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Impacts of Cover Crop and Residue Removal on Soil Hydraulic and Thermal Properties

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IMPACTS OF COVER CROP AND RESIDUE REMOVAL ON SOIL HYDRAULIC AND THERMAL PROPERTIES

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IMPACTS OF COVER CROP AND RESIDUE REMOVAL ON SOIL HYDRAULIC AND THERMAL PROPERTIES

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Large-scale crop residue removal for livestock or biofuel production may negatively affect soil and water resources. A combination of management practices could be the key to manage such resources under increasingly variable climate. For instance, use of cover crops (CCs) could offset the negative impacts that corn (*Zea mays* L.) residue removal may have on soil water and energy balance. We studied: 1) the effect of corn residue removal (56%) with and without winter rye (*Secale cereale* L.) CC on soil hydraulic and thermal properties including water infiltration, water retention, pores-size distribution, thermal conductivity, specific heat capacity, and thermal diffusivity, 2) whether CCs offset any negative impacts of residue removal effects on the above properties, and 3) relationships of hydraulic and thermal properties with soil organic C and other properties. An experiment of corn residue removal and CCs in an irrigated no-till continuous corn located in south central Nebraska was used. All soil properties were measured 5 and 6 years after experiment onset except water infiltration and soil thermal properties, which were measured only after 6 years. Cover crops generally had no effect on soil hydraulic and thermal properties but increased soil organic C concentration (p = 0.10) in the 0 to 5 cm depth. However, corn residue removal consistently affected soil properties in the 0 to 10 cm soil depth. Residue removal reduced cumulative infiltration by 22 to 58% compared with no removal. It also reduced available water by 21 to 31%, thermal conductivity by 19 to 28%, specific heat capacity by 23 to 28%, soil wet aggregate stability by 17 to 30%, and soil organic C concentration by 25% in the 0 to 5 cm depth. The reduction in available water with residue removal was strongly correlated with a decrease in soil organic C concentration and wet aggregate stability. Thermal conductivity decreased with a decrease in soil water content, soil organic C, and bulk density due to residue removal. In conclusion, corn residue removal negatively impacted soil hydraulic and thermal properties and CCs were unable to completely offset but partially mitigated the negative impacts of residue removal.

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CHAPTER 1. INTRODUCTION AND OBJECTIVES

Introduction

Understanding how management practices affect soil water balance is critical to better manage soil water resources in the U.S. central Great Plains. In this region, precipitation is often supplemented with irrigation to meet production needs. Predictions from global climate models suggest increased variability in precipitation in the future (Winkler et al., 2012). Augmented agronomic management strategies are needed to address these concerns (Wienhold et al., 2018). Practices such as pairing crop residue management with CC adoption to sustain or increase surface residues could contribute to soil water management.

Cover crops can affect soil water resource management (Unger and Vigil, 1998; Blanco-Canqui et al., 2011). In semiarid regions, CCs could reduce early season available water needed for the main crop production (Nielsen et al., 2016; Alvarez et al., 2017). However, adoption of CCs can also contribute to water storage by improving water infiltration and retention in the long term. The few published studies on this topic have reported inconsistent CC effects on water infiltration and available water (Blanco-Canqui et al., 2011; Steele et al., 2012, Basche et al., 2016; Rorick and Kladivko, 2017).

Furthermore, CCs can alter the soil energy balance and have been shown to reduce soil temperature by 1 to 5 °C (Teasdale and Mohler, 1993; Kahimba et al., 2008 Blanco-Canqui et al., 2011). Previous studies have primarily measured soil temperature but not other thermal properties such as soil thermal conductivity, soil specific heat capacity, and soil thermal diffusivity, which also influence soil energy balance. Only one study has evaluated how CCs affect soil thermal properties and found that CC can decrease soil specific heat capacity and thermal diffusivity (Haruna et al., 2017). The literature review on CCs indicates that more research is necessary to understand how CCs will affect water infiltration and retention, which directly influence soil water balance. Additional studies on thermal properties also are needed to better discern changes in soil water and energy balance as affected by the adoption of CCs.

Assessing the effects of crop residue removal on soil water dynamics is essential to managing soil water. High rates (>50%) of residue removal could negatively affect water infiltration and water retention but field data are limited (Blanco-Canqui et al., 2007; Johnson et al., 2016; Tormena et al., 2017). Water retention and available water can be correlated with soil organic C concentration (Hudson, 1994; Rawls et al., 2004; Saxton and Rawls, 2006). Because residue removal removes C with residues (Blanco-Canqui and Lal, 2009), it may reduce soil organic C concentration, which could directly reduce water retention capacity. Additionally, crop residue removal could alter soil thermal properties. However, studies on soil thermal properties, specifically thermal conductivity, specific heat capacity, and thermal diffusivity are few and short term (<3 yr; Sauer et al., 1996; Dahiya et al., 2007). Reduction in soil organic C concentration and water content with residue removal could adversely affect soil thermal properties, as these properties are inter-related (Abu-Hamdeh and Reeder, 2000; Adhikari et al., 2014; Haruna et al., 2017).

Cover crops could be used to offset crop residue removal impacts. However, studies on the ability of CCs to ameliorate the possible impacts of residue removal on hydraulic and thermal properties are few. Only three studies have evaluated how CCs planted after residue removal affect soil properties and found limited or no effects of CC on offsetting residue removal effects on soil properties (Blanco et al., 2014; Wegner et al., 2015; Ruis et al., 2017). Because CCs can increase water infiltration and available water in the long-term (Blanco et al., 2011; Basche et al., 2016), there is potential for CCs to offset the negative impacts of residue removal on infiltration and available water by restoring soil organic C lost with residue removal. The scant literature suggests the need for more research into CCs potential to ameliorate the negative impacts of crop residue removal on soil hydraulic and thermal properties.

Objectives

The overall objective of this project was to evaluate whether corn residue removal with and without CCs induces changes in soil physical properties on an irrigated no-till continuous corn in south central Nebraska. The specific objectives are to:

Objective 1: Determine the impact of corn residue removal (56%) with and without the use of winter rye CC on soil hydraulic properties and thermal properties.

Hypothesis 1: Corn residue removal reduces cumulative water infiltration, water retention, plant available water, soil thermal conductivity, specific heat capacity, and thermal diffusivity.

Objective 2: Determine if CCs could ameliorate the negative effects of crop residue removal on soil hydraulic properties and thermal properties.

Hypothesis 2: Cover crops will ameliorate residue removal effects on soil hydraulic and thermal properties.

Objective 3: Determine relationships of soil hydraulic and thermal properties with soil organic C and other properties.

Hypothesis 3: Soil hydraulic and thermal properties will be strongly correlated with changes in soil organic C and other soil properties under corn residue removal and addition of CCs.

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CHAPTER 2. REVIEW OF LITERATURE

Cover Crops

A cover crop (CC) is defined as a "close-growing crop that provides soil protection, seeding protection, and soil improvement between periods of normal crop production, or between trees in orchards and vines in vineyards. When plowed under and incorporated into the soil, CCs may be referred to as green manure crops" (SSSA, 2008). This means that a CC is grown to provide surface cover and protect the soil when the main crop is not present. Cover crops can be planted in either summer or winter, with CCs terminated prior to the planting of the next main crop.

There are multiple anecdotal claims from websites, magazines, and CC seed dealers on the benefits of CCs for agricultural production. Empirically, peer-reviewed studies support some CC benefits, such as improved sequestration of soil organic C in the long term (>10 yr; Blanco-Canqui et al., 2011; Olsen et al., 2014). However, in the short term (<3yr), ability of CCs to sequester C into the soil could be limited (Acuna and Villamil, 2014; Blanco-Canqui et al., 2014; Blanco-Canqu et al., 2017). Additionally, the potential to sequester soil C can vary with CC species and mixes (Blanco-Canqui et al., 2013). Cover crop mixes may sequester more soil C than single cover crops alone in some cases (Stavei et al., 2012). The use of CCs with no-till management has the highest potential to sequester C (Olsen et al., 2010; Olsen et al., 2014). It is well recognized that CCs can sequester soil C, reduce water and wind erosion, and improve soil fertility, but their impacts on soil properties specifically physical and hydraulic properties deserve further discussion.

Cover Crop Effects on Soil Hydraulic Properties

Cover crop effects on soil bulk density, which affect soil porosity, can be mixed. In Missouri, CCs reduced bulk density after 3 years (Haruna and Nkongolo, 2015), however, in Nebraska and Indiana, CCs had no effect on bulk density after 3 years (Blanco-Canqui 2014; Rodrick and Kladivko, 2017). These results indicate that CCs may not rapidly decrease soil bulk density in the short term. However, in the long term, CCs may reduce soil bulk density (Blanco-Canqu et al., 2011; Steele et al., 2012).

Cover crops can affect runoff and sediment loss from fields. In a 3-yr study in Iowa, runoff was reduced by up to 80% and sediment loss by 40 to 96% with the use of CC (Kasper et al., 2001). After 5 yr in Kansas, CCs reduced sediment loss by 230% when compared with fallow plots (Blanco-Canqui et al., 2013). The reduction in runoff with CCs can increase water storage (Blanco-Canqui et al., 2013). The reviewed literature suggests that water erosion can be reduced if enough CC biomass is produced.

Wet soil aggregate stability is an indicator of water erosion potential. Several studies have found that wet aggregate stability generally increases with CC use (Liu et al., 2005, Villamil et al., 2006; Blanco-Canqui et al., 2011; Steele et al., 2012; Acuna and Villamil, 2014; Blanco et al., 2014; Ruis et al., 2017;). Studies reporting no CC effect on wet aggregate stability were short term (<4 yr; Stetson et al., 2012; Wegner et al., 2015), suggesting that CCs may improve wet aggregate stability in the medium and long term.

There are few published studies on CC effects on water infiltration. These studies have reported inconsistent results. For example, winter rye CC increased water infiltration rate at three rainfed sites in Maryland after 13 yr, but the extent of increase varied seasonally or annually (Steele et al., 2012). In a 15-yr study in Kansas, cumulative water infiltration was increased by 3 times compared to no CC after using summer CCs of hairy vetch (*Vicia villosa* Roth) and sunn hemp (*Crotalaria juncea* L.) planted after the harvest of winter wheat (Blanco-Canqui et al., 2011). In contrast, after 3 yr in Nebraska, no CC effect was found on water infiltration (Blanco-Canqui et al., 2014). The reviewed literature suggests that: 1) CCs may not affect water infiltration in the short term (<3 yr), 2) CC effects on water infiltration may be temporary, and 3) CCs have the potential to increase water infiltration in the long term.

Cover crops could improve plant available water, which is the amount of water held against gravity that plants can easily extract. If CCs are able to increase the amount of water stored at field capacity (-0.033 MPa), but not affect water storage at permanent wilting point (-1.5 MPa), then CCs would be able to increase available water. However, if CCs do increase the amount of water stored at permanent wilting point, then there may be either no change or decrease in available water. Available water is calculated by subtracting the volumetric water content at permanent wilting point from the volumetric water content at field capacity. Unavailable water is adsorbed to the soil too tightly for plant use (Hillel, 2004). Increasing the amount of available water is of most interest in soil water research. After 5 yr in Illinois, cereal rye or hairy vetch CCs were able to increase the available water content by 4 to 8 % (Villamil et al., 2006). A more substantial increase in available water of 21% was found in Iowa after 13 yr of using a rye CC (Basche et al., 2016). However, no CC effect on available water was found when using a summer CC in Kansas after 15 yr (Blanco-Canqui et al., 2011). After 4 yr in Indiana, cereal rye CC had no effect on available water (Rorick and Kaldivko, 2017). These conflicting reports from both short and long-term studies require additional research to understand the effects of CCs on available water. Specifically: 1) Do CCs improve available water with time?, and 2) under what soil and management conditions do CCs have the highest potential to affect available water?

Cover Crop Effects on Soil Thermal Properties

One major knowledge gap is the possible effect that CCs may have on soil thermal properties. Both Kahimba et al. (2008) and Blanco et al. (2011) found that CCs decrease soil temperature by 2° to 4° C. Lower soil temperatures suggest that surface energy balance is altered by CCs through changes to either soil specific heat capacity or soil thermal conductivity.

On the soil surface, CC canopy and residues can affect soil temperature. The additional residue produced by CC can reduce the amount of incoming energy or net radiation. Simulated responses to different plant residue types and orientations found an interactive effect of residue orientation and type of plant residue on spring warming, evaporation, and frost depth (Flerchinger et al., 2003). Thus, additional aboveground biomass input by growing CCs could change the amount of net radiation that will reach the soil surface.

Below the soil surface, CCs may change the soil energy balance by altering soil thermal properties such as soil thermal conductivity, specific heat capacity, and thermal diffusivity. Soil thermal conductivity is the amount of heat transferred through an area, while specific heat is the amount of heat it takes to increase the soil by one degree Celsius, and thermal diffusivity is the ratio of thermal conductivity to specific heat capacity (Hillel, 2004). . Only one study has evaluated the effect of CCs on soil thermal conductivity, specific heat capacity, and thermal diffusivity (Haruna et al., 2017). In this study, CCs decreased soil specific heat capacity and soil thermal diffusivity but did not affect soil thermal conductivity (Haruna et al., 2017).

The three main thermal properties (soil thermal conductivity, specific heat capacity, and thermal diffusivity) are important because of their mechanistic effect on the soil surface energy balance. For example, thermal conductivity directly affects the soil surface as part of the soil heat flux density (G), which is described by Fourier's law of heat conduction:

$$G = -\lambda \frac{\partial T}{\partial z} \qquad [1]$$

where λ is the soil thermal conductivity (W m^{-1} K^{-1}) and $\partial T/\partial z$ is the vertical temperature gradient of the soil (K m^{-1}). In the soil energy balance equation, soil heat flux density is used to quantify the amount of heat moving deeper into the soil profile.

Residue Removal Effects on Soil Hydraulic Properties

Crop residue removal at high rates (>50%) has been found to decrease soil organic C concentrations, especially over time (Blanco-Canqui and Lal, 2009b). When crop residue is removed at high rates, there is an increased risk of wind and water erosion (Blanco-Canqui et al., 2014; Jin et al., 2015; Kenney et al., 2015; Blanco-Canqui et al., 2016; Blanco-Canqui et al., 2017). At high rates of residue removal, there is less C input available to replace soil organic C lost through erosion (Blanco-Canqui and Lal, 2009a; Smith et al., 2012). Thus, continuous removal of corn residue at high rates has a cumulative effect on soil organic C concentration, which, in turn, can affect soil hydraulic properties through the role of SOC in improving soil aggregation and structure.

Crop residue removal may have the potential to decreases aggregate stability. The positive relationship of aggregate stability to soil organic matter is well known (Blanco-Canqui and Lal, 2009a; Blanco-Canqui et al., 2011; Steele et al., 2012; Osborne et al., 2014; Jin et al., 2015). Although aggregate stability could also be reduced due to increased wheel traffic related to residue removal operations, the loss of SOC with residue removal contributes to destabilization of soil aggregates. Thus, the loss of soil organic C may be partially responsible for destabilization of soil aggregates when residue is removed, particularly at high rates (>50%; Blanco-Canqui and Lal, 2009a; Osborne et al., 2014; Jin et al., 2015). High rates of residue removal reduce surface cover for protecting the soil from water and wind erosion (Blanco-Canqui and Lal, 2009b). This establishes a negative feedback loop in which decreasing SOC and weakened soil aggregates further exacerbate soil erosion risk (Blanco-Canqui and Lal, 2009b).

Excessive crop residue removal can negatively affect water infiltration but not in the short term (Blanco-Canqui et al., 2014; Johnson et al., 2016). In Nebraska, after 3 yr of residue removal at 56%, water infiltration remained unchanged (Blanco-Canqui et al, 2014), but, after 7 yr in Minnesota, Johnson et al. (2016) found that high rates (60%) of residue removal reduced water infiltration. With only a limited number of available studies, the overall impact of excessive residue removal on water infiltration is unclear.

Similarly, there are few published studies on residue removal effects on soil water retention. After 1 yr, Blanco-Canqui et al. (2007) found a decrease in water retention at the -0.1 MPa matric potential at three sites when corn residue was removed at 75% and 100%. It is important to note that the magnitude of the decrease can be affected by soil texture. Residue removal has the potential to decrease soil's ability to absorb and store water. However, additional research data are needed to better understand residue removal effects.

Residue Removal Effects on Soil Thermal Properties

There are few studies that have looked at the effects of residue removal on soil thermal properties. One study in Iowa found no differences in soil thermal conductivity between soil monoliths with fresh corn residue, weathered corn residue, and without residue under laboratory conditions (Sauer et al., 1996). However, the cited study also reported that sensors in the surface of the monoliths were not functioning properly, which may have masked possible differences in thermal conductivity due to residue removal. In Germany, a 1-yr study found that soil thermal conductivity did not differ among bare soil, surface-applied wheat mulch, and incorporated wheat mulch (Dahiya et al., 2007). A major knowledge gap that needs to be addressed is the impact of crop residue removal on thermal properties, especially specific heat capacity and thermal diffusivity, after multiple years of residue removal.

Thermal conductivity, specific heat capacity, and thermal diffusivity are correlated with other soil properties. For example, there is a strong positive relationship of volumetric water content with thermal conductivity and specific heat capacity of the soil (Potter et. al., 1985; Abu-Hamdeh, 2000; Abu-Hamdeh and Reeder, 2000; Ochsner et al., 2001). Reinforcing the importance of soil structure and water storage, Ochsner et al. (2001) also found a strong negative relationship between air-filled pore space and thermal conductivity. However, most research has focused on thermal conductivity alone, leaving a need for information on how soil management affects soil specific heat capacity and thermal diffusivity.

