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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 is 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 including soil thermal conductivity, thermal diffusivity, volumetric heat capacity, and related properties under corn (*Zea mays* L.) residue removal with and without winter cereal rye (*Secale cereale* L.) under a 6-yr irrigated no-till continuous corn experiment on a silt loam in south central Nebraska. Cover crops did not affect thermal properties, but corn residue removal reduced field thermal conductivity by 12 to 41% and volumetric heat capacity by 6 to 49% during the growing season for the 0- to 5-cm depth. 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 volumetric 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.

Abbreviations: CC, Cover crop.

Core Ideas

- **Corn residue removal reduces soil thermal conductivity and volumetric heat capacity.**
- **Cover crops do not mitigate corn residue removal effects on thermal properties.**
- **Soil water content and soil bulk density are strong predictors of soil thermal properties.**

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 and Lal, 2007; Wilhelm et al., 2007; Karlen et al., 2011). The pertinent soil thermal properties include thermal conductivity, volumetric heat capacity, and thermal diffusivity. Soil thermal conductivity refers to the rate at which a soil can transfer heat, while volumetric 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 volumetric 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 discussed the effects of crop residue removal on soil properties (Wilhelm et al., 2007; Blanco-Canqui and Lal, 2009). For example, the influence of crop residues on the surface soil temperature and soil water content is well documented (Horton et al., 1996; Sauer et al., 1996). However, few specifically quantified how crop residue removal affects soil thermal properties such as thermal conductivity, volumetric heat capacity, and thermal diffusivity in the field and laboratory.

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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 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). Another study on a silt loam soil found no differences in soil thermal conductivity among control, rotary hoeing, winter wheat (*Triticum aestivum* L.) straw mulching, and wheat straw mulching with rotary hoeing (Dahiya et al., 2007). However, other studies on tillage and crop residue management 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). These few previous studies mostly focused on soil thermal conductivity and not all thermal properties.

If crop residue removal adversely affects soil thermal conductivity, volumetric heat capacity, and thermal diffusivity, CCs could be a companion management practice to mitigate the potential negative effects of crop residue removal on such soil properties (Fronning et al., 2008; Blanco-Canqui, 2013; Osborne et al., 2014). However, changes in soil thermal properties have not been widely studied under CCs in spite of their relevance to many soil processes. Only one study evaluated soil thermal properties under CCs (Haruna et al., 2017), which found that cereal rye, hairy vetch (*Vicia villosa* ssp. *villosa*), and Austrian winter pea (*Pisum sativum* ssp. *arvense*) increased volumetric heat capacity by 15% but did not affect thermal conductivity compared with 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 conentration, 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; Abu-Hamdeh and Reeder, 2000; Ochsner et al., 2001; Abu-Hamdeh, 2003; Adhikari et al., 2014). Soil volumetric heat capacity can have a positive relationship with volumetric water content, bulk density, and soil organic C concentration (Ghuman and Lal, 1985; Potter et al., 1985; Abu-Hamdeh, 2003; Adhikari et al., 2014; Lu et al., 2014). However, correlations of other soil thermal properties with soil properties have not been 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, volumetric 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 (Ruis et al., 2017) and may affect soil thermal properties differently.

The objectives of this study were to assess: (i) the impact of corn residue removal and CCs on soil thermal conductivity, volumetric heat capacity, thermal diffusivity and their relationships with measured soil properties, and (ii) 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, volumetric 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 using 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, Natural Resources Conservation Service, United States Department of Agriculture, 2017). 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: (i) two irrigation levels (100 and 60%), (ii) three amelioration practices (none, manure, and cereal rye CC), (iii) two corn residue removal rates (0 and 56%), and (iv) 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 are found in Table 1. Temperature and rainfall data are in Table 2. Our study on soil hydraulic properties was conducted on two study factors within the larger experiment. The first factor was CC (control and CC) and corn residue removal (no removal and 56% removal) was the second factor. 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 full experiment design 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, volumetric heat capacity, and thermal dif-

Table 1. Information on the experiment management.

