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No-till cover crop effects on the thermal properties of a Paleudult

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ABSTRACT

Soil thermal properties play an important role in crop productivity, but the influence of a multi-species cover crops (CCs) on these properties are not well understood. This study evaluated the effects of no-till CCs (winter wheat [*Triticum aestivum* L.], crimson clover [*Trifolium incarnatum* L.], triticale [*Triticale hexaploide* Lart], hairy vetch [*Vicia villosa*], oats [*Avena sativa*], and cereal rye [*Secale cereale* L.]) on soil physical (bulk density [BD], and volumetric water content [Θ] at 0, −33, and −100 kPa soil water pressures) and thermal properties (thermal conductivity [λ], volumetric heat capacity [C_V], and thermal diffusivity [D]). Soil samples were collected just before CC termination at 0–10, 10–20, and 20–30 cm depths from CC and no cover crop (NC) plots during 2021 and 2022. Results showed that, after 2 years, CCs reduced BD by 17% and increased Θ at 0, − 33, and − 100 kPa soil water pressures by 23%, 25%, and 28%, respectively relative to NC management. Thus, λ under NC was 16%, 19%, and 20% higher at 0, − 33, and − 100 kPa soil water pressures, respectively, compared with CC management. Conversely, C_V was 17%, 14%, and 15% higher under CC compared with NC management at 0, − 33, and − 100 kPa soil water pressures. Regression analysis further demonstrated that while plant root was the most important factor influencing λ at saturation, Θ played the greatest role in λ at other soil water pressures. Expectedly, Θ was the most important factor influencing C_V at all measured soil water pressures. Conclusively, no-till CCs can improve laboratory measured soil thermal properties by moderating heat transfer.

1. Introduction

Soil thermal properties influence heat flow, and some soil ecosystem benefits and processes; provisioning services (e.g., seed germination and plant root growth), climate regulation (e.g., microbial decomposition of soil organic carbon [SOC] stock), and environmental sustainability (e.g., water and nutrient transport) (Blanco-Canqui and Ruis, 2020; Haruna et al., 2020). These thermal properties include thermal conductivity (λ), volumetric heat capacity (C_V), and thermal diffusivity (D).

Thermal conductivity is the ability of a material to transfer heat by conduction though a unit area of the material and it is the sum of all components representing thermal excitation (Yang, 2005). For soils, compaction allows heat to spread out more effectively and slowly over a large depth. Conversely, the C_V is the ability of a material to resist heat change per volume over a given temperature gradient and it depends on several soil properties including volumetric water content (Θ) and SOC (Ju et al., 2011). Due to their high heat capacity, higher Θ and SOC in the soil often results in higher C_V (Bristow, 2002). Thermal diffusivity provides information about the balance between heat conduction and storage (Dante, 2016) and is related to how quickly a material can achieve thermal equilibrium. As such, higher D can result in rapid heat transfer.

Although soil thermal properties can be influenced by pedogenic factors and processes (e.g., particle size distribution, climatic conditions, slope aspect, etc.) in the long-term, anthropogenic factors, through soil manipulation and management, influence these properties in the short-term. An important soil management practice that has been reported to influence soil thermal properties is tillage. Abu-Hamdeh (2000) reported that the λ of a loam soil was 39% higher under no-till (NT) management compared with rotary plow. Further, Potter et al. (1985) reported that NT had 20% higher λ than conventional tillage. This was attributed to the tillage systems relieving soil compaction, reducing the contact between soil particles, and consequently reducing soil λ.

Besides tillage, the use of cover crops (CCs) in crop rotation cycles

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Abbreviations: CC, cover crop; NC, no cover crop; BD, bulk density; C_V, volumetric heat capacity; D, thermal diffusivity; λ, thermal conductivity; θ, volumetric water content.

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can also influence soil thermal properties. For example, Haruna et al. (2017) reported that CCs, by significantly increasing SOC and Θ, increased C_V by 13% at saturation compared with no cover crop (NC) management. At − 33 kPa soil water pressures, these authors reported that C_V was 16% higher under CC compared with NC management. Sindelar et al. (2019) reported similar findings.