Cover Crops versus Residue Removal Interaction

Since previous research has indicated that high rates of residue removal can have negative impacts on soil properties (Blanco-Canqui et al., 2007; Blanco-Canqui and Lal, 2009b; Osborne et al., 2014; Jin et al., 2015; Kenney et al., 2015; Johnson et al., 2016), there is a need to ameliorate the expected adverse effects of high rates of residue removal. The use of CCs after the removal of crop residue may ameliorate the negative impacts of residue removal by maintaining or improving the soil properties that crop residue removal can degrade.

There are few reported results on the ability of CCs to completely or partially offset the negative impacts of residue removal on soil properties. Two published studies found limited responses of the soil to residue removal and no effect of CC on soil properties in the short term (Blanco-Caqui et al., 2014; Ruis, et al., 2017). After 5 yr in South Dakota, high rates of residue removal (98%) reduced soil organic C concentration, aggregate stability, and water retention, but CCs did not ameliorate these negative impacts (Wegner et al., 2015). The limited published information on the potential for CC to offset the negative impacts of residue removal on soil properties warrants further research.

Research Needs

Some of research needs include:

- Further evaluate if CCs can ameliorate the negative impacts of corn residue removal on soil organic C concentration, water retention, water infiltration, soil thermal conductivity, soil specific heat capacity, and soil thermal diffusivity.
- Assess the impacts of crop residue removal on water retention, water infiltration, soil thermal conductivity, and soil thermal diffusivity.
- Study relationships between plant available water and soil organic C as affected by residue removal and CC use.
- Study relationships of thermal conductivity and specific heat capacity with soil organic C concentration, volumetric water content, bulk density, soil texture, and other soil properties

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CHAPTER 3. IMPACTS OF COVER CROPS AND CORN RESIDUE REMOVAL ON SOIL HYDRAULIC PROPERTIES AND CARBON RELATIONSHIPS

Abstract

Large-scale crop residue removal may have negative effects on soil water dynamics and overall soil productivity. Integrating cover crops (CCs) with crop residue management can be a strategy to manage soil water and ameliorate or offset potential adverse effects of residue removal on soil physical and hydraulic properties. We studied: 1) the impact of corn residue removal (56%) with and without the use of winter rye (*Secale cereale* L.) CC on soil hydraulic properties including water infiltration, water retention, pores-size distribution, and available water, 2) whether CCs would ameliorate residue removal effects on hydraulic properties, and 3) relationships of hydraulic properties with soil organic C and other properties under an irrigated no-till continuous corn on a silt loam in south central Nebraska after 6 yr of management. Cover crops did not improve any of the measured soil hydraulic properties. However, residue removal reduced cumulative water infiltration by 22 to 58%. It also reduced available water by 21 to 31%, wet aggregate size by 17 to 30%, and soil organic C by 25% in the 0 to 5 cm depth. Cover crops increased soil organic C concentration by 22% in the 0 to 5 cm depth but did not offset the decrease in organic C due to residue removal. The decrease in plant available water with residue removal was correlated with the decrease in organic C concentration and water-stable aggregates. Overall, after 6 yr, corn residue removal adversely affected soil hydraulic properties and soil C concentration, but CC was unable to fully offset the residue removal impacts.

Introduction

Proper management of soil and water resources is critical to sustain agricultural production under fluctuating climatic conditions with changes in precipitation patterns, heat waves, droughts, and others. Particularly, in the central Great Plains, management of soil water resources is of special interest where precipitation is often supplemented with irrigation to meet production goals. Improved agronomic management strategies are needed to address the above concerns (Wienhold et al., 2018). Practices such as cover crop (CC) and crop residue management that maintain or increase surface residue cover can increase precipitation capture, reduce evaporation, and increase water holding capacity.

Cover crops can contribute to soil water management (Unger and Vigil, 1998; Daigh et al., 2012; Basche et al., 2016b). In water-limited regions, CCs could reduce available water needed for main crop production (Nielsen et al., 2016; Alvarez et al., 2017). However, CCs may be able to also contribute to water storage by increasing water infiltration, retention, and plant available water in the long term. Improved management of CCs may ameliorate the negative impacts of precipitation fluctuations (Daigh et al., 2012; Steele et al., 2012; Basche et al., 2016a; Basche et al., 2016b).

Many have studied CC effects on wind and water erosion, soil organic C pools, and soil chemical and biological properties (Villamil et al., 2006; Dinesh et al., 2009; Blanco-Canqui et al., 2011, Premrov et al., 2012; Hubbard et al., 2013; Abdollahi et al., 2014). However, few have studied impacts of CCs on properties that affect soil water dynamics such as water infiltration, retention, and plant available water. The few published studies have reported conflicting results. For example, in Maryland, after 13 yr across three rainfed sites, winter rye CC had inconsistent effects on water infiltration rate (Steele et al., 2012). However, a 15-yr study in Kansas found that summer CCs [hairy vetch (*Vicia villosa* Roth) and sunn hemp (*Crotalaria juncea* L.)] planted after winter wheat (*Triticum aestivum* L.) harvest increased cumulative water infiltration by 3 times compared with no CC (Blanco-Canqui et al., 2011).

Likewise, the few studies on soil water retention and available water have reported some mixed effects of CCs. In Iowa, after 13 yr, rye CC increased available water by 21% (Basche et al., 2016b). Similarly, in Illinois, after 5 yr, cereal rye or hairy vetch CC increased available water by 4 to 8% (Villamil et al., 2006). However, a 15-yr study in Kansas found no summer CC effects on available water (Blanco-Canqui et al., 2011). Additionally, a 4-yr study in Indiana reported that cereal rye had no effect on available water (Rorick and Kladivko, 2017). The conflicting reports from both short-term and long-term studies on CCs warrant additional research on CC impacts on soil hydraulic properties. Moreover, previous studies have focused on rainfed systems. Data are lacking from irrigated cropping systems.

Crop residue management can also affect soil water dynamics. The retention of plant residues on the soil surface helps conserve soil water, maintain soil fertility, and provide other ecosystem services (Graham et al., 2007; Fronning et al., 2008; Blanco-Canqui et al., 2014), but as the demand for livestock feed and biofuel feedstock increases, the pressure to remove crop residues can increase in the future. Short term (<3 yr) studies have indicated that corn residue removal at high rates can have positive effects on early season N mineralization, soil temperature, seed germination, and early root growth in regions with high residue production such as under irrigated conditions (Kenney et al., 2013; Wortmann et al., 2015). At the same time, however, high rates of residue removal can have some negative effects on long-term soil productivity by increasing water and wind erosion and evaporation, which can reduce soil water storage and recharge (Kenney et al., 2013). Similar to CCs, few have specifically measured changes in soil hydraulic properties after crop residue removal to better understand water capture, retention, and losses after residue removal. Some have suggested that corn residue removal at high rates (>50%) could negatively affect soil water storage and recharge by reducing water infiltration and available water (Blanco-Canqui et al., 2007; Johnson et al., 2016; Tormena et al., 2017), but measured data on the latter hydraulic properties are limited. In Minnesota, a 7-yr study found that corn residue removal at about 70% reduced hydraulic conductivity by 20% compared with plots without removal (Johnson et al., 2016). In Ohio, high rates of residue removal (≥50%) reduced water retention at low matric potentials within the first year following residue removal although the magnitude differed with soil textural class (Blanco-Canqui et al., 2007)

The few studies suggest that corn residue removal at high rates can negatively affect soil hydraulic properties. Adding CCs after residue removal could be one of the strategies to reduce such negative effects. This combination of both management strategies could enhance soil properties and agricultural production more than managing crop residues or using CCs alone. However, information on this combination is limited. Short term (< 3 yr) studies in Michigan and Nebraska have found limited or no effects of CCs on offsetting the negative impacts of residue removal on soil organic C and wet aggregate stability (Fronning et al., 2008; Blanco-Canqui et al., 2014). Even in the medium term, CCs may have limited effect on ameliorating residue removal effects on hydraulic properties in some soils. For example, in South Dakota, CC had no effect on offsetting the negative impact of 98% crop residue removal on water content at any matric potentials (Wegner et al., 2015). The reviewed studies are short term and suggest the need for additional studies on crop residue removal with CCs.

It is also imperative to understand how CCs and crop residue removal can affect soil properties that are indicators of changes in soil hydraulic properties such as soil organic C concentration. Some of the questions include: 1) Does crop residue removal reduce water retention capacity by reducing soil C concentration? 2) Can CC offset such effects of residue removal by replacing the soil C lost with residue removal? It is well recognized that a decrease in soil C can result in a corresponding decrease in available water (Hudson, 1994; Rawls et al., 2004; Saxton and Rawls, 2006). However, such relationship can vary among soils due to differences in the amount of residue removed, CC management, and initial soil C concentration, among others. The relationships between changes in soil hydraulic properties and soil organic C have not been much discussed based on field data.

The objectives of this study were to assess: 1) the impact of corn residue removal (56%) with and without the use of winter rye (*Secale cereale* L.) CC on soil hydraulic properties including water infiltration, water retention, pores-size distribution, and available water, 2) whether CCs would ameliorate residue removal effects on hydraulic properties, and 3) relationships of hydraulic properties with soil organic C and other properties. The first hypothesis was that corn residue removal would reduce cumulative water infiltration, water retention, and plant available water. The second hypothesis was that CC would ameliorate residue removal effects on soil hydraulic properties. The third hypothesis was that CCs and residue removal would reduce water retention and available water by reducing soil organic C concentration.

Materials and Methods

Study Site

This study was conducted on an ongoing experiment established in 2010 at the University of Nebraska-Lincoln (UNL)'s South Central Agricultural Laboratory near Clay Center, NE (40.582° N lat; 98.144°W long; 552 m asl). The soil is classified as Hastings silt loam (fine, smectitic, mesic Udic Argiustolls) with an average slope of less than 3% (Soil Survey Staff, 2017). The experiment is under irrigated no-till continuous corn. The experimental design is a completely randomized split-split-split block in quadruplicate with four study factors. The factors are: 1) two irrigation levels [full, deficit], 2) three amelioration practices [none, cereal rye cover crop, surface broadcast animal manure], 3) two corn residue removal rates [none, maximum], and 4) two inorganic N fertilizer rates [125, 200 kg N ha^{-1} yr^{-1}). This results in a total of 96 experimental units (2×3×2×2×4 reps = 96). Agronomic operations for 2015 to 2017 are shown in Table 3.1. In the present study, residue removal and CC effects on soil hydraulic properties were evaluated for only a subset of treatments that best represented producer practices for irrigation (full) and N management (200 kg N ha^{-1} yr^{-1}).

Experiment Design

Main Plot: The experiment has eight 24-m by 155-m main plots for each irrigation treatment. Full irrigation treatments have 45 to 90% of total available water holding capacity within 1.2-m soil profile. An irrigation event is set to occur when plant available water content is at 45% in the full irrigation treatment. The deficit irrigation treatment applies 60% of the water inputs of the fully irrigated treatment. Deficit irrigation events are applied at the same time as full irrigation events. Irrigation timings are based on a soil matric potential sensor (Irrometer Co. Inc., Riverside, CA) measurements in the full irrigation plots and supplementary neutron soil moisture gauge measurements from an adjacent study within this field (Troxler Electronic Labs., Research Triangle Park, NC). Soil matric potential sensors are installed every 0.3 m to a 1.2-m soil depth within the crop row.

Split Plot: Each irrigation level main plot is split into three 24-m by 52-m amelioration plots to compare winter rye cover crop (*Secale cereale* L.), animal manure, or control (no manure or cover crop). The manure application is surface applied in the fall after residue removal using a mechanical manure spreader. Manure is applied at a phosphorus (P) rate using approximate crop P removal as described by Blanco-Canqui et al. (2014), which results in manure applications every 2 yr. Winter rye is planted in fall after corn residue harvest using a no-till drill and terminated using glyphosate in spring of each year before corn planting. The winter rye was seeded at an average rate of 112 kg ha^{-1} at a depth of 3 cm with 15 cm row width.

Spit–Split Plot: Each split plot is subdivided into two 12-m by 52-m plots for corn residue management, where corn residue is either removed or retained. Residue removal occurred in late October of each year following grain harvest. Residue was removed with a 3-pass system (mow, rake into windrows, round bale) in 2010, and with a 2-pass system (mow-windrow, round bale) from 2011 to 2016. The corn residue was mowed at a 5 cm cutting height to allow the maximum amount of mechanically removable residue under field conditions. The mean residue removal rate was 56 ± 3% (5.6 ± 0.5 Mg dry matter ha^{-1}) from 2010 to 2015.

Split–Split–Split Plot: The residue management plots are additionally divided into two 12-m by 26-m N fertilizer treatment plots to compare 125 vs 200 kg N ha^{-1}. Nitrogen source is solution of urea and ammonium nitrate (UAN) applied at post-emergence between corn rows using a coulter injection application system. Manure treatment plots are credited for first, second, and third-year mineralizable N from applied manure, as per University of Nebraska recommendations (Shapiro et al., 2006).

Water Infiltration

Water infiltration was measured in-situ during spring, summer, and fall 2016 using a double ring infiltrometer under a constant head (Reynolds et al., 2002). Water infiltration in spring was measured in the spring after corn emergence, while infiltration in summer was measured approximately 7 days after an irrigation event. Infiltration in fall was conducted after harvest, but prior to the residue removal and planting of the winter rye CC. The double rings (75 cm outer ring and 25 cm inner ring) were placed on the shoulder of the corn row and inserted to 10 cm depth in non-trafficked rows. The row shoulder was selected to avoid soil disturbance left from an application of N fertilizer that was knifed into the center of the interrow.

The constant head for the infiltrometer was established and maintained by a custom Mariotte bottle fabricated out of polyvinyl chloride (PVC) pipe with an inner diameter of 15.25 cm. At times of 1, 2, 3, 5, 10, 30, 60, 90, 120, 150, and 180 min, the height of the water in the Mariotte bottle was recorded for the 3 h duration. The infiltration rate for each time interval was calculated along with the cumulative water infiltration. Soil samples for antecedent water content were collected with a hand probe (diameter of 3.1 cm) for depths of 0 to 5 and 5 to 10 cm near the infiltration sites prior to the start of each measurement. The samples were weighed, and a sub sample collected and dried at 105° C for 24 hr to determine gravimetric water content and then multiplied by the corresponding bulk density to determine volumetric water content.

Laboratory Measurements of Water Retention

For the laboratory measurements of soil water retention, 5 × 5 cm intact soil cores were collected in spring of 2015 and 2016 from representative non-trafficked row shoulders in each plot. Two soil cores were collected from the 0 to 15 cm soil depth from each plot. The cores were carefully inserted into the soil by hand until soil occupied the full volume of the core to avoid compacting the soil. The cores were transported and stored in the cold room at 2.2 °C until further processing.

The intact soil cores were carefully trimmed flush with the top and bottom of the metal core. The soil cores were saturated slowly by capillary action over the course of about 3 d. Water retention was determined at 0, -0.001, and -0.003 MPa, -0.01, -0.033, -0.1 and -1.5 MPa. For the 0, -0.001, and -0.003 MPa points, a tension table was used to equilibrate the soil cores at each pressure head. Soil cores were weighed at each step to determine change in volumetric water content. To determine volumetric water content at -0.01, -0.033, -0.1 MPa, the intact soil cores were transferred from the tension table to the low suction pressure extractor, corresponding air pressure applied, and soil cores weighed at each pressure step (Klute 1986). Afterwards, a subsample of soil was collected from each intact core, dried in an oven at 105 °C for 24 h, and used to calculate bulk density by the core method (Grossman and Reinsch, 2002). Then, the intact soil cores were air dried, ground, and passed through a 5-mm sieve. The sieved sample was packed in 1 cm by 5 cm plastic rings on top of a -1.5 MPa ceramic plate and allowed to saturate for 24 h. The ceramic plate along with the samples were then placed in a high-pressure extractor to determine water content at -1.5 MPa (Dane and Hopmans, 2002).

Plant available water was calculated by subtracting the volumetric water content at permanent wilting point (-1.5 MPa) from field capacity (-0.033 MPa). Pore-size distribution was computed from the water retention data using the capillary equation (Dane and Hopmans, 2002). Pore size classes were divided into macropores (> 300 µm diameter), mesopores (10-300 µm diameter), and micropores based on pore diameter (< 10 µm diameter; Luxmoore, 1981).

Other Soil Properties

At the time of intact soil core sampling, six hand-probe samples (3.1 cm diameter) were collected from each plot from 0 to 15 cm depth and split into 5 cm depth increments and composited by depth. The composite samples were gently broken up along natural planes of weakness and allowed to air dry. These samples were used to measure wet aggregate stability and soil organic C concentration.

A fraction of the initial air-dry sample was crushed and passed through a 2-mm sieve for the analysis of soil organic C concentration. The sieved sample was cleaned to remove visible residues, placed in a glass vial, and ground on a roller mill for 24 h. About 90 mg of the ground sample were used to determine soil organic C concentration by the dry combustion method using an EA Flash 2000 Analyzer equipped with a MAS auto sampler (Nelson and Sommers, 1996).

Wet aggregate stability was determined by the wet sieving method (Nimmo and Perkins, 2002). A portion of the air-dry sample was passed through 4.75- to 8-mm sieves to collect about 50 g of aggregates ranging from 4.75- to 8-mm diameter. The collected aggregates were then placed on the top of sieves with 4.75, 2.00, 1.00, 0.50, and 0.25-mm openings and saturated by capillarity for 10 min. The samples were then mechanically sieved in a column of water at 30 cycles per min for 10 min. The aggregates from each sieve were transferred to pre-weighed beakers and oven-dried at 105 °C and weighed. Samples were then treated with sodium hexametaphosphate dispersing agent and passed through a 0.053-mm sieve for sand correction. The sand particles on the sieves were recovered and oven dried at 105 °C. Mean weight diameter (MWD) of water-stable aggregates was then computed as described by Nimmo and Perkins (2002).