Year	Date	Field operation
2015	27 Jan	P fertilizer surface broadcasted (11–52–0; 112 kg ha^{-1}) to the whole field
	17 Apr	Herbicide applied to whole field (Roundup Power Max [$C_3H_8NO_5P$] 2.34 L ha^{-1}); termination of winter rye (*Secale cereale* L.)
	1 May	Corn planted (Dekalb 60–67 [Bayer]; 84,000 seeds ha^{-1}); Starter fertilizer (10–34–0; 65.5 kg ha^{-1})
	22 Jun	N fertilizer injected (UAN† 32–0–0; 125 or 200 kg N ha^{-1}; banded at a 12-cm depth)
	20, 27 Jul; 3, 17, 26, 31 Aug	Irrigation water applied (3.4 and 2 cm water for full and deficit irrigation, respectively)
	16 Oct	Corn (*Zea mays* L.) grain harvested
	27 Oct	Corn residue removed
	3 Nov	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
2016	27 Jan	Broadcasted P fertilizer (11–52–0; 112 kg ha^{-1}) to whole field.
	22 Apr	Herbicide applied to whole field (Roundup Power Max 2.34 L ha^{-1}); 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 (5.84 L ha^{-1} Lumax [Syngenta] + 2.34 L ha^{-1} Roundup)
	16 Jun	Nitrogen fertilizer injected (UAN 32–0–0; 125 or 200 kg N ha^{-1}; banded at a 12-cm depth)
	17 Jun	Herbicide applied to whole field (Roundup at 2.92 L ha^{-1})
	20 Jun; 1, 8, 19, 27 Jul; 2, 17 Aug	Irrigation water applied (3.4 and 2 cm water for full and deficit irrigation, respectively)
	14 Oct	Corn grain harvested
	27 Oct	Corn residue removed
	31 Oct	Winter rye cover crop planted (112 kg ha^{-1}) with no-till drill
	6 Nov	Beef (*Bos taurus*) feedlot manure surface broadcasted to amelioration treatment plots (~25 fresh Mg ha^{-1})
	Dec	Surface broadcasted phosphorus fertilizer (11–52–0; 112 kg ha^{-1}) to whole field
2017	11 Apr	Herbicide applied to whole field (Roundup Power Max 3.50 L ha^{-1}); 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 (7.01 L ha^{-1} Lumax + 3.51 L ha^{-1} Roundup PowerMax)
	13 Jun	N fertilizer injected (UAN 32–0–0; 125 or 200 kg N ha^{-1}; banded at a 12-cm depth)
	27 Jun; 5, 11, 26 Jul; 15 Aug	Irrigation water applied (3.4 and 2 cm water for full and deficit irrigation, respectively)
	19 Oct	Corn grain harvested
	2 Nov	Corn residue removed

† UAN, urea ammonium nitrate.

fusivity using the transient line heat source method (Bristow, 1998). Field measurements were collected 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 1 and 2). Thermal properties were measured at one location per plot on non-trafficked rows. A probe guide was carefully placed flush with the soil and then the SH-1 metal pins were then gently inserted vertically 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 min to allow the probe and surrounding soil to reach equilibrium temperatures. The thermal properties were then measured and recorded. All measurements were collected between 1000 and 1200 h. Measurements were conducted by block rather than by treatment.

Table 2. Monthly precipitation and temperature from 2015 to 2017 for the experimental site in south central Nebraska.

