-NT = cover crop with no till; NC-Till = no cover crop with tillage; NC-NT = no cover crop with no-till; Till = tillage; NT = no till; Till x CC = Tillage by cover crop interaction; Treatment x Depth = Treatment by Depth interaction.
[b)] Mean comparisons were only made when *P values* for the main effects were ≤ 0.05. Means with different letters for a soil water pressure are significantly different at the 0.05 probability level.

Table 3.4 Means and analysis of variance of pore size distributions for the treatments and soil depths two weeks after cover crop termination and one week prior to cover crop termination. Tillage also occurred two weeks after cover crop termination.

	Pore sizes (m^3 m^{-3}) two weeks after cover crop termination				
	Macropores (> 1,000 µm)	Coarse Mesopores (>60 to 1,000 µm)	Fine Mesopores (10 to 60 µm)	Micropores (< 10 µm)	Total pores (m^3 m^{-3})
Treatment					
CC-Till[a]	0.058ab[b]	0.071a	0.055	0.292	0.476
CC-NT	0.068a	0.048c	0.055	0.315	0.486
NC-Till	0.058ab	0.067b	0.065	0.302	0.493
NC-NT	0.043b	0.046c	0.051	0.323	0.462
Depth					
0-10 cm	0.068a	0.086a	0.068a	0.306	0.529a
10-20 cm	0.044c	0.054b	0.055b	0.301	0.454b
20-30 cm	0.051b	0.045b	0.050b	0.304	0.450b
30-40 cm	0.063ab	0.047b	0.053b	0.321	0.485b
Analysis of variance p > F					
Treatment	0.02	0.01	0.07	0.61	0.73
Till vs NT[a]	0.71	< 0.01	0.23	0.16	0.56
CC vs NC	0.09	0.40	0.58	0.55	0.84
Till x CC	0.03	0.13	0.15	0.51	0.40
Depth	0.05	< 0.01	< 0.01	0.06	< 0.01
Treatment x Depth	0.39	0.03	0.03	0.46	0.01

	Pore sizes (m^3 m^{-3}) one week prior cover crop termination				
	Macropores (> 1,000 µm)	Coarse Mesopores (>60 to 1,000 µm)	Fine Mesopores (10 to 60 µm)	Micropores (< 10 µm)	Total pores (m^3 m^{-3})
Treatment					
CC-Till	0.045	0.046	0.062	0.325	0.477
CC-NT	0.056	0.028	0.056	0.333	0.474
NC-Till	0.050	0.040	0.069	0.314	0.472
NC-NT	0.036	0.041	0.064	0.331	0.472
Depth					
0-10 cm	0.055a	0.037	0.084a	0.327	0.504a
10-20 cm	0.038b	0.041	0.041b	0.324	0.444b
Analysis of variance p > F					
Treatment	0.62	0.08	0.96	0.92	0.99
Till vs NT	0.90	0.08	0.76	0.57	0.96
CC vs NC	0.51	0.39	0.67	0.78	0.90
Till x CC	0.28	0.05	0.97	0.84	0.95
Depth	0.01	0.62	0.06	0.81	0.01
Treatment x Depth	0.77	0.45	0.93	0.80	0.59

[a)] CC-Till = cover with tillage; CC-NT = cover crop with no till; NC-Till = no cover crop with tillage; NC-NT = no cover crop with no-till; Till = tillage; NT = no till; Till x CC = Tillage by cover crop interaction; Treatment x Depth = Treatment by Depth interaction.

[b)] Mean comparisons were only made when *P values* for the main effects were ≤ 0.05. Means with different letters for a pore size are significantly different at the 0.05 probability level.

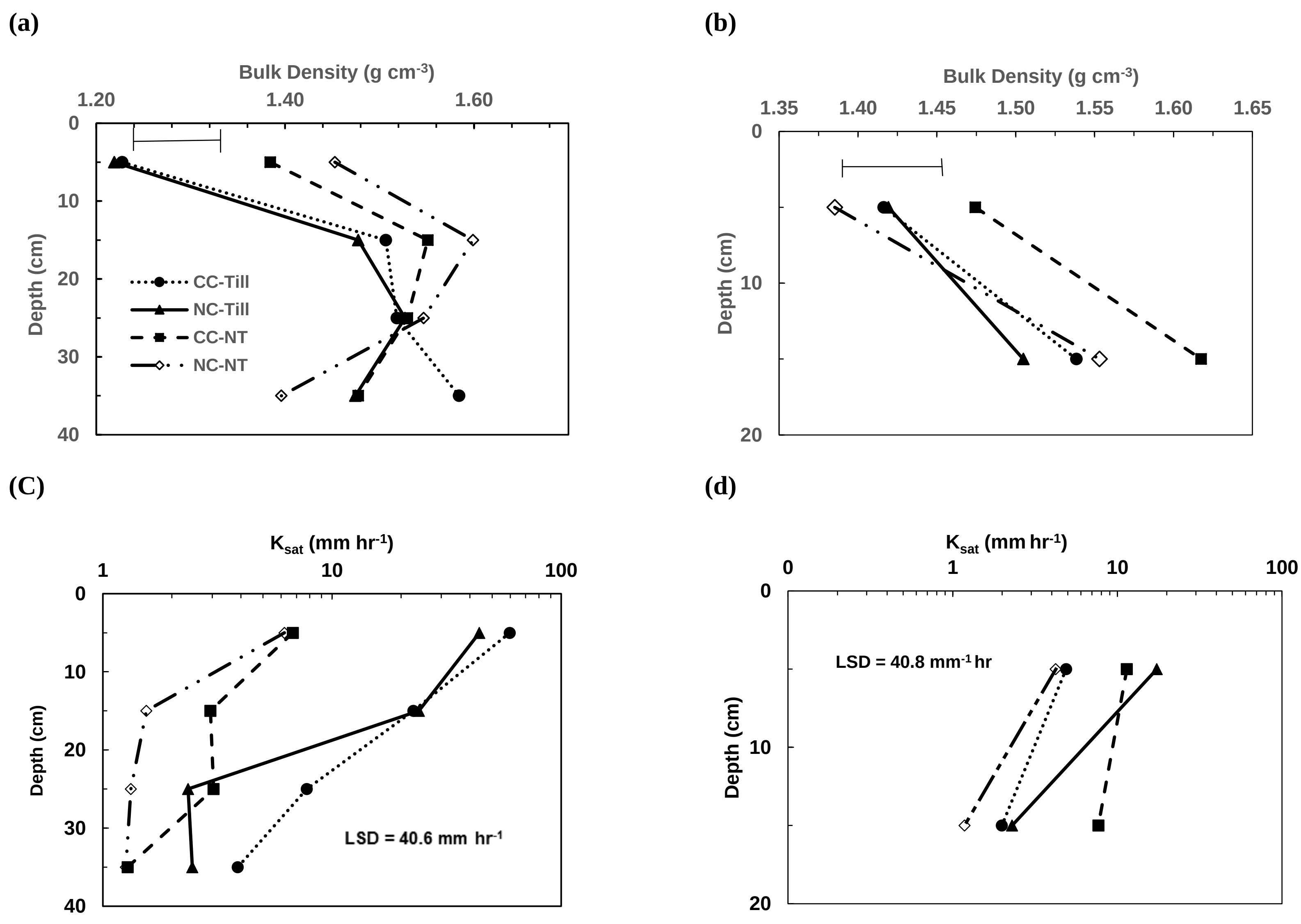

(a)
Bulk Density (g cm-3)
1.20
1.40
1.60
Depth (cm)
0
10
20
30
40
CC-Till
NC-Till
CC-NT
NC-NT
(b)
Bulk Density (g cm-3)
1.35
1.40
1.45
1.50
1.55
1.60
1.65
Depth (cm)
0
10
20
(C)
Ksat (mm hr-1)
1
10
100
Depth (cm)
0
10
20
30
40
LSD = 40.6 mm hr-1
(d)
Ksat (mm hr-1)
0
1
10
100
Depth (cm)
0
10
20
LSD = 40.8 mm-1 hr

Figure 3.1 (a) soil bulk density two weeks after cover crop termination (b) soil bulk density one week before cover crop termination (c) saturated hydraulic conductivity (K_{sat}) two weeks after cover crop termination and (d) K_{sat} one week before cover crop termination at various depths as influenced by cover crop with tillage (CC-Till), no cover crop with tillage (NC-Till), cover crop with no till (CC-NT), and no cover crop with no till (NC-NT) managements. Note: (a) Bar indicates least significant difference (0.05) value for bulk density. (b) The least significant difference (LSD) (0.05) value for Ksat is listed on the graph due to log scale.

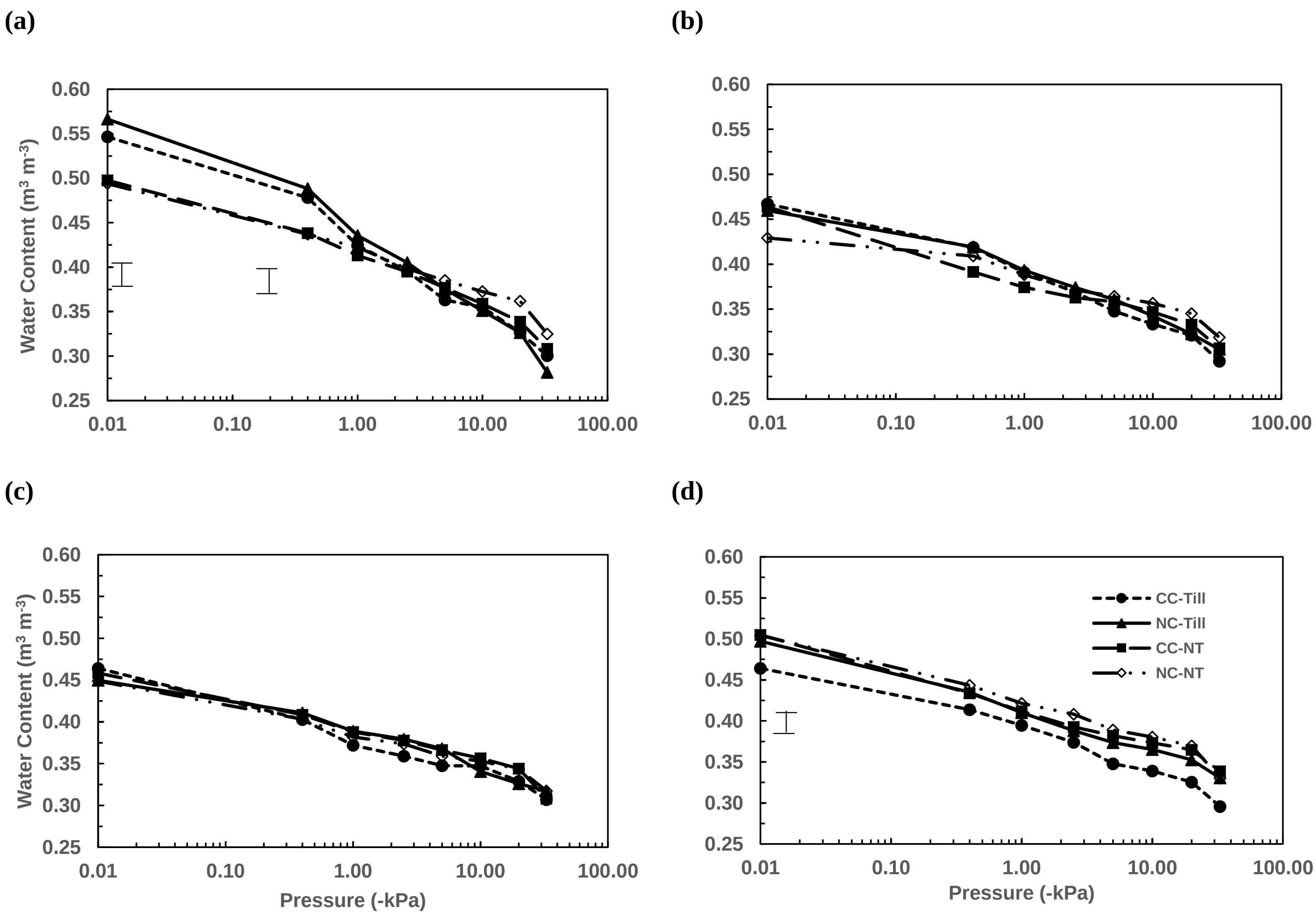
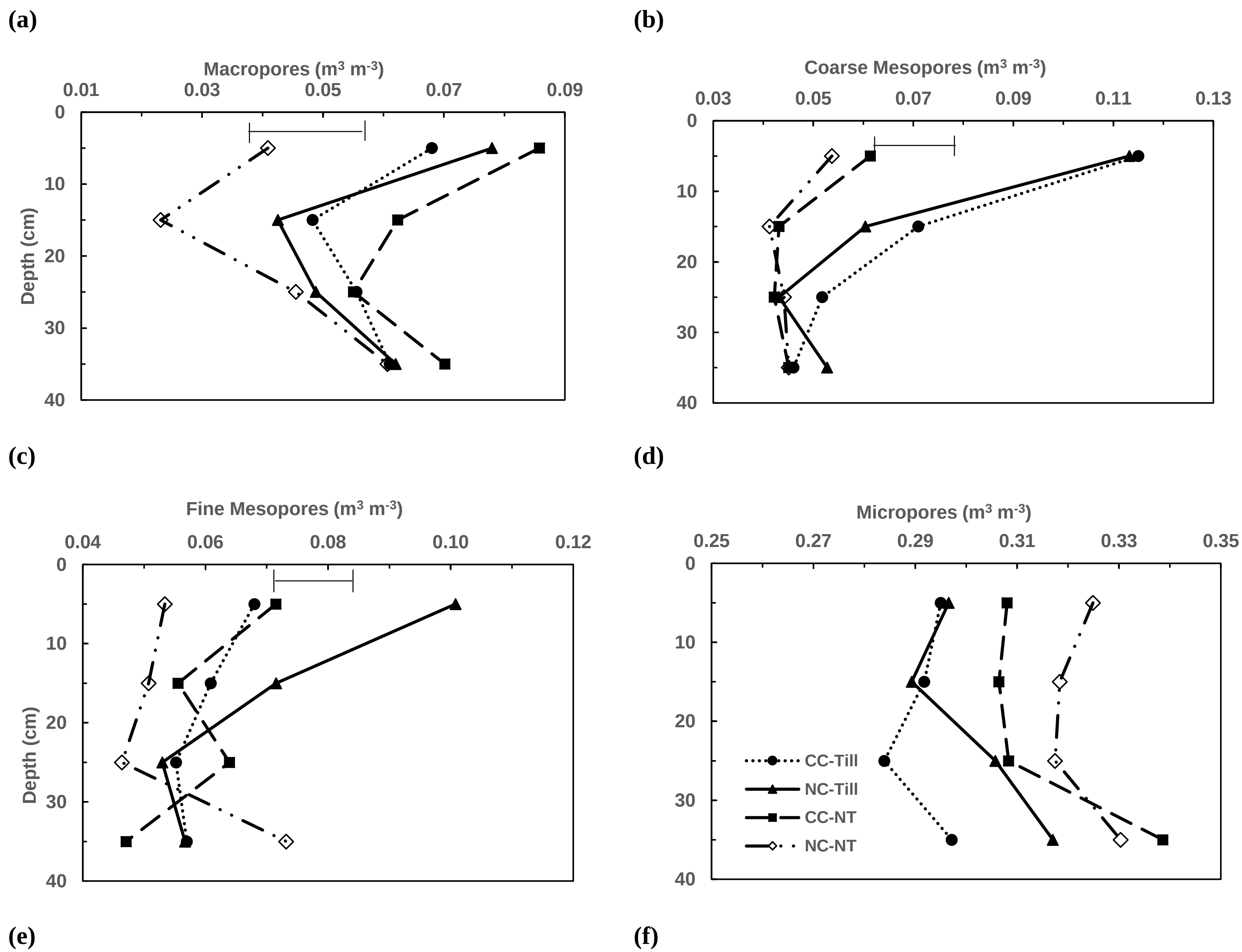


Figure 3.2 Soil water retention curves at (a) 0 to 10 cm (b) 10 to 20 cm (c) 20-30 cm (d) 30 to 40 cm depths as influenced by cover crop with tillage (CC-Till), no cover crop with tillage (NC-Till), cover crop with no till (CC-NT), and no cover crop with no till (NC-NT) treatments two weeks after cover crop termination. Note: Bar indicates least significant difference (0.05) value for water retention.


(a)
Macropores (m³ m⁻³)
0.01 0.03 0.05 0.07 0.09
Depth (cm)
0 10 20 30 40
(b)
Coarse Mesopores (m³ m⁻³)
0.03 0.05 0.07 0.09 0.11 0.13
0 10 20 30 40
(c)
(d)
Fine Mesopores (m³ m⁻³)
0.04 0.06 0.08 0.10 0.12
Depth (cm)
0 10 20 30 40
Micropores (m³ m⁻³)
0.25 0.27 0.29 0.31 0.33 0.35
0 10 20 30 40
CC-Till
NC-Till
CC-NT
NC-NT
(e)
(f)

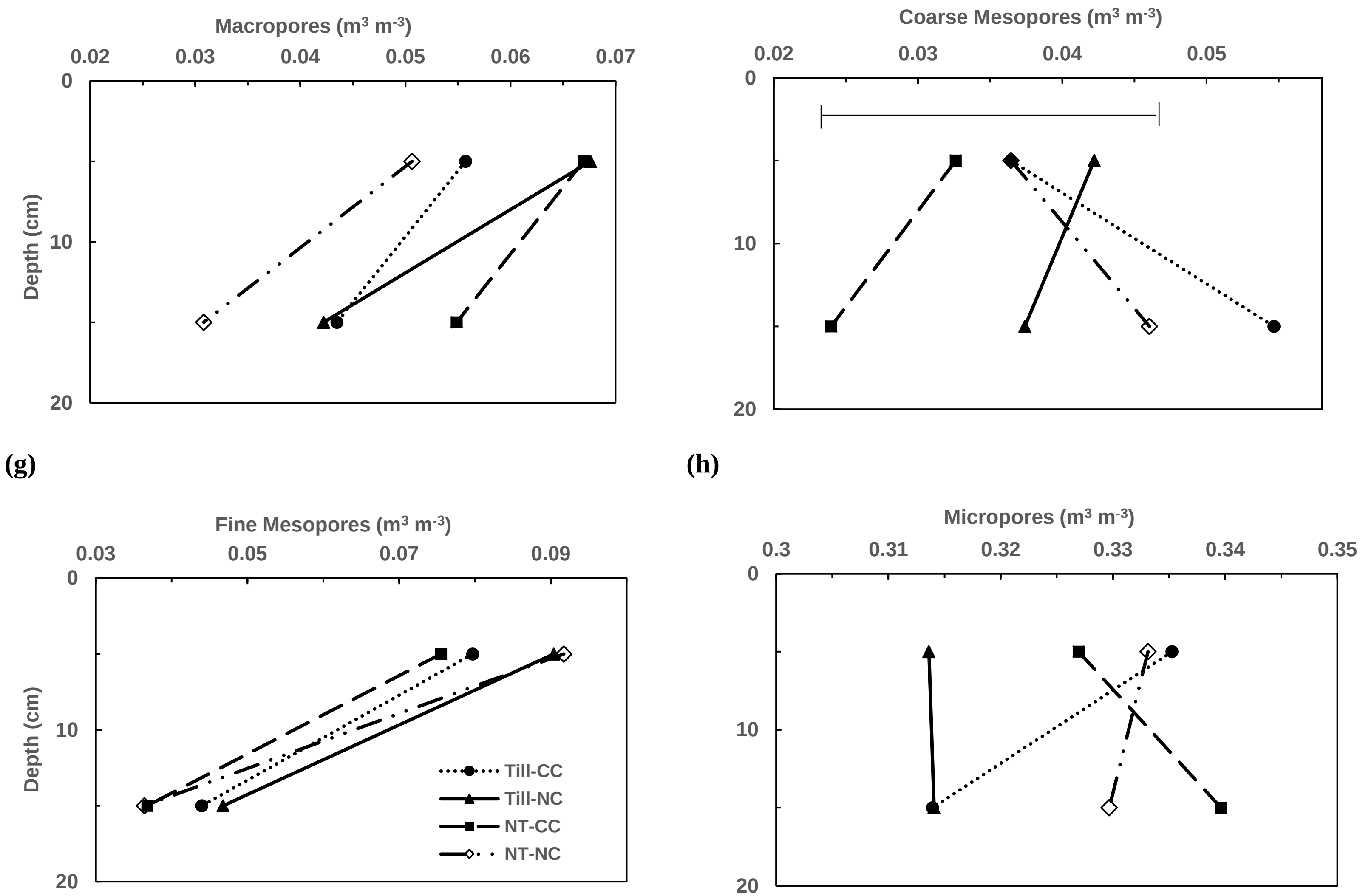


Figure 3.3 Pore size distributions at various depths; (a-d) two weeks after cover crop termination (e-h) one week before cover crop termination as influenced by cover crop with tillage (CC-Till), no cover crop with tillage (NC-Till), cover crop with no till (CC-NT), and no cover crop with no till (NC-NT) treatments. Note: Pore size classes include; macropores (> 1000 µm diameter), coarse mesopores (60-1000 µm), fine mesopores (10-60 µm diameter), micropores (< 10 µm diameter). Bar indicates least significant difference (0.05) value for pore size distribution.