Statistical Analysis

All collected data were tested for normality using PROC UNIVARIATE in SAS (SAS Institute Inc., 2017) and data were found to be normally distributed. Data were analyzed using a randomized complete block design with a split plot. The main plot was the CC treatment and the split plot was the corn residue removal treatment. Analysis of water retention, plant available water content, pore size distribution, MWD, soil organic C concentration, and bulk density data was conducted by depth and date. Water infiltration data were analyzed by date. All data were analyzed using PROC MIXED to determine main effects and interactions. All differences among treatments were tested using LSMEANS in SAS and declared significant at the 0.05 probability level unless otherwise noted. Relationships of water retention, pore size distribution, and plant available water content with other soil properties were studied using PROC CORR and PROC STEPWISE in SAS. Simple predictive equations for estimating plant available water from other soil properties were developed using linear regression analysis. After initial data analysis, analysis of water retention, plant available water content, pore size distribution, MWD, soil organic C concentration, and bulk density was pooled across dates as neither the main nor interactive effects of date were significant.

To identify whether the CC could fully offset or partially offset the potential negative impacts of residue removal on soil organic C concentration, MWD, water retention, pore size distribution, plant available water, and cumulative infiltration, two contrasts statements were tested using CONTRASTS in SAS (SAS Institute Inc., 2017). The contrast between control (no residue removal and no CC) and residue removal with CC tested if the CC could fully offset the negative impacts of residue removal on soil properties. The contrast between residue removal with CC and residue removal without CC was studied to test if the CC could partially offset the negative impact of residue removal on soil properties.

Results and Discussion

Soil Organic C and Water-Stable Aggregates

Cover crop effect on soil organic C concentration was marginally significant for the 0 to 5 cm soil depth ($p = 0.09$; Table 3.2). Cover crop had no effect at deeper soil depths. However, corn residue removal (at 56%) had a significant effect on soil organic C concentration for all soil depth intervals (0 to 5, 5 to 10, and 10 to 15 cm; Table 3.2). Cover crop × residue removal interaction was significant for soil organic C concentration for the 0 to 5 cm and 5 to 10 cm soil depth. Specifically, CC did not affect soil organic C concentration when residue was retained, but increased soil organic C concentration by 22% and 12% when residue was removed in 0 to 5 and 5 to 10 cm depths, respectively. When no CC was used, residue removal alone reduced soil organic C concentration by 25% in the 0 to 5 cm depth and 10% in the 5 to 10 cm depth compared to when residue was retained (Table 3.2). Cover crop had no effect on MWD at any soil depth, but residue removal had an effect for the 0 to 5 cm and 5 to 10 cm depths. Residue removal × CC interaction was not significant for MWD. Residue removal reduced MWD by 45% in the 0 to 5 cm and by 35% in the 5 to 10 cm depth (Table 3.2).

The contrast between control (no CC and no residue removal) and residue removal followed by CC was significant for both soil organic C concentration and MWD in the 0 to 5 cm depth (Table 3.2). This suggests that CC did not offset the residue removal-induced decrease in soil organic C and MWD near the soil surface after 6 years. Note that even though CC significantly increased soil organic C concentration (p = 0.09), it did not completely offset the residue removal effect on soil organic C in the 0 to 5 cm depth. However, in the 5 to 10 cm, CC was able to offset the lesser effect of residue removal on reducing soil organic C concentration. Cover crop did not offset residue removal-induced decrease in MWD at any soil depth. Similar to this study, Wegner et al. (2015) and Ruis et al. (2017) found that CCs had limited or no effect on offsetting the negative effects of high rates of residue removal on soil organic C and aggregate stability.

Our results also show that CCs had a lesser effect than residue removal on soil organic C concentration (Table 3.2) and MWD (Fig. 3.1) in this study. On average, 5.9 Mg ha^{-1} yr^{-1} of corn residue was removed from the residue removal plots. This removal rate was 7 times greater than the amount of CC aboveground biomass produced (0.8 Mg ha^{-1} yr^{-1}), which most probably explains the larger effect of residue removal on soil organic C and MWD than CC.

Comparison of results from the present study with those reported by Blanco-Canqui et al. (2014) for the same experiment after 3 yr provide valuable insights into CC and residue removal effects on soil properties on a temporal scale. In the present study, CC affected soil organic C concentration near the soil surface after 6 yr, but CC did not have any effect after 3 years (Blanco-Canqui et al., 2014). This suggests that CC effects on soil organic C concentration can develop with time. In other words, CCs may change soil organic C concentration in the long term but not in the short term (<3 yr).

Additionally, the same study by Blanco-Canqui et al. (2014) found that residue removal reduced soil organic C concentration only in the 2.5 cm of the soil profile after 3 yr, but in the present study after 6 yr, residue removal reduced soil organic C concentration for the 0 to 15 cm depth. This suggests that residue removal can have a cumulative effect on reducing soil organic C concentration. It is clear that the cumulative residue removal effect on soil organic C became more pronounced and measurable at deeper soil depths after 6 yr (Table 3.2). These results suggest that in order to fully understand CC and residue removal effects on soil properties, long term (> 3 yr) experiments are needed. Additionally, the potential of CCs to mitigate or offset crop residue removal effects may manifest only in the long term (Table 3.2).

Water Retention, Pore-Size Distribution, and Available Water

There was no CC effect on water retention, pore-size distribution, or plant available water at any of the measured depths. However, corn residue removal significantly affected water retention, pore size distribution, and plant available water content in the 0 to 10 cm depth of soil. Residue removal × CC interaction was not significant. Cover crop and residue removal treatments had no effect on soil bulk density at any depth (data not shown) depth.

These results support our first hypothesis that corn residue removal would decrease water retention and plant available water. However, the lack of CC effects did not support our first hypothesis. Our results agree with some studies which concluded that CC had no effect on water retention and plant available water (Blanco-Canqui et al., 2011; Rorick and Kladivko, 2017) but disagree with some other that found increased available water under CCs (Villamil et al., 2006; Basche et al., 2016b).

Corn residue removal at 56% significantly affected volumetric water content at the -0.010, -0.033, and -0.100 MPa matric potentials. In the 0 to 5 cm depth, residue removal reduced the volumetric water content by 18 to 23% at the above matric potentials compared to no residue removal (Fig. 3.2A). In the 5 to 10 cm depth, residue removal reduced volumetric water content at the -0.033 and -0.100 MPa matric potentials by 10% and 9% (Fig. 3.2B). In the 10 to 15 cm depth, residue removal reduced volumetric water content at the 0.10 probability level for the -0.033 and -0.100 MPa matric potentials (Fig. 3.2C). It reduced water content by 5% and 9%. The significant decrease in water retention with residue removal is similar to that reported by Blanco-Canqui et al. (2007) and by Wegner et al. (2015).

Residue removal did not affect the volume of macropores (> 300 µm in diameter) at any depth (Fig. 3A). However, it increased the volume of mesopores (10 to 300 µm in diameter) by 30% in the 0 to 5 cm depth and by 20% in the 5 to 10 cm depth (Fig. 3.3B). There was no treatment effect on the volume of mesopores in the 10 to 15 cm depth. Crop residue removal reduced the volume of micropores (<10 µm) by 20% in the 0 to 5 cm depth and by 14% in the 5 to 10 cm depth (Fig. 3.3C). In the 10 to 15 cm depth, the treatment effect on mesopores was not significant.

Residue removal significantly reduced plant available water content in the 0 to 5 cm and 5 to 10 cm depth (Fig 3.4). Plant available water decreased by 31% in the 0 to 5 cm and by 21% in the 5 to 10 cm depth. Residue removal did not affect plant available water below 10 cm depth.

The contrast between control (CC and no residue removal) and residue removal with CC was significant for volumetric water content at all matric potentials, mesopores, micropores, and plant available water content at the measured soil depths. These significant contrasts suggested that CC was unable to offset the negative effects of residue removal on, water retention, pore size distribution, and plant available water. The contrast between residue removal with CC and residue removal without CC was not significant for water retention, pore size distribution, and plant available water. These non-significant contrasts suggested that CC was unable to offset the effects of residue removal on water retention, pore size distribution, and plant available water. This rejects our second hypothesis, which stated that CC would ameliorate residue removal effect on water retention, pore-size distribution, and plant available water. Studies on the potential of CCs to offset crop residue removal are very few. Similar to this study, in eastern South Dakota, Wegner et al. (2015) found that CCs did not offset the negative impact of high rates of corn residue removal on water retention.

Water Infiltration

Differences in antecedent soil water content measured prior to water infiltration measurements did not differ among treatments. Across treatments, mean antecedent water content for the spring was 0.32 ± 0.06 cm^3 cm^{-3}, summer was 0.30 ± 0.08 cm^3 cm^{-3}, and fall was 0.23 ± 0.05 cm^3 cm^{-3}. Cover crop effect on cumulative water infiltration was not significant in spring and summer measurements, but residue removal reduced cumulative water infiltration at all (spring, summer, and fall) measurement dates. There was a CC × residue removal interaction effect on fall cumulative water infiltration. These results did partly support our first hypothesis stating that residue removal can reduce water infiltration while CCs would increase cumulative water infiltration.

In spring, residue removal reduced total cumulative water infiltration by 50% when residue was removed compared to no residue removal (Fig. 3.5). Differences between residue removal and no removal were significant after 60 min. In summer, residue removal reduced total cumulative water infiltration by 130% times (Fig. 3.6). At this measurement date, cumulative water infiltration between removal and no removal significantly differed after 10 min.

The interactive effect between residue removal and CC use on cumulative infiltration in fall suggested that the magnitude at which residue removal decreased infiltration depended on CC treatment. In fall, when residue was retained, CC had no effect on cumulative water infiltration, but when residue was removed, CC increased cumulative water infiltration by 96% compared to no CC (Fig. 7). Under plots without CC, residue removal reduced soil organic C concentration by 159% (Fig. 3.7).

The contrast between control (no CC and no residue removal) and residue removal with CC was significant for cumulative water infiltration in the spring (p <0.0001), summer (p < 0.0001), and fall (p = 0.0276). This suggests that CC did not completely offset the residue removal-induced decrease in cumulative infiltration after 6 yr. The contrast between residue removal followed by CC and residue removal without CC was not significant for the spring (p = 0.5129) and summer (p = 0.3465) but was significant for the fall (p = 0.0369). These results indicated that CC ameliorated or partly offset the negative impacts of residue removal on water infiltration in fall.

The results of this study indicate that CCs were unable to increase water infiltration compared to the control after 6 yr of use. The results appear to disagree with two previous CC studies (Blanco-Canqui et al., 2011; Steele et al., 2012), which found that CCs increased water infiltration after 12 to 13 yr. The latter two studies suggest that CCs can increase water infiltration in the long term. Because our experiment was only 6 yr old, we expect that changes in water infiltration and other soil properties can further develop with time.

A comparison of water infiltration results after 6 yr (this study) with those reported after 3 yr for the same experiment (Blanco-Canqui et al. 2014) highlights how crop residue removal effects develop with time. Blanco-Canqui et al. (2014) did not find residue removal effect on cumulative water infiltration after 3 yr, but, in the present study, cumulative water infiltration decreased with residue removal. This comparison clearly suggests that residue removal can affect water infiltration with time after several consecutive years of residue removal. The larger decrease in aggregate stability and organic C with residue removal after 6 yr compared with that after 3 yr most likely explain the reduction in water infiltration.

Relationships of Hydraulic Properties with Soil Organic C and Other Properties

To understand interrelationships of plant available water with other soil properties as affected by CCs and residue removal, correlations were studied. The correlation of most interest was that between available water and soil organic C (Hudson, 1994; Rawls et al., 2004; Saxton et al., 2006). Plant available water content was correlated with soil organic

C concentration, MWD, and the volume of micropores for the 0 to 10 cm depth (Table 3.3). In the 0 to 5 cm depth, available water content was correlated the most with the volume of micropores, followed by soil organic C concentration, and then MWD (Table 3.3). However, in the 5 to 10 cm depth, available water was most correlated with MWD followed by soil organic C concentration, and the volume of micropores (Table 3.3). In the 10 to 15 cm depth, available water content was correlated only with the volume of micropores (Table 3.3).

Based on the correlations, a predictive equation of available water was developed through stepwise linear regression analysis for the upper two depth intervals. The potential equations to predict available water were:

Depth: 0 to 5 cm depth

$$PAW = -0.40 + 0.01 \times SOC + 0.49 \times Porosity \qquad (R^2=0.74). \qquad [1]$$

Depth: 5 to 10 cm depth

$$PAW = -0.08 + 0.03 \times MWD + 0.01 \times SOC \qquad (R^2 = 0.55). \qquad [2]$$

where PAW is plant available water ($cm^3\ cm^{-3}$), SOC is the soil organic C concentration ($g\ kg^{-1}$), and MWD is the mean weight diameter of water-stable aggregates (mm). For the 0 to 5 cm depth, soil organic C concentration accounted for 63% of the variability in plant available water, while total porosity accounted only accounted for 4% of the variability in available water data. For the 5 to 10 cm depth, MWD accounted for 47% of the variability in plant available water and soil organic C concentration accounted for only 9% of the variability in available water data. These results support our third hypothesis, which stated that CCs and residue removal alter available water by changing soil organic C concentration and other soil properties. The results from the 0 to 5 cm depth were similar to Rawls et al. (2004) and Saxton et al. (2006) who found soil organic C to be an important predictor of plant available water.

Summary and Conclusions

Results from this 6-yr study on a silt loam in south central Nebraska indicated that winter rye CC had generally no effect on soil properties except soil organic C concentration, which increased marginally with CC. However, corn residue removal at 56% from irrigated no-till continuous corn had adverse and consistent effects on soil hydraulic properties and soil organic C. Results also indicated that CC did not offset the negative impacts of residue removal on water retention, plant available water, MWD, soil organic C, and water infiltration. However, CC was able to partially mitigate the reduction in soil organic C concentration but only in the surface 0 to 5 cm and 5 to 10 cm depths and cumulative water infiltration. It is most likely that CC could offset the negative effects of residue removal on soil properties in the longer term (>6 yr).

Note that for the same experiment, CC increased soil organic C concentration after 6 yr (this study) but had no effect after 3 yr (Blanco-Canqui et al., 2014). This demonstrates that CC effects can increase with time after adoption. Similarly, corn residue removal had no effect on water infiltration after 3 yr (Blanco-Canqui et al., 2014), but, after 6 yr (this study), it increased infiltration. This also corroborates that residue removal for many consecutive years can have cumulative effects. In other words, residue removal at high rates can have more negative effects in the long term than in the short term. The correlation and regression results suggest that the decrease in available water with residue removal is partly due to residue removal-induced decrease in soil organic C concentration. The large and significant effects of corn residue removal suggest that removal at high rates (56%) may not be sustainable. We suggest that threshold levels of corn residue removal should be established for this region to reduce degradation of soil hydraulic properties and soil organic C levels. Otherwise, residue removal at high rates could negatively impact soils' ability in the region to sustainable produce crops by reducing water infiltration, plant available water, and soil organic C levels. For example, the reduction in water infiltration could lead to increased risks of water erosion and runoff, and reduced water storage. Additionally, this study suggests the need for the development of CC management strategies or guidelines (planting date, planting method, termination date) to increase CC biomass production and the probability of improving soil properties with CCs. In this study, as discussed, CC biomass production was 0.8 Mg ha^{-1} yr^{-1}, which may not be sufficient to exert significant changes in soil properties and offset the negative effects of the high rate (5.9 Mg ha^{-1} yr^{-1} or 56%) of corn residue removal. Overall, corn residue removal adversely affected soil hydraulic properties and soil organic C concentration after 6 yr, but CC was unable to completely offset the effects of residue removal on soil properties.

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Table 3.1. Information of the experiment management

Year	Date	Field Operation
2015	27 Jan	Surface broadcast phosphorus fertilizer (11-52-0; 112 kg ha-1) to whole field.
	17 Apr	Herbicide applied to whole field (Roundup Power Max 32 oz/ac); termination of winter rye
	1 May	Corn planted (Dekalb 60-67; 84,000 seeds ha^{-1}); Starter fertilizer (10-34-0; 65.5 kg ha^{-1})
	22 Jun	Nitrogen fertilizer injected (UAN 32-0-0; 125 or 200 kg N ha^{-1}; banded at 12 cm depth)
	20, 27 Jul; 3, 17, 26, 31 Aug	Irrigation events (3.4 cm or 2 cm per event for full or deficit irrigation, respectively)
	16 Oct	Combine harvest
	27 Oct	Residue removal
	3 Nov	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
2016	27 Jan	Surface broadcast phosphorus fertilizer (11-52-0; 112 kg ha^{-1}) to whole field.
	22 Apr	Herbicide applied to whole field (Power Max 32 oz/ac); termination of winter rye
	13 May	Corn planted (Dekalb, 60-67; 84,000 seeds ha^{-1}) with starter fertilizer (10-34-0; 65.5 kg ha^{-1})
	18 May	Herbicide applied to whole field (2.5 qt/ac Lumax + 1 qt/ac Round up)
	16 Jun	Nitrogen fertilizer injected (UAN 32-0-0; 125 or 200 kg N ha^{-1}; banded at 12 cm depth)
	17 Jun	Herbicide applied to whole field (Roundup @ 40 oz/ac)
	20 Jun; 1, 8, 19, 27 Jul; 2, 17 Aug	Irrigation events (3.4 cm or 2 cm per event for full or deficit irrigation, respectively)
	14 Oct	Combine harvest
	27 Oct	Residue removal
	31 Oct	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
	6 Nov	Beef feedlot manure surface broadcast to amelioration treatment plots (~25 fresh Mg ha^{-1})
	Dec	Surface broadcast phosphorus fertilizer (11-52-0; 112 kg ha^{-1}) to whole field.
2017	11 Apr	Herbicide applied to whole field (Power Max 48 oz/ac); termination of winter rye
	6 May	Corn planted (Dekalb, 60-67; 84,000 seeds ha^{-1}) with starter fertilizer (10-34-0; 65.5 kg ha^{-1})
	9 May	Herbicide applied to whole field (3 qt/ac Lumax + 1.5 qt/ac Round up PowerMax)
	13 Jun	Nitrogen fertilizer injected (UAN 32-0-0; 125 or 200 kg N ha^{-1}; banded at 12 cm depth)
	27 Jun; 5, 11, 26 Jul; 15 Aug	Irrigation events (3.4 cm or 2 cm per event for full or deficit irrigation, respectively)
	19 Oct	Combine harvest
	2 Nov	Residue removal
	3 Nov	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
2018	Jan	Surface broadcast phosphorus fertilizer (11-52-0; 150 lb/ac) to whole field.