	Precipitation (mm)				Mean temperature (°C)					
Month	2015	2016	2017		2015		2016		2017	
					Min	Max	Min	Max	Min	Max
January	5.3	0.0	0.0		–10.4	5.6	–8.4	2.1	–7.8	1.3
February	0.8	0.0	0.0		12.2	2.2	–5.3	7.4	–4.7	10.4
March	4.8	0.3	0.0		–3.6	15.8	–1.2	15.5	–1.4	12.4
April	61.7	138.4	81.3		3.6	18.4	3.7	18.2	3.7	17.1
May	144.5	172.5	153.9		9.0	20.9	8.7	22.0	8.7	22.5
June	225.8	5.08	22.6		15.7	27.9	17.0	31.3	15.4	30.1
July	54.9	63.5	50.8		17.2	29.7	18.0	30.1	18.5	31.2
August	32.5	63.0	89.6		15.1	28.2	16.7	28.3	14.3	27.2
September	38.4	66.8	23.9		15.5	27.8	13.0	25.4	12.3	26.8
October	37.1	5.6	0.0		5.5	20.9	5.6	21.5	4.2	18.4
November	6.1	0.0	0.0		–0.6	12.1	–0.2	14.0	–2.9	11.9
December	0.0	0.0	X		–5.7	5.1	–10.3	2.8	X	X
Total	611.9	515.1	422.1	Mean	4.0	17.9	4.8	18.2	5.5	19.0

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 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 intact cores were carefully extracted using hand trowels to minimize disturbance of both the intact cores and the experimental plot. The cores were then stored in a cold room at 2.2°C until further processing. Also, six hand-probe samples (3.1-cm diam.) were collected 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 and other related soil 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% (w/v) 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).

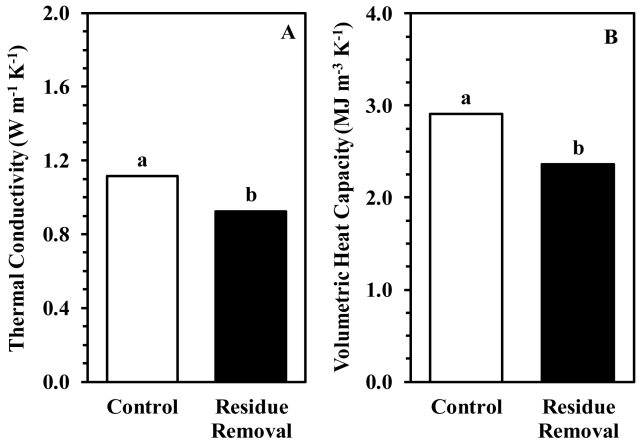

Fig. 1. Field measured soil thermal conductivity (A) and volumetric heat capacity (B) averaged across cover crop treatments and measurement dates as affected by corn residue removal at 56% for the 0- to 5-cm soil depth under irrigated no-till continuous corn on a silt loam in south central Nebraska. Different lowercase letters indicate significant differences between control and residue removal.

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 this 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 volumetric 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 volumetric 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. 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. 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. 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. 2B). 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.

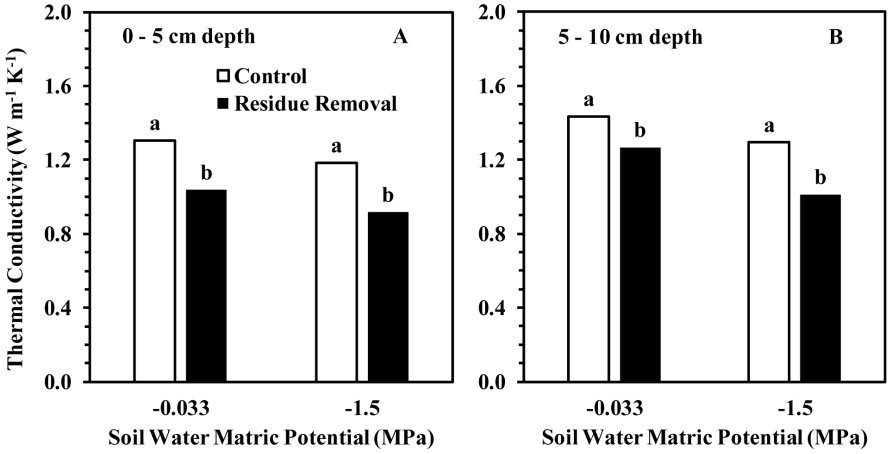

Fig. 2. Laboratory measured soil thermal conductivity measured at –0.033- and –1.5-MPa matric potentials for two corn residue removal treatments averaged across cover crop treatments for the 0- to 5-cm (A) and 5- to 10-cm (B) soil depths in an irrigated no-till continuous corn on a silt loam in south central Nebraska after 6 yr of management. Different lowercase letters indicate significant differences between control and residue removal.