CHAPTER 4

IN SITU INFILTRATION AS AFFECTED BY COVER CROP AND TILLAGE MANAGEMENT

ABSTRACT

Water is usually the most limiting factor in agricultural grain crop production. Various agricultural management practices such as tillage and use of cover crops have the potential to influence water infiltration into soil. This study was conducted on a Waldron silt loam (fine, smectictic, calcareous, mesic Aeric Fluvaquents) soil to evaluate the influence of cover crop and tillage management on in situ infiltration. The field site included three replicate blocks in a randomized complete block design with each plot measuring 21.3 m (69.9 ft) length and 12.2 m (40.0 ft) width. The two treatment factors included cover crop at two levels (cereal rye [*Secale cereal* L.] cover crop vs. no cover crop) and tillage at two levels (moldboard plow tillage vs. no till). Continuous corn (*Zea mays* L.) was grown. Infiltration rates were measured in all the treatments using a Mariotte system with single ring infiltrometers during the 2014 and 2015 growing seasons. Water infiltration parameters were estimated using the Parlange and Green-Ampt infiltration equations. Parlange and Green-Ampt models appeared to fit measured data well with coefficient of variation ranging from 0.92 to 0.99. Results also showed that in 2014, the Parlange model saturated hydraulic conductivity (K_S) parameter value for no-till (NT) was 30.4 mm h^{-1}, about 42% greater than till. The Green-Ampt K_S parameter value for NT was 25.9 mm h^{-1}, about 54% greater than till. In 2015, the Parlange model sorptivity (S)

parameter value for cover crops (CC) was 38.6 mm $h^{-0.5}$, about 82% greater than no cover crop (NC). The Green-Ampt model *S* parameter value for CC was 34.0 mm $h^{-0.5}$, about 90% greater than NC. Cover crop management can increase water infiltration which can improve soil quality and enhance the sustainability of crop production systems.

Key words: Green-Ampt equation - Parlange equation - ponded infiltration - quasi-steady infiltration rate - saturated hydraulic conductivity - sorptivity.

INTROUCTION

Soil water conservation and runoff reduction and control are essential for improved agricultural productivity and environmental sustainability. Rain occurring on the soil surface can either infiltrate into the soil or pond on the surface and potentially runoff. A combination of these processes can also occur, especially if the rate of rainfall is high. In order to identify water conservation strategies and runoff and erosion control, knowledge of water infiltration into soil is essential (Shukla et al., 2003).

Infiltration involves the entry of water through the air-soil interface into the vadoze zone. Infiltration is affected by several soil properties including soil structure, texture, soil organic matter, soil cover, antecedent soil water content, and landscape position. Some of these properties can be influenced by management systems such as tillage and use of cover crops (Radke and Berry, 1993; Shukla, 2014). Infiltration may be a good indicator of changes in soil physical properties.

Cover crops are grown for various reasons, especially for their ability to protect and condition the soil during periods when the soil is left bare (Troeh et al., 2004). Cover crops influence infiltration by reducing soil bulk density (Villamil et al., 2006; Blanco-Canqui et al., 2011) and improving macroporosity (Auler et al., 2014). In a study by Kemper and Derpsch (1981) on two soils (Oxisols and Alfisols), cover crops were found to increase the infiltration rate by 416% into an Oxisol and by about 629% into an Alfisol compared to no cover crop. They attributed this increase in infiltration rate to the bio-pores formed by the cover crop roots. Wilson et al. (1982) reported an increase in macro-pores and infiltration rate with the use of cover crops compared with no cover crop on an eroded Alfisol in southern Nigeria. More recently, Joyce et al. (2002) reported improved rainfall infiltration in cover crop management compared with a fallow rotation.

Cover crops can also influence infiltration indirectly by improving soil structure. Several researchers (e.g. Sainju et al., 2002; Villamil et al., 2006) have reported higher organic matter content when cover crop roots decompose and when their above ground biomass is incorporated into the soil. Organic matter increases can improve soil structure and water infiltration. The leaves of cover crops can also intercept raindrops, reduce their kinetic energy and reduce splash detachment. Haramoto and Gallandt, (2004) reported that Brassicas (*Brassica juncea* L.) can provide more than 80% soil coverage when used as a winter cover crop. This higher surface cover can improve agricultural sustainability after a few decades.

Besides cover crops, producers also use tillage management as a means of seedbed preparation and fertilizer incorporation. The process of tilling the soil can induce changes in soil structure, which can influence infiltration into the soil. Lipeic et al. (2006) studied the effect of long-term tillage on water infiltration. They reported that deep plowing to a depth of 200 mm (8 in) significantly increased the cumulative infiltration rate by 62% compared with shallow tillage (50 mm [2 in] deep) and by 61% compared with no tillage. They attributed this to the higher proportion of flow-active pores induced by deep tillage. Similar results were reported by Pikul et al. (1996). However, Lal and Vandoren (1990) did not find any significant differences in infiltration rate between tillage and no till management. They attributed the maintenance of infiltration rate in no-till management to the development of continuous biopores and worm channels. Pikul and Zuzel (1994) and Capoweiz et al. (2009) reported similar findings. The contrast in these studies may have resulted from the fact that the benefits of tillage in improving macropores at the tilled depth are not usually sustained over time (Haruna et al., 2017).

Reduced infiltration can hinder underground water recharge and this can have negative consequences on agricultural productivity (Connolly et al., 1997). Water infiltration is therefore important for improved agricultural productivity necessitated by the current global human population increase (Reicosky et al., 2011). Several researchers (e.g. Singh and Woolhiser, 2002; Jury and Horton, 2004; Liu et al., 2008) have used physically based models as a means of better understanding infiltration and water distribution in the soil. Physically based hydrologic models (e.g. Green and Ampt, 1911; Parlange et al., 1981) fit infiltration data over time with physical parameters: saturated hydraulic conductivity (K_s) and sorptivity (S). The K_s parameter has been defined as the maximum water flow, in a completely saturated soil, due to gravity alone, while the S parameter is the ability of the soil to conduct water by capillarity and this varies with initial water content (Touma et al., 2007). Both parameters can reflect the changes in soil properties caused by various management practices that could influence cumulative infiltration.

Northern Missouri is an agriculturally intensive region with management practices that reflect those applied throughout the Midwestern United States, the 'breadbasket' region of the country. It is therefore important to understand the individual and combined influence of these practices on in situ infiltration. The specific objective of this study was to evaluate the influence of cover crop and tillage management practices on water infiltration parameters.

MATERIALS AND METHODS

Site Description

Lincoln University's Freeman Farm was used for this study which is located about 8 km (5 miles) north-east of Jefferson City, Missouri, USA (38^{o}58'16"N, 92^{o}10'53"W). The soil was classified as Waldron silt loam (fine, smectictic, calcareous, mesic Aeric Fluvaquents) by the USDA. Table 4.1 shows selected physical and chemical properties of the soil. The field site is located about 166 m (506 ft) above sea level, with a 2% slope. For 50 yrs prior to the establishment of this research in 2010, the study site was in a corn *(Zea mays* L.) and soybean (*Glycine max* L.) rotation with a moldboard plow tillage to a depth of 150 mm (6 in). For this study, the field site was set up using a randomized complete block design with treatments that included tillage (moldboard plow) at two levels (tillage vs no tillage) and cereal rye cover crop (*Secale cereal* L.) at two levels (cover crop vs. no cover crop), with three replicates.

The main crop grown on the field site was corn, planted in late April or early May, depending on weather variability, and harvested in September or October of each growing season. The cover crop was planted by broadcasting in late October or early November of each year, after harvesting corn. The cover crops were allowed to grow during winter and spring months and terminated in April using glyphosate (*N*-[phosphonomethyl] glycine) prior to tillage and planting of corn. For the tillage plots, the soil was moldboard-plowed to a depth of 150 mm (6 in). This was done in late April or early May of each agricultural season. All corn plots received 26 kg ha^{-1} (23 lbs ac^{-1}) N, 67 kg ha^{-1} (60 lbs ac^{-1}) P_2O_5, and 67 kg ha^{-1} (60 lbs ac^{-1}) K_2O. However, an additional 202 kg ha^{-1} (180 lbs ac^{-1}) N was applied from urea (Kladivko et al., 2014; Haruna and Nkongolo, 2015).

The 50-year annual average temperature for the study site is 13 ^{o}C (55 ^{o}F) with January (- 6 ^{o}C [21 ^{o}F]) being the coldest and July (31^{o}C [88 ^{o}F]) being the warmest months. Average temperature in July 2014 was 23 ^{o}C (74 ^{o}F), while the average temperature in July 2015 was 25 ^{o}C (78 ^{o}F). The 50-year average annual precipitation for the area is 1095 mm (43 in) with January (48 mm [2 in]) being the driest and May (131 mm [5 in]) being the wettest months. The total precipitation in July 2014 was 68 mm (3 in) while the total precipitation in July 2015 was 153 mm (6 in) (NOAA, 2016).

Ponded Infiltration Measurements

For this study, ponded infiltration was measured once in each of the three replicates with the following treatments; cover crop with tillage (CC-Till), cover crop with no tillage (CC-NT), no cover crop with tillage (NC-Till) and no cover crop with no tillage (NC-NT). Each plot measured 12.2 x 21.3 m (40 x 70 ft). Three infiltration measurements were also taken from a non-treated area in perennial fescue grass (*festuca arundinacea*), adjacent to the field, for comparison purposes only. A total of 15 measurements were made each year (4 treatments x 3 replicates + 3 perennial grass); in early July of 2014 and 2015. Measurements were made in the middle of each plot, in non-trafficked mid-row crop areas (Kladivko et al., 2014).

Infiltration rates were measured using single-ring infiltrometer units (Bouwer, 1986). The steel rings have an inside diameter of 250 mm (10 in), a length of 300 mm (12 in) and a wall thickness of 3 mm (0.1 in). The rings were inserted vertically into the soil by manually driving the ring into the soil to a depth of about 150 mm (6 in). At the time of measurement, soil samples were taken from areas around the ring at depths of 0 to 100 mm (0 to 4 in) and 100 to 200 mm (4 to 8 in) using a soil probe for antecedent volumetric soil water content determination. These samples were taken about 2 m from the infiltration ring to prevent bypass flow of the infiltrating water into these holes.

For the ponded infiltration measurements, a 50 mm (2 in) head was maintained inside the ring using a Mariotte system. Infiltration measurements were conducted for about 120 mins. Two infiltration models were used to fit the measured infiltration data; Green and Ampt (1911) and Parlange et al. (1982) (henceforth referred to as Green-Ampt and Parlange models respectively). The Green-Ampt and Parlange models provide the best infiltration data fit and confidence intervals for a two-parameter model (Clausnitzer et al., 1998). The Green-Ampt (1911) infiltration model was modified by Philip (1957a) for time (t) versus cumulative infiltration (I), as follows:

$$t = \frac{I}{K_s} - \frac{[S^2 \ln(1 + \frac{2IK_s}{S^2})]}{2K_s^2} \tag{4.1}$$

where t (T) is time (hr), I (L) is the cumulative infiltration (mm), S (L $T^{-0.5}$) is the sorptivity (mm $hr^{-0.5}$) and K_S (L T^{-1}) is the saturated hydraulic conductivity (mm hr^{-1}).

Modified from Talsma and Parlange (1972), the physically based Parlange model for t versus I is as follows:

$$t = \frac{I}{K_s} - \frac{S^2 \left[1 - \exp\left(-\frac{2IK_s}{S^2}\right)\right]}{2K_s^2} \tag{4.2}$$

The S and K_S parameters for the Green-Ampt and Parlange models were estimated based on cumulative infiltration using methods proposed by Clothier and Scotter (2002). A non-linear fitting procedure was used to fit measured I vs t data to the Green-Ampt (eqn 1) and

Parlange (egn. 2) models. The initial parameter values represent the initial starting value for the non-linear curve fitting procedure. The measured infiltration data was fitted to the models by determining the volume of water infiltrated. Volume of water infiltrated was determined by multiplying the volume of the infiltrometer by the volume of the water delivery tube. Depth of water infiltration (D_i) (mm) was then calculated by the following relationship;

$$D_i = \left(\frac{V_i}{A_i}\right) \times 10 \tag{4.3}$$

where V_i is the volume of water infiltrated (cm^3) and A_i is the area of the steel infiltration ring (cm^2). The next step was to calculate the rate of infiltration (R_i) (mm hr^{-1}). This was calculated using the following relationship;

$$R_i = \frac{D_i t_1 - D_i t_0}{t_1 - t_0} \tag{4.4}$$

where $D_i t_1$ is the depth of infiltration at the next infiltration time (after the initial infiltration time), $D_i t_0$ is the depth of infiltration at the initial infiltration time, t_1 is the next infiltration time, and t_0 is the initial infiltration time. The initial S parameter was estimated by dividing the initial infiltration by time $(t)^{0.5}$, while the initial K_S parameter value was the steady infiltration rate (mm h^{-1}).

Fitted parameters that suitably describe data can be used for predictive purposes (Hopmans et al., 1997). The S parameter is highly dependent on initial infiltration rate and the initial infiltration rate depends on the antecedent soil water content. Therefore, the S parameter is dependent on the antecedent soil water content. The Green-Ampt and

Parlange models can be used to evaluate the consistency in estimated physical parameters of S and K_S.

Field saturated hydraulic conductivity (K_{fs}) was estimated using the method of Reynolds et al. (2002). Assuming a one dimensional flow in the infiltration ring and a divergent three-dimensional flow below the ring, Reynolds et al. (2002) uses the following equation:

$$K_{fs} = \frac{q_s}{\left(\frac{H}{C_1 d + C_2 a}\right) + \left\{\frac{1}{[\alpha^*(C_1 d + C_2 a)]}\right\} + 1} \tag{4.5}$$

where K_{fs} is the field-saturated hydraulic conductivity (mm hr^{-1}), q_s is the quasi-steady infiltration rate (mm hr^{-1}), a is the radius of the infiltration ring (mm), H is the hydraulic head of ponded water in the ring (mm), d is the depth of ring insertion into the soil (mm), C_1 and C_2 are dimensionless constants (C_1 = 0.993 and C_2 = 0.578 for this infiltrometer), and α^* is the soil macroscopic capillary length (Reynolds et al. 2002) estimated from the water retention data. (The soil macroscopic capillary length was obtained from Haruna et al. (2017) fitted to the van Genuchten equation [van Genuchten, 1980; Lu et al. 2008]). The α^* values used were 0.026, 0.005, 0.031 and 0.002 mm^{-1} (0.066, 0.127, 0.787 and 0.0508 in^{-1}) for CC-Till, CC-NT, NC-Till and NC-NT treatments respectively. The fitted α^* parameters used represented 0 to 100 mm (0 to 4 in) depth for each treatment. Saturated hydraulic conductivity (K_{sat}) values were obtained from soil core data (Haruna et al., 2017), for comparison with field estimated K_{fs} values.

An important distinction exists between two types of saturated hydraulic conductivities (K_S and K_{sat}) as used in the current study. The saturated hydraulic conductivity parameter estimated from both models (Parlange and Green-Ampt) is denoted as K_S. The saturated hydraulic conductivity measured on soil cores in the laboratory (extracted from Haruna et al., 2017) is denoted as K_{sat}.

Statistical Analysis

Analysis of variance (ANOVA) was conducted using the SAS statistical software (SAS institute 2013) using the general linear model (GLM) procedure. Single degree of freedom contrasts for the treatment (tillage and cover crop) effects were divided into ‘no till vs. tillage (NT vs. Till)’ and ‘cover crop vs. no cover crop (CC vs. NC)’ and ‘tillage*cover crop interaction (Till*CC)’. Statistical differences were declared to exist at $p \leq 0.05$ probability level.

RESULTS AND DISCUSSION

Ponded Infiltration Measurements

After infiltration measurements were conducted in the field, two infiltration models (Parlange and Green-Ampt) were fitted to the measured cumulative infiltration data as a function of time. Typical replicates for the cover crop with tillage (CC-Till), cover crop with no tillage (CC-NT), no cover crop with tillage (NC-Till) and no cover crop with no tillage (NC-NT) treatments are shown in fig. 4.1. These figures illustrate the rapid initial increase in cumulative infiltration at early times and the more constant increase in cumulative infiltration near 1.5 to 2 hours after initiating infiltration.

The models fit the data well with coefficients of variation (r^2) greater than 0.92, and most of the coefficients near 0.99. Both models (Parlange and Green-Ampt) appeared to fit the measured data well.

Bulk density (Db) and antecedent volumetric water content (VWC)

Results for bulk density and antecedent soil water content are shown in table 4.2. There were no significant differences between cover crop and tillage managements for these properties. However, bulk density at the 100 to 200 mm (4 to 8 in) depth was 1.26 g cm^{-3}, about 27% greater than that at the 0 to 100 mm (0 to 4 in) depth.

Averaged across tillage in 2014 and 2015, volumetric water content (VWC) tended to be lower in CC compared to NC management. Cover crops have been reported to increase evapotranspiration from the soil (Dabney et al., 2001). This may be the reason for the lower water content in cover crop plots. In 2014, VWC was very similar between tillage and no-till (NT) management. In 2015, however, VWC tended to be lower in tillage compared with NT management (table 4.2). One possible reason for the lower water content in tillage compared to NT plots in 2015 could be an increased soil water evaporation caused by soil tillage.

Sorptivity (S) Parameter

The geometric means of the *S* parameter values estimated using both models (Parlange and Green-Ampt) were significantly affected by treatments in 2015 ($p < 0.05$) (table 4.3). In 2015, the cover crop vs. no cover crop contrast (CC vs. NC) was significant for the *S* parameter in each model. The Parlange *S* parameter for CC was 38.6 mm $h^{-0.5}$, about 82% greater than that for NC, while the Green-Ampt *S* parameter for CC was 34.0 mm $h^{-0.5}$, about 90% greater than that for NC (table 4.3). Although differences were not significant for this contrast in 2014, the *S* parameter estimated from both models tended to be greater for CC compared to NC management.

Sorptivity is highly dependent on antecedent soil water content. The higher *S* parameter values in cover crop management compared to no cover crop management (averaged across tillage) in 2014 (Parlange: CC = 36.3 mm $h^{-0.5}$, NC = 20.0 mm $h^{-0.5}$; Green-Ampt: CC = 29.1 mm $h^{-0.5}$, NC = 19.4 mm $h^{-0.5}$) and 2015 (Parlange: CC = 38.6 mm $h^{-0.5}$, NC = 7.04 mm $h^{-0.5}$; Green-Ampt: CC = 34.0 mm $h^{-0.5}$, NC = 3.56 mm $h^{-0.5}$) appeared to be a function of lower antecedent soil water content. This result shows the ability of cover crops to transpire water from the field as evidenced by the numerically lower antecedent volumetric water content in these plots (averaged across tillage) (table 4.2). The cover crop's ability to reduce near-surface soil water content through transpiration can be important in very wet early growing seasons as cover crops may help increase the growing season of the cash crop by removing soil water from the field. The differences in soil water content between cover crop and no cover crop management may not be significant enough to reduce crop productivity, even in a drier growing season as reported by Daigh et al. (2014). In fact, Daigh et al. (2014) reported that in a drought year, cover crops probably enhanced infiltration and maintained better soil water content compared with no cover crop. Despite the near-surface soil water transpiration by cover crops, Sims (1989) and Gardner (1992) suggested that cash crop yield can be maintained or improved through appropriate specie selection and proper termination timing of cover crops.

Tillage may be performed for various reasons, one of which is seedbed preparation. When used as a means of seedbed preparation, tillage may help aerate the soil, thus drying it up in wet seasons, as evidenced in the numerically higher *S* parameter value estimated from both models in 2014 (this result was not consistent over both years of the study). Sorptivity is related to the variables or parameters controlling the hydraulic conductivity of porous materials. These variables include grain size distribution and porosity of the porous medium as well as viscosity, density and relative permeability of the infiltrating liquid (Schulte et al., 2007). Therefore, sorptivity can be viewed as a property that can affect the ability of a porous material to absorb or desorb water in zones and regions affected by capillarity, like the vadoze zone.

Saturated Hydraulic Conductivity (Ks) Parameter

The geometric means of the K_S parameter values estimated from the Parlange and Green-Ampt models were significantly affected by treatments in 2014 ($p < 0.01$) (table 4.3). In 2014, the cover crop vs. no cover crop (CC vs. NC) and no-till vs. tillage (NT vs. Till) contrasts were significant for the K_S parameter in each model. The Parlange K_S parameter for CC was 38.4 mm h^{-1}, about 75% greater than that of NC. The Green-Ampt K_S parameter for CC was 31.4 mm h^{-1}, about 80% greater than that of NC. The Parlange K_S parameter for NT was 30.4 mm h^{-1}, about 42% greater than that of Till. Similarly, the Green-Ampt K_S parameter for NT was 25.9 mm h^{-1}, about 54% greater than that of Till (table 4.3).

In 2014, the quasi-steady infiltration rate and field saturated hydraulic conductivity parameter values estimated from infiltration measurements in perennial fescue grass were higher compared with the adjacent main treatments (cover crop and tillage). However, values were not significantly different between the perennial grass and cover crop treatments, although perennial grass had numerically higher values (Appendix A. 2.7). The trend for greater water infiltration in perennial grass systems compared with CC and tillage management practices is presumed to be as a result of the extensive roots of perennial grass systems and these roots may be present for several years.

Studying the same site, Haruna et al. (2017) reported that cover crops had 30% more macropores compared to no cover crop management, averaged over two depths [0 to 100 and 100 to 200 mm (0 to 4 and 4 to 8 in)] two weeks after cover crop termination and spring tillage (150 mm [6 in] deep moldboard plow done in May; the same tillage practice for this study). This suggests that the macropores generated by cover crops may persist for some time. Haruna et al. (2017) also reported a trend of lower soil bulk density and higher saturated hydraulic conductivity (measured on cores in the laboratory) in CC compared to NC management. Cover crop roots have been reported to reduce soil bulk density (Villamil et al. 2006; Blanco-Canqui et al. 2011) and improve pore size distribution and pore connectivity (Villamil, 2006). When these roots die out, they can increase soil organic matter (Sainju et al. 2002; Villamil et al. 2006), thus increasing aggregate stability (Dapaah and Vyn, 1998). The leaves of cover crops can also provide soil cover (Haramoto and Gallandt, 2004) and reduce splash detachment and surface crusting (Folorunso et al. 1992). All these factors can potentially improve soil properties and may have accounted for increased infiltration in CC compared to NC found in the current study. Other researchers (e.g. McVay et al. 1989; Folorunso et al. 1992; Gulick et al. 1994; Joyce et al. 2002) have reported similar findings. The ability of cover crops to increase water infiltration can potentially lead to reduced water runoff and nutrient loss and increased grain crop productivity.