Table 3.2. Mean soil organic C concentration averaged across 2015 and 2016 as affected by cover crop (CC) and corn residue removal (RR) treatments for three soil depth intervals. Different uppercase letters within a column indicate significant differences between cover crop treatments, while different lowercase letters within a column indicate significant differences between corn residue removal treatments.

Treatments		**Depth**	**Soil Organic C**
		cm	g kg^{-1}
No CC	No RR	0-5	24.1Aa
	56% RR	0-5	18.0Bb
CC	No RR	0-5	23.2Aa
	56% RR	0-5	21.9Aa
No CC	No RR	5-10	16.8Aa
	56% RR	5-10	15.0Bb
CC	No RR	5-10	16.5Aa
	56% RR	5-10	16.3Aa
No CC	No RR	10-15	14.3a
	56% RR	10-15	13.8b
CC	No RR	10-15	14.6a
	56% RR	10-15	13.8b
Statistical significance (P > F)			
CC		0-5	0.09
RR		0-5	<0.0001
CC × RR		0-5	0.0001
CC		5-10	ns
RR		5-10	0.0022
CC × RR		5-10	0.0095
CC		10-15	ns
RR		10-15	ns
CC × RR		10-15	ns
Contrasts of interest and significance level (P > F)			
(No CC + No RR) vs (CC + 56% RR)		0-5	0.0200
(No CC + 56% RR) vs (CC + 56% RR)		0-5	0.0013
(No CC + No RR) vs (CC + 56% RR)		5-10	ns
(No CC + 56% RR) vs (CC + 56% RR)		5-10	0.0446

Table 3.3. Correlations among soil organic C concentrations (SOC), total porosity, mean weight diameter of water-stable aggregates (MWD), volumetric water content at -0.033 MPa matric potential, volumetric water content at -1.5 MPa matric potential, plant available water (PAW), macropores, mesopores, and micropores across both cover crop and residue removal treatments by depth in an irrigated no-till continuous corn on a silt loam soil in south central Nebraska.

	MWD	**Volumetric water content at -0.033**	**Volumetric water content at -1.5**	**PAW**	**Macropores**	**Mesopores**	**Micropores**
			0 to 5 cm depth				
SOC (g kg^{-1})	0.44**	0.59***	-0.38*	0.79***	0.16	0.30	0.59***
MWD (mm)		0.53**	0.03	0.50**	-0.05	-0.06	0.53**
Volumetric water content at -0.033 (cm^3 cm^{-3})			0.23	0.83***	-0.12	-0.40*	1
Volumetric water content at -1.5 (cm^3 cm^{-3})				-0.34†	-0.29	-0.13	0.23
PAW (cm^3 cm^{-3})					0.05	-0.33†	0.83***
Macropores (cm^3 cm^{-3})						0.14	-0.12
Mesopores (cm^3 cm^{-3})							-0.39*
			5 to 10 cm depth				
SOC (g kg^{-1})	0.54**	0.19	-0.46	0.62***	0.28	0.12	0.19
MWD (mm)		0.44**	-0.29	0.68***	0.44*	0.28	0.44**
Volumetric water content at -0.033 (cm^3 cm^{-3})			-0.57**	0.44**	0.27	-0.68***	1
Volumetric water content at -1.5 (cm^3 cm^{-3})				-0.57***	-0.19	-0.47**	0.47**
PAW (cm^3 cm^{-3})					0.38*	-0.15	0.44*
Macropores (cm^3 cm^{-3})						0.01	0.27
Mesopores (cm^3 cm^{-3})							-0.68***

	MWD	Volumetric water content at 0.033	Volumetric water content at -1.5	PAW	Macropores	Mesopores	Micropores
			10 to 15 cm depth				
SOC (g kg-1)	0.48	0.29	0.05	0.28	0.07	-0.26	0.29
MWD (mm)		0.15	-0.04	0.20	0.13	0.30	0.15
Volumetric water content at -0.033 (cm^3 cm^{-3})			0.57***	0.60***	0.05	-0.69	1
Volumetric water content at -1.5 (cm^3 cm^{-3})				-0.29	-0.14	-0.46**	0.59*
PAW (cm^3 cm^{-3})					0.16	-0.32†	0.60***
Macropores (cm^3 cm^{-3})						0.20	0.05
Mesopores (cm^3 cm^{-3})							-0.69***

*, **, and ***, significant at 0.05, 0.01, and 0.001 probability levels
† Significant at 0.10 probability level

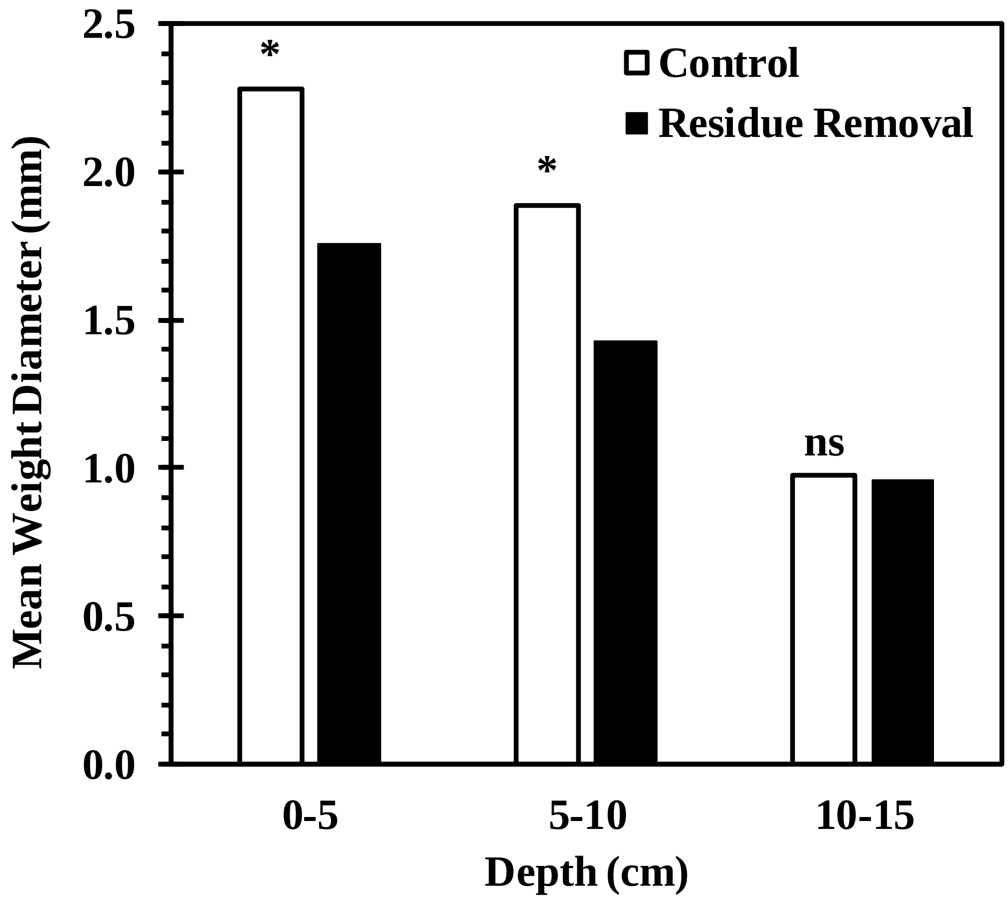

Figure 3.1. Mean weight diameter of water-stable aggregates averaged across cover crop treatments as affected by residue removal at 56% under no-till irrigated continuous corn in south central Nebraska. * denotes significate difference between control (no residue removal) and residue removal.

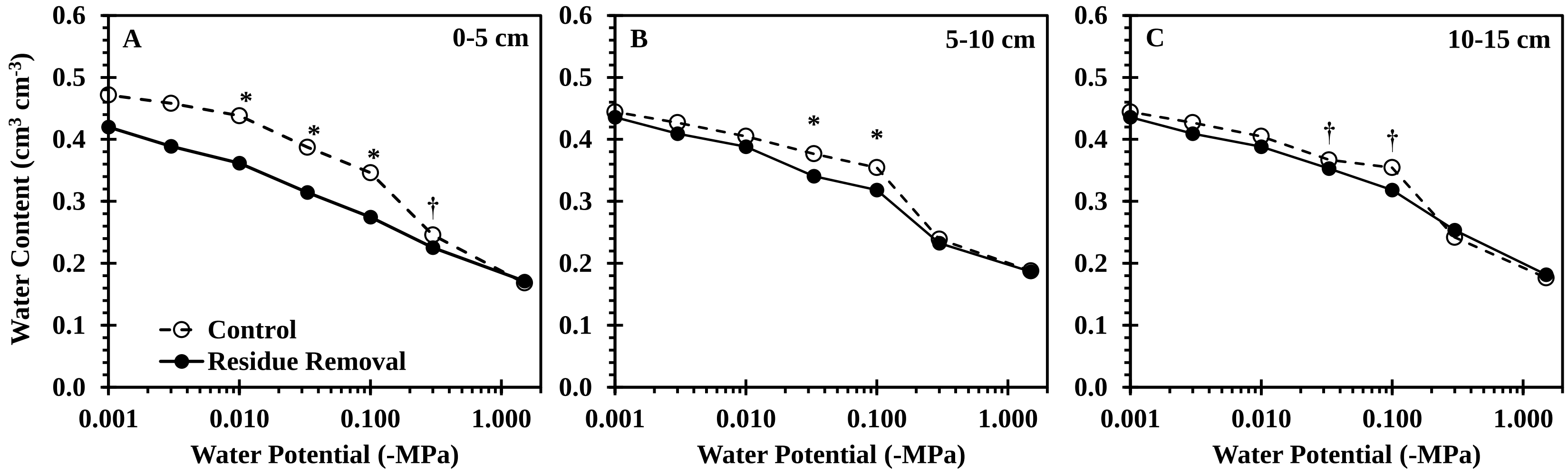

Figure 3.2. Laboratory measured water retention curves for 0 to 5 cm (A), 5 to 10 cm (B), and 10 to 15 cm (C) depth, averaged across cover crop treatments as affected by corn residue removal at 56% under irrigated no-till continuous corn on a silt loam in south central Nebraska. * indicate significant differences between control and residue removal at $p = 0.05$ and † denote differences at $p = 0.10$.

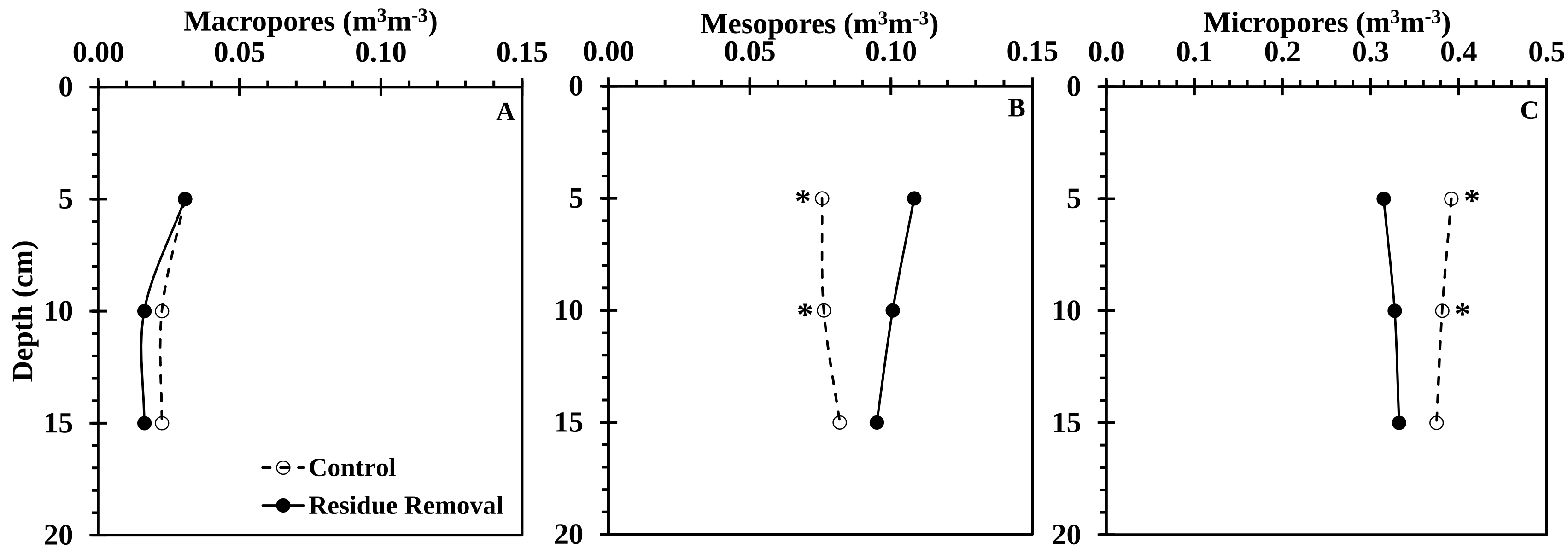

Figure 3.3. Laboratory measured volume of macropores (A), mesopores (B), and micropores (C) by depth, averaged across cover crop treatments as affected by corn residue removal at 56% under irrigated no-till continuous corn on a silt loam in south central Nebraska. Asterisks indicate significant differences between control and residue removal.

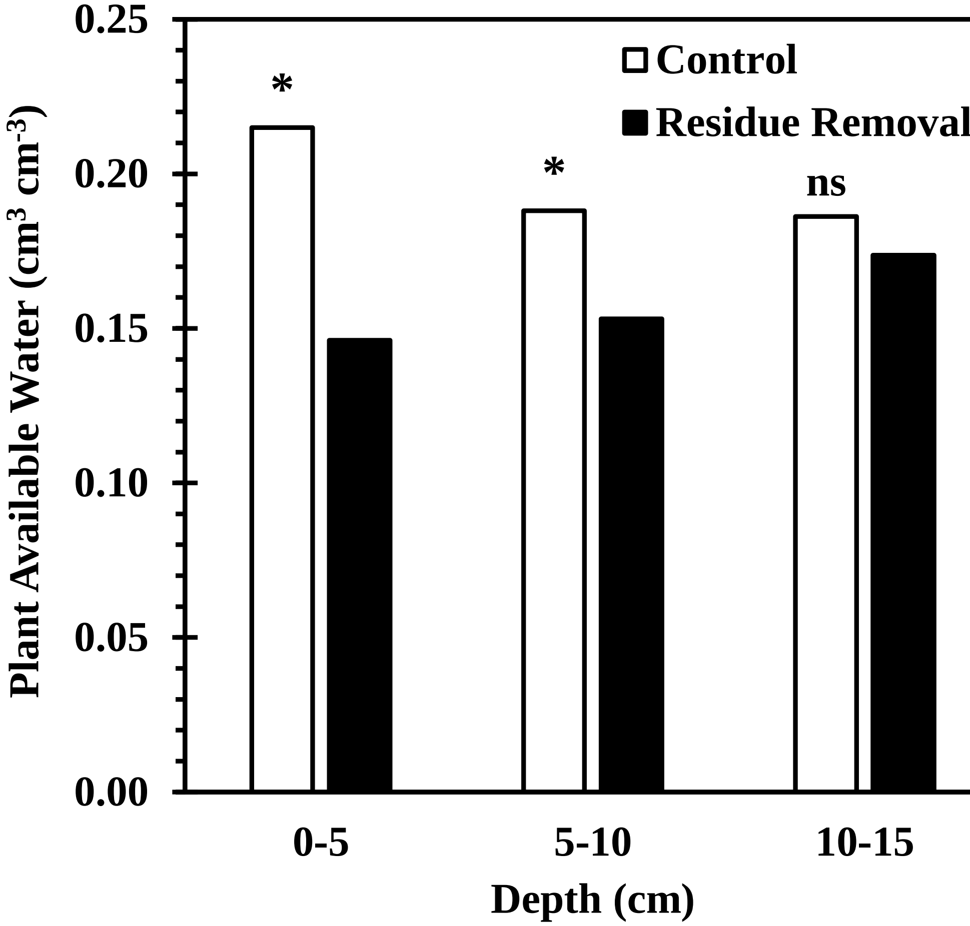

Figure 3.4. Laboratory measured plant available water content by depth, averaged across cover crop treatments as affected by corn residue removal at 56% under irrigated no-till continuous corn on a silt loam in south central Nebraska. Asterisks indicate significant differences between control and residue removal.