Soil Volumetric Heat Capacity

Under field conditions, residue removal reduced soil volumetric heat capacity by 19% in the 0- to 5-cm soil depth from spring 2016 to summer 2017 (Fig. 1B). Under laboratory conditions, at the 0- to 5-cm soil depth, residue removal reduced volumetric heat capacity by 21% at −0.03 MPa and by 26% at −1.5 MPa matric potential compared with no removal (Fig. 3A). At the 5- to 10-cm depth, residue removal reduced volumetric heat capacity by 6% at −0.033 MPa and by 19% at −1.5 MPa (Fig. 3B). Mean volumetric 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 3). Cover crop had no effect on soil water content and bulk density, but residue removal affected water content throughout the sampling times (Table 3). Corn residue removal reduced volumetric water content by 13 to 40% compared with no removal (Table 3). Residue removal had no effect on soil bulk density.

Soil thermal conductivity was positively correlated with volumetric water content (Fig. 4A) and bulk density (Fig. 4B). It was more strongly correlated with volumetric water content (r = 0.68) than with bulk density (r = 0.36). Volumetric heat capacity was also positively correlated with volumetric water content (Fig. 5A) and bulk density (Fig. 5B). Similar to thermal conductivity, volumetric 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, and Soil Organic C

Cover crop treatments had no effect on soil water content, bulk density, and soil organic C concentration (Table 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

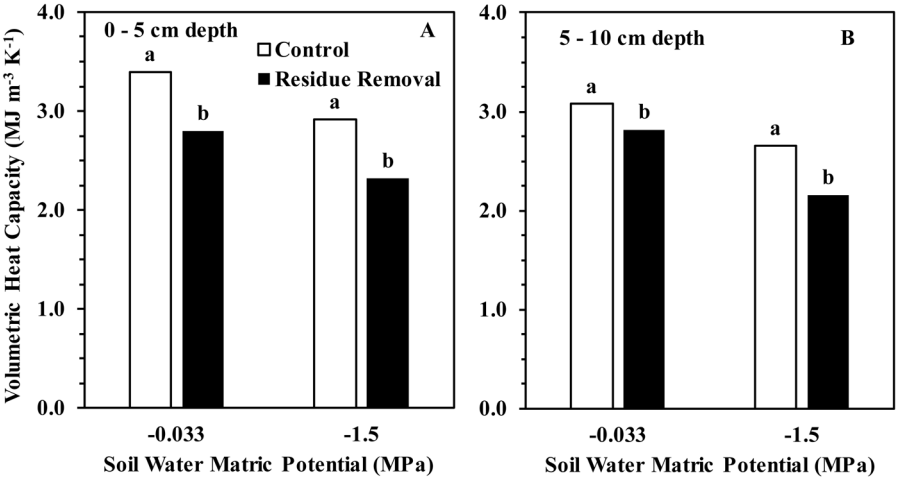

Fig. 3. Laboratory measured soil volumetric heat capacity at –0.033- and –1.5-MPa matric potentials for two corn residue removal treatments averaged across cover crop treatments for the 0- to 5-cm (A) and 5- to 10-cm (B) soil depths in an irrigated no-till continuous corn on a silt loam in south central Nebraska after 6 yr of management. Different lowercase letters indicate significant differences between control and residue removal.

depth (Table 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). 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 5). Residue removal reduced soil organic C concentration, but the 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 5).

Thermal conductivity and volumetric heat capacity were correlated with the above soil properties more for the −0.033-MPa than for the −1.5-MPa matric potential (Table 6). They were correlated more with bulk density and water content than with 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 volumetric heat capacity increased with an increase in bulk density and water content. 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 volumetric heat capacity were positively correlated with bulk density 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, volumetric heat capacity was positively correlated with soil organic C concentration and water content (Table 6).