Haruna et al. (2017) also reported that tillage reduced soil bulk density by 10% and increased coarse mesopores (defined as soil pores with effective diameter of 60 – 1000 μm) by 80% (averaged over two depths [0 to 100 and 100 to 200 mm; 0 to 4 and 4 to 8 in] two weeks after cover crop termination and spring tillage). However, these improved soil properties are temporal and may not persist over time (Haruna et al. 2017). The lack of significant differences in infiltration between tillage and no-till management from the current study supports this fact, since infiltration studies were conducted about two months after tillage. Another reason for the lack of significant differences in infiltration between both tillage management practices could be because tillage can interrupt capillary pores and reduce pore connectivity (Azooz et al., 1996) both of which can reduce water infiltration. Lipiec et al. (2006) reported higher water infiltration in tillage compared to no-till management. In contrast, Abid and Lal (2005) reported that tillage reduced infiltration, partly due to a decrease in pore connectivity caused by tillage.

Field Saturated Hydraulic Conductivity (Kfs) Parameter.

In order to estimate the field-saturated hydraulic conductivity, the quasi-steady state infiltration rate (q_s) was used. The quasi-steady state infiltration rate was affected by treatment in 2014 and by the CC vs. NC contrast in 2014 and (at $p<0.06$) in 2015 (table 4.4). In 2014, the q_s parameter value for CC was 69.0 mm h^{-1}, about 63% greater than that for NC. In 2015, the q_s parameter value for CC was 47.5 mm h^{-1}, about 48% greater than that for NC.

The quasi-steady infiltration rate has been equated to the saturated hydraulic conductivity of the surface layer when infiltration takes place (Philip, 1957b). More recently, the q_s parameter was related to the point, during water infiltration, when the volume of water entering the soil at fixed time intervals becomes constant (Amoozegar, 2004). Arriaga et al. (2010) stated that the quasi-steady infiltration rate is assumed to be achieved when the slope of the cumulative infiltration at two infiltration times is within 5%

of each other. It is therefore presumed that a higher q_s parameter value means higher cumulative infiltration.

The field saturated hydraulic conductivity (K_{fs}) parameter was affected by treatment and by the CC vs. NC contrast in 2014. In 2015, the K_{fs} parameter was affected (at $p<0.06$) by the CC vs. NC contrast (table 4.4). In 2014, the K_{fs} parameter value for CC was 27.8 mm h^{-1}, about 63% greater than that for NC. In 2015, the K_{fs} parameter value was 38.3 mm h^{-1}, about 48% greater than that for NC. This suggests that the inclusion of cover crops in crop production may enhance the performance of tillage in improving some infiltration parameters.

Correlation between Kfs and Ksat.

In order to evaluate the consistency of the parameters obtained from the field infiltration data with the laboratory measured data (Haruna et al., 2017), comparisons were made between the K_{fs} parameter and the saturated hydraulic conductivity (K_{sat}) data measured previously in the laboratory. These K_{sat} data were measured in 2014 at the 0 to 100 mm (0 to 4 in) depth and extracted from Haruna et al. (2017). These K_{sat} data were correlated with the K_{fs} estimated parameter values from 2014. The correlation coefficient for the regression between K_{fs} and K_{sat} was found to be 0.48. The slope of the regression was estimated to be 0.37 (Apendix A2.13). The K_{fs} parameter value could be estimated as $0.5*K_{sat}$ (Bouwer, 1986) and $0.67*K_{sat}$ (Rachman et al. 2004). In the current study, this coefficient is estimated to be $0.4*K_{sat}$, which is slightly lower than the other two studies but similar to the one proposed by Kumar et al. (2012). By reducing or eliminating the diverging and horizontal flow through macropores, laboratory measured K_{sat} can better relate to the K_{fs} (Rachman et al., 2004).

SUMMARY AND CONCLUSIONS

Single-ring infiltrometers were used to measure ponded infiltration into cover crop (CC) and tilled plots once in 2014 and once in 2015. In 2014, the Parlange model K_S parameter value for CC was 38.416 mm h^{-1}, about 75% greater than that for no cover crop (NC), while the Green-Ampt model K_S parameter for CC was 31.4 mm h^{-1}, about 80% greater than that for NC. In 2015, the Parlange model S parameter for CC was 38.6 mm $h^{-0.5}$, about 82% greater than that for NC, while the Green-Ampt S parameter for CC was 34.0 mm $h^{-0.5}$, about 90% greater than that for NC. The sorptivity (S) parameter value estimated using both models tended to be greater in tilled than no-tilled plots in 2014. The quasi-steady state infiltration rate and field saturated hydraulic conductivity parameters were significantly higher in cover crop compared with no cover crop management.

Cover crops increased infiltration. This can possibly lead to reduced water and nutrient runoff, and increase productivity. Tillage slightly increased infiltration but only for one year, likely because tillage increased pore tortuosity in the next year. Therefore, management practices, like cover crops, that have the potential to increase water infiltration are encouraged.

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Table 4.1
Selected soil physical and chemical properties of the Waldron silt loam at various soil depths and horizons.

Depth (cm)	Horizon	Clay (g kg^{-1})	Silt (g kg^{-1})	Sand (g kg^{-1})	OC[#] (g kg^{-1})	pH (H_2O)
0-10	Ap	200	650	150	8.4	6.71
10-20	Ap	210	630	160	8.3	6.80
20-40	C1	200	630	170	8.3	6.79
40-60	Cg1	210	640	150	8.3	6.85

[#] Organic carbon. May be converted to organic matter using a factor of 2.0 (Prybil, 2010)

Table 4.2

Means and standard deviation for bulk density (Db) and antecedent volumetric water content (VWC) in the cover crop with tillage (CC-Till), cover crop with no-till (CC-NT), no cover crop with tillage (NC-Till), and no cover crop with no-till (NC-NT) treatments in 2014 and 2015.

	Year			
	2014		**2015**	
Treatment	Db (g cm^{-3})	VWC (cm^3 cm^{-3})	Db (g cm^{-3})	VWC (cm^3 cm^{-3})
CC-Till	1.21±0.08	0.18±0.06	1.16±0.06	0.13±0.05
CC-NT	1.17±0.14	0.14±0.05	1.23±0.07	0.16±0.06
NC-Till	1.14±0.04	0.15±0.02	1.19±0.12	0.19±0.03
NC-NT	1.12±0.08	0.20±0.11	1.23±0.11	0.20±0.03
Depth (mm)				
0-100	1.11±0.08	0.16±0.05	0.92±0.06b	0.12±0.03
100-200	1.20±0.09	0.18±0.06	1.26±0.10a	0.19±0.04
Analysis of Variance p > F				
Treatment	0.65	0.75	0.69	0.26
NT vs Till	0.62	0.86	0.30	0.46
CC vs NC	0.28	0.71	0.72	0.08
CC*Till[#]	0.87	0.35	0.79	0.77

Mean comparisons were only made when *P values* for the main effects were ≤ 0.05. Within a soil property, treatment means with different letters for a soil property are significantly different at the 0.05 probability level.

[#] Tillage by cover crop interaction

Table 4.3

Geometric means for saturated hydraulic conductivity (K_s) and sorptivity (S) parameters estimated by the Parlange and Green-Ampt models in the cover crop with tillage (CC-Till), cover crop with no-till (CC-NT), no cover crop with tillage (NC-Till), and no cover crop with no-till (NC-NT) treatments in 2014 and 2015.

	Year			
	2014		**2015**	
Treatment	S (mm $h^{-0.5}$)	K_s (mm h^{-1})	S (mm $h^{-0.5}$)	K_s (mm h^{-1})
Parlange				
CC-Till	38.7	27.9b	36.6a	35.7
CC-NT	33.8	49.0a	40.6a	40.0
NC-Till	24.3	7.31c	4.45b	27.8
NC-NT	15.7	11.8c	9.62b	24.0
Analysis of Variance p > F				
Treatment	0.57	0.01	0.02	0.67
NT vs Till	0.57	0.02	0.12	0.96
CC vs NC	0.24	0.01	0.03	0.27
CC*Till	0.76	0.81	0.22	0.69
Green-Ampt				
CC-Till	31.1	19.5b	32.2a	27.8
CC-NT	27.1	43.3a	35.9a	31.8
NC-Till	24.1	4.31d	1.78b	26.2
NC-NT	14.7	8.49c	5.35b	21.5
Analysis of Variance p > F				
Treatment	0.81	0.01	0.01	0.91
NT vs Till	0.60	0.02	0.22	0.94
CC vs NC	0.48	<0.01	0.02	0.59
CC*Till[#]	0.77	0.68	0.30	0.69

Mean comparisons were only made when *P values* for the main effects were ≤ 0.05. Within a model, treatment means with different letters for a soil property are significantly different at the 0.05 probability level.

[#] Tillage by cover crop interaction

Table 4.4

Geometric means of quasi-steady state infiltration rate (q_s) and field-saturated hydraulic conductivity (K_{fs}) in the cover crop with tillage (CC-Till), cover crop with no-till (CC-NT), no cover crop with tillage (NC-Till), and no cover crop with no-till (NC-NT) treatments in 2014 and 2015.

	Year			
	2014		**2015**	
Treatment	q_s (mm h^{-1})	K_{fs} (mm h^{-1})	q_s (mm h^{-1})	K_{fs} (mm h^{-1})
CC-Till	38.3a	30.9a	56.5	45.6
CC-NT	30.7a	24.8a	38.6	31.1
NC-Till	12.5b	10.1b	21.9	17.7
NC-NT	13.3b	10.7b	27.6	22.3
Analysis of Variance p > F				
Treatment	0.01	0.01	0.26	0.26
NT vs Till	0.49	0.49	0.36	0.36
CC vs NC	0.02	0.02	0.06	0.06
CC*Till[#]	0.68	0.68	0.812	0.82

Mean comparisons were only made when *P values* for the main effects were ≤ 0.05. Within a model, treatment means with different letters for a soil property are significantly different at the 0.05 probability level.

[#] Tillage by cover crop interaction

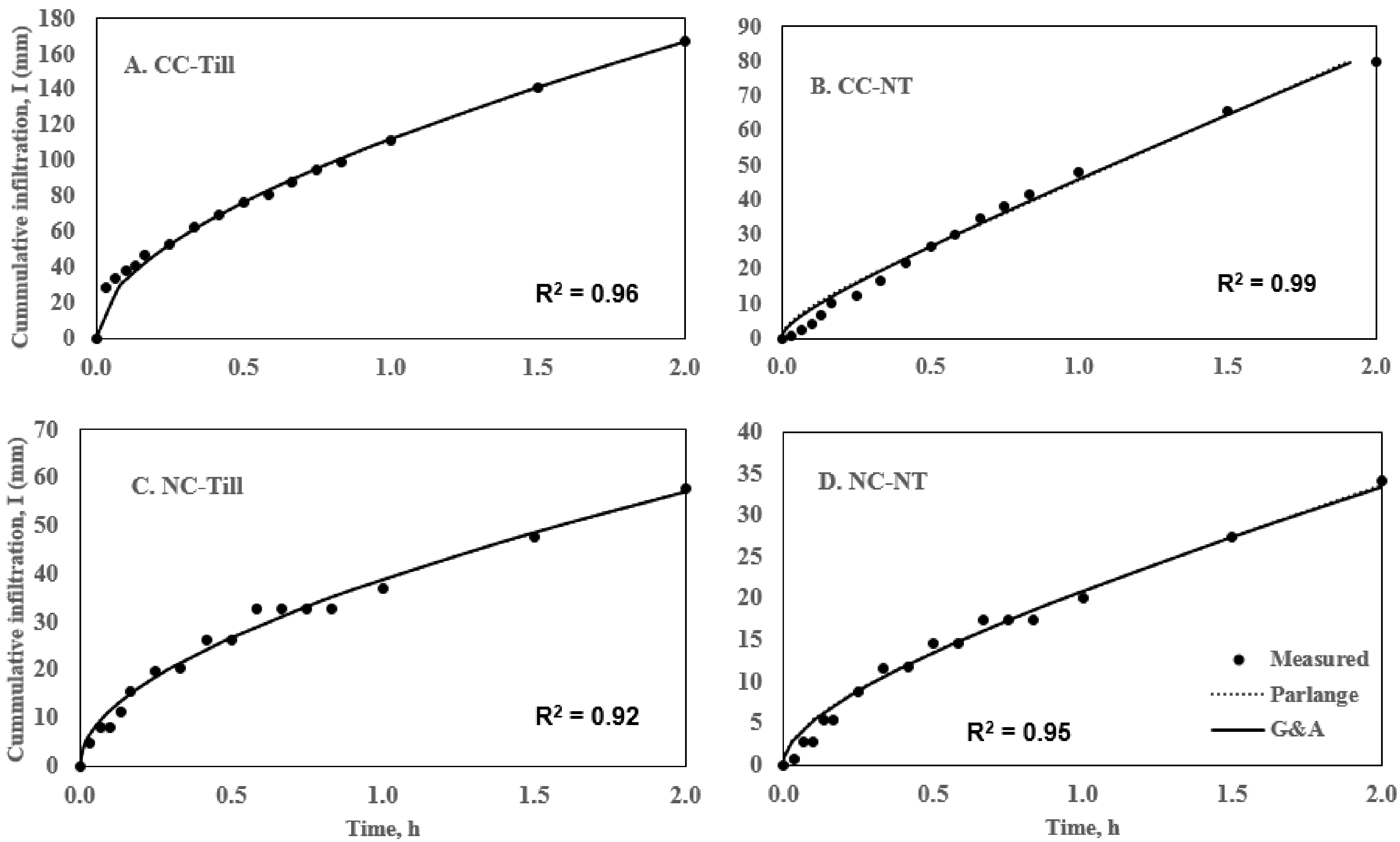

Figure 4.1. The Parlange and Green-Ampt (G&A) models fitted to measured ponded infiltration data for typical replicate under (A) cover crop with tillage (CC-Till), (B) cover crop with no tillage (CC-NT), (C) no cover crop with tillage (NC-Till) and (D) no cover crop with no tillage (NC-NT) treatments for 2014. Please note that the *y*-axis scale is different for the four treatments.
Please also note that the Parlange fit lies directly below the Green-Ampt fit in all figures.

CHAPTER 5

SOIL THRMAL PROPERTIES INFLUENCED BY PERENNIAL BIOFUEL AND COVER CROP MANAGEMENT

ABSTRACT

Heat transport is an important factor that can influence the soil environment. A study was conducted at the University of Missouri Bradford Research Center to evaluate the influence of perennial biofuel and cover crops on soil thermal properties. The experimental design included three replicate blocks in a completely randomized design with four treatments. The four treatments included two levels of cover crops (cover crops [CC] vs. no cover crops [NC]) collectively called row crops (RC) and two treatments of biofuel crops. Cover crops used included Cereal rye (*Secale cereal* L.), Hairy vetch (*Vicia villosa* L.) and Austrian winter pea (*Pisum sativum subsp. arvense*). The two biofuel treatments included perennial biofuel crops (PB): giant miscanthus (*Miscanthus x gigantus* J.M. Geef & Deuter ex Hodkinson & Renvoize) and switchgrass (*Panicum vergatum* L.), both collectively called PB. Soil samples were collected at 10 cm depth increments from the soil surface to a depth of 30 cm. Soil thermal properties (thermal conductivity [λ], volumetric heat capacity [C_V], and thermal diffusivity [D]) and volumetric water content (θ) were determined at 0, -33, -100 and -300 kPa soil water pressures. Additionally, bulk density and soil organic carbon (SOC) were determined. Results showed that PB had significantly higher θ at all pressures measured and also higher SOC compared to RC. As

a result, PB had 11% higher C_V at saturation compared to RC. Cover crops had 18% higher θ at saturation and 26% higher SOC compared to no cover crop; this led to 13% higher C_V in cover crops compared to no cover crop management. Row crops had significantly higher λ and D compared to perennial biofuel crops. Results from the current study imply that CC and PB can change soil thermal properties by reducing λ and D and increasing C_V; this indicates that these management systems can improve the ability of the soil to better handle a more variable climate.

Abbreviations: CC, cover crops; NC, no cover crops; PB, perennial biofuel crops; SG, switchgrass; GM, giant miscanthus; RC, row crops; SOC, soil organic carbon.

INTRODUCTION

Heat transport through the vadoze zone is an important environmental factor that influences several components and processes of the soil such as water and nutrient transport. Heat transport also plays an important role in microbial activity, seed germination and plant root survival and growth within the soil (Shukla, 2014). It is therefore an important factor that can determine crop productivity. Heat transport within a material can be estimated by measurement of its thermal conductivity (λ), volumetric heat capacity (C_V) and thermal diffusivity (D) (Hopmans et al., 2002). These thermal properties can provide information about the ability of the material to transfer heat, buffer against rapid heat change and diffuse heat internally; all of which are essential in estimating heat transport.

Thermal conductivity (λ) of a material represents its ability to transport heat and it depends on several factors including mineralogical composition, bulk density, volumetric water content (θ), soil organic carbon (SOC) (Wierenga et al., 1969; Ren et al., 1999; Ochsner et al., 2001; Heitman et al., 2007; Lu et al., 2007; Heitman et al., 2008; Ju et al., 2011) and soil management (Yardev and Sexana, 1973). Generally, management practices that increase soil compaction tend to increase λ since the λ of soil minerals is higher than that of air and water (Wierenga et al., 1982; Bristow, 2002). Abu-Hamdeh and Reeder (2002) reported significant differences in λ between sand, sandy loam and clay loam soils. These researchers also reported that the smaller particles in the clay loam soils generated more thermal resistance, thus reducing λ. Also, clays tend to have a higher porosity and this can reduce the contact between soil minerals, thus increasing thermal resistance and reducing λ.

Volumetric heat capacity (C_V) measures the ability of a material to resist changes in temperature and it depends on several factors such as θ and SOC (Yardev and Sexana, 1973; Ochsner et al., 2001; Abu-Hamdeh, 2003; Ju et al., 2011). Since C_V of water and SOC are higher than values of air (Bristow, 2002), management practices that increase θ and SOC have the potential to increase C_V (Abu-Hamdeh, 2003).

Thermal diffusivity (D) is a ratio of λ and C_V (Shukla, 2014) and it can be viewed as a description of the relative ease with which a material transfers heat. Thus, soil management practices that increases λ and reduces C_V will conduct more heat and buffer less heat change than management practices that have the potential to increase C_V and decrease λ. This may cause higher evaporation of water from the soil, leading to a further decrease in θ and it may potentially reduce crop productivity.

Thermal conductivity of the soil can be measured by the steady-state method. However, this method involves many significant assumptions such as equal heat flux through the soil and glass and one-dimensional vertical heat flow through the soil (Shukla, 2014). The steady-state method also has a significant limitation of creating a non-uniform profile within the column, primarily due to the redistribution of water under a steady state temperature gradient (Jury and Miller, 1974). To overcome these limitations, the transient method can be used.

The transient method involves the application of heat, either periodically or as a pulse, resulting in periodic (phase signal output) or transient (amplitude signal output) signal changes in the sample, respectively. This method may involve the use of heat probes inserted directly into the soil. This eliminates the need to account for the heat flux through glass. By measuring the phase or amplitude of the pulsed heat wave, the transient method accounts for the multi-dimensional heat flow through the soil. The transient method includes minimal soil disturbance, resulting in more uniform distribution of water within the column. All these often leads to better λ measurement (Shukla, 2014).

The thermal properties of the soil can be measured quickly and conveniently by the transient method by utilizing heat pulse probes (Campbell et al., 1991; Bristow et al., 1993, 1994a, 1994b; Kluitenberg et al., 1993; Jury and Horton, 2004). The probe consists of two parallel needle-like probes (approximately 1 mm outer diameter) separated by a distance, r. One probe contains a heater while the other contains a temperature sensor. A heat pulse is applied to the heater probe, and the temperature response is recorded at the sensor probe. If an instantaneous heat pulse is introduced into a material, Campbell et al. (1991) estimated that the maximum temperature rise at a distance, r, from the heat source is inversely related to the specific heat capacity and directly related to the amount of heat liberated at the source. This allows for the determination of the thermal properties of the material.

Anthropogenic land management such as tillage, conservation practices and irrigation can alter heat transport within the soil (Adhikari et al., 2014). Abu-Hamdeh and Reeder (2000) reported that tillage could increase soil bulk density, reduce the spaces between soil particles, reduce θ and alter soil thermal properties. Ochsner et al. (2001) also reported similar findings. Adhikari et al. (2014) reported significant effects of various land management practices on soil thermal properties. These researchers reported that both natural and restored prairies significantly increased SOC and θ thereby increasing C_V compared to a corn and soybean rotation.

Cover crop adoption into crop rotation systems has seen some increases over the past decade, both in acreage and percentage of farm managers using them, due to their benefits in improving crop productivity, and these benefits have been well documented (Dabney, 2001; Hartwig, 2002; Singer et al., 2007; Blanco-Canqui et al., 2011; Daigh et al., 2014; Haruna and Nkongolo, 2015). Living cover crops can reduce daily maximum soil temperature (Voss and Surmani, 1997; Blanco-Canqui et al., 2011) and provide shade that can reduce evaporation of soil water and maintain θ (Wagger and Mengel, 1988; Dabney, 2001). By incorporating their biomass into the soil, cover crops can improve SOC (Dabney, 2001). All these factors are hypothesized to alter soil thermal properties.

As a result of the need to find an alternative energy source, several plants including giant miscanthus (*Miscanthus x gigantus*) and switchgrass (*Panicum vergatum*) are being grown for conversion to biofuel (Gressel, 2008). Miscanthus is a perennial, warm-season grass native to Asia with the C4 photosynthetic pathway. Miscanthus species have been used for forage and roofing in Japan for many decades, and they were managed through grazing and burning (Stewart et al., 2009). They have been studied in several European countries and are now being used commercially for heat and power generation (Jones & Walsh, 2001). In the USA, research into miscanthus began in 2001 (Pyter et al., 2007) and it has been proposed for use as a supplement for heat and power generation (Heaton et al., 2004, Khanna et al., 2008).