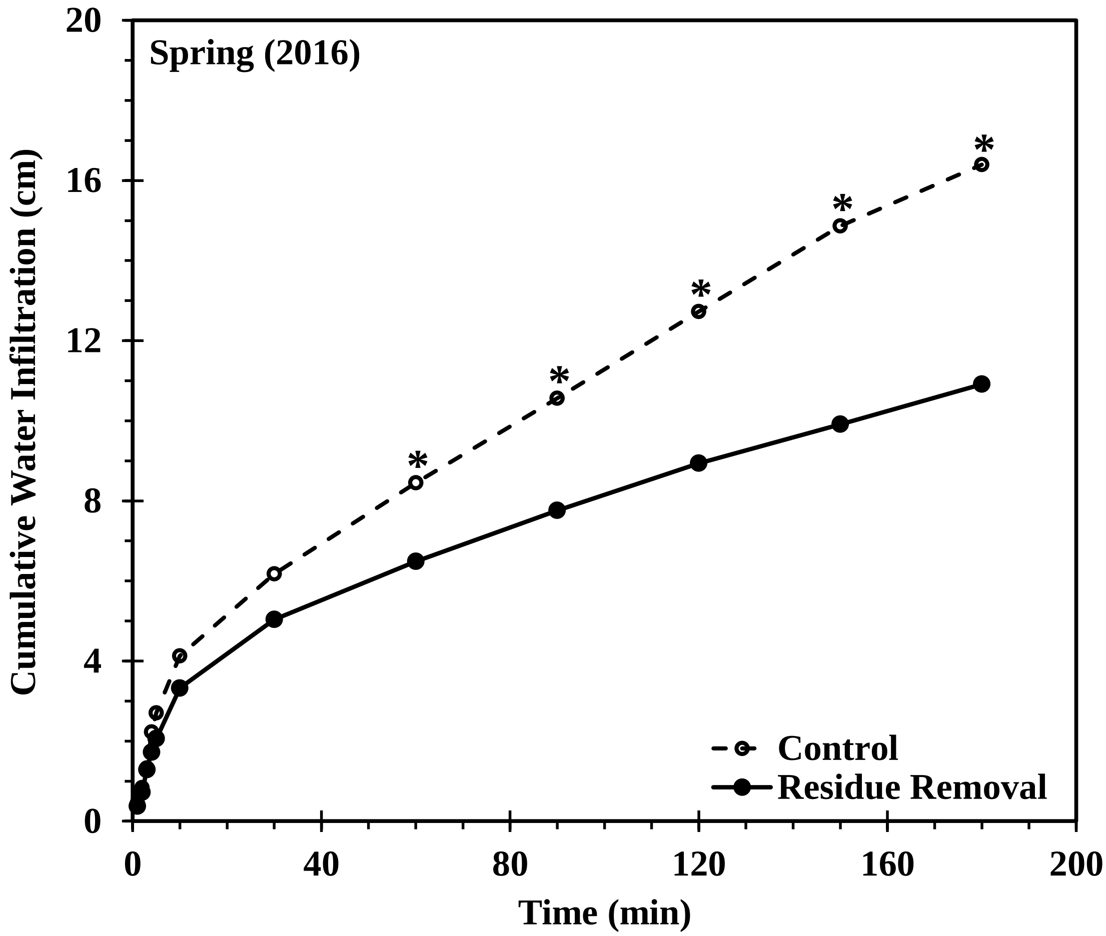

Figure 3.5. Cumulative water infiltration in spring of 2016 averaged across cover crop treatments as affected by corn residue removal at 56% under irritated no-till continuous corn on a silt loam in south central Nebraska. Asterisks denote significant differences between control and residue removal.

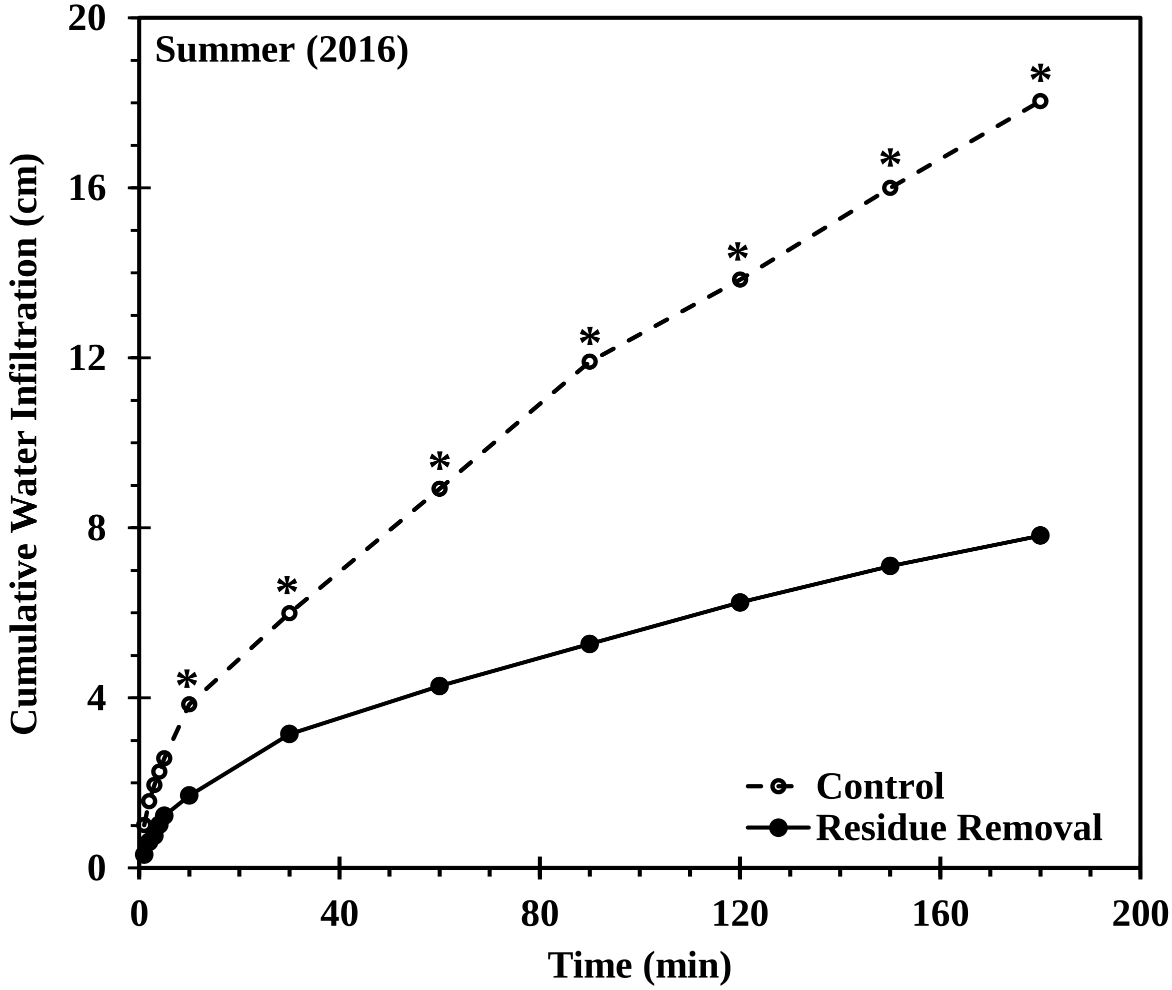

Figure 3.6. Cumulative water infiltration in summer of 2016 averaged across cover crop treatments as affected by corn residue removal at 56% under irrigated no-till continuous corn on a silt loam in south central Nebraska. Asterisks denote significant differences between control and residue removal.

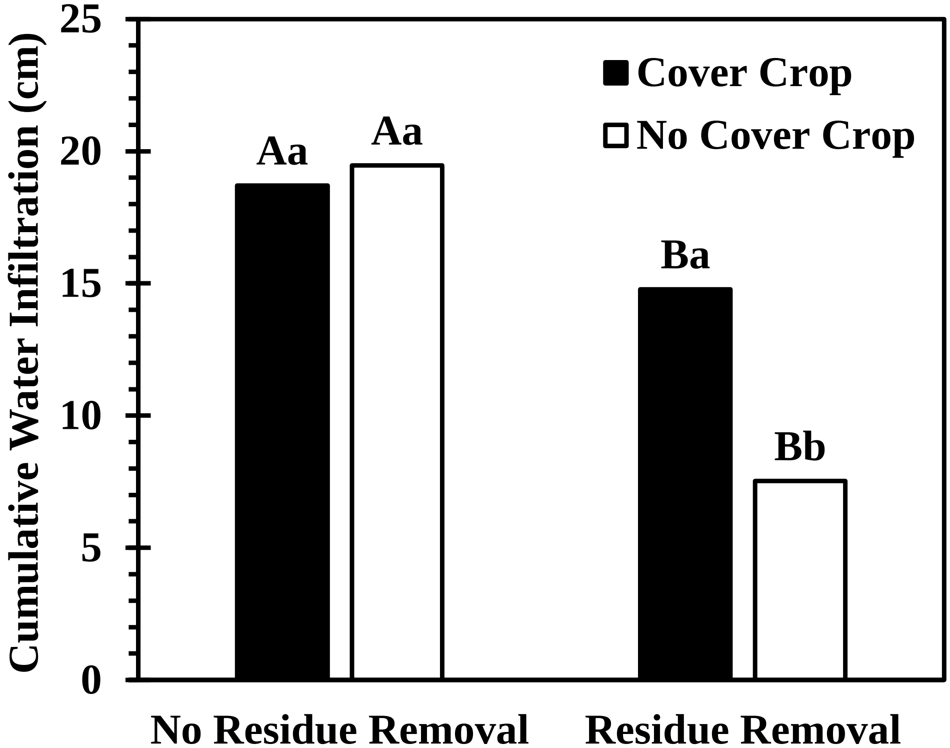

Figure 3.7. Cumulative water infiltration in fall of 2016 as affected by corn residue removal at 56% under and cover crop use under irrigated no-till continuous corn on a silt loam in south central Nebraska. Upper case letters denote significant differences residue removal and no removal. Lower case letters denote significant between cover crop treatments.

CHAPTER 4. DO COVER CROPS AND CORN RESIDUE REMOVAL AFFECT SOIL THERMAL PROPERTIES?

Abstract

Soil thermal properties govern the transport and storage of heat in the soil. How management practices such as crop residue removal and cover crop (CC) use affect these soil properties are not well understood. For example, CCs could provide physical cover and improve soil properties after main crop residue removal and thus ameliorate the negative effects of residue removal on soil thermal properties. We measured changes in soil thermal properties for corn (*Zea mays* L.) residue removal with and without winter cereal rye (*Secale cereale* L.) under a 6-year irrigated no-till continuous experiment on a silt loam in south central Nebraska. We measured soil thermal conductivity, thermal diffusivity, specific heat capacity, and related properties for the 0 to 5 cm depth in the field and for the 0 to 5 and 5 to 10 cm depths in the laboratory. Cover crops did not affect thermal properties, but corn residue removal reduced thermal conductivity by 12 to 41% and specific heat capacity by 6 to 49% in the field during the growing season. Residue removal also reduced laboratory thermal conductivity by 19% at -0.03 MPa and by 28% at -1.5 MPa matric potential. Residue removal also reduced specific heat capacity in the laboratory by 23% at both matric potentials in the 0 to 10 cm depth. Neither residue removal nor CC affected thermal diffusivity. Thermal conductivity was more strongly correlated with soil water content than with bulk density and soil organic C. Overall, CC had no effect on thermal properties, but corn residue removal could reduce the soil's ability to conduct heat relative to no removal.

Introduction

Excessive crop residue removal for livestock, cellulosic ethanol, fiber production, and other off-farm uses could negatively affect soil physical properties such as thermal properties (Blanco-Canqui et al., 2007; Wilhelm et al., 2007; Karlen et al., 2008). The pertinent soil thermal properties include thermal conductivity, specific heat capacity, and thermal diffusivity. Soil thermal conductivity refers to the rate at which a soil can transfer heat, while specific heat capacity is the amount of heat needed to raise the temperature of the unit mass of soil by one degree. Thermal diffusivity is the ratio of soil thermal conductivity to soil specific heat capacity and refers to how fast heat travels through the soil (Hillel, 2004). These properties influence many soil processes including soil temperature distribution, soil water storage, seed germination, microbial activities, surface-energy balance, and resilience of soil to potential climatic fluctuations (Richard and Cellier, 1998; Hillel, 2004; Adhikari et al., 2014).

Many have discussed the effects of crop residue removal on soil properties in general (Wilhelm et al., 2004; Blanco-Canqui and Lal, 2009). For example, the role of crop residues in influencing surface soil temperature and soil water content is well documented (Horton et al., 1996; Sauer et al., 1996). However, few have specifically quantified how crop residue removal affects soil thermal properties such as thermal conductivity, specific heat capacity, and thermal diffusivity in the field and laboratory. Knowledge of changes in these specific thermal properties can be important to discern how residue management affects the rate and speed of heat movement in the soil and overall soil energy balance. The few previous studies have found some inconsistent effects of crop residue management on soil thermal conductivity. For example, a laboratory study using clay loam and silty loam soil monoliths found no difference in thermal conductivity among bare soil, soil with fresh corn residue, and soil with weathered corn residue (Sauer et al., 1996). On another study on a silt loam soil, Dahiya et al. (2007) observed no differences in soil thermal conductivity among control, rotary hoeing, winter wheat (*Triticum aestivum* L.) straw mulching, and wheat straw mulching with rotary hoeing. However, other studies on tillage and crop residue management have generally found higher soil thermal conductivity under no-till than under conventionally tilled systems (Potter et al., 1985; Azooz and Arshad, 1995; Abu-Hamdeh, 2000). The few previous studies have mostly focused on soil thermal conductivity and not all thermal properties.

If crop residue removal adversely affects soil thermal conductivity, specific heat capacity, and thermal diffusivity, CCs could be a companion management practice to crop residue removal to mitigate the potential negative effects of crop residue removal on such soil properties (Fronning et al., 2008; Osborne et al., 2014; Blanco-Canqui et al., 2013). However, changes in soil thermal properties have not been widely studied under CC management practices in spite of their relevance to many soil processes. Only one study evaluated soil thermal properties under CCs (Haruna et al., 2017). Haruna and colleagues found that cereal rye, hairy vetch (*Vicia villosa subs, villosa*), and Austrian winter pea (*Pisum sativum subsp. arvense*) increased specific heat capacity by 15% but did not affect thermal conductivity compared to no CCs on a silt loam in Missouri after 4 yr of management.

Soil thermal properties can be correlated with other soil properties including volumetric water content, bulk density, organic C, and others. Thermal conductivity is often positively correlated with volumetric water content and bulk density and negatively with air-filled porosity and soil organic C concentration (Ghuman and Lal 1985; Potter et al., 1985; Ochsner et al., 2001; Abu-Hamdeh, 2003; Abu-Hamdeh and Reeder, 2003; Adhikari et al., 2014). Soil specific heat capacity has been reported to have positive relationship with volumetric water content, bulk density, and soil organic C concentration (Potter et al., 1985; Abu-Hamdeh, 2003; Adhikari et al., 2014;). Additionally, texture of a soil can influence soil thermal conductivity (Ghuman and Lal, 1985; Abu-Hamdeh, 2000; Lu et al., 2014). Correlations of soil thermal properties with soil properties have not been, however, studied under the potentially interacting effects of crop residue removal and CC addition.

Furthermore, soil thermal properties have been mostly measured in the laboratory and not under field conditions over time. Field measurements better reflect the *in situ* soil behavior relative to laboratory measurements. Measuring thermal properties during the growing season can characterize temporal changes associated with wetting and drying cycles, surface sealing, crusting, and residue decomposition. These and other processes have the potential to alter soil, porosity, soil organic C concentration, and other properties, which can directly change the extent to which crop residue and CC management affects thermal properties. Growing CCs may alter soil thermal properties differently from CC residues after CC termination.

Specifically, information on how soil thermal conductivity, specific heat capacity, and thermal diffusivity change under CC, crop residue management, and their interactions in irrigated cropping systems is needed. Most studies on thermal properties have been conducted in rainfed systems (Potter et al., 1985; Adhikari et al., 2014; Haruna et al., 2017). Crop residue production and CC performance often differ between irrigated and rainfed systems and may affect soil thermal properties differently (Ruis et al., 2017).

The objectives of this study were to assess: 1) the impact of corn residue removal and CCs on soil thermal conductivity, specific heat capacity, and thermal diffusivity and their relationship with measured soil properties, and 2) how thermal properties change throughout the growing season under field conditions on an irrigated silt loam in south central Nebraska. Our first hypothesis was that corn residue removal would reduce thermal conductivity, specific heat capacity, and thermal diffusivity. Our second hypothesis was that CCs would ameliorate residue removal effects on soil thermal properties in spring when main crops are absent.

Materials and Methods

Study Site

This study was conducted on an ongoing experiment established in 2010 at the University of Nebraska-Lincoln (UNL)'s South Central Agricultural Laboratory near Clay Center, NE (40.582° N lat; 98.144°W long; 552 m asl). The soil was a silt loam (fine, smectitic, mesic Udic Argiustolls) with slope of <3% (Soil Survey Staff). The site was under irrigated no-till continuous corn. The experimental design was a completely randomized split-split-split block in quadruplicate with four study factors. The factors were: 1) two irrigation levels (100% and 60%), 2) three amelioration practices (none, manure, and cereal rye CC), 3) two corn residue removal rates (0% and 56%), and 4) two inorganic N fertilizer rates (125 and 200 kg N ha^{-1}) for a total of 96 experimental units (2×3×2×2×4 = 96; Blanco-Canqui et al., 2014). Agronomic operations for crop years 2015 to 2017 can be found in table 4.1. Temperature and rainfall data can be found in table 4.2. Our study on soil hydraulic properties was conducted on two study factors within the larger experiment. The first factor was corn residue removal (no removal and 56% removal) CC (control and CC). These factors resulted in a total of 16 experimental units (2×2×4 = 16). These 16 units were under full irrigation and 200 kg N ha^{-1} treatments. Additional details of the study can be found in Blanco-Canqui et al. (2014).