Volumetric water content, bulk density, and organic C concentrations were important predictors of thermal conductivity and volumetric heat capacity (Table 7). The predictive ability of the three soil properties were in this order: volumetric water content > bulk density > organic C concentration. Volumetric water content and bulk density were the best predictors of thermal conductivity and volumetric heat capacity for −0.03 MPa matric potential at the 0- to 5-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 7). Soil organic C concentration was only a significant predictor of soil volumetric heat capacity for the 5- to 10-cm depth at −1.5 MPa.

Table 3. Mean volumetric water content and soil bulk density as affected by cover crop (CC) and corn residue removal treatments in an irrigated no-till continuous corn on a silt loam in south central Nebraska. The lowercase 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 2017	No CC	No	0.38a	1.24
		Yes	0.25b	1.25
	CC	No	0.38a	1.28
		Yes	0.24b	1.25
May 2017	No CC	No	0.32a	1.25
		Yes	0.22b	1.27
	CC	No	0.32a	1.26
		Yes	0.24b	1.27
June 2017	No CC	No	0.34a	1.26
		Yes	0.19b	1.28
	CC	No	0.32a	1.29
		Yes	0.20b	1.26
May 2016	No CC	No	0.39a	1.28
		Yes	0.28b	1.25
	CC	No	0.40a	1.29
		Yes	0.30b	1.20
June 2016	No CC	No	0.35a	1.28
		Yes	0.25b	1.25
	CC	No	0.38a	1.29
		Yes	0.28b	1.20
July 2016	No CC	No	0.39a	1.28
		Yes	0.28b	1.25
	CC	No	0.40a	1.29
		Yes	0.30b	1.20
August 2016	No CC	No	0.45a	1.28
		Yes	0.33b	1.25
	CC	No	0.45a	1.27
		Yes	0.40b	1.20
September 2016	No CC	No	0.40a	1.28
		Yes	0.27b	1.25
	CC	No	0.41a	1.29
		Yes	0.31b	1.20

DISCUSSION

This study indicates that corn residue removal at about 56% for 6 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, volumetric heat capacity, and thermal diffusivity. The residue removal effect on thermal conductivity and volumetric 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 volumetric heat capacity. An increase in volumetric 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 because of the extended period of study (six consecutive years of corn residue removal at 56%), whereas the previous studies were short term (<1 yr).

Cover crop had no effect on soil thermal properties, which did not support our second hypothesis. We hypothesized that CC use for 6 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