Switchgrass is also a perennial warm-season grass with a C4 photosynthetic pathway and it is native to most of North America (Vogel, 2004). Switchgrass has several characteristics that make it a desirable biomass energy crop: it has consistently high yield relative to other species in varied environments, it requires minimal agricultural inputs, and it is relatively easy to establish from seed (McLaughlin and Kzsos, 2005; Parrish and Fike, 2005; Sanderson et al., 2007).

Currently, several studies have quantified the influence of cover crops, miscanthus and switchgrass on soil physical properties such as bulk density, θ, and pore size distributions. However, studies on the influence of cover crops, miscanthus and switchgrass on soil thermal properties are currently lacking. Therefore, the objective of this study was to evaluate the influence of perennial biofuel and cover crops on θ, SOC, bulk density and soil thermal properties.

MATERIALS AND METHODS

Site Description

The study was conducted at the University of Missouri Bradford Research Center, located about 18 km east of Columbia. The soil was classified by the United States Department of Agriculture (USDA) as Mexico silt loam (fine, smectitic, mesic Vertic Epiaqualf). Table 5.1 shows soil texture for the three sampling depths of the study. The average annual precipitation for the area is about 1083 mm, with the months of January (49 mm) and May (126 mm) being the driest and wettest months, respectively. The average annual temperature is about 12.5^{o}C with the months of July (31^{o}C) and January (-6^{o}C) being the warmest and coldest months, respectively.

The experimental design included three replicate blocks in a completely randomized design, with two levels of cover crops (cover crops [CC] vs. no cover crop [NC]), also collectively referred to as row crops (RC) and two perennial biofuel crops. A suite of three cover crops was used for the cover crop treatment; Cereal rye (*Secale cereal*

L.), Hairy vetch (*Vicia villosa* L.) and Austrian winter pea (*Pisum sativum subsp. arvense*). The main grain crop grown was continuous corn (*Zea mays* L.), planted in May and harvested in September of each growing season. The soil was under no tillage management. The perennial biofuel crops (PB) included giant miscanthus (GM) (*Miscanthus x gigantus* J.M. Geef & Deuter ex Hodkinson & Renvoize) and Switchgrass (SG) (*Panicum vergatum* L.), both referred to as perennial biofuel crops henceforth.

The cover crop plots were established in 2010. The cover crops were seeded every year in September and October, allowed to grow throughout the winter months, and then terminated in late spring of the next year. For this study, the cover crops were over-seeded on September 8, 2014 and then drilled in on October 1, 2014 at the following rates; Cereal rye (50 kg ha^{-1}), Hairy vetch (17 kg ha^{-1}) and Austrian winter pea (34 kg ha^{-1}) using a Kinze® 38 cm row planter with special blades that allowed small seeded cover crops to be planted. The cover crops were allowed to grow during the winter months and terminated in June using glyphosate (*n-[phosphonomethyl] glycine*). The perennial biofuel crops were established in 2007. Miscanthus seedlings were hand planted (plugs) in a 0.9 x 0.9 m grid (1984 plants ha^{-1}). Switchgrass was planted using a Tye Drill in 19 cm spacing at 7 kg ha^{-1}. The PB were harvested with a silage chopper each year and the biomass was removed and used for simulated biofuel production. All plots were rain-fed throughout the study.

Soil Sampling and Analysis

Soil samples were collected to determine bulk density, soil organic carbon (SOC), volumetric water content and thermal properties using a sampler with a cylindrical core measuring 76.2 mm diameter by 76.2 mm long. The samples were collected from non-trafficked row areas just before cover crop termination in early June 2015 at three soil depths; 0-10, 10-20 and 20-30 cm. A total of 36 samples were collected (4 treatments x 3 replicates x 3 depths). After the samples were collected, they were trimmed, labelled and secured with plastic caps at both ends using masking tape. They were stored in a cold storage room at 4^{o} C until analysis was done.

After removing the soil cores from the cold storage, the plastic caps were gently removed. Cheesecloth was placed at the bottom of each core and secured using rubber bands. They were placed in a tub and saturated with tap water for about 48 hours by gently raising the water level. The electrical conductivity of the water was 0.68 dS m^{-1}. After saturation, the samples were weighed, placed on pressure plates and equilibrated to -33, -100 and -300 kPa (Dane and Hopmans, 2002) pressures in a temperature-controlled room (25^{o}C). The soils were weighed after equilibration at each pressure and water content was determined at each of those pressures.

Thermal properties were determined using a KD2 (Decagon Devices) dual-probe heat-pulse sensor. This sensor is similar to the one used by several researchers (e.g Campbell et al., 1991; Bristow et al., 1993; Kluitenberg et al., 1993; Dahiya et al., 2007). The probe was calibrated before measurement and its accuracy was tested using performance verification standards. The probe was inserted vertically into the soil and thermal properties were recorded at each pressure (0, -33, -100 and -300 kPa). Care was taken to ensure proper contact between the soil and the probes as improper contact can lead to errors in measurement (Abu-Hamdeh, 2001). This was done by inserting the probe into new areas during each measurement and also avoiding core walls. Due to the presence of shrink-swell clays, thermal properties were not measured beyond -300 kPa since there might be a risk of crack development at lower pressures.

After thermal properties and volumetric water content (θ) were measured, the soil was oven dried at 105°C and bulk density was measured using the core method (Grossman and Reinsch, 2002). The soil was then ground, passed through a 2 mm sieve. 50g of the < 2 mm particles were used for soil texture determination using the pipette method (Gee and Or, 2002). Another 10g of the < 2 mm aggregates were used for SOC determination. Soil organic carbon was determined by combustion analysis in a Leco C-144 carbon analyzer at the University of Missouri Soil Health Laboratory.

Statistical Analysis

A test of normality was conducted within each treatment, depth and water pressure for bulk density, SOC, water content and thermal properties using Anderson-Darling at $P = 0.05$ using SAS ver 9.4 (SAS Institute). Normality tests showed that all data were normally distributed. Analysis of variance (ANOVA) was further conducted using the general linear method (GLM). Single degree of freedom contrasts for the four treatments (row crop and perennial biofuel crops) effects were divided into 'row crop vs perennial biofuel crops', 'no cover crop vs cover crop', and 'switchgrass vs miscanthus'. Analysis of variance was also conducted to determine the treatment*depth interaction on bulk density, SOC, water content and all thermal properties measured. Statistical differences were declared to exist at $p \leq 0.05$.

RESULTS AND DISCUSSION

Soil Organic Carbon and Bulk Density

The soil organic carbon (SOC) and bulk density means (with standard errors) averaged over the three depths and analysis of variance are shown in Table 5.2. Results show significant treatment effects on both SOC ($p < 0.001$) and bulk density ($p < 0.01$). The contrast between row crop and perennial biofuel crops (RC vs. PB) was significant for both SOC and bulk density. Soil organic carbon and bulk density were also significantly different between cover crops and no cover crop (CC vs. NC) management. Besides these contrasts, sampling depth and treatment by depth interaction (treatment*depth) were also significant for both SOC and bulk density ($p < 0.001$) (Table 5.2).

Soil organic carbon under PB management was 21 g kg^{-1}, about 29% higher than that under RC management. Perennial biofuel crops have higher above ground biomass that can grow for several years. They (PB) also have more extensive roots compared to RC management. The decomposition of this biomass may have resulted in higher SOC in PB compared to RC. Furthermore, anthropogenic factors such as annual row crop production may lead to a faster SOC depletion compared to the perennial crops. Soil organic carbon under CC management was 17 g kg^{-1}, about 26% higher than that under NC management (Table 5.2). This is presumed to be a result of the decomposition of below ground cover crop biomass (roots). Kuo et al (1997), Sainju et al. (2002) and Villamil et al., (2006) reported 7%, 12% and 9% increases in SOC respectively with the use of various cover crops (CC) compared with no cover crops (NC). The difference in SOC between CC and NC was higher in the current study compared to previous studies. This may be because a suite of different cover crops was used in the current study as opposed to a single cover crop. The various cover crops will increase belowground biomass significantly, which may lead to increased SOC.

Improvements in SOC have been related to increased carbon sequestration (Allmaras et al., 2000; Post and Kwon, 2000; West and Post, 2002; Lal, 2004;

Franzluebbers, 2005). Lal (2004) reported that besides enhancing food security, carbon sequestration has the potential to offset global fossil fuel emissions by 5 to 15% (0.4 to 1.2 gigatons of carbon) per year. Results from the current study suggest that PB may significantly improve carbon sequestration compared to RC management while CC may lead to improved carbon sequestration compared to NC management and these management systems (PB and CC) may help counteract fossil fuel emissions.

As expected, SOC decreased with increasing depth probably due to reduced biomass with increasing depth. Treatment by depth interactions showed that SOC was significantly different among all treatments in the 0-10 cm depth, with SOC in GM > SG > CC > NC. However, in the 10-20 and 20-30 cm depths, SOC was not significantly different among the PB treatments but was different between PB and RC and also between CC and NC (GM = SG > CC > NC) (Table 5.2).

Results show that bulk density under RC management was 1.38 g cm^{-3}, about 7% higher than that under PB management. This corresponds to SOC results. Results also show that bulk density was significantly higher in NC compared to CC management (Table 5.2). Bulk density increased with depth from 0-10 cm to 10-20 cm but was similar between 10-20 cm and 20-30 cm depths. Treatment by depth interactions showed that bulk density was significantly different ($p < 0.05$) between RC and PB management at the first depth, but was not different among the RC and the PB treatments for this depth (NC = CC > SG = GM). The presence of plant roots at this depth was presumed to be responsible for lowering bulk density in both PB and CC management compared with NC. There were no significant differences in bulk density among all management systems at the 20-30 cm depth.

Generally, SOC decreased with increasing bulk density among various management systems and between the first two soil depths. The addition of plant biomass and plant roots has been reported to increase SOC, reduce bulk density and improve soil structure (Mishra et al., 2003). The significant differences in SOC and bulk density between PB and RC management systems are presumed to be because of higher below ground biomass and root density in PB management noticed during sample collection. Similarly, Tufekcioglu et al. (1998) reported about 33% higher root density in PB (switchgrass) compared to RC management. These roots can relieve soil compaction and thus soil bulk density.

Volumetric Water Content

The volumetric water content (θ) means (with standard errors) averaged over the three depths and analysis of variance for all treatments at 0, -33, -100 and -300 kPa pressures are shown in Table 5.2. The treatment effect was significant at all soil water pressures measured ($p < 0.05$). The RC vs. PB contrast was significant at all pressures measured. Results showed that θ under PB management at 0, -33, -100, and -300 kPa pressures were 0.54, 0.37, 0.35, and 0.33 $cm^3\ cm^{-3}$, respectively. Under RC management, θ at 0, -33, -100, and -300 kPa pressures were 23, 10, 10 and 9% lower, respectively, than that under PB management at these pressures. The NC vs. CC contrast was significant at 0 and -33 kPa pressures. At saturation, θ under CC management was 0.45 $cm^3\ cm^{-3}$, about 18% higher than that under NC management. At -33 kPa pressure, θ under CC was 0.35 $cm^3\ cm^{-3}$, about 11% higher than that under NC management.

Soil organic carbon can improve soil structure, and associated with improved soil structure is higher porosity. Also, growing plant roots can create new pores while dead and decaying roots can leave empty pores (Murphy et al., 1993; Fuentes et al., 2004), thus increasing porosity. Besides higher SOC, PB also have higher root densities compared to RC (Tufekcioglu et al., 1998) and these roots (switchgrass) can grow up to 300 cm depth (Ma et al., 2000; Mann et al., 2012). These roots can increase pore size distribution and the volume of transmission pores. Zaibon et al., (2016) reported that switchgrass had 53 and 27% higher macropores (> 1000 µm diameter) and coarse mesopores (60–1000 µm diameter) compared to RC management respectively. Furthermore, Mitchell et al. (1995) reported that PB could create more stable macropores compared to RC. All these factors are presumed to be responsible for the higher θ found in PB compared to RC management and the lower θ found in NC management between 0 and -33 kPa pressures.

In a study by Haruna et al. (2017), it was reported that cereal rye CC had 30% more macropores compared to NC management, averaged over two depths (0-10 and 10-20 cm) two weeks after CC termination and spring tillage. Villamil et al. (2006) reported significant increases in the volume of interconnected pores in cover crop compared to no cover crop management. Water drainage occurs rapidly through these interconnected macropores and may account for the higher θ in CC compared to NC managements between 0 and -33 kPa pressure noticed in the current study. The higher θ in CC compared to NC at -33 kPa suggests that CC may have higher mesopores (10–1000 µm diameter) compared to NC.

Soil sampling depth also had significant effects at all pressures measured ($p < 0.001$) (Table 5.2). Volumetric water content reduced with depth from 0-10 to 10-20 cm but was not significantly different between 10-20 and 20-30 cm depths. This was in concert with bulk density results (Table 5.2). The treatment by depth interaction was also significant at all pressures measured ($p < 0.005$). Results show that at saturation, θ was significantly higher in PB compared to RC and also in CC compared to NC but not significantly different among the PB at all depths (SG = GM > CC > NC). However, θ was numerically higher in SG compared to GM at 0-10 and 20-30 cm, while θ was numerically higher in GM compared to SG at 10-20 cm depths.

Thermal Conductivity

The thermal conductivity (λ) means (with standard errors) averaged over the three depths and analysis of variance for all treatments at 0, -33, -100 and -300 kPa pressures are shown in Table 5.3. Figure 5.1 a-h shows the λ data plotted as a function of water pressure for each of the depths measured, an additional graph shows the data presented as a function of depth. Averaged over three depths, results show a significant treatment effect on λ values at saturation. The RC vs. PB contrast was significant at 0, -33 and -100 kPa pressures and it showed that RC had 10, 5 and 5% higher λ values compared to PB respectively. The SG vs. GM contrast was significant at 0 kPa and it showed that SG had 9% higher λ values compared to GM management.

The λ values observed from the current study at saturation ranged between 1.10 and 1.42 W m^{-1} K^{-1}. Abu-Hamdeh (2000) reported λ values ranging from 0.40 to 0.79 W m^{-1} K^{-1} for a no-till loam soil at water contents between 0.10 to 0.18 cm^3 cm^{-3}. The higher λ values from the current study are probably due to the higher water content (0.29 to 0.54 cm^3 cm^{-3}). At each soil depth, the highest and lowest λ values were observed in NC and GM management respectively (Fig. 5.1a-c). The NC management had the highest bulk density and lowest SOC values while GM management had the highest SOC and lowest bulk density values. The higher λ values in NC are probably due to the fact that λ increases with an increase in bulk density and a decrease in SOC (Abu-Hamdeh and Reeder, 2003). As bulk density increases, the contact between soil particles also increases, thus increasing λ. Furthermore, the λ of SOC (0.25 W m^{-1} K^{-1}) is lower than that of clay minerals (2.9 W m^{-1} K^{-1}) (Bristow, 2002), and SOC can also reduce bulk density; thus higher SOC can reduce λ.

In general, λ values decreased rapidly with decreasing soil water pressure from saturation to -33 kPa for all treatments and all depths measured (Fig. 5.1a-c). This was presumed to be because of the significant water drainage between these pressures (Table 5.2). Significant water drainage from soil pores causes air to replace the drained water. The λ value of air (0.025 W m^{-1} K^{-1}) is significantly lower than that of water (0.57 W m^{-1} K^{-1}) (Bristow, 2002), thus reducing λ values from saturation to -33 kPa pressures. Several researchers working on different soils and management practices (e.g. Ghuman and Lal, 1985; Ochsner et al., 2001; Abu-Hamdeh et al., 2001; Mori et al., 2003) all reported that λ values decreased with decreasing θ. However, the decrease in λ values between saturation and -33 kPa pressures was higher in the current study compared to the previous studies. This is probably due to the increased water drainage at these pressures (0 and -33 kPa), especially under the PB and CC managements. Between -33 and -300 kPa, λ values decreased slightly for all treatments and all depths measured (Fig. 5.1).

At all pressures measured, λ values were numerically highest at the 10-20 cm soil depth compared to other depths (Table 5.3). This was expected since the distance between soil particles was lower at this depth due to slightly higher bulk density.

At saturation, λ values were significantly lower in GM compared with other treatments at all depths (Fig. 5.1d). This was presumed to be as a result of higher SOC and lower bulk density under this management. At -33 kPa pressure, there were no significant differences in λ values between CC and NC. However, RC had higher λ values in the 0-10 cm depth compared to PB (Fig. 5.1e). Between -100 and -300 kPa pressures, NC had significantly higher λ values compared to other management at the top 10 cm depth only (Fig. 5.1f-g). This result shows that as the soil dries out, λ values were only different in the 0-10 cm depth. Therefore, as θ reduces the role of SOC and bulk density become even more evident, especially at the soil surface. The higher SOC and lower bulk density in PB and CC compared to NC at this depth (Table 5.2) may reduce λ. This demonstrates the influence of the management practices in maintaining optimum soil temperatures for plant growth, especially in the warmer summer months.

Volumetric Heat Capacity

The volumetric heat capacity (C_V) means (with standard errors) averaged over the three depths and analysis of variance for the treatments at 0, -33, -100 and -300 kPa pressures are shown in Table 5.3. Figure 5.2 shows C_V data plotted as a function of water pressure for each of the depths measured, an additional graph shows the data presented as a function of depth. The C_V data estimated using the de Vries (1965) model was very similar to the measured values with a root mean square error (RMSE) of 0.013. Averaged over the three depths, there was a significant treatment effect ($p < 0.001$) on C_V at all pressures measured. Significant contrasts included RC vs. PB and NC vs. CC ($p < 0.001$). At 0, -33, -100 and -300 kPa pressures, PB had 11, 9, 9, and 9% higher C_V values respectively compared to RC. At 0, -33, -100 and -300 kPa pressures, CC had 13, 16, 16 and 16% higher C_V values compared to NC respectively.

Generally, C_V values were observed to decrease significantly from saturation to -33 kPa pressures at all depths measured (Fig. 5.2a-c). Between -33 and -300 kPa pressures, C_V values reduced slightly for some management practices (e.g. CC, GM and SG) and leveled off for other management practice (e.g. NC) at all depths. This was consistent with the results of Abu-Hamdeh (2003) who reported that there was a linear relationship between C_V and θ for both sandy and clayey soils. The reason for the sharp decrease in C_V values between saturation and -33 kPa pressure was presumed to be due to higher water drainage between these pressures. The C_V values of water (4.18 MJ m^{-3} K^{-1}) and organic carbon (2.50 MJ m^{-3} K^{-1}) are both relatively higher than the C_V values of clay minerals (1.20 MJ m^{-3} K^{-1}) (Bristow, 2002). Higher water content encouraged by improved soil structure and porosity caused by SOC and plant roots were presumed to be the reason for the relatively higher C_V values in PB and CC compared to NC at all pressures and depths measured (Fig. 5.2). The higher SOC values under these management systems were also believed to have helped increase the C_V values. Besides acting as a buffer, SOC with its higher surface area, can also increase the amount of water films held between soil particles, thus increasing C_V values in soils with higher SOC.

Depending on the depth sampled and the time of the season, plant canopy may serve as a shade, thus reducing soil water evaporation. Daigh et al., (2014) reported that in a drought year, CC improved water conservation by reducing water evaporation from the soil compared to NC. Blanco-Canqui et al., (2011) reported similar findings. This effect may be more pronounced on the soil surface (Table 5.2). Living vegetation, like PB and CC, can increase soil coverage (Haramoto and Gallandt, 2005) and this can reduce soil water loss due to evaporation (Blanco-Canqui et al., 2011). Increased water content due to reduced soil water evaporation may also help increase C_V values in PB and CC compared to NC management.

Averaged across all management practices, C_V values decreased numerically with an increase in soil depth (Table 5.3). This was consistent with SOC results. At the 0-10 cm depth at saturation, the increasing order of C_V values were NC (3.11 MJ m^{-3} K^{-1}), CC (3.66 MJ m^{-3} K^{-1}), SG (3.74 MJ m^{-3} K^{-1}) and GM (3.84 MJ m^{-3} K^{-1}) (Fig. 5.2d). At 10-20 and 20-30 cm depths, PB had 12 and 11% higher C_V values compared to RC, while CC had 14 and 5% higher C_V values compared to NC respectively. Between -33 and -300 kPa pressures, NC had the lowest C_V values at all depths.

Due to their higher C_V values noticed in the current study, CC and PB can help provide optimum soil temperature for plant growth and microbial activity by resisting rapid heat change and transport. This is important since most plants are more sensitive to soil temperature than aboveground air temperature (Brady and Weil, 2008). Maintaining optimal soil temperature is also important because most plants have a narrow range of soil temperatures for optimal root growth (Kasper and Bland, 1992) and plant development. For example, in temperate regions, cold soil temperature can limit the productivity of grain crops like corn (*Zea mays* L.) and soybean (*Glycine max.*). The rates of microbial activity, such as respiration, also doubles for every 10^0C rise in temperature (MacDonalds et al., 1995). Thus, maintaining optimal soil temperature is important for microbial nutrient cycling.

Furthermore, optimal soil temperature is also dependent on net radiation and surface albedo. As a result of their higher C_V values and dull appearance, wetter soils have lower albedo values compared to drier soils (Shukla, 2014). In a world with increasing concerns over climate variability, cover crops (CC) and perennial biofuel crops (PB) may help improve the C_V of soils by increasing SOC and soil water content and this may lead to more sustainable crop production system. Besides CO_2 sequestration (Lal, 2002), these crops (CC and PB) can also reduce CO_2 emissions from soils by delaying organic matter decomposition due to their higher C_V.