Field Measurements of Thermal Properties

The commercially available KD2 Pro in tandem with a SH-1 sensor (Decagon Devices) was used to determine thermal conductivity, specific heat capacity, and thermal diffusivity (Bristow, 1998). The measurements in the field were taken every 30 d from May to September in 2016 and from April to June in 2017. The measurement date in 2017 was moved up due to warmer spring conditions and an earlier planting date than in the previous year (Tables 4.1, 4.2). The thermal properties were measured on non-trafficked rows. One measurement per plot was performed. A probe guide was carefully placed flush with the soil and then the SH-1 metal pins were then gently inserted vertical into the soil until the bottom of the sensor head was flush with the probe guide. The probe was then left in the soil for 5 minutes to allow the probe and surrounding soil to reach equilibrium temperatures. The thermal properties were then measured and recorded. All measurements were taken between 10:00 am and 12:00 pm.

At the time of thermal property measurements, 5 cm by 5 cm undisturbed soil cores were collected to determine bulk density and volumetric water content in the laboratory. Soil cores were then collected adjacent to the soil thermal property measurement point. The cores were taken to the laboratory, trimmed, weighed, and then a subsample was oven dried at 105° C for 24 h to determine gravimetric water content. Bulk density was determined by the core method (Grossman and Reinsch, 2002). The gravimetric water content was multiplied by the bulk density to calculate volumetric water content.

Laboratory Measurements of Thermal Properties

For the laboratory measurements of soil thermal properties, 5 cm by 5 cm soil cores were collected in spring of 2016 from 0 to 5 cm and 5 to 10 cm soil depths from each plot. To avoid soil compaction during sampling, the cores were carefully inserted into the soil by hand until soil occupied the full volume of the cores. The cores were then stored in the cold room at 2.2° C until further processing. At the same time that intact soil cores were collected, six hand-probe samples (3.1 cm diameter) were taken from each plot from 0 to 10 cm depth and split into 5 cm depth increments and composited by depth. The composite samples were gently broken up along natural breakage lines and allowed to air dry. These samples were used to measure soil organic C concentration, and soil particle-size distribution, which were then used to study correlations with thermal properties.

A portion of the initial air-dried sample was crushed and passed through a 2-mm sieve to determine soil organic C concentration by the dry combustion method (Nelson and Sommers, 1996). Soil particle-size distribution was determined by the hydrometer method (Gee and Or, 2002). Briefly, 50 g of air-dried soil passed through a 2 mm sieve were mixed with 5% sodium hexametaphosphate and deionized water and allowed to stand for 24 h. After dispersion using a multi-mix machine, the hydrometer readings were performed at 40 s and 3 h to determine the percentage of sand and silt (Gee and Or, 2002).

Soil cores taken for laboratory analysis of thermal properties were removed from cold storage and carefully trimmed so that the soil was flush with the top and bottom of the metal core. A serrated blade was used to avoid smearing the soil and blocking soil pores. The cores were then slowly saturated for about 48 h. The saturated cores were weighed and transferred to a pressure extractor to equilibrate the water content of soil cores at -0.033 MPa matric potential and measure thermal properties at -0.033 MPa potential. After equilibrium, which took about 15 d, the cores were then removed, weighed, and the dual probe SH-1 sensor was inserted into the core to measure soil thermal conductivity, soil specific heat capacity, and soil thermal diffusivity. Two measurements per core were performed by inserting the probes at least 1 cm from the edge of the core to avoid an edge effect during the measurement. The cores were then placed into a high pressure extractor to equilibrate the soil cores at -1.5 MPa matric potential and after equilibrium, which took about 28 d, thermal properties were measured at -1.5 MPa matric potential. Next, soil cores were weighed and oven-dried to determine gravimetric water content. The latter soil property was multiplied by the bulk density to calculate volumetric water content at each matric potential.

Statistical Analysis

Both laboratory and field measured data were tested for normality using PROC UNIVARIATE in SAS (SAS Institute Inc., 2017). Data were analyzed using a randomized complete block design with a split plot. The main plot was CC treatment and the split plot was the corn residue removal treatment. All laboratory data analysis was conducted by depth and soil matric potential. All data were analyzed using PROC MIXED to determine main effects and interactions. Significant differences among treatments were tested using LSMEANS in SAS at the 0.05 probability level unless otherwise noted. Relationships between soil thermal properties and other soil properties were studied using PROC CORR and PROC STEPWISE in SAS. Simple predictive equations for estimating thermal conductivity and specific heat capacity from other soil properties were developed using linear regression analysis.

Results

Cover crop treatment had no effect on field or laboratory measured soil thermal properties. Laboratory measured data indicated that CCs had no effect at any soil depth. Similarly, CCs did not affect thermal properties at any measurement date in the field. However, corn residue removal had significant effects on both field and laboratory measured soil thermal properties except thermal diffusivity (Fig. 4.1A-B). Mean thermal diffusivity averaged across CC treatments was 0.40 ± 0.09 mm^2 s^{-1} for no residue removal and 0.39 ± 0.04 mm^2 s^{-1} for residue removal.

Soil Thermal Conductivity

Under field conditions, residue removal reduced soil thermal conductivity by 17% in the 0 to 5 cm soil depth from spring 2016 to summer 2017 (Fig. 4.1A). Under laboratory conditions, residue removal reduced soil thermal conductivity at both matric potentials (-0.033 and -1.5 MPa) for the 0 to 5 cm and 5 to 10 cm soil depth

(Fig. 4.2A-B). At the 0 to 5 cm soil depth, residue removal reduced thermal conductivity by 26% at -0.03 MPa and by 29% at -1.5 MPa matric potentials compared with no residue removal. At the 5 to 10 cm depth, residue removal also reduced thermal conductivity at both matric potentials, but to a lesser extent than at the 0 to 5 cm soil depth. At this depth, residue removal reduced thermal conductivity by 13% at -0.03 MPa and by 27% at -1.5 MPa matric potentials (Fig. 4.2B). Residue removal did not affect laboratory measured thermal conductivity for the 10 to 15 cm soil depth. Mean thermal conductivity averaged across CC treatments and matric potentials was 1.24 ± 0.15 W m^{-1} K^{-1} for no residue removal and 1.14 ± 0.13 W m^{-1} K^{-1} for residue removal.

Soil Specific Heat Capacity

Under field conditions, residue removal reduced soil specific heat capacity by 19% in the 0 to 5 cm soil depth from spring 2016 to summer 2017 (Fig. 4.1B). Under laboratory conditions, at the 0 to 5 cm depth of soil, specific heat capacity was reduced by residue removal by 21% at -0.03 MPa and by 26% at -1.5 MPa matric potential compared with no removal (Fig. 4.3A). At the 5 to 10 cm depth, residue removal reduced specific heat capacity by 6% at -0.033 MPa and by 19% at -1.5 MPa (Fig. 4.3B). Mean specific heat capacity averaged across CC treatments and matric potentials was 2.86 ± 0.27 mm^2 s^{-1} for no residue removal and 2.66 ± 0.28 mm^2 s^{-1} for residue removal.

Correlation of Field Thermal Properties with Soil Water Content and Bulk Density

Volumetric water content and bulk density measured on soil samples collected at the time of field thermal property measurements were used to study interrelationships among soil properties for the measurement depth (0 to 5 cm depth; Table 4.3). Cover crop had no effect on soil water content and bulk density, but residue removal affected water content throughout the sampling times (Table 4.3). Corn residue removal reduced volumetric water content by 13 to 40% compared with no removal (Table 4.3). Residue removal had no effect on soil bulk density.

Soil thermal conductivity was positively correlated with volumetric water content (Fig. 4.4A) and bulk density (Fig. 4.4B). It was more strongly correlated with volumetric water content (r = 0.68) than with bulk density (r= 0.36). Specific heat capacity was also positively correlated with volumetric water content (Fig. 4.5A) and bulk density (Fig. 4.5B). Similar to thermal conductivity, specific heat capacity was more strongly correlated with volumetric water content (r= 0.66) than with bulk density (r= 0.20). Correlations of soil thermal diffusivity with soil volumetric water content and bulk density were not significant.

Correlation of Laboratory Thermal Properties with Water Content, Bulk Density, Texture, and Soil Organic C

Cover crop treatments had no effect on soil water content, bulk density, and soil organic C concentration (Table 4.5). Residue removal reduced water content by 29% at -0.033 MPa but had no effect at the -1.5 MPa potential for the 0 to 5 cm depth (Table 4.4). In the 5 to 10 cm depth, CC × residue removal interaction was significant for water content at -0.033 MPa potential, indicating that the magnitude by which residue removal decreased the water content depended on the presence of CCs (Table 4.4). Residue removal reduced water content by 15% at -0.033 MPa in plots without CC, while, averaged across CC treatments, it reduced water content by 11% at -1.5 MPa. Residue removal did not affect bulk density and particle size at any depth (Table 4.5). Residue removal reduced soil organic C concentration, but CC × removal interaction was significant. Under plots without CC, residue removal reduced organic C concentration by 42% in the 0 to 5 cm and by 12% in the 5 to 10 cm depth. As expected, soil particle-size distribution did not significantly differ among treatments (Table 4.5).

Thermal conductivity and specific heat capacity were correlated with the above soil properties more for the -0.033 MPa than for the -1.5 MPa matric potential (Table 4.6). They were correlated more with water content and bulk density than with texture and organic C at both depths (0 to 5 cm and 5 to 10 cm depths). In the 0 to 5 cm depth at -0.033 MPa potential, both thermal conductivity and specific heat capacity increased with an increase in water content, bulk density, and sand content. The correlation between thermal properties and sand content was only significant at the 0.10 probability level. At the same matric potential, however, at the 5 to 10 cm depth, thermal conductivity was positively correlated with soil organic C concentration and negatively correlated with clay content. At -1.5 MPa potential, thermal conductivity and specific heat capacity were positively correlated with bulk density and sand content at the 0 to 5 cm depth. At the 5 to 10 cm depth, thermal conductivity was positively correlated with soil organic C concentration, bulk density, and water content. At the same depth, specific heat capacity was positively correlated with soil organic C concentration and water content (Table 4.6).

Volumetric water content, bulk density, sand, and organic C were important predictors of thermal conductivity and specific heat capacity (Table 4.7). The predictive ability of the four soil properties were in this order: Volumetric water content > bulk density > sand > organic C. Volumetric water content and bulk density were the best predictors of thermal conductivity and specific heat capacity for -0.03 MPa matric potential at the 0 to 5 cm depth. Sand content was the best predictor of thermal conductivity at -1.5 MPa for the 0 to 5 cm depth and specific heat capacity at -0.03 MPa for the 5 to 10 cm depth. Soil organic C concentration was a significant predictor of soil thermal conductivity at both matric potentials, but only at the 5 to 10 cm depth (Table 4.7). Soil organic C was only a significant predictor of soil specific heat capacity for the 5 to 10 cm depth at -1.5 MPa.

Discussion

This study indicates that corn residue removal at about 56% for 6 to 7 yr had significant effects on soil thermal properties except thermal diffusivity in the 0 to 10 cm soil depth. These results partly support our first hypothesis, which stated that corn residue removal could decrease soil thermal conductivity, specific heat capacity, and thermal diffusivity. The residue removal effect on thermal conductivity and specific heat capacity were of a similar magnitude and direction, which resulted in no changes in thermal diffusivity. The latter is calculated as the ratio of thermal conductivity over specific heat capacity. An increase in specific heat capacity directly reduces thermal diffusivity (Horton et al., 1996).

Unlike in previous studies where residue removal had no effect on thermal conductivity (Sauer et al., 1996; Dahiya et al., 2007), in this study, thermal conductivity was reduced by residue removal. The significant residue removal effect on soil thermal conductivity was most likely due to extended period of study (6 yr consecutive years of corn residue removal at 56%), whereas the previous studies were short term (< 1 yr). Our study results were similar to tillage studies, which have shown that burial or mixing of crop residues with soil can reduce thermal conductivity and/or specific heat capacity (Johnson and Lowery, 1985; Potter et al., 1985; Azooz and Arshad, 1995; Abu-Hamdeh, 2000).

Cover crop had no effect on soil thermal properties, which did not support our second hypothesis. We hypothesized that CC use for 6 or 7 yr would have altered soil thermal properties by providing additional surface cover, and affecting soil porosity, soil organic C concentration, and other properties. We also hypothesized that CC use would mitigate residue removal effects on thermal properties. The lack of CC effect on thermal properties in this study can be attributed to the 1) lack of CC effects on other soil properties (Table 4.5) and 2) low CC biomass production. The aboveground CC biomass yield averaged across 6 yr was 0.8 Mg ha^{-1}. This amount of yield is lower compared to that (1.66 to 3.24 Mg ha^{-1} yr^{-1}) found in some recent studies under different CC management scenarios (Kaspar et al., 2015; Blanco-Canqui et al., 2017). The lower CC biomass yield is probably due to the short CC growing period (late November to early April) in our study. Another study in Nebraska found that late-terminated CC (late May) can produce significantly more biomass than early-terminated CC (April; Ruis et al., 2017).

Changes in soil thermal properties could depend on the belowground CC biomass input as studies have shown that more soil organic C is gained from the roots of cereal rye than from the shoots (Puget and Drinkwater, 2001; Kong and Six, 2010, 2012). In our study, based on the low aboveground biomass yield, root biomass yield was also probably low although we did not quantify the amount of root biomass. For example, cereal rye has been reported to have a 2.4-5 shoot to root ratio (Amanullah, 2014; Sheng and Hunt 1991), which suggests that the rye biomass yield in our study (0.8 Mg ha^{-1} yr^{-1}) would equal 0.16 to 0.40 to Mg ha^{-1} yr^{-1} of root biomass. Thus, it is estimated that winter rye added 0.96 to 1.20 Mg ha^{-1} yr^{-1} of total biomass (aboveground and belowground biomass). This amount of CC biomass input was well below the amount of corn residue removed in this study, which, on average, amounted to 5.9 Mg ha^{-1} yr^{-1}. Residue amount as well as plant residue type and residue orientation (standing vs. flat) can be important factors that affect soil heat fluxes (Flerchinger et al., 2003).

There is only one study from Missouri that has measured CC effects on soil thermal conductivity, specific heat capacity, and thermal diffusivity (Haruna et al., 2017), which can be used to compare with our study results. While we did not find CC effects on thermal properties, Haruna et al., (2017) reported that CCs increased specific heat capacity and decreased thermal diffusivity but had no effect on soil thermal conductivity. The contrasting results may be due the agronomic differences. For example, our experiment used a single CC species with early spring termination under irrigated conditions, while Haruna et al. (2017) used three-species CC mix with late spring termination in a rainfed system. In particular, the later spring termination date likely facilitated greater CC biomass accumulation and concomitant changes in soil thermal properties in the study by Haruna et al. (2017).

Results from this study suggest that changes in thermal conductivity and specific heat capacity due to corn residue removal are associated with changes in volumetric water content, bulk density, and soil organic C concentration. Volumetric water-content had the strongest correlation with thermal conductivity at both depths (0 to 5 cm and 5 to 10 cm depth) at the -0.033 MPa matric potential compared to other measured soil properties (Table 4.6). Additionally, volumetric water content explained 52% of variability in thermal conductivity for the 0 to 5 cm depth at the -0.033 MPa potential (Table 4.7). The positive correlation of thermal conductivity with volumetric water content and bulk density is similar to the relationships reported by previous studies (Abu-Hamdeh and Reeder, 2000; Adhikari et al., 2014; Haruna et al., 2017). Water films between soil particles and within aggregates act as heat conducting bridges (Ghuman and Lal 1985; Abu-Hamdeh and Reeder, 2000). Thus, a reduction in volumetric water content may have resulted in less bridging water films decreasing thermal conductivity. Additionally, it is well known that water-filled pore space has higher thermal conductivity and specific heat values compared to air-filled pore space because water (0.57 W m^{-1} K^{-1}) has higher thermal conductivity than air (0.025 W m^{-1} K^{-1}; Hillel 2004). The drier the soil, the lower the thermal conductivity and specific heat capacity.

Although residue removal and CC had no effects on soil bulk density, bulk density generally correlated with more changes in thermal properties compared with soil organic C concentration. An increase in bulk density most likely decreased the space required by heat to travel between soil particles increasing thermal conductivity (Abu-Hamdeh 2003). In this study, soil organic C had a positive relationship with thermal conductivity although most previous studies found a negative relationship (Abu-Hamdeh and Reeder, 2000; Adhikari et al., 2014; Haruna et al., 2017). While an increase in soil organic C concentration often reduces thermal conductivity (Hillel, 2004), we suggest that, in our study, a decrease in organic C concentration with residue removal may have reduced soil thermal conductivity by reducing the ability of the soil to retain water.

The decrease in soil thermal conductivity and soil specific heat capacity with residue removal in this study can have implications for soil-surface energy balance (Horton et al., 1996). The lower thermal conductivity and specific heat capacity under residue removal suggests that the soil surface in fields with residue removed can warm and cool more rapidly than fields with residues because soils without residues will have reduced ability to transfer and distribute heat to lower soil depths. In addition, the lower specific heat capacity of soils with residue removed imply that these soils could require less heat to increase soil temperature when compared to fields with residues (Kenney et al., 2015). The extra amount of heat on the surface can lead to increased surface temperature and conversion to latent heat as evapotranspiration. Overall, soils with residue removed can reduce both heat distribution in the soil profile and water storage but may increase freeze-thaw and dry-wet cycles, increase residue decomposition, and possibly facilitate early planting of crops in spring.