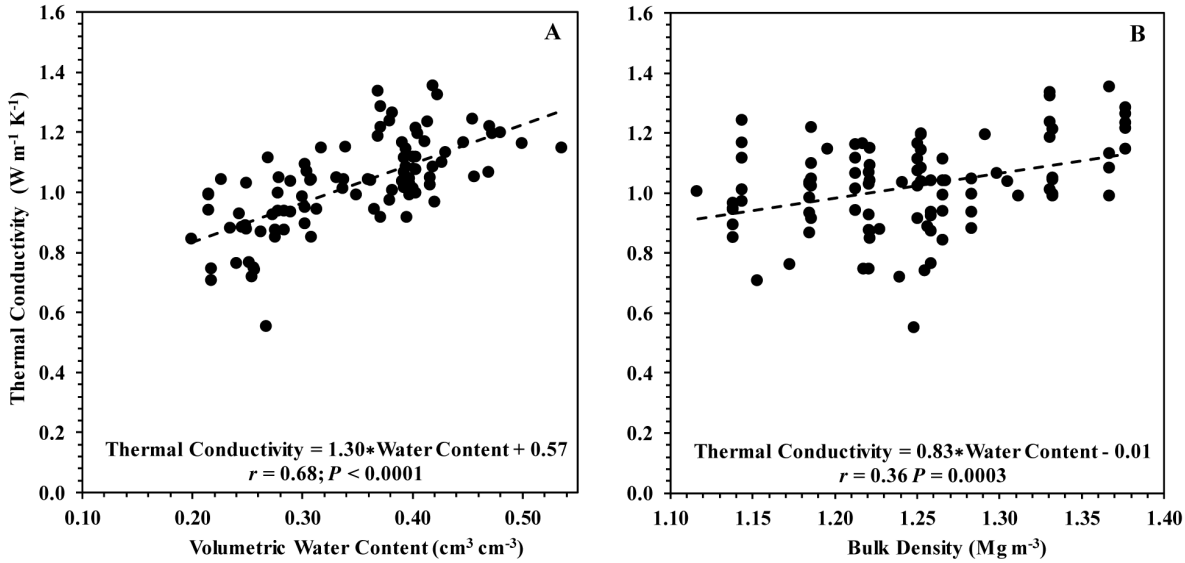

Fig. 4. Relationship of field measured soil thermal conductivity with volumetric water content (A) and bulk density (B) across corn residue removal and winter rye cover crop treatments under irrigated no-till continuous corn on a silt loam in south central Nebraska.

can be attributed to 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 with that (1.66 to 3.24 Mg ha^{-1} yr^{-1}) found in some recent studies under different CC management scenarios (Kaspar and Bakker, 2015; Blanco-Canqui et al., 2017). The lower CC biomass yield is probably because of the short CC growing period (early November to early April) in our study. Another study in Nebraska found that late-terminated CC (early May) can produce significantly more biomass than early-terminated CC (mid-April; Ruis et al., 2017).

Changes in soil thermal properties could depend on 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 to 5 shoot/root ratio (Sheng and Hunt, 1991; Amanullah and Ullah, 2015), 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, volumetric heat ca-

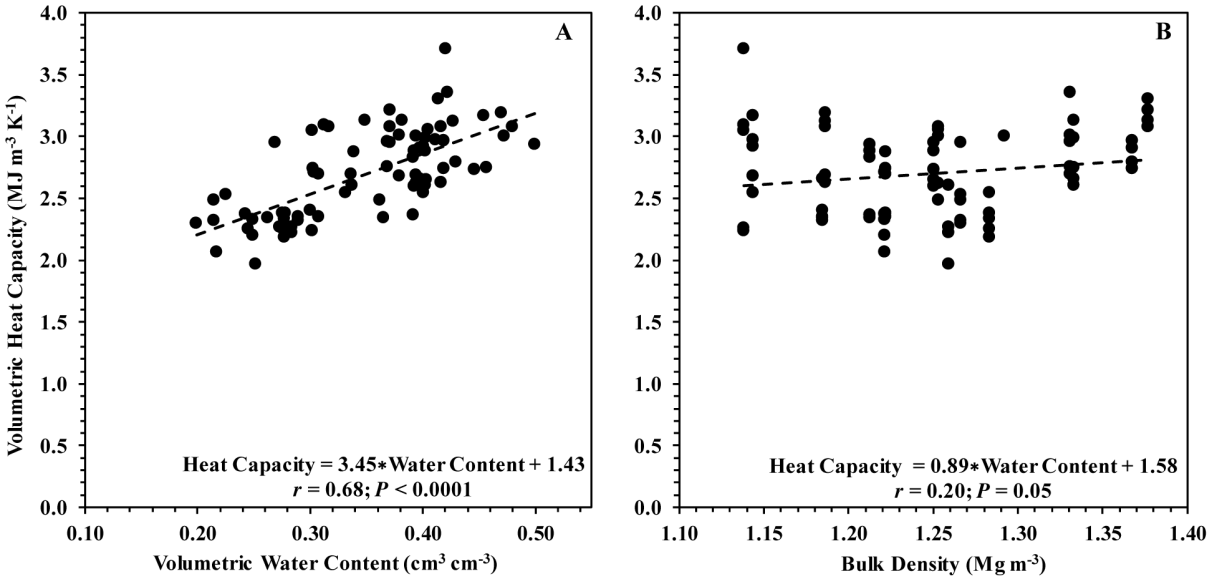

Fig. 5. Relationship of soil volumetric heat capacity with volumetric water content (A) and bulk density (B) across corn residue removal and winter rye cover crop treatments under irrigated no-till continuous corn on a silt loam in south central Nebraska after 6 yr of management.

pacity, 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 volumetric heat capacity and decreased thermal diffusivity but had no effect on soil thermal conductivity. The contrasting results may be due to 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).