Thermal Diffusivity

The thermal diffusivity (*D*) means (with standard errors) averaged over the three depths and analysis of variance for the treatments at 0, -33, -100 and -300 kPa pressures are shown in Table 5.3. Figure 5.3 shows *D* data plotted as a function of water pressure for each of the depths measured, an additional graph shows the data presented as a function of depth. Averaged over the three depths at saturation, *D* was significantly different among the various treatments ($p < 0.001$). The RC vs PB contrast was significant and it showed that RC had 21% higher *D* values compared to PB management. The NC vs CC contrast was also significant at saturation and it showed that *D* values were 14% higher in NC compared to CC treatment. Thermal diffusivity was significantly different among PB treatments at saturation and it showed that *D* values were 9% higher in switchgrass (SG) compared to miscanthus (GM) (Table 5.3). At -33, -100 and -300 kPa pressure, *D* was 14, 15 and 14% higher in RC compared to PB management respectively. At -33, -100 and -300 kPa pressure, *D* was 17, 18 and 16% higher in NC compared to CC management respectively.

No cover crop management had the highest *D* values compared to other management at all pressures measured and this suggests that NC conducts more heat and buffers less heat change compared to the other management practices. Due to less soil vegetative cover in NC, soil water evaporation may be higher in NC compared to the other treatments. However, this would depend on soil conditions like texture and structure and on atmospheric conditions like temperature and relative humidity. Higher temperature and lower humidity often leads to increased soil water evaporation. On bare soils, such as NC, soil water evaporation may occur in two stages. The first stage involves evaporation at the soil surface and it is limited by the atmospheric evaporative demand. The second stage begins to occur after the surface moisture is depleted and evaporation shifts from the soil surface to the subsurface. The second stage is controlled by soil properties and may lead to the formation of dry soil surface layer (Yamanaka et al., 1998). Thus, excessive evaporation of water and the formation of dry surface layer may reduce soil water and nutrient availability, microbial activity and it may potentially reduce crop yields.

Thermal diffusivity can also increase crop productivity by increasing the length of the growing season of crops. Lower C_V (thus increased λ) can lead to rapid soil temperature increase in spring. This can help warm up the soil and lead to earlier planting and seed emergence. This is of great importance for frozen soils.

Generally, D values increased with a decrease in water pressure from saturation to -33 kPa for all treatments at all depths (Fig. 5.3a-c). Also, the rate of decrease in C_V was faster than the rate of decrease in λ at these pressures. Therefore, the non-linear effect of θ on these properties (λ and C_V) may have resulted in the higher D between saturation and -33 kPa pressures. In contrast, Porter at al. (1985), Usowich et al. (2009) and Adhikari et al. (2014) all reported that increased water drainage between these pressures increased λ by increasing the contact area between soil particles, thus increasing D. However, Abu-Hamdeh (2003) only found this relationship to be true for sandy soils and not clay soils.

Thermal diffusivity values, in the current study, reduced from -33 to -100 kPa and leveled off between -100 and -300 kPa.

At each sampled depth and all soil water pressures measured, D values were highest in NC management (Fig. 5.3). Compared to NC, CC management had lower D values probably due to higher SOC and lower bulk density in CC compared to NC management. Furthermore, CC had a more pronounced influence on C_V compared to λ and this was probably why CC had a significant influence on D. At all depths sampled, D values were highest in NC management compared with other management, with the greatest difference occurring at the 0-10 cm depth (Fig. 5.3d-g).

SUMMARY AND CONCLUSIONS

This study was conducted to evaluate the influence of cover crops and perennial biofuel crops on heat transport parameters under laboratory controlled conditions. Results show that soil organic carbon was about 29% higher under perennial biofuel compared to row crop management due to higher vegetation density and this lead to 7% higher bulk density under row crop compared to perennial biofuel management. Soil organic carbon was also about 26% higher in cover crop compared to no cover crop management.

Thermal conductivity and volumetric heat capacity decreased while thermal diffusivity increased with a decrease in pressure from saturation to -33 kPa in all treatments probably due to the equilibrium relationship between water and air. At saturation, row crops had 10% higher thermal conductivity compared to perennial biofuel crops, while cover crops had 13% higher volumetric heat capacity compared to no cover crops. At all pressures measured, perennial biofuel crops had significantly higher volumetric heat capacity compared to row crops, while cover crops had significantly higher volumetric heat capacity compared to no cover crops. Thermal diffusivity was significantly higher in row crops compared to perennial biofuel and also significantly higher in no cover crop compared to cover crops at all pressures measured.

Cover crops have been advocated for their ability to improve soil health and crop productivity. In addition, the current study demonstrates the influence of cover crops on soil thermal properties. Cover crops can buffer excessive soil heat and this can help increase crop productivity. Furthermore, increasing concerns over climate variability have led to alternate biofuel sources. Apart from providing cleaner energy, some of these biofuel crops can also influence soil thermal properties positively. Therefore, cover crops and biofuel crops can improve soil thermal properties and enable the soil to buffer against extreme temperature changes.

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LIST OF FIGURES

Table 5.1 Soil textural properties as a function of soil depth for the study site (Mexico silt loam).

Depth	Horizon	Sand	Silt	Clay
		----------------------------------	%	----------------------------------
0-10	Ap	5.4	75.9	18.7
10-20	Ap	4.8	77.2	18.0
20-30	Btg1	4.6	71.9	23.5

Table 5.2 Soil organic carbon (SOC), bulk density (Db) and volumetric water content (at selected water pressures).

			Volumetric Water Content (θ)			
	SOC	**Db**	**0 kPa**	**-33 kPa**	**-100 kPa**	**-300 kPa**
Treatment	**(g kg^{-1})**	**(g cm^{-3})**	------------(cm^3 cm^{-3})------------			
CC†	17.20 ± 0.70b‡	1.36 ± 0.04b	0.45 ± 0.02b	0.35 ± 0.01a	0.32 ± 0.01b	0.30 ± 0.01b
NC	12.67 ± 1.25c	1.40 ± 0.03a	0.37 ± 0.01c	0.31 ± 0.01b	0.30 ± 0.01b	0.29 ± 0.01b
GM	21.37 ± 0.86a	1.27 ± 0.07c	0.53 ± 0.02a	0.36 ± 0.02a	0.34 ± 0.02a	0.33 ± 0.02a
SG	20.52 ± 0.83a	1.29 ± 0.06c	0.54 ± 0.02a	0.37 ± 0.02a	0.35 ± 0.02a	0.32 ± 0.01a
Depth (cm)						
0-10	20.98 ± 0.84a	1.14 ± 0.04b	0.53 ± 0.03a	0.39 ± 0.02a	0.36 ± 0.02a	0.33 ± 0.01a
10-20	18.19 ± 1.18b	1.44 ± 0.01a	0.44 ± 0.02b	0.33 ± 0.04b	0.30 ± 0.03b	0.29 ± 0.01b
20-30	14.82 ± 1.15c	1.41 ± 0.02a	0.45 ± 0.02b	0.33 ± 0.01b	0.31 ± 0.01b	0.30 ± 0.01b
Treatment*Depth						
0-10						
CC	19.53±0.18c	1.22±0.01a	0.51±0.08b	0.39±0.03b	0.35±0.06b	0.33±0.07b
NC	17.20±0.17d	1.30±0.01a	0.37±0.07c	0.30±0.01c	0.30±0.01c	0.29±0.01c
GM	24.13±0.32a	1.00±0.01b	0.62±0.09a	0.43±0.02a	0.40±0.02a	0.39±0.02a
SG	23.07±0.24b	1.05±0.05b	0.63±0.02a	0.43±0.02a	0.41±0.02a	0.37±0.01a
10-20						
CC	17.30±0.23b	1.44±0.02b	0.41±0.02b	0.33±0.04a	0.30±0.01b	0.28±0.01b
NC	12.17±0.23c	1.47±0.01a	0.35±0.03c	0.30±0.06b	0.30±0.05b	0.29±0.05b
GM	21.70±0.26a	1.43±0.03b	0.50±0.06a	0.33±0.01a	0.31±0.01ab	0.29±0.01a
SG	21.60±0.21a	1.43±0.01b	0.49±0.01a	0.34±0.03a	0.32±0.05a	0.30±0.01a
20-30						
CC	14.77±0.32b	1.41±0.01a	0.43±0.01b	0.34±0.01a	0.31±0.01a	0.29±0.01a
NC	8.63±0.33c	1.45±0.02a	0.38±0.06c	0.32±0.02a	0.32±0.02a	0.31±0.02a
GM	18.27±0.30a	1.38±0.05a	0.49±0.01a	0.32±0.02a	0.30±0.02a	0.29±0.01a
SG	17.60±0.25a	1.39±0.02a	0.50±0.08a	0.34±0.02a	0.33±0.01a	0.30±0.01a
Analysis of Variance p > F						
Treatment	<0.001	0.002	<0.001	0.010	0.033	0.007
RC vs PB	<0.001	0.003	<0.001	0.009	0.008	0.001
NC vs CC	<0.001	0.051	<0.001	0.010	0.351	0.211
SG vs GM	0.093	0.390	0.762	0.343	0.266	0.870
Depth	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Treatment*Depth	<0.001	<0.001	0.001	0.001	0.002	0.002

† CC = cover crops; NC = no cover crops; GM = giant miscanthus; SG = switchgrass; RC = row crops (CC and NC); PB = perennial biofuel crops (GM and SG). Treatment*Depth = treatment by depth interaction.

‡ Mean ± standard error. Means with different letters for a soil property are significantly different at the 0.05 probability level.

Table 5.3 Thermal conductivity (λ), volumetric heat capacity (C_V) and thermal diffusivity (D) at selected water pressures.

	0 kPa			-33 kPa			-100 kPa			-300 kPa		
Treatment mean	**λ (W m^{-1} K^{-1})**	**C_V (MJ m^{-3} K^{-1})**	**D (mm^2 s^{-1})**	**λ (W m^{-1} K^{-1})**	**C_V (MJ m^{-3} K^{-1})**	**D (mm^2 s^{-1})**	**λ (W m^{-1} K^{-1})**	**C_V (MJ m^{-3} K^{-1})**	**D (mm^2 s^{-1})**	**λ (W m^{-1} K^{-1})**	**C_V (MJ m^{-3} K^{-1})**	**D (mm^2 s^{-1})**
CC†	1.34 ± 0.01a‡	3.56 ± 0.05b	0.38 ± 0.02b	1.18 ± 0.02a	3.07 ± 0.02a	0.38 ± 0.01b	1.13 ± 0.02ab	3.07 ± 0.02ba	0.37 ± 0.01b	1.12 ± 0.02a	3.04 ± 0.01b	0.37 ± 0.01b
NC	1.37 ± 0.01a	3.11 ± 0.01c	0.44 ± 0.03a	1.19 ± 0.01a	2.57 ± 0.01b	0.46 ± 0.01a	1.16 ± 0.01a	2.57 ± 0.01b	0.45 ± 0.03a	1.13 ± 0.01a	2.55 ± 0.03c	0.44 ± 0.01a
GM	1.17 ± 0.02c	3.79 ± 0.03a	0.31 ± 0.03d	1.10 ± 0.02b	3.06 ± 0.02a	0.36 ± 0.01c	1.07 ± 0.02c	3.07 ± 0.02a	0.35 ± 0.01c	1.07 ± 0.02a	3.06 ± 0.01ab	0.35 ± 0.01c
SG	1.28 ± 0.02b	3.73 ± 0.01a	0.34 ± 0.04c	1.14 ± 0.02b	3.13 ± 0.02a	0.36 ± 0.01c	1.11 ± 0.03bc	3.13 ± 0.01a	0.35 ± 0.01bc	1.10 ± 0.03ab	3.10 ± 0.01a	0.35 ± 0.01bc
Depth mean (cm)												
0-10	1.30 ± 0.02a	3.59 ± 0.09a	0.37 ± 0.02ab	1.16 ± 0.02a	2.99 ± 0.07a	0.39 ± 0.02ab	1.12 ± 0.02b	2.98 ± 0.07	0.38 ± 0.01ab	1.10 ± 0.02ab	2.95 ± 0.07	0.38 ± 0.01ab
10-20	1.31 ± 0.02a	3.57 ± 0.08a	0.37 ± 0.02a	1.18 ± 0.02a	2.96 ± 0.07a	0.40 ± 0.01a	1.15 ± 0.02a	2.94 ± 0.07	0.39 ± 0.01a	1.13 ± 0.02a	2.94 ± 0.07	0.39 ± 0.01a
20-30	1.25 ± 0.03b	3.49 ± 0.04b	0.36 ± 0.02b	1.13 ± 0.02b	2.93 ± 0.06b	0.39 ± 0.01b	1.08 ± 0.02c	2.97 ± 0.07	0.44 ± 0.01b	1.07 ± 0.01b	2.92 ± 0.07	0.37 ± 0.01b
Analysis of Variance p > F												
Treatment	0.002	<0.001	<0.001	0.259	<0.001	0.001	0.179	<0.001	0.003	0.355	<0.001	0.007
RC vs PB	0.001	<0.001	<0.001	0.046	<0.001	0.001	0.047	<0.001	0.003	0.141	<0.001	0.007
NC vs CC	0.267	<0.001	<0.001	0.906	<0.001	0.002	0.406	<0.001	0.003	0.701	<0.001	0.008
SG vs GM	0.007	0.090	0.002	0.473	0.063	0.842	0.345	0.064	0.669	0.383	0.233	0.659
Depth	0.002	0.010	0.031	0.010	0.009	0.090	0.001	0.062	0.015	0.004	0.491	0.053
Treatment*Depth	0.728	0.086	0.071	0.552	0.156	0.541	0.871	0.246	0.769	0.493	0.757	0.682

† CC = cover crops; NC = no cover crops; GM = giant miscanthus; SG = switchgrass; RC = row crops (CC and NC); PB = perennial biofuel crops (GM and SG). Treatment*Depth = treatment by depth interaction.

‡ Mean ± standard error. Means with different letters for a soil property are significantly different at the 0.05 probability level.

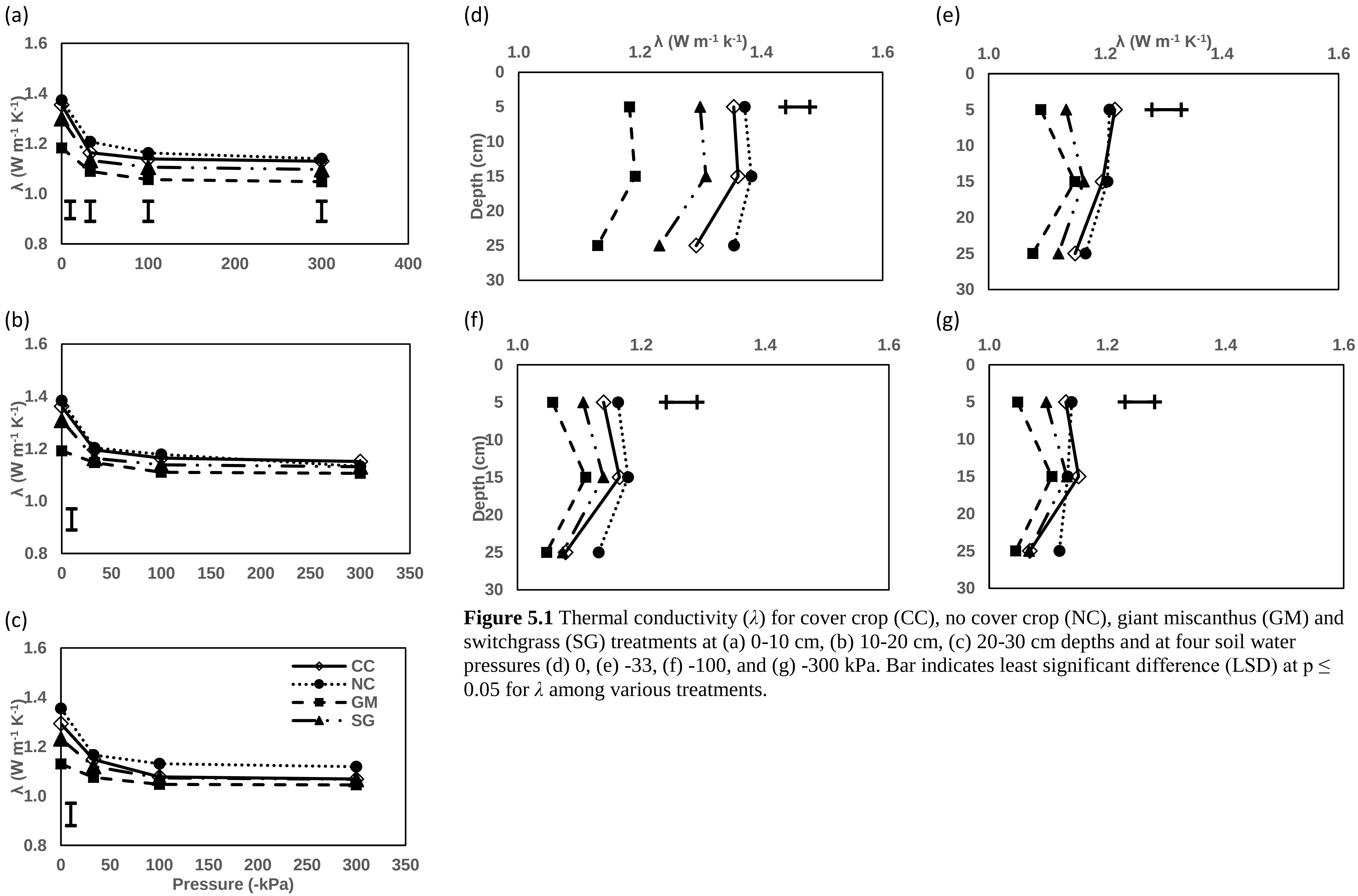
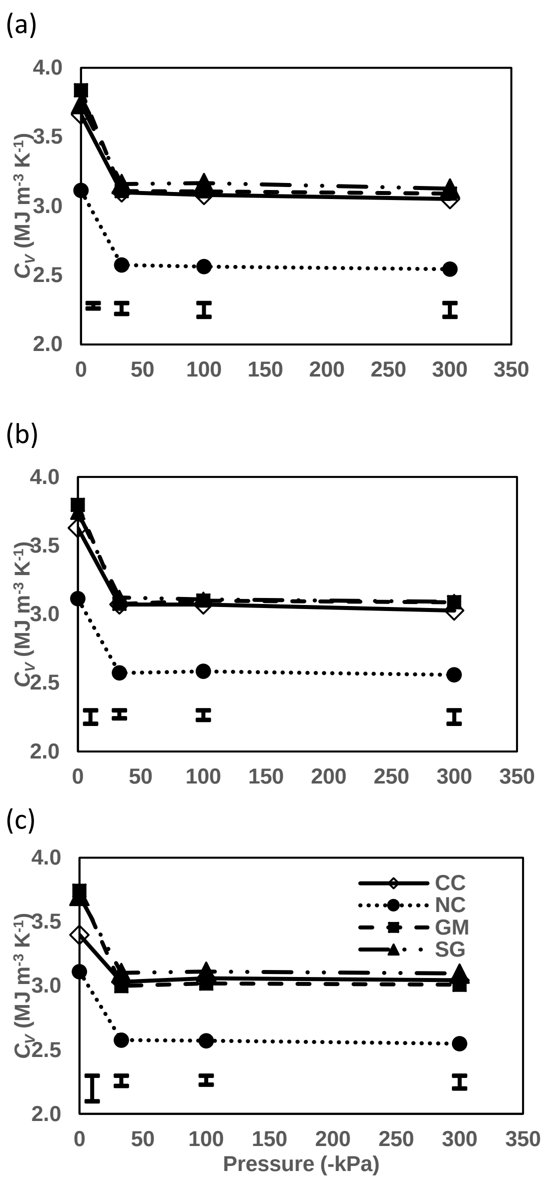


Figure 5.1 Thermal conductivity (λ) for cover crop (CC), no cover crop (NC), giant miscanthus (GM) and switchgrass (SG) treatments at (a) 0-10 cm, (b) 10-20 cm, (c) 20-30 cm depths and at four soil water pressures (d) 0, (e) -33, (f) -100, and (g) -300 kPa. Bar indicates least significant difference (LSD) at $p \leq 0.05$ for λ among various treatments.