Although some studies have been conducted to evaluate the influence of CCs on soil thermal properties (e.g., Haruna et al., 2017; Sindelar et al., 2019; Haruna, 2019; Mendis et al., 2022), these studies were conducted over one growing season. Further, the soil property and mechanisms responsible for changes in thermal properties at different soil water pressures have not been studied or fully understood. In a changing global climate with increasingly more variable soil water content, knowledge of soil properties influencing soil thermal properties at various soil water pressures is important for ensuring cropping systems sustainability. The objectives of this study include; 1) evaluate the influence of No-till CC management alone on soil thermal properties during 2 years, 2) quantify the effects of plant roots on soil thermal properties, 3) investigate the influence of Θ, SOC, and soil bulk density (BD) on soil thermal properties at various soil water pressures, and 4) evaluate the interaction effects of CCs, sampling depth, and sampling year on soil thermal properties. It is hypothesized that 1) CCs alone will not significantly improve soil thermal properties during 2 years, 2) plant roots, like SOC, will increase volumetric heat capacity of soils, 3) due to water drainage at each soil water pressure, Θ will be the most important factor influencing soil thermal properties, and 4) treatment by depth interaction will increase λ and reduce C_V, while year by depth treatment will reduce C_V under CC management alone.

2. Materials and methods

2.1. Site description

This study was conducted on a farmer's field in Coffee County, Tennessee, USA (35.330 N, −86.012 W). The site was at an average elevation of 310 m above sea level and a 0–2% slope. The USDA classification of the soil is a Holston sandy loam (Fine-loamy, siliceous, semiactive, thermic Typic Paleudults). Particle size distribution relative to soil depth is shown in Table 1. The study area's climate is humid subtropical (Koppen Climate Classification). The average 40-year precipitation is 1422 mm, with December (122 mm) and August (51 mm) receiving the highest and lowest amount of precipitation, respectively. The cumulative precipitation during the CC growing season was 31 and 29 mm during 2021 and 2022, respectively. The average 40- year air temperature at the study site is 15 °C, with July (31 °C) and January (−1°C) being the warmest and coldest months, respectively.

2.2. Management description

The field was laid out using a completely randomized design with two levels of CCs (CCs vs NC) with three replicates. The tillage management type was NT for this field. A 6-way CC mix was selected to reflect the agronomic practice in this region and for their soil health benefits. These CCs included winter wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), triticale (*Triticale hexaploide* Lart), hairy vetch (*Vicia villosa*), oats (*Avena sativa*), and cereal rye (*Secale cereale* L.). The cash crop grown after CC termination was corn (*Zea mays*) planted in April and harvested in September of each year.

The field was under 20 years of CC management and 25 years of NT management prior to the establishment of the current research in 2020. After the harvest of the cash crop in 2020, the research plots were delineated. Each plot was 20.1 m long and 7.4 m wide. During October of 2020 and 2021, the CCs were overseeded and later drilled into the soil at the following rates: 22.4 kg ha^{-1} for winter wheat, 5.9 kg ha^{-1} for crimson clover, 22.4 kg ha^{-1} for triticale, 5.6 kg ha^{-1} for hairy vetch, 29.1 kg ha^{-1} for oats, and 17.8 kg ha^{-1} for cereal rye. These seeding

Table 1
Particle size distribution as a function of depth for the study site (Holston sandy loam).

Depth (cm)	Clay	Silt	Sand
	%		
0–10	14.17	22.50	63.33
10–20	16.67	21.67	61.66
20–30	15.83	20.83	63.34

rates were based on the recommendations of the University of Tennessee Cooperative Extension. The CCs were terminated in April of each year using 4.15 kg ha^{-1} acid equivalent of glyphosate (*N*-[phosphonomethyl] glycine). About 3 hrs. after spraying, a 9 m CC roller was used to complete the CC termination. All plots were rain-fed during this study.

2.3. Soil sampling and analysis

Soil samples were collected just prior to CC termination using a cylindrical core with a diameter of 5.5 cm and a height of 6 cm during 2021 and 2022 at three depths; 0–10, 10–20, and 20–30 cm. Plant root proportion per soil sample was analyzed after the samples were oven-dried, crushed and sieved (Zhou and Shangguan, 2005). The proportion of plant roots in the soil samples at 0–10, 10–20, and 20–30 cm depths were about 20%, 10%, and 5%, respectively under CC management. Under NC management, the proportion of plant roots was 5%, 3%, and 1% of the soil volume at 0–10, 10–20, and 20–30 cm depths, respectively. During each year, a total of 18 (2 treatments x 3 depths x 3 replicates) soil samples were collected. Each sample was trimmed, placed in pre-labelled plastic bags and stored in the refrigerator at 4 °C until analysis.