Table 4. Mean volumetric water content (θ_v) at matric potentials of –0.033 and –1.5 MPa as affected by covercrop and corn residue removal treatments 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 lowercase letters denote the statistical difference between residue management treatments.

Treatment	Depth	θ_v	
		at –0.033MPa	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 5. Mean soil organic C concentration, soil bulk density, particle density, and particle-size analysis as affected by cover crop (CC) and corn residue removal treatments 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 lowercase 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	298	576
CC	No	5–10	16.4	1.44	235	615
	Yes	5–10	15.9	1.40	299	571

Table 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	Soil organic C
	cm	$cm^3\ cm^{-3}$	$Mg\ m^{-3}$	$g\ kg^{-1}$
	–0.033 MPa Soil Water Matric Potential			
Thermal conductivity, $W\ m^{-1}\ K^{-1}$	0–5	0.72**	0.50*	0.28
Volumetric heat capacity, $MJ\ m^{-3}\ K^{-1}$	0–5	0.65**	0.62**	0.43†
Thermal conductivity, $W\ m^{-1}\ K^{-1}$	5–10	0.59*	0.59*	0.74**
Volumetric heat capacity, $MJ\ m^{-3}\ K^{-1}$	5–10	0.62**	0.45†	0.45
	–1.5 MPa Soil Water Matric Potential			
Thermal conductivity, $W\ m^{-1}\ K^{-1}$	0–5	0.16	0.41†	0.28
Volumetric heat capacity, $MJ\ m^{-3}\ K^{-1}$	0–5	–0.10	0.64**	0.18
Thermal conductivity, $W\ m^{-1}\ K^{-1}$	5–10	0.71**	0.51*	0.55*
Volumetric heat capacity, $MJ\ m^{-3}\ K^{-1}$	5–10	0.71**	0.34	0.48†

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

Results from this study suggest that changes in thermal conductivity and volumetric heat capacity because of 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 with other measured soil properties (Table 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 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 with 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 volumetric 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 volumetric 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 volumetric heat capacity under residue removal suggests that the soil surface in fields with residue removed can warm and cool

Table 7. Predictive equations of soil thermal conductivity and volumetric heat capacity using measured soil properties as input parameters across both cover crop and residue removal treatments by soil depth in an irrigated no-till continuous corn on a silt loam soil in south central Nebraska.

Depth, cm	Variable	–0.033 MPa Matric potential			–1.5 MPa Matric potential		
		Partial r^2	Model r^2	$P > F$	Partial r^2	Model r^2	$P > F$
				Soil Thermal Conductivity			
0–5	Water content, $cm^3\ cm^{-3}$	0.52	0.52	0.04	0.20	0.40	0.05
	Bulk density, $Mg\ m^{-3}$	0.17	0.69	0.02			
5–10	Soil organic C, $g\ kg^{-1}$	0.55	0.55	< 0.01	0.23	0.74	< 0.01
	Bulk density, $Mg\ m^{-3}$	0.09	0.64	0.03			
	Water content, $cm^3\ cm^{-3}$	0.07	0.84	0.09	0.53	0.53	< 0.01
				Soil Volumetric Heat Capacity			
0–5	Water content, $cm^3\ cm^{-3}$	0.42	0.42	< 0.01			
	Bulk density, $Mg\ m^{-3}$	0.30	0.72	0.03	0.41	0.41	< 0.01
5–10	Bulk density, $Mg\ m^{-3}$	0.50	0.50	0.04			
	Water content, $cm^3\ cm^{-3}$				0.50	0.50	< 0.01
	Soil organic C, $g\ kg^{-1}$				0.17	0.67	0.02

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 volumetric heat capacity of soils with residue removed imply that these soils could require less heat to increase soil temperature when compared with 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 yr reduced soil thermal conductivity and volumetric 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 volumetric 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 volumetric heat capacity followed by bulk density, and 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 volumetric 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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