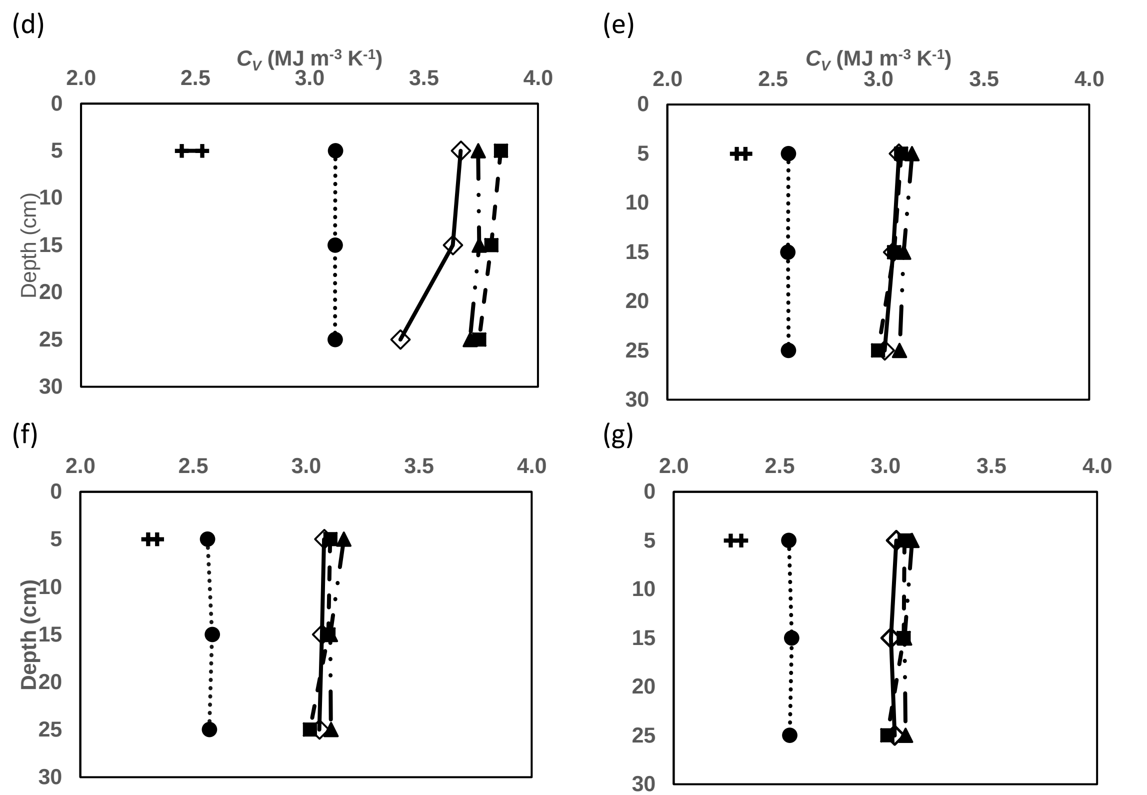
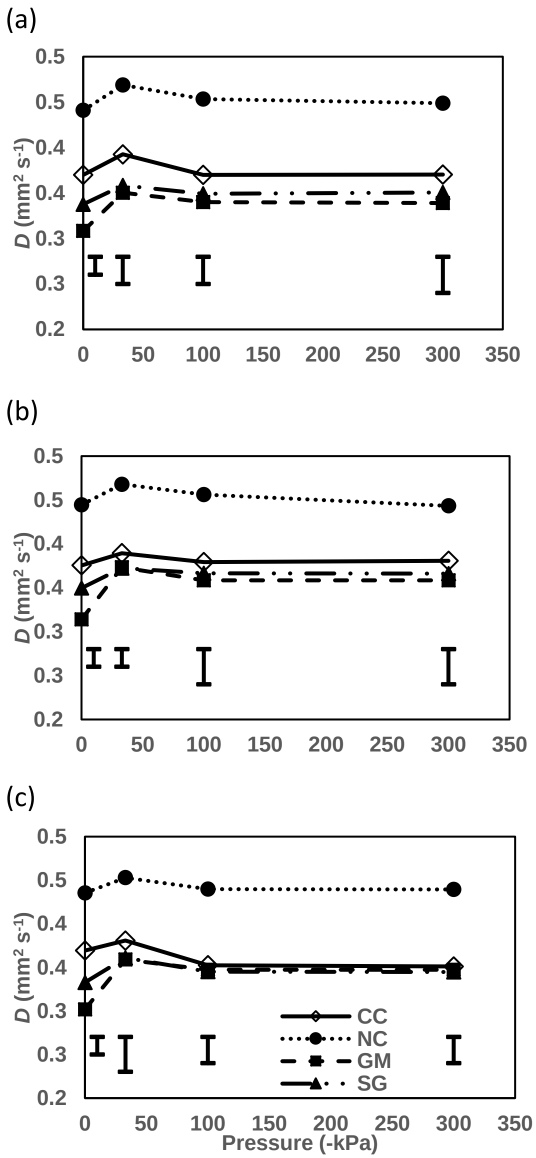


Figure 5.2 Volumetric heat capacity (C_V) for cover crop (CC), no cover crop (NC), giant miscanthus (GM) and switchgrass (SG) treatments at (a) 0-10 cm, (b) 10-20 cm, (c) 20-30 cm depths and at four soil water pressures (d) 0, (e) -33, (f) -100, and (g) -300 kPa. Bar indicates least square difference (LSD) at $p \leq 0.05$ for C_V among various treatments.



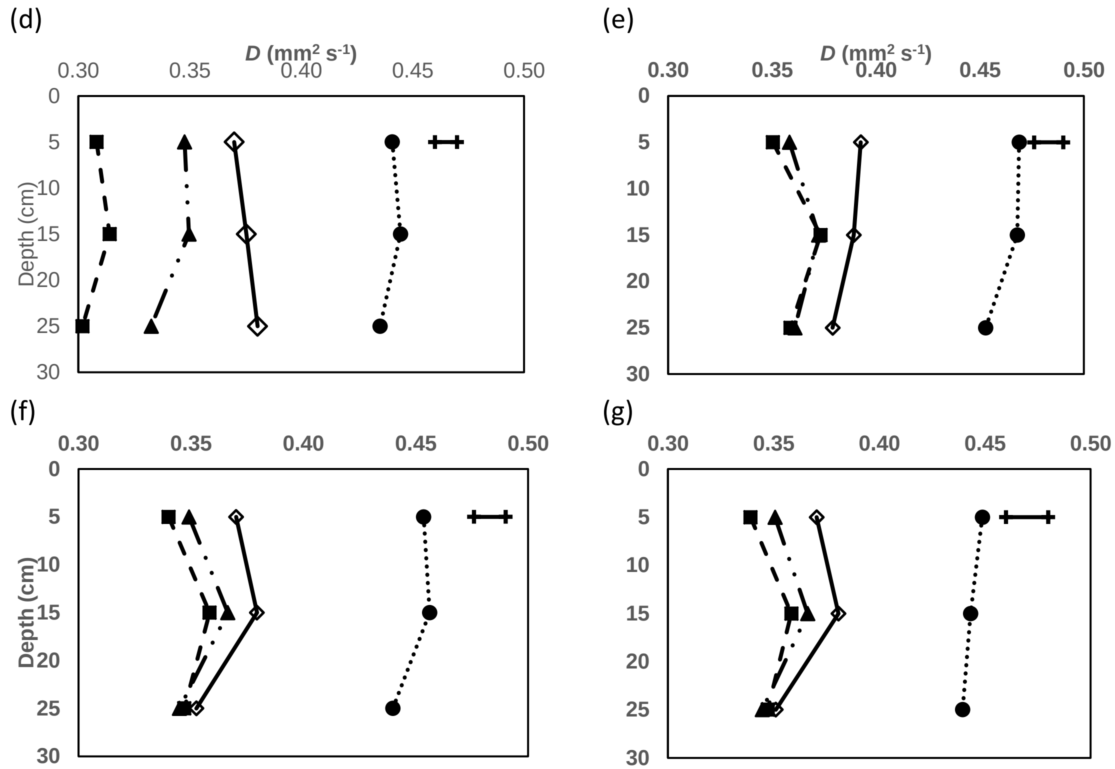


Figure 5.3 Thermal diffusivity (*D*) for cover crop (CC), no cover crop (NC), giant miscanthus (GM) and switchgrass (SG) treatments at (a) 0-10 cm, (b) 10-20 cm, (c) 20-30 cm depths and at four soil water pressures (d) 0, (e) -33, (f) -100, and (g) -300 kPa. Bar indicates least significant difference (LSD) at $p \leq 0.05$ for *D* among various treatments.

CHAPTER 6

CONCLUSIONS

The effects of cover crops and tillage land management practices on soil physical and hydraulic properties were studied during 2014 and 2015. Two experimental sites were used: 1) Lincoln University Freeman Research Center, managed with continuous corn (*Zea mays*), cereal rye (*Secale cereal*) cover crop or no cover crop, with moldboard plow tillage or no tillage; and 2) University of Missouri Bradford Research Center, managed with perennial switchgrass (*Panicum vergatum*), miscanthus (*Miscanthus x gigantus*), or continuous corn with and without cover crops [cereal rye, hairy vetch (*Vicia villosa*) and Austrian winter pea (*Pisum sativum subsp. arvense*)] with no tillage. Soils on the first site were Waldron silt loam (fine, smectitic, calcareous, mesic Aeric Fluvaquents) while soils on the second site were Mexico silt loam (fine, smectitic, mesic Vertic Epiaqualfs). Three studies were conducted for this research and the following specific conclusions were drawn from these experiments.

Study 1: Soil Hydraulic Properties

1. Tillage management caused significantly lower bulk density compared to no-till management right after tillage. Thus, volumetric water content at 0.0 and -0.4 kPa soil water pressure were significantly higher under tillage management compared to no-till management right after tillage. However, this trend did not last for one year.
2. Cover crops had significantly higher macroporosity (> 1,000 μm diameter) compared to no cover crop management, while tillage had significantly higher coarse mesoporosity (60-1,000 μm diameter) compared to no-till right after tillage. A combination of cover crops

and tillage also improved macroporosity. Pore sizes were not significantly different between both tillage systems after one year.

3. Tillage significantly improved saturated hydraulic conductivity (K_{sat}) compared to no-till management right after tillage which was related to the significantly higher coarse mesoporosity observed under tillage management. However, this trend did not last for one year.

Study 2: Ponded Infiltration

1. During 2014 and 2015, Parlange and Green-Ampt models fit measured data well with most coefficients of variation near 0.99.
2. In 2014, the saturated hydraulic conductivity (K_S) parameter values estimated from the Parlange and Green-Ampt models were 75% and 80% higher in cover crop management compared to no cover crop management, respectively.
3. In 2015, results showed that the sorptivity (S) parameter values estimated from the Parlange and Green-Ampt models were 82% and 90% higher in cover crop management compared to no cover crop management, respectively.
4. The quasi-steady infiltration rate (q_s) and field saturated hydraulic conductivity (K_{fs}) parameter values were significantly higher under cover crop compared to no cover crop management in 2014. Thus, cumulative infiltration was higher in cover crop management compared to no cover crop management. Cumulative infiltration was numerically higher under tillage compared to no-till management for both years of study.

Study 3: Soil Thermal Properties

1. After eight years of treatment, perennial biofuel crops (miscanthus and switchgrass) improved soil organic carbon (SOC) by 29% compared to row crop management (cover

crops and no cover crops), while SOC was 26% higher in cover crop management compared to no cover crop management.

2. Soil bulk density was significantly higher in row crop management compared to perennial biofuel management, and numerically higher in no cover crop management compared to cover crop management.
3. Thermal conductivity and volumetric heat capacity decreased while thermal diffusivity increased with a change in pressure from saturation to -33 kPa soil water pressure for both row crop management and perennial biofuel crops treatments probably due to the water drainage between these pressures.
4. At saturation, row crop management had 10% higher thermal conductivity compared to perennial biofuel crops, while cover crops had 13% higher volumetric heat capacity compared to no cover crops.
5. At all soil water pressures measured, perennial biofuel crops had significantly higher volumetric heat capacity compared to row crops, while cover crops had significantly higher volumetric heat capacity compared to no cover crops.

SUMMARY

For an alluvial soil, tillage management improved some hydraulic properties immediately after these operations. However, these improvements did not last over one year. This suggests that the effects of tillage in the context of changes in soil hydraulic properties are often only immediate and may diminish with time. Results from this study also revealed that some hydraulic properties improved with a combination of both tillage and cover crop management practices. This study demonstrated that cover crops improved water infiltration due to their consumptive use of soil water early in the season. These effects may improve grain crop production in some years by enhancing water storage. The effects of cover crops will compensate for some of the challenges associated with tillage management effects on soil properties.

For a claypan soil, perennial biofuel and cover crops add organic carbon to soil and improve soil water retention – these properties can help buffer against temperature changes and reduce heat transport. These effects are beneficial for seed germination and microbial activity in soils. Over time, cover crops showed consistent positive effects on soil thermal properties.

Incorporating cover crops into crop production cycles can help reduce soil and nutrient loss by providing cover to intercept raindrop energy. Furthermore, the leaves of cover crops can intercept solar energy, which can buffer the soil; this can lead to a reduction in soil water evaporation and enhanced microbial activity. Leguminous cover crops can reduce the dependence on synthetic nitrogen fertilizers through atmospheric nitrogen fixation. Non-leguminous cover crops can help in recycling excess soil nitrate, and this can lead to better surface and ground water quality. The roots of cover crops can also reduce soil loss by holding soil particles in place. Cover crops may also add organic carbon lost due to annual tillage. The humus in organic carbon can bind soil particles together, thus improving aggregate stability and soil porosity. Earthworms find organic carbon palatable and higher organic carbon can lead to increased earthworm activity in soil. Increased earthworm activity can improve soil aeration and water infiltration through biopores generated by their activity. Therefore, cover crops can affect soil physical properties in various ways. Further studies will improve our understanding of these effects.

This study demonstrated that cover crop management practices can improve some soil health indicators, specifically physical properties. These changes are important for improving crop productivity and environmental sustainability. However, due to the renewed interest in cover crops, more studies are needed to better quantify the short and long term effects of cover crops on soil physical and hydraulic properties. Such studies should ensure good management methods for cover crop establishment to maximize the beneficial effects of these cover crops. In order to ensure good establishment, winter cover crops may be seeded into the growing cash crop just before harvest. Cover crop management also requires a considerable length of time in order for the soil to equilibrate and for cover crops to provide these benefits. Therefore, future studies should include longer term experiments (> 5 years).

Currently, there are some inconsistencies in the results of cover crop studies done over several years. One of the reasons may be due to the increased variability in weather conditions during these studies. Therefore, there is a need to study the effects of weather conditions on cover crop density and how it affects soil physical properties. Soil type may also affect the influence of cover crops on soil physical properties associated with specific weather conditions. Further information on the effects of interactions between weather conditions and soils on cover crop growth and how these effect soil physical properties are also needed.

Besides improving cover crop density, there is a need to accurately quantify the soil pores generated by cover crop roots. These types of experiments will provide a better understanding of pore size distribution and connectivity. One of the ways to accurately quantify soil pore parameters is through the use of X-ray computed tomography (X-ray

CT). X-ray CT can be used to effectively measure the shape, distribution and arrangement of pores generated by cover crops.

APPENDICES

Appendix 1

A 1.1. Laboratory measurements for saturated hydraulic conductivity (K_{sat}) and bulk density for soil cores measured in 2014 right after cover crop termination and spring tillage used in chapter 3. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop, NT-NC=no tillage with no cover crop, PG=Perennial grass (fescue).

Treatment	Replicate	Depth (cm)	K_{sat} (mm hr^{-1})	Bulk Density (g cm^{-3})
Till-CC	1	0-10	30.98	1.39
Till-CC	2	0-10	95.45	1.17
Till-CC	3	0-10	71.84	1.13
Till-NC	1	0-10	39.12	1.27
Till-NC	2	0-10	44.17	1.27
Till-NC	3	0-10	49.22	1.11
NT-CC	1	0-10	6.76	1.34
NT-CC	2	0-10	7.24	1.42
NT-CC	3	0-10	6.28	1.40
NT-NC	1	0-10	2.45	1.39
NT-NC	2	0-10	12.77	1.54
NT-NC	3	0-10	7.61	1.42
PG	1	0-10	42.44	1.28
PG	2	0-10	58.42	1.38
PG	3	0-10	26.45	1.41
Till-CC	1	10-20	69.69	1.58
Till-CC	2	10-20	6.56	1.48
Till-CC	3	10-20	25.51	1.46
Till-NC	1	10-20	29.59	1.69
Till-NC	2	10-20	19.10	1.43
Till-NC	3	10-20	24.35	1.32
NT-CC	1	10-20	6.48	1.50
NT-CC	2	10-20	2.71	1.56
NT-CC	3	10-20	1.46	1.59
NT-NC	1	10-20	1.56	1.56
NT-NC	2	10-20	1.74	1.60
NT-NC	3	10-20	1.37	1.64
PG	1	10-20	6.75	1.48
PG	2	10-20	3.80	1.53
PG	3	10-20	1.38	1.62
Till-CC	1	20-30	31.55	1.60
Till-CC	2	20-30	1.13	1.43
Till-CC	3	20-30	13.08	1.53
Till-NC	1	20-30	1.24	1.54
Till-NC	2	20-30	4.23	1.53
Till-NC	3	20-30	2.48	1.51
NT-CC	1	20-30	1.44	1.60
NT-CC	2	20-30	5.59	1.57

A 1.1 cont'd

Treatment	Replicate	Depth (cm)	K_{sat} (mm hr^{-1})	Bulk Density (g cm^{-3})
NT-CC	3	20-30	3.49	1.43
NT-NC	1	20-30	1.42	1.40
NT-NC	2	20-30	1.44	1.66
NT-NC	3	20-30	1.13	1.58
PG	1	20-30	2.06	1.51
PG	2	20-30	2.41	1.65
PG	3	20-30	1.93	1.60
Till-CC	1	30-40	23.84	1.65
Till-CC	2	30-40	1.51	1.56
Till-CC	3	30-40	1.62	1.53
Till-NC	1	30-40	1.33	1.44
Till-NC	2	30-40	4.20	1.45
Till-NC	3	30-40	2.66	1.53
NT-CC	1	30-40	1.24	1.50
NT-CC	2	30-40	1.28	1.58
NT-CC	3	30-40	1.32	1.35
NT-NC	1	30-40	1.23	1.28
NT-NC	2	30-40	1.47	1.44
NT-NC	3	30-40	1.11	1.47
PG	1	30-40	1.56	1.42
PG	2	30-40	2.15	1.55
PG	3	30-40	3.61	1.50

A 1.2. Laboratory measurements for saturated hydraulic conductivity (K_{sat}) and bulk density for soil cores measured in 2014 before cover crop termination used in chapter 3. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop, NT-NC=no tillage with no cover crop.

Treatment	Replicate	Depth (cm)	K_{sat} (mm hr^{-1})	Bulk Density (g cm^{-3})
Till-CC	1	0-10	6.80	1.43
Till-CC	2	0-10	1.73	1.46
Till-CC	3	0-10	9.93	1.35
Till-NC	1	0-10	47.52	1.48
Till-NC	2	0-10	25.89	1.36
Till-NC	3	0-10	4.26	1.42
NT-CC	1	0-10	101.76	1.50
NT-CC	2	0-10	2.15	1.45
NT-CC	3	0-10	6.82	1.47
NT-NC	1	0-10	1.35	1.27
NT-NC	2	0-10	5.53	1.45
NT-NC	3	0-10	10.16	1.43
Till-CC	1	10-20	2.70	1.50
Till-CC	2	10-20	1.16	1.47
Till-CC	3	10-20	2.50	1.64
Till-NC	1	10-20	1.16	1.54
Till-NC	2	10-20	1.95	1.50
Till-NC	3	10-20	5.36	1.47
NT-CC	1	10-20	61.49	1.63
NT-CC	2	10-20	5.32	1.57
NT-CC	3	10-20	1.38	1.65
NT-NC	1	10-20	1.10	1.49
NT-NC	2	10-20	1.26	1.55
NT-NC	3	10-20	1.18	1.62

A 1.3. Volumetric water content (cm^3 cm^{-3}) values for soil cores at 0, -0.4, -1.0, -2.5, -5.0, -10.0, -20.0, -33.0, -100.0, and -1500.0 kPa soil water pressure measured in 2014 right after cover crop termination and spring tillage used in chapter 3. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop, NT-NC=no tillage with no cover crop, PG=Perennial grass (fescue).

Treatment	**Replication**	**Depth**	**Soil Water Pressure (kPa)**									
		(cm)	**0.0**	**-0.4**	**-1.0**	**-2.5**	**-5.0**	**-10.0**	**-20.0**	**-33.0**	**-100.0**	**-1500.0**
Till-CC	1	0-10	0.52	0.45	0.40	0.37	0.35	0.34	0.31	0.29	0.17	0.10
Till-CC	2	0-10	0.55	0.49	0.44	0.42	0.39	0.37	0.34	0.31	0.23	0.15
Till-CC	3	0-10	0.57	0.49	0.44	0.40	0.36	0.35	0.32	0.30	0.20	0.10
Till-NC	1	0-10	0.53	0.47	0.42	0.39	0.36	0.33	0.29	0.28	0.19	0.12
Till-NC	2	0-10	0.57	0.47	0.46	0.42	0.39	0.37	0.35	0.31	0.25	0.13
Till-NC	3	0-10	0.60	0.52	0.43	0.40	0.38	0.35	0.33	0.25	0.17	0.12
NT-CC	1	0-10	0.51	0.44	0.42	0.39	0.38	0.36	0.34	0.32	0.25	0.12
NT-CC	2	0-10	0.49	0.42	0.40	0.39	0.37	0.35	0.33	0.30	0.25	0.13
NT-CC	3	0-10	0.49	0.45	0.42	0.40	0.38	0.37	0.34	0.31	0.25	0.18
NT-NC	1	0-10	0.47	0.45	0.42	0.40	0.41	0.39	0.38	0.33	0.25	0.16
NT-NC	2	0-10	0.47	0.40	0.37	0.35	0.36	0.35	0.34	0.32	0.25	0.15
NT-NC	3	0-10	0.47	0.43	0.41	0.39	0.39	0.38	0.37	0.33	0.29	0.16
PG	1	0-10	0.55	0.52	0.50	0.49	0.48	0.47	0.46	0.32	0.26	0.12
PG	2	0-10	0.56	0.51	0.48	0.46	0.44	0.43	0.41	0.26	0.20	0.10
PG	3	0-10	0.51	0.50	0.45	0.43	0.42	0.41	0.39	0.33	0.22	0.12
Till-CC	1	10-20	0.48	0.40	0.36	0.34	0.32	0.30	0.29	0.26	0.20	0.12
Till-CC	2	10-20	0.47	0.43	0.41	0.39	0.37	0.36	0.35	0.32	0.27	0.19
Till-CC	3	10-20	0.45	0.43	0.40	0.37	0.34	0.33	0.32	0.29	0.24	0.13
Till-NC	1	10-20	0.42	0.38	0.35	0.35	0.34	0.33	0.32	0.30	0.23	0.14
Till-NC	2	10-20	0.44	0.42	0.39	0.38	0.36	0.34	0.33	0.30	0.28	0.15
Till-NC	3	10-20	0.54	0.44	0.44	0.40	0.38	0.35	0.32	0.31	0.23	0.15
NT-CC	1	10-20	0.48	0.41	0.39	0.37	0.37	0.35	0.33	0.31	0.25	0.11
NT-CC	2	10-20	0.44	0.38	0.36	0.35	0.34	0.34	0.32	0.30	0.25	0.14
NT-CC	3	10-20	0.47	0.39	0.37	0.37	0.37	0.36	0.35	0.32	0.28	0.18
NT-NC	1	10-20	0.42	0.40	0.39	0.39	0.37	0.37	0.36	0.32	0.24	0.16
NT-NC	2	10-20	0.44	0.41	0.37	0.36	0.35	0.34	0.33	0.31	0.28	0.18
NT-NC	3	10-20	0.43	0.41	0.40	0.38	0.37	0.36	0.35	0.32	0.31	0.18