Prior to analysis, soil samples were removed from the plastic bags, a cheesecloth placed on the bottom of the cores using rubber bands, placed in a tub and saturated with water (electrical conductivity of 0.3 dS/m at 20 °C) from below until there was no tension on the soil surface. Each soil was weighed, placed on pressure plates and equilibrated to − 33 and − 100 kPa soil water pressures on ceramic plates using a pressure chamber (Dane and Hopmans, 2002). After equilibration at each pressure, the soil samples were weighed and Θ was determined at each pressure using BD data.

A KD2 (Decagon Devices, Pullman, WA) heat-pulse sensor was used to determine soil thermal properties; λ, C_V, and D. Prior to measurement, the accuracy of the probe was verified using performance verification standards. At each soil water pressure (0, −33, and −100 kPa), the probe was inserted vertically into the soil and the λ, C_V, and D were recorded. During insertion, previous insertion locations and core walls were avoided.

After measuring soil thermal properties and Θ, the soil samples were oven-dried for at least 24 hrs. and BD was determined using the core method (Grossman and Reinsch, 2002). The oven-dried soil was ground, passed through a 2 mm sieve. About 20 g of the < 2 mm particles was used for soil textural analysis using the pipette method (Gee and Or, 2002). At least 250 mg of the < 2 mm particles was used for SOC determination using the combustion method (Loss-on-Ignition at 1200 °C) (Schulte and Hopkins, 1996) in a Skalar SNC (Skalar Analytical B.V., The Netherlands) analyzer.

The model of Fu et al. (2019) was used to quantify the effects of plant roots (P_r) on soil thermal properties;

$$\lambda = \frac{\left(\frac{V_w}{V} + \frac{V_{rw}}{V}\right)\lambda_w + k_r\frac{V_r}{V}\lambda_r + k_s\frac{m_s}{\rho sV}\lambda_s + k_a\left(1 - \left(\frac{V_w}{V} + \frac{V_{rw}}{V}\right) - \frac{V_r}{V} - \frac{m_s}{\rho sV}\right)\lambda_a}{\left(\frac{V_w}{V} + \frac{V_{rw}}{V}\right) + k_r\frac{V_r}{V} + k_s\frac{m_s}{\rho sV}k_a\left(1 - \left(\frac{V_w}{V} + \frac{V_{rw}}{V}\right) - \frac{V_r}{V} - \frac{m_s}{\rho sV}\right)} \tag{1}$$

$$C_v = \frac{m_s}{V}c_s + \left(\frac{V_w}{V} + \frac{V_w}{V}\right)C_w + \frac{V_r}{V}\rho_r c_r \tag{2}$$

where V, V_w, V_{rw} V_r are the volumes of the whole soil (including all constituents), soil water, root water, and dry roots, respectively; λ_w, λ_s, and λ_a are the thermal conductivities of water (0.57 W m^{-1} K^{-1}), soil solids, and air (0.025 W m^{-1} K^{-1}), respectively; ρ_s and ρ_r are the densities of soil solids and dry roots, λ_r is assumed to be equal to the λ of organic materials (0.25 W m^{-1} K^{-1}), C_s, C_w, and C_r are the specific heat of soil solids, soil water (4.18 MJ m^{-3} K^{-1}), and dry roots (assumed to be equal to the specific heat of organic materials, 1.92 J g^{-1} K^{-1}), k_r, k_s, and k_a are weighing factors for the dry plant roots, soil solids, and air, respectively. For mathematical convenience, the effects of plant roots on thermal diffusivity was determined as a ratio of Eqs. 1 and 2. For more details about these weighing factors, please see Fu et al. (2019).