Conclusions

Our study indicates that corn residue removal at 56% for 6 or 7 yr reduced soil thermal conductivity and specific heat capacity in the upper 10 cm depth of soil but had no effect on soil thermal diffusivity in an irrigated no-till continuous corn on a silt loam in south central Nebraska. The presence of winter rye CC, however, did not ameliorate the negative effects of residue removal on soil thermal conductivity and specific heat capacity in this system. We attribute the lack of CC effect to the limited CC biomass production in this study. Planting CC after corn grain harvest in late October or early November and terminating CC in early spring about a month before corn planting resulted in low CC biomass accumulation (< 0.8 Mg ha^{-1} yr^{-1}). Similarly, other soil properties related to thermal properties were significantly affected by corn residue removal but not by CC. In this study, soil volumetric water content was the most common predictor of soil thermal conductivity and specific heat capacity followed by bulk density, sand content, and lastly soil organic C concentration. Results indicate that residue removal at approximately 56% could create a soil microclimate by reducing heat flow through the soil profile and increasing surface soil temperature. In summary, our study indicates that corn residue removal can alter soil thermal conductivity and specific heat capacity, but winter rye CC may not be able to mitigate the negative effects of residue removal on such properties under the conditions of this study.

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Table 4.1. Information of the experiment management.

Year	Date	Field Operation
2015	Jan	Surface broadcast phosphorus fertilizer (11-52-0; 112 kg ha-1) to whole field.
	17 Apr	Herbicide applied to whole field (Roundup Power Max 32 oz/ac); termination of winter rye
	1 May	Corn planted (Dekalb 60-67; 84,000 seeds ha^{-1}); Starter fertilizer (10-34-0; 65.5 kg ha^{-1})
	22 Jun	Nitrogen fertilizer injected (UAN 32-0-0; 125 or 200 kg N ha^{-1}; banded at 12 cm depth)
	20, 27 Jul; 3, 17, 26, 31 Aug	Irrigation events (3.4 cm or 2 cm per event for full or deficit irrigation, respectively)
	16 Oct	Combine harvest
	27 Oct	Residue removal
	3 Nov	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
2016	27 Jan	Surface broadcast phosphorus fertilizer (11-52-0; 112 kg ha^{-1}) to whole field.
	22 Apr	Herbicide applied to whole field (Power Max 32 oz/ac); termination of winter rye
	13 May	Corn planted (Dekalb, 60-67; 84,000 seeds ha^{-1}) with starter fertilizer (10-34-0; 65.5 kg ha^{-1})
	18 May	Herbicide applied to whole field (2.5 qt/ac Lumax + 1 qt/ac Round up)
	16 Jun	Nitrogen fertilizer injected (UAN 32-0-0; 125 or 200 kg N ha^{-1}; banded at 12 cm depth)
	17 Jun	Herbicide applied to whole field (Roundup @ 40 oz/ac)
	20 Jun; 1, 8, 19, 27 Jul; 2, 17 Aug	Irrigation events (3.4 cm or 2 cm per event for full or deficit irrigation, respectively)
	14 Oct	Combine harvest
	27 Oct	Residue removal
	31 Oct	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
	6 Nov	Beef feedlot manure surface broadcast to amelioration treatment plots (~25 fresh Mg ha^{-1})
	Dec	Surface broadcast phosphorus fertilizer (11-52-0; 112 kg ha^{-1}) to whole field.
2017	11 Apr	Herbicide applied to whole field (Power Max 48 oz/ac); termination of winter rye
	6 May	Corn planted (Dekalb, 60-67; 84,000 seeds ha^{-1}) with starter fertilizer (10-34-0; 65.5 kg ha^{-1})
	9 May	Herbicide applied to whole field (3 qt/ac Lumax + 1.5 qt/ac Round up PowerMax)
	13 Jun	Nitrogen fertilizer injected (UAN 32-0-0; 125 or 200 kg N ha^{-1}; banded at 12 cm depth)
	27 Jun; 5, 11, 26 Jul; 15 Aug	Irrigation events (3.4 cm or 2 cm per event for full or deficit irrigation, respectively)
	19 Oct	Combine harvest
	2 Nov	Residue removal
	3 Nov	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
2018	Jan	Surface broadcast phosphorus fertilizer (11-52-0; 150 lb/ac) to whole field.

Table 4.2. Monthly precipitation and temperature from 2015 to 2017 for the experimental site in south central Nebraska.

Month	Precipitation (mm)				Mean Temperature (°C)					
	2015	2015	2017		2015		2016		2017	
					Min	Max	Min	Max	Min	Max
January	5.33	0.00	0.00		-10.36	5.55	-8.36	2.11	-7.83	1.31
February	0.76	0.00	0.00		12.24	2.22	-5.30	7.41	-4.67	10.37
March	4.83	0.25	0.00		-3.53	15.79	-1.18	15.53	-1.38	12.40
April	61.72	138.43	81.28		3.61	18.40	3.66	18.24	3.73	17.07
May	144.53	172.47	153.92		8.96	20.86	8.72	21.99	8.70	22.51
June	225.81	5.08	22.61		15.72	27.90	17.00	31.33	15.41	30.09
July	54.86	63.50	50.80		17.22	29.72	18.00	30.08	18.49	31.16
August	32.51	62.99	89.64		15.12	28.18	16.56	28.29	14.32	27.15
September	38.35	66.80	23.85		15.51	27.82	12.97	25.35	12.32	26.81
October	37.08	5.59	0.00		5.54	20.85	5.62	21.49	4.21	18.38
November	6.10	0.00	0.00		-0.64	12.11	-0.21	13.97	-2.93	11.85
December	0.00	0.00	X		-5.74	5.11	-10.34	2.82	X	X
Total	*611.89*	*515.11*	*422.10*	*Mean*	*4.01*	*17.88*	*4.76*	*18.22*	*5.49*	*19.01*

Table 4.3. Mean volumetric water content and soil bulk density for the cover crop (CC) and 56% corn residue removal in an irrigated no-till continuous corn on a silt loam in south central Nebraska. The lower case letters denote the statistical difference between residue management treatments by month under the same level of cover crop treatment.

Date	Cover Crop	Residue Removal	Volumetric Water Content	Bulk Density
			$cm^3\ cm^{-3}$	$Mg\ m^{-3}$
April	No CC	No	0.38a	1.24
		Yes	0.25b	1.25
	CC	No	0.38a	1.28
		Yes	0.24b	1.25
May	No CC	No	0.32a	1.25
		Yes	0.22b	1.27
	CC	No	0.32a	1.26
		Yes	0.24b	1.27
June	No CC	No	0.34a	1.26
		Yes	0.19b	1.28
	CC	No	0.32a	1.29
		Yes	0.20b	1.26
May	No CC	No	0.39a	1.28
		Yes	0.28b	1.25
	CC	No	0.40a	1.29
		Yes	0.30b	1.20
June	No CC	No	0.35a	1.28
		Yes	0.25b	1.25
	CC	No	0.38a	1.29
		Yes	0.28b	1.20
July	No CC	No	0.39a	1.28
		Yes	0.28b	1.25
	CC	No	0.40a	1.29
		Yes	0.30b	1.20
August	No CC	No	0.45a	1.28
		Yes	0.33b	1.25
	CC	No	0.45a	1.27
		Yes	0.40b	1.20
September	No CC	No	0.40a	1.28
		Yes	0.27b	1.25
	CC	No	0.41a	1.29
		Yes	0.31b	1.20

Table 4.4. Mean volumetric water content at matric potentials of -0.033 MPa and -1.5 MPa for cover crop (CC) and 56% corn residue removal in an irrigated no-till continuous corn on a silt loam in south central Nebraska. Cover crop and residue removal interaction was significant for the 5 to 10 cm depth. The lower case letters denote the statistical difference between residue management treatments.

Treatment		Depth	Volumetric Water Content at -0.033 MPa	Volumetric Water Content at -1.5 MPa
		cm	$cm^3\ cm^{-3}$	$cm^3\ m^{-3}$
No Residue Removal		0-5	0.40a	0.18
56% Residue Removal		0-5	0.31b	0.17
No Cover Crop	No Residue Removal	5-10	0.38a	0.24a
	56% Residue Removal	5-10	0.33b	0.22b
Cover Crop	No Residue Removal	5-10	0.40	0.25a
	56% Residue Removal	5-10	0.38	0.22b

Table 4.5. Mean soil organic C concentration, soil bulk density, particle density, and particle size analysis for cover crop (CC) and 56% corn residue removal in an irrigated no-till continuous corn on a silt loam in south central Nebraska. Cover crop and residue removal interaction was significant for both soil depths. The lower case letters denote the statistical difference between residue management treatments.

Cover Crop	Residue Removal	Depth	Soil Organic C	Bulk Density	Clay	Silt
		cm	g kg^{-1}	Mg m^{-3}	g kg^{-1}	g kg^{-1}
No CC	No	0-5	25.4 a	1.34	288	570
	Yes	0-5	17.9 b	1.24	300	578
CC	No	0-5	23.7	1.23	218	625
	Yes	0-5	22.4	1.26	283	590
No CC	No	5-10	16.7 a	1.43	284	572
	Yes	5-10	14.9 b	1.41	2980	576
CC	No	5-10	16.4	1.44	235	615
	Yes	5-10	15.9	1.40	299	571

Table 4.6. Correlations between laboratory thermal properties and other laboratory soil properties across both cover crop and residue removal treatments by depth in an irrigated no-till continuous corn on a silt loam soil in south central Nebraska.

Property	**Depth**	**Water Content**	**Bulk Density**	**Sand**	**Clay**	**Soil Organic C**
	cm	cm^3 cm^{-3}	Mg m^{-3}	g kg^{-1}	g kg^{-1}	g kg^{-1}
			-0.033 MPa Soil Water Matric Potential			
Thermal Conductivity (W m^{-1} k^{-1})	0-5	0.72**	0.50*	0.46†	-0.33	0.28
Specific Heat Capacity (MJ m^{-3} K^{-1})	0-5	0.65**	0.62**	0.47†	-0.35	0.43†
Thermal Conductivity (W m^{-1} k^{-1})	5-10	0.59*	0.59*	0.58*	-0.52*	0.74**
Specific Heat Capacity (MJ m^{-3} K^{-1})	5-10	0.62**	0.45†	0.45†	-0.08	0.45
			-1.5 MPa Soil Water Matric Potential			
Thermal Conductivity (W m^{-1} k^{-1})	0-5	0.16	0.41†	0.45†	-0.08	0.28
Specific Heat Capacity (MJ m^{-3} K^{-1})	0-5	-0.10	0.64**	0.59*	-0.08	0.18
Thermal Conductivity (W m^{-1} k^{-1})	5-10	0.71**	0.51*	0.27	-0.11	0.55*
Specific Heat Capacity (MJ m^{-3} K^{-1})	5-10	0.71**	0.34	0.26	-0.01	0.48†

*, **, and ***, significant at 0.05, 0.01, and 0.001 probability levels

† Significant at 0.10 probability level

Table 4.7. Predictive equations of soil thermal conductivity and specific heat capacity using measured soil properties as input parameters across both cover crop and residue removal treatments by depth in an irrigated no-till continuous corn on a silt loam soil in south central Nebraska.

					Soil Thermal Conductivity			
		-0.033 MPa Potential				**-1.5 MPa Potential**		
Depth (cm)	**Variable**	**Partial r^2**	**Model r^2**	**P > F**	**Variable**	**Partial r^2**	**Model r^2**	**P > F**
0-5	Water Content (cm^3 cm^{-3})	0.52	0.52	0.04	Sand (g kg^{-1})	0.20	0.20	0.01
	Bulk density (Mg m^{-3})	0.17	0.69	0.02	Water Content (cm^3 cm^{-3})	0.20	0.40	0.05
5-10	Soil Organic C (g kg^{-1})	0.55	0.55	<0.01	Water content (cm^3 cm^{-3})	0.53	0.53	<0.01
	Sand (g kg^{-1})	0.13	0.68	0.04	Soil Organic C (g kg^{-1})	0.23	0.74	<0.01
	Bulk density (Mg m^{-3})	0.09	0.77	0.03				
	Water Content (cm^3 cm^{-3})	0.07	0.84	0.09				
					Soil Specific Heat Capacity			
0-5	Water content (cm^3 cm^{-3})	0.42	0.42	<0.01	Bulk density (Mg m^{-3})	0.41	0.41	<0.01
	Bulk density (Mg m^{-3})	0.30	0.72	0.03	Sand (%)	0.13	0.54	0.08
5-10	Sand (g kg^{-1})	0.35	0.35	0.02	Water Content (cm^3 cm^{-3})	0.50	0.50	<0.01
	Bulk density (Mg m^{-3})	0.15	0.50	0.04	Soil Organic C (g kg^{-1})	0.17	0.674	0.02
	Clay (g kg^{-1})	0.11	0.61	0.08				

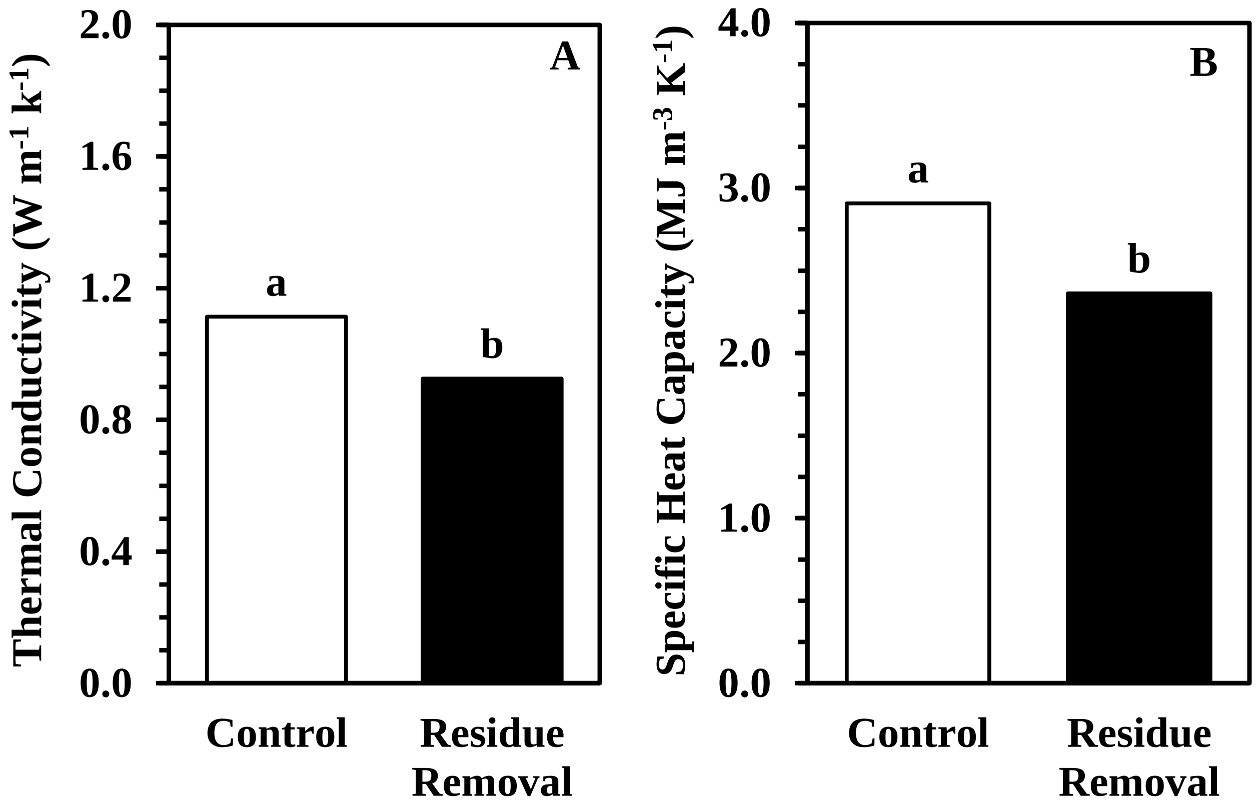

Figure 4.1. Field measured soil thermal conductivity (A) and specific heat capacity (B) averaged across cover crop treatments and measurement dates as affected by corn residue removal at 56% for the 0 to 5 cm soil depth under irrigated no-till continuous corn on a silt loam in south central Nebraska. Different lowercase letters indicate significant differences between control and residue removal.