A 1.3. Cont'd

Treatment	Replication	Depth (cm)	Soil Water Pressure (kPa) 0.0	-0.4	-1.0	-2.5	-5.0	-10.0	-20.0	-33.0	-100.0	-1500.0
PG	1	10-20	0.48	0.46	0.44	0.43	0.42	0.41	0.39	0.35	0.28	0.13
PG	2	10-20	0.45	0.44	0.40	0.37	0.37	0.35	0.34	0.32	0.27	0.13
PG	3	10-20	0.44	0.38	0.36	0.35	0.35	0.34	0.33	0.32	0.26	0.14
Till-CC	1	20-30	0.47	0.38	0.32	0.29	0.32	0.31	0.24	0.27	0.22	0.08
Till-CC	2	20-30	0.46	0.41	0.39	0.38	0.37	0.37	0.36	0.32	0.27	0.20
Till-CC	3	20-30	0.46	0.41	0.40	0.37	0.33	0.32	0.33	0.28	0.22	0.14
Till-NC	1	20-30	0.43	0.40	0.37	0.36	0.35	0.35	0.33	0.31	0.26	0.15
Till-NC	2	20-30	0.47	0.42	0.40	0.39	0.38	0.34	0.33	0.33	0.31	0.14
Till-NC	3	20-30	0.45	0.42	0.39	0.38	0.37	0.33	0.32	0.32	0.25	0.16
NT-CC	1	20-30	0.46	0.41	0.38	0.38	0.37	0.36	0.34	0.31	0.29	0.13
NT-CC	2	20-30	0.45	0.39	0.38	0.36	0.34	0.33	0.32	0.28	0.28	0.13
NT-CC	3	20-30	0.47	0.42	0.40	0.40	0.38	0.38	0.38	0.33	0.31	0.23
NT-NC	1	20-30	0.43	0.42	0.40	0.39	0.38	0.37	0.36	0.32	0.28	0.17
NT-NC	2	20-30	0.43	0.39	0.36	0.35	0.34	0.34	0.33	0.31	0.28	0.16
NT-NC	3	20-30	0.46	0.40	0.38	0.36	0.35	0.35	0.34	0.32	0.30	0.17
PG	1	20-30	0.46	0.43	0.41	0.41	0.40	0.39	0.38	0.31	0.29	0.12
PG	2	20-30	0.43	0.40	0.36	0.36	0.34	0.32	0.31	0.22	0.23	0.11
PG	3	20-30	0.49	0.45	0.42	0.41	0.39	0.38	0.35	0.27	0.24	0.11
Till-CC	1	30-40	0.42	0.36	0.33	0.31	0.30	0.29	0.28	0.26	0.21	0.11
Till-CC	2	30-40	0.47	0.43	0.41	0.40	0.38	0.38	0.36	0.33	0.29	0.21
Till-CC	3	30-40	0.45	0.39	0.39	0.38	0.36	0.35	0.33	0.29	0.25	0.13
Till-NC	1	30-40	0.50	0.45	0.41	0.38	0.36	0.35	0.34	0.32	0.30	0.18
Till-NC	2	30-40	0.48	0.43	0.42	0.39	0.38	0.37	0.36	0.35	0.34	0.20
Till-NC	3	30-40	0.51	0.43	0.40	0.39	0.38	0.37	0.36	0.33	0.25	0.16
NT-CC	1	30-40	0.49	0.43	0.41	0.40	0.39	0.38	0.37	0.34	0.32	0.16
NT-CC	2	30-40	0.51	0.42	0.40	0.38	0.37	0.36	0.35	0.34	0.32	0.19

A 1.3 Cont'd

Treatment	Replication	Depth (cm)	Soil Water Pressure (kPa) 0.0	-0.4	-1.0	-2.5	-5.0	-10.0	-20.0	-33.0	-100.0	-1500.0
NT-CC	3	30-40	0.52	0.45	0.42	0.40	0.39	0.38	0.38	0.34	0.32	0.26
NT-NC	1	30-40	0.50	0.47	0.42	0.40	0.39	0.38	0.37	0.33	0.30	0.20
NT-NC	2	30-40	0.50	0.44	0.43	0.40	0.39	0.38	0.37	0.33	0.32	0.23
NT-NC	3	30-40	0.51	0.43	0.42	0.40	0.39	0.38	0.38	0.33	0.31	0.17
PG	1	30-40	0.50	0.45	0.44	0.43	0.41	0.40	0.38	0.32	0.29	0.11
PG	2	30-40	0.50	0.48	0.43	0.42	0.39	0.36	0.36	0.32	0.25	0.12
PG	3	30-40	0.47	0.44	0.41	0.40	0.39	0.37	0.33	0.31	0.28	0.09

A 1.4. Volumetric water content (cm^3 cm^{-3}) values for soil cores at 0, -0.4, -1.0, -2.5, -5.0, -10.0, -20.0, -33.0, -100.0, and -1500.0 kPa soil water pressure measured in 2014 before cover crop termination used in chapter 3. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop, NT-NC=no tillage with no cover crop.

Treatment	**Replication**	**Depth**	**Soil Water Pressure (kPa)**									
		(cm)	**0.0**	**-0.4**	**-1.0**	**-2.5**	**-5.0**	**-10.0**	**-20.0**	**-33.0**	**-100.0**	**-1500.0**
Till-CC	1	0-10	0.50	0.44	0.42	0.41	0.40	0.39	0.37	0.33	0.24	0.16
Till-CC	2	0-10	0.50	0.46	0.44	0.43	0.43	0.42	0.41	0.37	0.29	0.21
Till-CC	3	0-10	0.51	0.46	0.44	0.43	0.42	0.41	0.39	0.30	0.21	0.15
Till-NC	1	0-10	0.46	0.42	0.40	0.39	0.38	0.37	0.35	0.27	0.21	0.13
Till-NC	2	0-10	0.57	0.47	0.43	0.42	0.41	0.41	0.39	0.35	0.25	0.18
Till-NC	3	0-10	0.50	0.45	0.43	0.43	0.42	0.41	0.40	0.32	0.23	0.16
NT-CC	1	0-10	0.49	0.43	0.41	0.41	0.40	0.39	0.38	0.35	0.24	0.16
NT-CC	2	0-10	0.52	0.45	0.42	0.41	0.40	0.40	0.38	0.27	0.20	0.12
NT-CC	3	0-10	0.47	0.43	0.42	0.41	0.40	0.40	0.39	0.36	0.26	0.19
NT-NC	1	0-10	0.57	0.52	0.51	0.49	0.48	0.47	0.46	0.33	0.23	0.16
NT-NC	2	0-10	0.48	0.43	0.40	0.39	0.38	0.37	0.36	0.29	0.23	0.16
NT-NC	3	0-10	0.48	0.43	0.42	0.42	0.41	0.40	0.40	0.37	0.28	0.20
Till-CC	1	10-20	0.42	0.37	0.35	0.34	0.33	0.33	0.32	0.29	0.21	0.14
Till-CC	2	10-20	0.49	0.48	0.41	0.40	0.39	0.38	0.37	0.35	0.29	0.21
Till-CC	3	10-20	0.44	0.38	0.36	0.36	0.35	0.35	0.33	0.30	0.27	0.18
Till-NC	1	10-20	0.38	0.36	0.33	0.33	0.32	0.31	0.28	0.26	0.19	0.10
Till-NC	2	10-20	0.47	0.42	0.40	0.40	0.38	0.37	0.36	0.32	0.30	0.21
Till-NC	3	10-20	0.45	0.41	0.39	0.39	0.39	0.38	0.37	0.36	0.26	0.18
NT-CC	1	10-20	0.45	0.40	0.39	0.38	0.37	0.37	0.35	0.34	0.23	0.15
NT-CC	2	10-20	0.46	0.41	0.39	0.39	0.38	0.38	0.37	0.35	0.25	0.17
NT-CC	3	10-20	0.44	0.39	0.38	0.37	0.37	0.37	0.35	0.33	0.27	0.18
NT-NC	1	10-20	0.48	0.46	0.44	0.43	0.42	0.42	0.40	0.37	0.23	0.16
NT-NC	2	10-20	0.42	0.41	0.34	0.34	0.33	0.32	0.31	0.28	0.24	0.15
NT-NC	3	10-20	0.42	0.37	0.36	0.35	0.35	0.34	0.34	0.34	0.28	0.20

A 1.5. Pore size distribution values for soil core samples measured in 2014 right after cover crop termination and spring tillage used in chapter 3. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop, NT-NC=no tillage with no cover crop, PG=Perennial grass (fescue).

Treatment	Replication	Depth (cm)	Macropores (> 1,000 µm)	Coarse Mesopores (60–1,000 µm)	Fine Mesopores (10 – 60 µm)	Micropores (< 10 µm)	Total Pores
Till-CC	1	0-10	0.068	0.104	0.052	0.293	0.517
Till-CC	2	0-10	0.059	0.104	0.081	0.306	0.551
Till-CC	3	0-10	0.078	0.138	0.055	0.301	0.572
Till-NC	1	0-10	0.058	0.109	0.074	0.284	0.525
Till-NC	2	0-10	0.097	0.083	0.077	0.313	0.570
Till-NC	3	0-10	0.079	0.147	0.130	0.247	0.603
NT-CC	1	0-10	0.064	0.063	0.064	0.316	0.507
NT-CC	2	0-10	0.071	0.055	0.065	0.301	0.492
NT-CC	3	0-10	0.044	0.066	0.077	0.307	0.494
NT-NC	1	0-10	0.017	0.044	0.075	0.331	0.468
NT-NC	2	0-10	0.067	0.041	0.043	0.317	0.467
NT-NC	3	0-10	0.039	0.041	0.062	0.327	0.469
PG	1	0-10	0.032	0.040	0.158	0.318	0.548
PG	2	0-10	0.048	0.075	0.174	0.263	0.560
PG	3	0-10	0.007	0.083	0.088	0.329	0.508
Till-CC	1	10-20	0.081	0.075	0.060	0.264	0.479
Till-CC	2	10-20	0.035	0.058	0.058	0.316	0.466
Till-CC	3	10-20	0.030	0.081	0.050	0.295	0.455
Till-NC	1	10-20	0.044	0.036	0.041	0.299	0.421
Till-NC	2	10-20	0.017	0.061	0.057	0.304	0.439
Till-NC	3	10-20	0.094	0.061	0.068	0.312	0.535
NT-CC	1	10-20	0.072	0.043	0.059	0.306	0.481
NT-CC	2	10-20	0.063	0.038	0.045	0.296	0.442
NT-CC	3	10-20	0.083	0.018	0.051	0.317	0.469

A 1.5 Cont'd

Treatment	Replication	Depth (cm)	Macropores (> 1,000 µm)	Coarse Mesopores (60–1,000 µm)	Fine Mesopores (10 – 60 µm)	Micropores (< 10 µm)	Total Pores
NT-NC	1	10-20	0.017	0.029	0.052	0.322	0.419
NT-NC	2	10-20	0.032	0.063	0.038	0.311	0.444
NT-NC	3	10-20	0.021	0.043	0.047	0.322	0.433
PG	1	10-20	0.014	0.043	0.064	0.354	0.475
PG	2	10-20	0.011	0.075	0.048	0.317	0.451
PG	3	10-20	0.058	0.032	0.035	0.316	0.440
Till-CC	1	20-30	0.089	0.068	0.044	0.272	0.473
Till-CC	2	20-30	0.047	0.037	0.053	0.371	0.508
Till-CC	3	20-30	0.048	0.082	0.053	0.279	0.462
Till-NC	1	20-30	0.035	0.049	0.039	0.309	0.431
Till-NC	2	20-30	0.046	0.035	0.051	0.333	0.465
Till-NC	3	20-30	0.035	0.046	0.054	0.317	0.453
NT-CC	1	20-30	0.055	0.035	0.060	0.312	0.461
NT-CC	2	20-30	0.052	0.052	0.062	0.281	0.447
NT-CC	3	20-30	0.044	0.040	0.052	0.332	0.468
NT-NC	1	20-30	0.014	0.040	0.062	0.316	0.432
NT-NC	2	20-30	0.042	0.043	0.032	0.312	0.429
NT-NC	3	20-30	0.060	0.049	0.030	0.325	0.464
PG	1	20-30	0.026	0.029	0.090	0.312	0.457
PG	2	20-30	0.030	0.052	0.121	0.223	0.427
PG	3	20-30	0.042	0.058	0.117	0.273	0.489
Till-CC	1	30-40	0.063	0.055	0.041	0.261	0.420
Till-CC	2	30-40	0.038	0.046	0.052	0.332	0.467
Till-CC	3	30-40	0.051	0.037	0.063	0.295	0.445
Till-NC	1	30-40	0.049	0.086	0.044	0.317	0.497
Till-NC	2	30-40	0.052	0.055	0.028	0.349	0.484
Till-NC	3	30-40	0.085	0.043	0.057	0.326	0.511

A 1.5 Cont'd

Treatment	Replication	Depth (cm)	Macropores (> 1,000 µm)	Coarse Mesopores (60–1,000 µm)	Fine Mesopores (10 – 60 µm)	Micropores (< 10 µm)	Total Pores
NT-CC	1	30-40	0.057	0.043	0.051	0.336	0.487
NT-CC	2	30-40	0.087	0.052	0.030	0.339	0.507
NT-CC	3	30-40	0.070	0.060	0.049	0.341	0.521
NT-NC	1	30-40	0.027	0.079	0.057	0.332	0.496
NT-NC	2	30-40	0.064	0.051	0.057	0.328	0.500
NT-NC	3	30-40	0.085	0.034	0.062	0.331	0.511
PG	1	30-40	0.045	0.040	0.095	0.318	0.498
PG	2	30-40	0.016	0.095	0.069	0.318	0.498
PG	3	30-40	0.029	0.055	0.078	0.308	0.470

A 1.6. Pore size distribution values for soil core samples measured in 2014 before cover crop termination used in chapter 3. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop.

Treatment	**Replication**	**Depth (cm)**	**Macropores (> 1,000 μm)**	**Coarse Mesopores (60–1,000 μm)**	**Fine Mesopores (10 – 60 μm)**	**Micropores (< 10 μm)**	**Total Pores**
Till-CC	1	0-10	0.059	0.046	0.068	0.328	0.501
Till-CC	2	0-10	0.039	0.029	0.055	0.373	0.495
Till-CC	3	0-10	0.055	0.035	0.116	0.305	0.510
Till-NC	1	0-10	0.041	0.040	0.107	0.272	0.460
Till-NC	2	0-10	0.094	0.058	0.061	0.354	0.566
Till-NC	3	0-10	0.053	0.029	0.103	0.315	0.500
NT-CC	1	0-10	0.067	0.023	0.056	0.347	0.494
NT-CC	2	0-10	0.077	0.046	0.133	0.269	0.525
NT-CC	3	0-10	0.042	0.029	0.037	0.365	0.473
NT-NC	1	0-10	0.044	0.037	0.153	0.331	0.565
NT-NC	2	0-10	0.050	0.046	0.090	0.294	0.480
NT-NC	3	0-10	0.043	0.026	0.032	0.375	0.476
Till-CC	1	10-20	0.046	0.037	0.046	0.289	0.418
Till-CC	2	10-20	0.010	0.092	0.040	0.349	0.491
Till-CC	3	10-20	0.059	0.035	0.046	0.304	0.443
Till-NC	1	10-20	0.017	0.040	0.060	0.260	0.378
Till-NC	2	10-20	0.052	0.046	0.053	0.323	0.474
Till-NC	3	10-20	0.043	0.026	0.027	0.359	0.455
NT-CC	1	10-20	0.058	0.023	0.034	0.340	0.455
NT-CC	2	10-20	0.052	0.026	0.036	0.348	0.461
NT-CC	3	10-20	0.040	0.023	0.041	0.331	0.435
NT-NC	1	10-20	0.015	0.037	0.053	0.371	0.476
NT-NC	2	10-20	0.012	0.081	0.044	0.282	0.419
NT-NC	3	10-20	0.051	0.020	0.012	0.336	0.419

Appendix 2

A 2.1. van Genutchen parameter values calculated from water retention values right after cover crop termination and spring tillage used in chapter 4. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop, NT-NC=no tillage with no cover crop, PG=Perennial grass (fescue).

Treatment	**Replication**	**Depth (cm)**	**α (mm^{-1})**	***n***	***r^2***
Till-CC	1	0-10	0.029	1.156	0.93
Till-CC	2	0-10	0.021	1.139	0.97
Till-CC	3	0-10	0.027	1.161	0.96
Till-NC	1	0-10	0.021	1.155	0.97
Till-NC	2	0-10	0.031	1.106	0.98
Till-NC	3	0-10	0.040	1.254	0.93
NT-CC	1	0-10	0.002	1.211	0.92
NT-CC	2	0-10	0.004	1.162	0.94
NT-CC	3	0-10	0.010	1.128	0.98
NT-NC	1	0-10	0.002	1.191	0.94
NT-NC	2	0-10	0.002	1.089	0.89
NT-NC	3	0-10	0.002	1.156	0.91
PG	1	0-10	0.001	1.683	0.94
PG	2	0-10	0.001	1.446	0.91
PG	3	0-10	0.001	1.300	0.95
Till-CC	1	10-20	0.006	1.123	0.95
Till-CC	2	10-20	0.006	1.116	0.96
Till-CC	3	10-20	0.005	1.153	0.97
Till-NC	1	10-20	0.001	1.249	0.94
Till-NC	2	10-20	0.003	1.150	0.96
Till-NC	3	10-20	0.002	1.132	0.97
NT-CC	1	10-20	0.001	1.212	0.92
NT-CC	2	10-20	0.001	1.178	0.92
NT-CC	3	10-20	0.002	1.134	0.88
NT-NC	1	10-20	0.001	1.115	0.98
NT-NC	2	10-20	0.005	1.107	0.93
NT-NC	3	10-20	0.003	1.123	0.92
PG	1	10-20	0.001	1.284	0.98
PG	2	10-20	0.001	1.191	0.94
PG	3	10-20	0.001	1.215	0.90
Till-CC	1	20-30	0.005	1.113	0.87
Till-CC	2	20-30	0.001	1.156	0.95
Till-CC	3	20-30	0.010	1.141	0.96

A 2.1 Cont'd

Treatment	**Replication**	**Depth (cm)**	**α (mm^{-1})**	***n***	***r*^{2}**
Till-NC	1	20-30	0.001	1.186	0.95
Till-NC	2	20-30	0.002	1.154	0.91
Till-NC	3	20-30	0.004	1.141	0.97
NT-CC	1	20-30	0.001	1.212	0.93
NT-CC	2	20-30	0.004	1.137	0.92
NT-CC	3	20-30	0.006	1.086	0.93
NT-NC	1	20-30	0.002	1.152	0.94
NT-NC	2	20-30	0.001	1.176	0.91
NT-NC	3	20-30	0.002	1.137	0.91
PG	1	20-30	0.001	1.282	0.96
PG	2	20-30	0.002	1.206	0.94
PG	3	20-30	0.002	1.229	0.96
Till-CC	1	30-40	0.002	1.111	0.92
Till-CC	2	30-40	0.003	1.114	0.96
Till-CC	3	30-40	0.001	1.205	0.96
Till-NC	1	30-40	0.003	1.101	0.92
Till-NC	2	30-40	0.001	1.229	0.87
Till-NC	3	30-40	0.005	1.137	0.91
NT-CC	1	30-40	0.001	1.166	0.91
NT-CC	2	30-40	0.010	1.072	0.92
NT-CC	3	30-40	0.005	1.062	0.98
NT-NC	1	30-40	0.009	1.094	0.95
NT-NC	2	30-40	0.018	1.069	0.96
NT-NC	3	30-40	0.001	1.172	0.93
PG	1	30-40	0.001	1.268	0.96
PG	2	30-40	0.002	1.201	0.96
PG	3	30-40	0.001	1.257	0.95

A 2.2. van Genutchen parameter values calculated from water retention values before cover crop termination. Till-CC=tillage with cover crop, Till-NC=tillage with no cover crop, NT-CC=no tillage with cover crop, NT-NC=no tillage with no cover crop.