2.4. Statistical analysis

A test of normality was conducted on SOC, BD, Θ at 0, − 33, and − 100 kPa soil water pressures, and thermal properties using the Anderson-Darling test at 0.05 probability level in SAS ver. 9.4 (SAS Institute, 2015). All data was normally distributed. ANOVA was conducted on soil properties to determine the treatment and depth effects during each year. Additionally, ANOVA was also conducted to determine the treatment X depth interaction on measured soil physical and thermal properties. Further, ANOVA was conducted on CC samples alone collected during 2021 and 2022 to determine the CC and year X depth interaction effects on soil properties. Significant differences were determined at the 0.05 probability level.

3. Results

3.1. Soil physical properties

The means (with SE) and ANOVA of selected soil physical properties between treatments and at different depths during 2021 and 2022 are provided in Table 2. Additionally, comparison was also made for soil physical properties under CC treatments alone between 2021 and 2022 to evaluate the temporal effects of CCs on these properties. In both years of study, treatment and sampling depth significantly influenced soil physical properties (Table 2). Averaged over sampled depths in 2021, BD was 15% higher under NC compared with CC management. During this same period, the depth averaged Θ at 0, − 33, and − 100 kPa soil water pressures were 29%, 83%, and 100% higher, respectively, under CC compared with NC management, with the greatest influence occurring at the 0–10 cm depth. Although not significant, SOC was numerically higher under CC management compared with NC management. While BD increased with an increase in soil depth, other measured soil physical properties reduced significantly with an increase in soil depth. In 2022, BD was 17% higher under NC compared with CC management. Soil organic carbon, Θ at 0, − 33, and − 100 kPa soil water pressures were 14%, 23%, 25%, and 28% higher, respectively, under CC compared with NC management. Although all soil physical properties were not significantly influenced by soil depth, the trend of soil physical properties with depth in 2022 was similar to 2021 (Table 2).

When soil physical properties under CC management alone were compared between 2021 and 2022, year X depth interaction was significant for BD. Results showed that BD was higher in 2021 compared with 2022 at the 0–10 and 10–20 cm depths. At the 20–30 cm depth, BD was higher in 2022 compared with 2021 (Fig. 1a). Although sampling year did not significantly influence all measured soil physical properties, the depth averaged soil physical properties were numerically higher in 2022 compared with 2021 (Table 2). Further, all soil physical properties (except BD) were reduced with an increase in soil depth. Soil BD followed the opposite trend.

3.2. Soil thermal properties

Table 3 shows the means (with SE) and ANOVA for soil thermal properties at selected soil water pressures between treatments and at different sampled depths in 2021 and 2022 and for CCs alone during both years. Averaged over sampled depths during 2021, λ was 18%, 16%, and 15% higher under NC compared with CC at 0, − 33, and − 100 kPa soil water pressures, respectively. Conversely, averaged over all sampled depths, C_V was 15%, 12%, and 10% higher under CC compared with NC at 0, − 33, and − 100 kPa soil water pressures, respectively. The depth averaged D was 35%, 30%, and 27% higher under NC compared with CC at 0, − 33, and − 100 kPa soil water pressure, respectively. At all pressures, λ and D increased significantly with an increase in soil depth, while C_V reduced with increasing soil depth

Table 2
Soil organic carbon (SOC), bulk density (BD), and volumetric water content at selected water matric potentials.