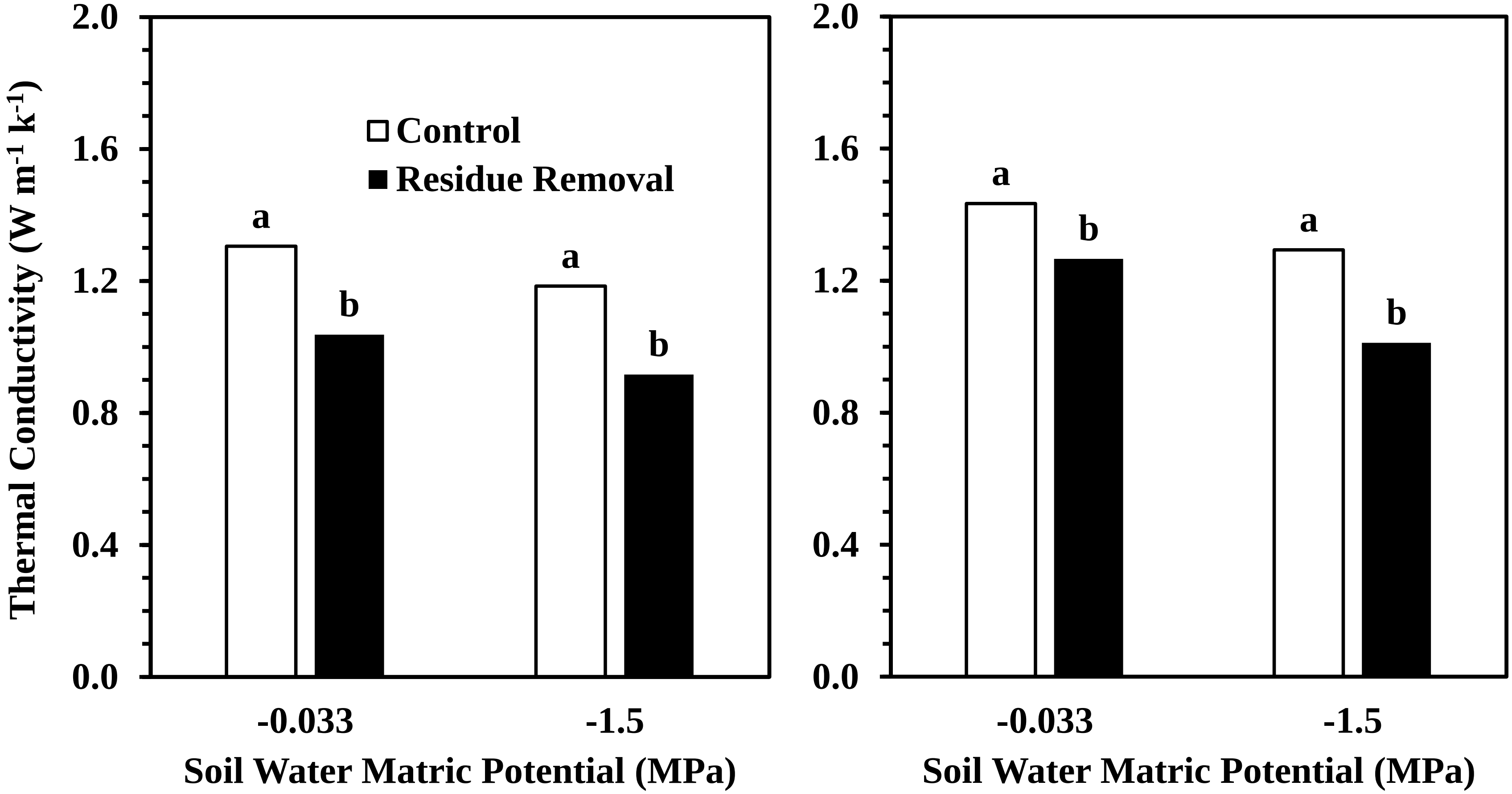

Figure 4.2. Laboratory measured soil thermal conductivity measured at -0.033 and -1.5 MPa matric potentials for two corn residue removal treatments averaged across cover crop treatments for the 0 to 5 cm (A) and 5 to 10 cm (B) soil depths in an irrigated no-till continuous corn on a silt loam in south central Nebraska after 6 yr of management. Different lowercase letters indicate significant differences between control and residue removal.

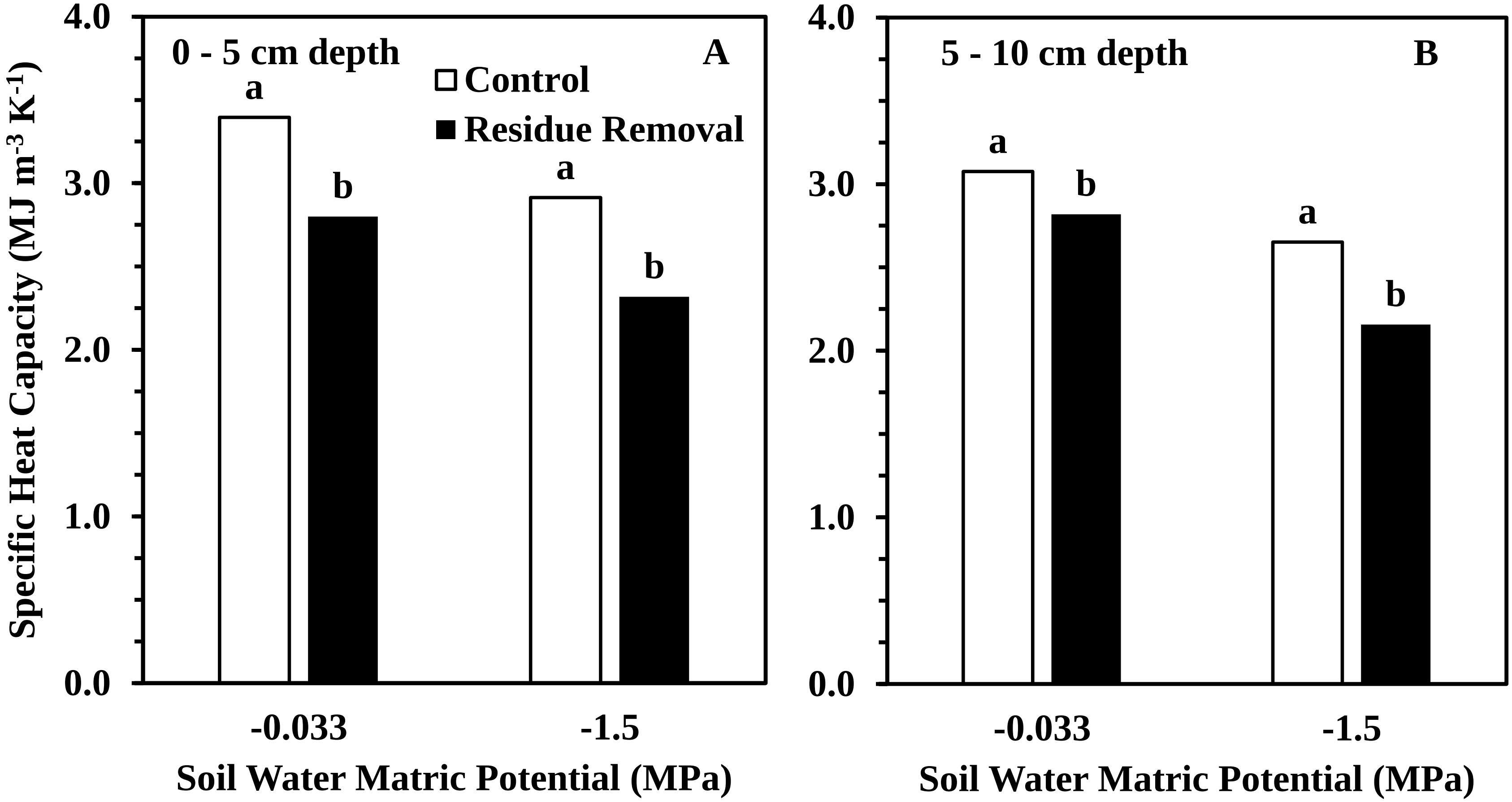

Figure 4.3. Laboratory measured soil specific heat capacity at -0.033 and -1.5 MPa matric potentials for two corn residue removal treatments averaged across cover crop treatments for the 0 to 5 cm (A) and 5 to 10 cm (B) soil depths in an irrigated no-till continuous corn on a silt loam in south central Nebraska after 6 yr of management. Different lowercase letters indicate significant differences between control and residue removal.

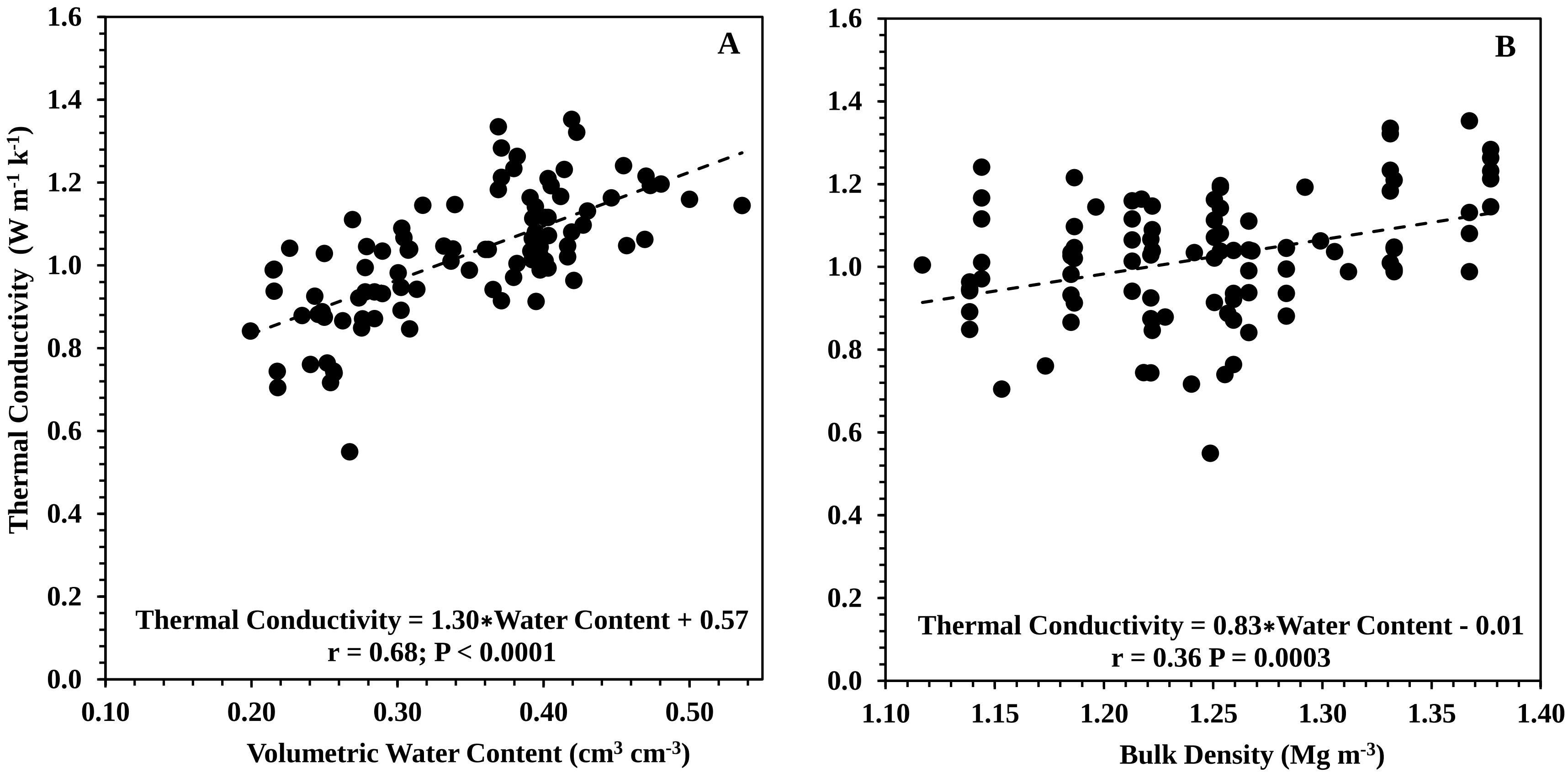

Fig. 4.4. Relationship of field measured soil thermal conductivity with volumetric water content (A) and bulk density (B) across corn residue removal and winter rye cover crop treatments under irrigated no-till continuous corn on a silt loam in south central Nebraska.

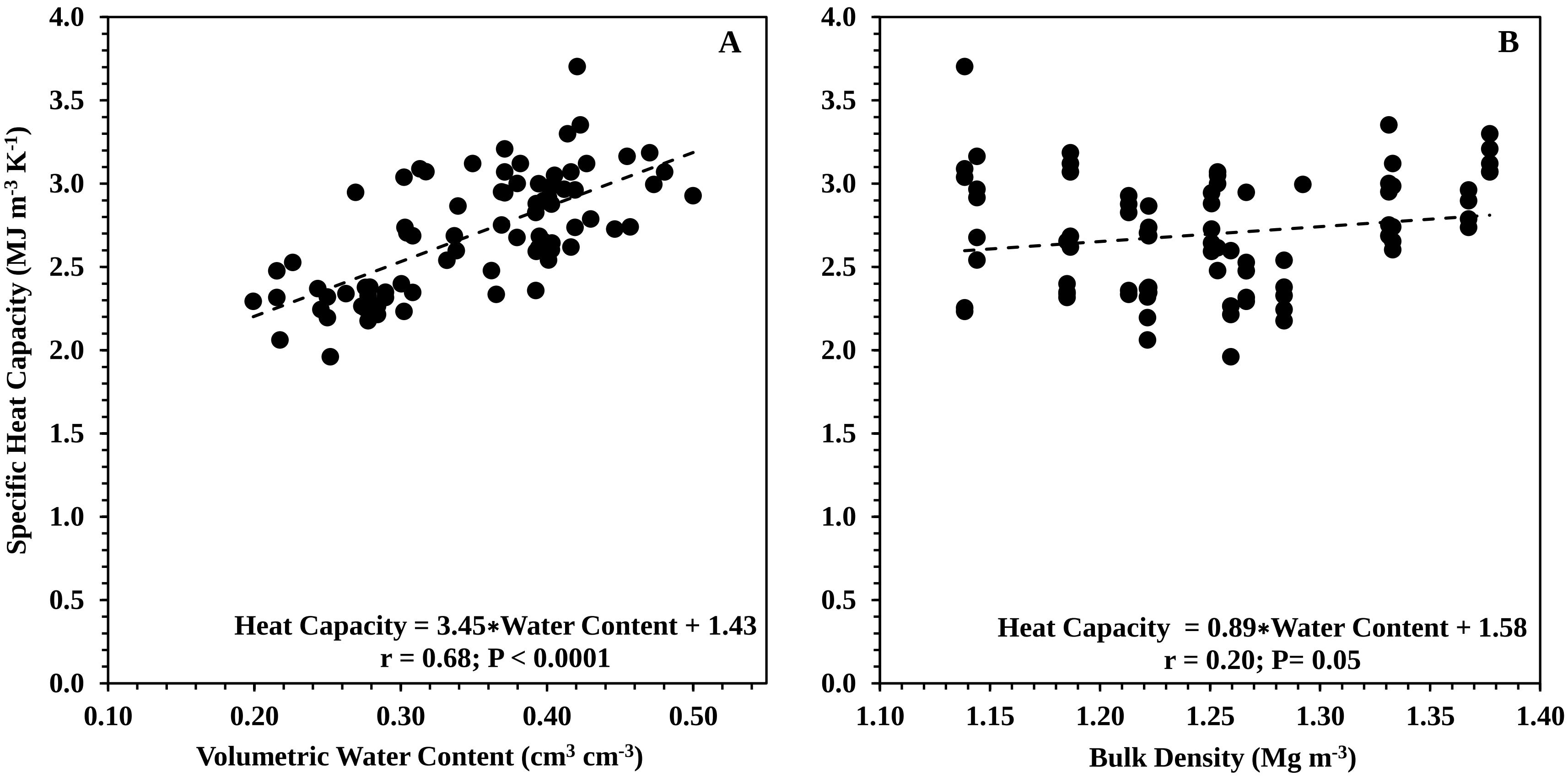

Fig.4.5. Relationship of soil specific heat capacity with volumetric water content (A) and bulk density (B) across corn residue removal and winter rye cover crop treatments under irrigated no-till continuous corn on a silt loam in south central Nebraska after 6 yr of management.

CHAPTER 5. CONCLUSIONS

This study was conducted to better understand the potential of CCs to offset the potential negative impact of corn residue removal (56%) on soil hydraulic and thermal properties. The key conclusions from this study are:

1) Cover crops had small or no effects on soil hydraulic and thermal properties, but corn residue removal at 56% had large and significant effects on most soil hydraulic and thermal properties after 6 yr.
2) Cover crops were unable to mitigate the impacts of reside removal on thermal conductivity, specific heat capacity, and water retention. However, CCs did partially offset the negative impact of residue removal on soil organic C and cumulative water infiltration.
3) Lack of CC effects on soil physical properties in this study is most likely due to the low amount of CC biomass (0.8 Mg ha^{-1}) produced.
4) Comparison of the results from the present study with those from a previous study for the same experiment (Blanco-Canqui et al., 2014) indicated that corn residue removal at high rates (>50%) may not negatively impact soil properties in the short term (<3 yr), but it can adversely affect most soil properties after 6 yr (this study).
5) The decrease in soil organic C concentration with residue removal explained in part the decrease in near-surface plant available water content, indicating that soil organic C was a strong predictor of plant available water.
6) Changes in soil thermal conductivity and specific heat capacity were related to changes in volumetric water content.

CHAPTER 6. REMAINING QUESTIONS

This thesis project provided valuable insights into the impacts of residue removal on soil hydraulic and thermal properties. However, more research is needed to:

1) Identify CC agronomic practices that will have the most potential to increase CC biomass production and thus improve soil properties.
2) Conduct an economic analysis of CC practices.
3) Identify the impacts of corn residue removal and CCs use on early season and off season evaporation and/or transpiration. These data are needed to make better soil water management decisions for increasing the sustainability of crop production in central Great Plains and decreasing the dependence on ground water for irrigation.
4) Analyze residue removal and CC use on soil properties related to soil water balance such as deep percolation and ground water flow. Residue removal could increase surface flow of water and increase nutrient loading of streams, but data on these topics are limited.
5) Analyze residue removal and CC use impacts on soil properties at watershed and field scales to identify other research opportunities and better manage surface water.
6) Conduct more research to determine the long-term (10 to 20 yr) effects of residue removal and CC use on soil hydraulic and thermal properties.
7) Explore the impacts of residue removal on soil properties for the whole soil profile in the medium and long term.