Treatment	**Replication**	**Depth (cm)**	**α (mm^{-1})**	***n***	***r*^{2}**
Till-CC	1	0-10	0.001	1.197	0.93
Till-CC	2	0-10	0.001	1.600	0.95
Till-CC	3	0-10	0.001	1.935	0.94
Till-NC	1	0-10	0.001	1.480	0.94
Till-NC	2	0-10	0.006	1.100	0.89
Till-NC	3	0-10	0.001	1.909	0.94
NT-CC	1	0-10	0.001	1.747	0.93
NT-CC	2	0-10	0.001	1.673	0.90
NT-CC	3	0-10	0.001	1.794	0.94
NT-NC	1	0-10	0.001	1.499	0.94
NT-NC	2	0-10	0.001	1.176	0.92
NT-NC	3	0-10	0.001	1.822	0.95
Till-CC	1	10-20	0.001	1.207	0.92
Till-CC	2	10-20	0.004	1.092	0.93
Till-CC	3	10-20	0.008	1.098	0.91
Till-NC	1	10-20	0.001	1.253	0.97
Till-NC	2	10-20	0.001	1.082	0.95
Till-NC	3	10-20	0.001	1.787	0.94
NT-CC	1	10-20	0.001	1.600	0.93
NT-CC	2	10-20	0.001	1.723	0.93
NT-CC	3	10-20	0.001	1.166	0.95
NT-NC	1	10-20	0.001	1.122	0.97
NT-NC	2	10-20	0.006	1.112	0.93
NT-NC	3	10-20	0.003	1.131	0.89

A 2.3. Cumulative infiltration in cover crop with tillage (CC-Till) management measured in 2014.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	3.25	28.12	28.12
4	3.25	33.92	33.92
6	3.25	38.07	38.07
8	3.25	40.56	40.56
10	4.91	46.69	46.69
15	4.91	52.99	52.99
20	6.57	62.94	62.94
25	8.22	69.90	69.90
30	9.88	76.20	76.20
35	11.54	81.18	81.18
40	14.03	87.65	87.65
45	14.86	94.77	94.77
50	16.51	99.09	99.09
60	18.17	111.02	111.02
90	28.12	140.87	140.87
120	36.41	167.40	167.40
150	48.02	-	-
180	57.97	-	-

A 2.4. Cumulative infiltration in cover crop with no tillage (CC-NT) management measured in 2014.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	0.90	18.17	0.90
4	2.56	21.49	2.56
6	4.22	24.80	4.22
8	6.71	29.78	6.71
10	10.02	29.78	10.02
15	12.51	36.41	12.51
20	16.66	43.04	16.66
25	21.63	48.85	21.63
30	26.60	51.33	26.60
35	29.92	63.77	29.92
40	34.89	77.86	34.89
45	38.21	87.81	38.21
50	41.53	97.76	41.53
60	48.16	117.66	48.16
90	65.57	177.35	65.57
120	79.66	193.93	79.66
150	-	231.23	-
180	-	249.47	-

A 2.5. Cumulative infiltration in no cover crop with tillage (NC-Till) management measured in 2014.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	1.05	1.05	4.69
4	1.05	1.05	8.01
6	7.68	7.68	8.01
8	7.68	7.68	11.33
10	7.68	7.68	15.47
15	10.99	10.99	19.78
20	11.82	11.82	20.44
25	14.31	14.31	26.25
30	14.31	14.31	26.25
35	17.63	17.63	32.88
40	18.46	18.46	32.88
45	18.79	18.79	32.88
50	19.28	19.28	32.88
60	23.43	23.43	37.03
90	28.40	28.40	47.80
120	33.38	33.38	57.75

A 2.6. Cumulative infiltration in no cover crop with no tillage (NC-NT) management measured in 2014.

Time (Minutes)	Replications		
	I (mm)	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	0.74	0.74	0.74
4	2.73	2.73	2.73
6	2.73	2.73	2.73
8	5.38	5.38	5.38
10	5.38	5.38	5.38
15	8.70	8.70	8.70
20	11.52	11.52	11.52
25	11.68	11.68	11.68
30	14.50	14.50	14.50
35	14.50	14.50	14.50
40	17.49	17.49	17.49
45	17.49	17.49	17.49
50	17.49	17.49	17.49
60	19.97	19.97	19.97
90	27.43	27.43	27.43
120	34.07	34.07	34.07

A 2.7. Cumulative infiltration in perennial grass (PG) measured in 2014.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	0.74	8.22	8.22
4	15.66	9.88	9.88
6	30.58	11.54	11.54
8	42.19	13.20	13.20
10	52.14	13.20	13.20
15	70.38	16.51	16.51
20	86.96	18.17	18.17
25	115.14	19.00	19.00
30	135.04	19.83	19.83
35	146.65	19.83	19.83
40	151.62	21.49	21.49
45	168.20	24.80	24.80
50	201.36	24.80	24.80
60	222.92	36.41	36.41
90	261.05	64.60	64.60
120	290.90	77.86	77.86

A 2.8. Cumulative infiltration in cover crop with tillage (CC-Till) management measured in 2015.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	15.14	23.43	23.43
4	21.77	23.43	23.43
6	23.43	26.75	26.75
8	23.43	26.75	26.75
10	23.43	26.75	26.75
15	23.43	28.40	28.40
20	25.92	31.72	31.72
25	25.92	32.88	32.88
30	30.06	35.04	35.04
35	31.72	38.35	38.35
40	31.72	39.18	39.18
45	33.38	41.67	41.67
50	33.38	45.81	45.81
60	38.35	54.10	54.10
90	48.30	86.44	86.44
120	69.86	118.77	118.77

A 2.9. Cumulative infiltration in cover crop with no tillage (CC-NT) management measured in 2015.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	2.49	0.83	2.49
4	5.81	10.78	5.81
6	8.29	24.05	8.29
8	12.44	29.02	12.44
10	15.76	30.68	15.76
15	19.07	33.99	19.07
20	20.73	37.31	20.73
25	25.70	43.94	25.70
30	30.68	47.26	30.68
35	33.99	57.21	33.99
40	38.97	65.50	38.97
45	43.94	70.47	43.94
50	47.26	72.13	47.26
60	55.55	77.10	55.55
90	68.81	108.61	68.81
120	87.05	130.16	87.05

A 2.10. Cumulative infiltration in no cover crop with tillage (NC-Till) management measured in 2015.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	1.87	1.87	0.22
4	3.53	3.53	1.87
6	5.19	5.19	1.87
8	6.85	6.85	3.53
10	7.68	7.68	3.53
15	10.17	10.17	5.19
20	13.48	13.48	7.68
25	16.80	16.80	8.51
30	21.77	21.77	9.34
35	25.09	25.09	10.99
40	28.40	28.40	10.99
45	33.38	33.38	12.65
50	36.69	36.69	15.14
60	43.33	43.33	15.14
90	66.54	66.54	22.60
120	86.44	86.44	25.92

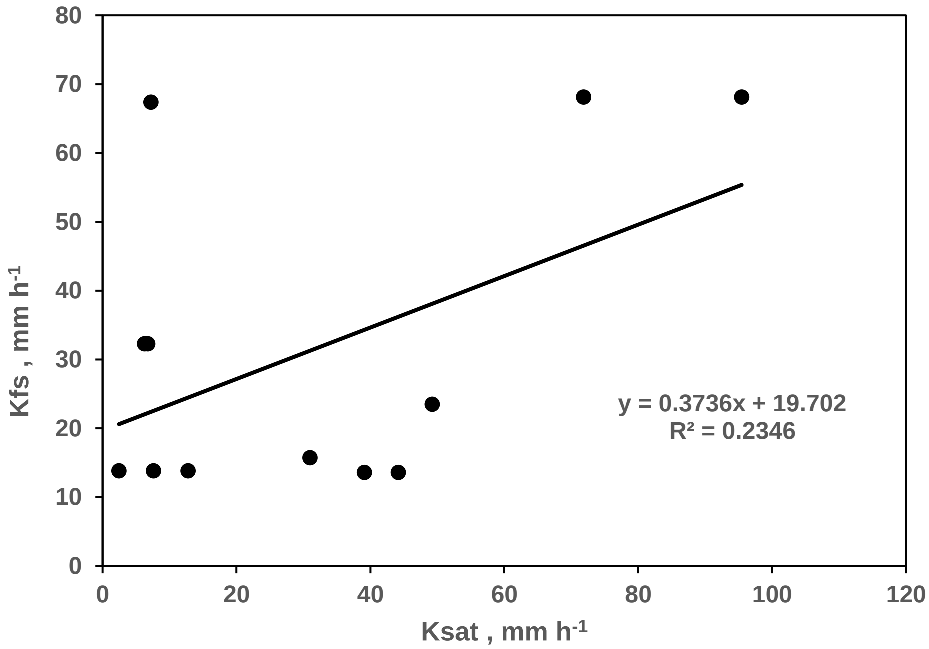
A 2.11. Cumulative infiltration in no cover crop with no tillage (NC-NT) management measured in 2015.

Time (Minutes)	Replications I (mm)	II (mm)	III (mm)
0	0.00	0.00	0.00
2	3.63	3.63	0.74
4	5.29	5.29	2.73
6	5.29	5.29	2.73
8	5.29	5.29	5.38
10	6.95	6.95	5.38
15	8.60	8.60	8.70
20	11.92	11.92	11.52
25	15.24	15.24	11.68
30	16.89	16.89	14.50
35	20.21	20.21	14.50
40	23.53	23.53	17.49
45	25.18	25.18	17.49
50	28.50	28.50	17.49
60	33.47	33.47	19.97
90	51.71	51.71	27.43
120	71.61	71.61	34.07

A 2.12. Cumulative infiltration in perennial grass (PG) measured in 2015.

	Replications		
Time (Minutes)	**I (mm)**	**II (mm)**	**III (mm)**
0	0.00	0.00	0.00
2	10.17	3.25	10.17
4	10.17	4.91	10.17
6	10.17	4.91	10.17
8	10.17	4.91	10.17
10	10.17	6.57	10.17
15	16.80	6.57	16.80
20	17.63	6.57	17.63
25	18.46	8.22	18.46
30	23.43	8.22	23.43
35	25.09	11.54	25.09
40	25.09	11.54	25.09
45	28.40	11.54	28.40
50	31.72	11.54	31.72
60	35.04	11.54	35.04
90	41.67	14.86	41.67
120	51.62	19.83	51.62

A 2.13. Field saturated hydraulic conductivity (K_{fs}, 2014 data) versus laboratory measured saturated hydraulic conductivity (K_{sat}, 2014 data).



Appendix 3

A 3.1. Soil organic carbon (SOC) and bulk density (Db) measured in 2015 and used in chapter 5. CC=cover crops, NC=no cover crop, GM=giant miscanthus, and SG=switchgrass.

Treatment	Replicate	Depth (cm)	SOC (g kg^{-1})	Db (g cm^{-3})
CC	1	0-10	19.80	1.21
NC	1	0-10	17.20	1.29
CC	2	0-10	19.60	1.23
NC	2	0-10	16.90	1.29
CC	3	0-10	19.20	1.22
NC	3	0-10	17.50	1.29
GM	1	0-10	23.60	0.99
GM	2	0-10	24.70	1.00
GM	3	0-10	24.10	1.00
SG	1	0-10	22.60	1.01
SG	2	0-10	23.40	0.99
SG	3	0-10	23.20	1.15
CC	1	10-20	17.30	1.44
NC	1	10-20	12.30	1.47
CC	2	10-20	17.70	1.44
NC	2	10-20	12.00	1.46
CC	3	10-20	16.90	1.44
NC	3	10-20	12.20	1.48
GM	1	10-20	21.80	1.43
GM	2	10-20	21.20	1.44
GM	3	10-20	22.10	1.43
SG	1	10-20	21.30	1.41
SG	2	10-20	22.00	1.45
SG	3	10-20	21.50	1.43
CC	1	20-30	14.80	1.41
NC	1	20-30	9.10	1.45
CC	2	20-30	15.30	1.42
NC	2	20-30	8.00	1.41
CC	3	20-30	14.20	1.40
NC	3	20-30	8.80	1.48
GM	1	20-30	17.70	1.28
GM	2	20-30	18.70	1.41
GM	3	20-30	18.40	1.45
SG	1	20-30	17.40	1.40
SG	2	20-30	18.10	1.34
SG	3	20-30	17.30	1.42

A 3.2. Thermal conductivity (λ), volumetric heat capacity (C_V), thermal diffusivity (D), and volumetric water content (θ) at saturation measured in 2015 and used in chapter 5. CC=cover crops, NC=no cover crop, GM=giant miscanthus, and SG=switchgrass.

Treatment	Rep	Depth (cm)	λ (W m^{-1} K^{-1})	C_V (MJ m^{-3} K^{-1})	D (mm^2 s^{-1})	θ (cm^3 cm^{-3})
CC	1	0-10	1.38	3.68	0.37	0.50
NC	1	0-10	1.39	3.11	0.45	0.38
CC	2	0-10	1.35	3.66	0.37	0.51
NC	2	0-10	1.37	3.12	0.44	0.36
CC	3	0-10	1.33	3.64	0.37	0.53
NC	3	0-10	1.36	3.11	0.44	0.38
GM	1	0-10	1.22	3.84	0.32	0.60
GM	2	0-10	1.13	3.83	0.29	0.64
GM	3	0-10	1.20	3.84	0.31	0.62
SG	1	0-10	1.26	3.74	0.34	0.64
SG	2	0-10	1.29	3.74	0.35	0.64
SG	3	0-10	1.35	3.74	0.36	0.59
CC	1	10-20	1.36	3.64	0.37	0.41
NC	1	10-20	1.42	3.11	0.46	0.38
CC	2	10-20	1.37	3.65	0.37	0.41
NC	2	10-20	1.34	3.11	0.43	0.37
CC	3	10-20	1.36	3.59	0.38	0.42
NC	3	10-20	1.38	3.11	0.44	0.29
GM	1	10-20	1.23	3.82	0.32	0.51
GM	2	10-20	1.13	3.67	0.31	0.49
GM	3	10-20	1.22	3.90	0.31	0.50
SG	1	10-20	1.26	3.73	0.34	0.51
SG	2	10-20	1.32	3.70	0.36	0.48
SG	3	10-20	1.35	3.80	0.36	0.48
CC	1	20-30	1.24	3.20	0.39	0.41
NC	1	20-30	1.38	3.11	0.44	0.37
CC	2	20-30	1.31	3.42	0.38	0.45
NC	2	20-30	1.35	3.11	0.43	0.37
CC	3	20-30	1.32	3.58	0.37	0.42
NC	3	20-30	1.34	3.11	0.43	0.39
GM	1	20-30	1.09	3.69	0.30	0.50
GM	2	20-30	1.11	3.67	0.30	0.50
GM	3	20-30	1.18	3.87	0.31	0.46
SG	1	20-30	1.17	3.67	0.32	0.49
SG	2	20-30	1.26	3.71	0.34	0.51
SG	3	20-30	1.26	3.73	0.34	0.49

A 3.3. Thermal conductivity (λ), volumetric heat capacity (C_V), thermal diffusivity (D), and volumetric water content (θ) at -33 kPa pressure measured in 2015 and used in chapter 5. CC=cover crops, NC=no cover crop, GM=giant miscanthus, and SG=switchgrass.

Treatment	Rep	Depth (cm)	λ (W m^{-1} K^{-1})	C_V (MJ m^{-3} K^{-1})	D (mm^2 s^{-1})	θ (cm^3 cm^{-3})
CC	1	0-10	1.18	3.07	0.39	0.38
NC	1	0-10	1.19	2.57	0.46	0.28
CC	2	0-10	1.26	3.08	0.41	0.39
NC	2	0-10	1.23	2.57	0.48	0.32
CC	3	0-10	1.21	3.15	0.38	0.39
NC	3	0-10	1.20	2.58	0.46	0.31
GM	1	0-10	1.04	3.09	0.33	0.39
GM	2	0-10	1.10	3.15	0.35	0.44
GM	3	0-10	1.14	3.09	0.37	0.45
SG	1	0-10	1.14	3.21	0.36	0.46
SG	2	0-10	1.06	3.11	0.34	0.43
SG	3	0-10	1.20	3.17	0.38	0.41
CC	1	10-20	1.22	3.06	0.40	0.34
NC	1	10-20	1.16	2.57	0.45	0.30
CC	2	10-20	1.22	3.07	0.40	0.33
NC	2	10-20	1.25	2.57	0.49	0.31
CC	3	10-20	1.15	3.08	0.37	0.33
NC	3	10-20	1.21	2.57	0.47	0.29
GM	1	10-20	1.10	3.06	0.36	0.31
GM	2	10-20	1.16	3.08	0.38	0.34
GM	3	10-20	1.18	3.08	0.38	0.34
SG	1	10-20	1.23	3.16	0.39	0.34
SG	2	10-20	1.04	3.09	0.34	0.33
SG	3	10-20	1.22	3.12	0.39	0.34
CC	1	20-30	1.16	2.96	0.39	0.34
NC	1	20-30	1.13	2.58	0.44	0.35
CC	2	20-30	1.08	3.07	0.35	0.37
NC	2	20-30	1.23	2.58	0.48	0.33
CC	3	20-30	1.20	3.06	0.39	0.32
NC	3	20-30	1.14	2.57	0.44	0.29
GM	1	20-30	1.03	3.05	0.34	0.28
GM	2	20-30	1.07	2.98	0.36	0.35
GM	3	20-30	1.13	2.97	0.38	0.32
SG	1	20-30	1.18	3.09	0.38	0.32
SG	2	20-30	1.04	3.06	0.34	0.37
SG	3	20-30	1.14	3.16	0.36	0.32

A 3.4. Thermal conductivity (λ), volumetric heat capacity (C_V), thermal diffusivity (D), and volumetric water content (θ) at -100 kPa pressure measured in 2015 and used in chapter 5. CC=cover crops, NC=no cover crop, GM=giant miscanthus, and SG=switchgrass.

Treatment	**Rep**	**Depth (cm)**	λ (W m^{-1} K^{-1})	C_V (MJ m^{-3} K^{-1})	D (mm^2 s^{-1})	θ (cm^3 cm^{-3})
CC	1	0-10	1.11	3.07	0.36	0.34
NC	1	0-10	1.16	2.50	0.46	0.28
CC	2	0-10	1.18	3.01	0.39	0.35
NC	2	0-10	1.16	2.59	0.45	0.31
CC	3	0-10	1.13	3.16	0.36	0.36
NC	3	0-10	1.17	2.60	0.45	0.31
GM	1	0-10	1.01	3.11	0.33	0.36
GM	2	0-10	1.05	3.10	0.34	0.41
GM	3	0-10	1.11	3.12	0.36	0.42
SG	1	0-10	1.11	3.21	0.35	0.44
SG	2	0-10	1.03	3.12	0.33	0.40
SG	3	0-10	1.18	3.17	0.37	0.39
CC	1	10-20	1.19	3.10	0.38	0.30
NC	1	10-20	1.17	2.59	0.45	0.30
CC	2	10-20	1.19	3.01	0.39	0.30
NC	2	10-20	1.17	2.59	0.45	0.30
CC	3	10-20	1.12	3.11	0.36	0.30
NC	3	10-20	1.19	2.57	0.46	0.29
GM	1	10-20	1.07	3.07	0.35	0.29
GM	2	10-20	1.13	3.11	0.36	0.32
GM	3	10-20	1.13	3.11	0.36	0.33
SG	1	10-20	1.20	3.12	0.39	0.33
SG	2	10-20	1.01	3.11	0.33	0.32
SG	3	10-20	1.20	3.10	0.39	0.32
CC	1	20-30	1.09	3.00	0.36	0.29
NC	1	20-30	1.14	2.59	0.44	0.35
CC	2	20-30	1.02	3.09	0.33	0.34
NC	2	20-30	1.12	2.59	0.43	0.32
CC	3	20-30	1.13	3.08	0.37	0.29
NC	3	20-30	1.14	2.53	0.45	0.29
GM	1	20-30	1.00	3.04	0.33	0.27
GM	2	20-30	1.03	3.01	0.34	0.33
GM	3	20-30	1.11	3.00	0.37	0.30
SG	1	20-30	1.09	3.11	0.35	0.31
SG	2	20-30	1.02	3.09	0.33	0.35
SG	3	20-30	1.11	3.13	0.35	0.32

A 3.5. Thermal conductivity (λ), volumetric heat capacity (C_V), thermal diffusivity (D), and volumetric water content (θ) at -300 kPa pressure measured in 2015 and used in chapter 5. CC=cover crops, NC=no cover crop, GM=giant miscanthus, and SG=switchgrass.

Treatment	**Rep**	**Depth (cm)**	λ **(W m^{-1} K^{-1})**	C_V **(MJ m^{-3} K^{-1})**	D **(mm^2 s^{-1})**	θ **(cm^3 cm^{-3})**
CC	1	0-10	1.11	3.03	0.36	0.32
NC	1	0-10	1.16	2.41	0.48	0.27
CC	2	0-10	1.16	3.00	0.39	0.34
NC	2	0-10	1.13	2.61	0.43	0.30
CC	3	0-10	1.12	3.12	0.36	0.34
NC	3	0-10	1.13	2.61	0.43	0.30
GM	1	0-10	1.00	3.09	0.32	0.38
GM	2	0-10	1.05	3.08	0.34	0.39
GM	3	0-10	1.10	3.10	0.35	0.38
SG	1	0-10	1.10	3.11	0.35	0.40
SG	2	0-10	1.02	3.12	0.33	0.36
SG	3	0-10	1.16	3.15	0.37	0.36
CC	1	10-20	1.17	3.03	0.38	0.28
NC	1	10-20	1.15	2.61	0.44	0.29
CC	2	10-20	1.18	2.96	0.40	0.28
NC	2	10-20	1.11	2.61	0.42	0.29
CC	3	10-20	1.11	3.09	0.36	0.28
NC	3	10-20	1.14	2.45	0.47	0.28
GM	1	10-20	1.06	3.07	0.35	0.27
GM	2	10-20	1.13	3.09	0.37	0.30
GM	3	10-20	1.13	3.10	0.36	0.30
SG	1	10-20	1.20	3.10	0.39	0.31
SG	2	10-20	1.01	3.10	0.33	0.29
SG	3	10-20	1.19	3.07	0.39	0.28
CC	1	20-30	1.08	3.00	0.36	0.28
NC	1	20-30	1.12	2.61	0.43	0.34
CC	2	20-30	1.01	3.07	0.33	0.32
NC	2	20-30	1.11	2.59	0.43	0.31
CC	3	20-30	1.12	3.07	0.36	0.28
NC	3	20-30	1.12	2.44	0.46	0.28
GM	1	20-30	1.00	3.02	0.33	0.29
GM	2	20-30	1.03	3.00	0.34	0.30
GM	3	20-30	1.11	3.00	0.37	0.28
SG	1	20-30	1.09	3.09	0.35	0.28
SG	2	20-30	1.01	3.08	0.33	0.33
SG	3	20-30	1.11	3.12	0.35	0.29

VITA

Samuel Idoko Haruna was born at Ogodu (Nigeria) to Mr. Stephen Haruna and Mrs. Grace Haruna. He received his B.S. (Geology) in 2008 from Kogi State University, Anyigba (Nigeria) and M.S. (Environmental Sciences) in 2013 from Lincoln University, Missouri. He joined the University of Missouri in 2013 and received his PhD (Soil, Environmental and Atmospheric Sciences) in 2017 under the supervision of Dr. Stephen H. Anderson. He has accepted the position of Assistant Professor of Plant and Soil Science at Middle Tennessee State University, Murfreesboro.