			Volumetric water content (cm^3 cm^{-3})		
Treatment	SOC (g kg^{-1})	BD (g cm^{-3})	0 kPa	-33 kPa	-100 kPa
2021					
CC	16.95 ± 1.16¶	1.17 ± 0.05b	0.510 ± 0.02a	0.110 ± 0.02a	0.102 ± 0.02a
NC	15.86 ± 1.01	1.35 ± 0.04a	0.395 ± 0.02b	0.059 ± 0.01b	0.051 ± 0.01b
Depth (cm)					
5	19.82 ± 1.19a	1.18 ± 0.19b	0.507 ± 0.03a	0.114 ± 0.02a	0.104 ± 0.02a
15	15.05 ± 0.87b	1.24 ± 0.15ab	0.463 ± 0.04a	0.089 ± 0.02ab	0.085 ± 0.02ab
25	14.34 ± 0.61b	1.36 ± 0.08a	0.387 ± 0.03b	0.044 ± 0.01b	0.044 ± 0.01b
ANOVA *P* > *F*					
Treatment	0.064	0.006	0.003	0.022	0.018
Depth	0.011	0.052	0.009	0.046	0.041
Treatment*depth	0.958	0.483	0.993	0.304	0.334
2022					
CC	18.34 ± 0.34a	1.19 ± 0.02b	0.490 ± 0.01a	0.119 ± 0.01a	0.114 ± 0.01a
NC	16.05 ± 0.84b	1.39 ± 0.04a	0.398 ± 0.02b	0.095 ± 0.01b	0.089 ± 0.01b
Depth (cm)					
5	18.60 ± 0.38a	1.18 ± 0.03b	0.472 ± 0.03a	0.111 ± 0.02	0.105 ± 0.02
15	17.39 ± 0.52ab	1.31 ± 0.06a	0.440 ± 0.06b	0.106 ± 0.01	0.100 ± 0.01
25	15.61 ± 1.15b	1.37 ± 0.05a	0.421 ± 0.05c	0.105 ± 0.01	0.099 ± 0.01
ANOVA *P* > *F*					
Treatment	0.018	0.032	0.016	0.038	0.043
Depth	0.038	0.003	< 0.001	0.746	0.724
Treatment*depth	0.370	0.147	0.060	0.074	0.080
2021 vs 2022					
Depth (cm)					
5	19.69 ± 0.92a	1.08 ± 0.05b	0.534 ± 0.02a	0.142 ± 0.01a	0.135 ± 0.01a
15	17.17 ± 0.95ab	1.16 ± 0.04ab	0.505 ± 0.02ab	0.118 ± 0.02ab	0.113 ± 0.01ab
25	16.08 ± 0.80b	1.29 ± 0.02a	0.460 ± 0.01b	0.083 ± 0.02b	0.077 ± 0.02b
ANOVA *P* > *F*					
Year	0.052	0.655	0.526	0.724	0.637
Depths	0.044	0.024	0.039	0.037	0.042
Year*Depth	0.226	0.035	0.252	0.254	0.637

Means with different letters for a soil property are significantly different at the 0.05 probability level.
¶Mean ± S.E.
*interaction
CC, cover crops; NC, no cover crop.

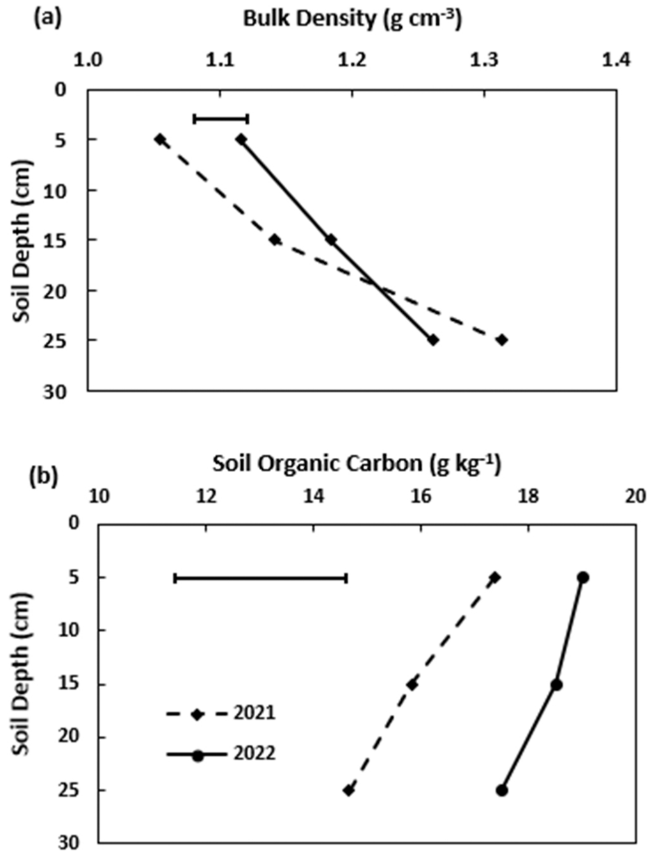

Fig. 1. (a) Soil bulk density relative to soil depth for cover crops during 2021 and 2022, and (b) soil organic carbon relative to soil depth for cover crops during 2021 and 2022.

(Table 3). During 2022, soil thermal properties followed a similar trend with treatment and depth as it did during 2021.

A comparison of soil thermal properties under CC management alone between 2021 and 2022 showed that sample year, depths and year X depth interaction significantly influenced soil thermal properties at various soil water pressures (Figs. 2–4). At − 33 kPa soil water pressures, λ and C_V were 10% and 4% higher, respectively, in 2022 compared with 2021. Further, λ and D increased with increasing soil depth at all measured soil water pressures. At saturation, year X depth interaction showed that λ and D were higher in 2021 compared with 2022 at the 0–10 cm depth. Below this depth, the trend was reversed (Fig. 2d & 4d).

In order to determine the influence of the measured soil physical properties and CC plant roots (P_r) on soil thermal properties, regression analysis was conducted on each soil thermal property at each measured soil water pressure. The following equations provided the best estimate for λ, C_V, and D at each measured soil water pressure;.

At saturation.

$$\lambda = 0{\cdot}786 + 0{\cdot}038\Theta + 0{\cdot}408BD + 0{\cdot}003SOC + 0{\cdot}438\ P_r\ r^2 = 0{\cdot}79 \tag{3}$$

$$C_V = 2{\cdot}048 + 2{\cdot}026\Theta - 0{\cdot}194BD + 0{\cdot}019SOC + 0{\cdot}022\ P_r\ r^2 = 0{\cdot}77 \tag{4}$$

$$D = 0{\cdot}301–0{\cdot}113\Theta + 0{\cdot}127BD - 0{\cdot}001SOC – 0{\cdot}435\ P_r\ r^2 = 0{\cdot}78 \tag{5}$$

At − 33 kPa.

$$\lambda = 0{\cdot}263 + 1{\cdot}019\Theta + 0{\cdot}638BD + 0{\cdot}002SOC + 0{\cdot}321\ P_r\ r^2 = 0{\cdot}92 \tag{6}$$

$$C_V = 2{\cdot}934 + 0{\cdot}818\Theta - 0{\cdot}619BD + 0{\cdot}042SOC + 0{\cdot}021\ P_r\ r^2 = 0{\cdot}97 \tag{7}$$

$$D = 0{\cdot}118 – 0{\cdot}323\Theta + 0{\cdot}210BD – 0{\cdot}002SOC – 0{\cdot}394\ P_r\ r^2 = 0{\cdot}94 \tag{8}$$

At − 100 kPa.

$$\lambda = 0{\cdot}264 + 0{\cdot}973\Theta + 0{\cdot}619BD + 0{\cdot}002SOC + 0{\cdot}371\ P_r\ r^2 = 0{\cdot}83 \tag{9}$$

$$C_V = 2{\cdot}525 + 0{\cdot}630\Theta - 0{\cdot}288BD + 0{\cdot}032SOC + 0{\cdot}045\ P_r\ r^2 = 0{\cdot}76 \tag{10}$$

$$D = 0{\cdot}135 – 0{\cdot}449\Theta + 0{\cdot}163BD – 0{\cdot}001SOC – 0{\cdot}492\ P_r\ r^2 = 0{\cdot}86 \tag{11}$$

The models were significant ($p < 0.001$) ($n = 36$) with r^2 ranging between 0.76 and 0.97 at all soil water pressures. While P_r was the most significant factor influencing λ at saturation, Θ was the most important measured variable that influenced λ at − 33 and − 100 kPa soil water pressures. For C_V, Θ had the greatest influence at all measured soil water pressures. The proportion of P_r was the most significant factor affecting D at all measured soil matric potentials.

Table 3
Thermal conductivity (λ), volumetric heat capacity (C_V), and thermal diffusivity (D) at selected water matric potentials.

	0 kPa			-33 kPa			-100 kPa		
Treatment	λ (W m^{-1}K^{-1})	C_V (MJ m^{-3}K^{-1})	D (mm^2 s^{-1})	λ (W m^{-1}K^{-1})	C_V (MJ m^{-3}K^{-1})	D (mm^2 s^{-1})	λ (W m^{-1}K^{-1})	C_V (MJ m^{-3}K^{-1})	D (mm^2 s^{-1})
2021									
CC	1.30 ± 0.01[¶] b	3.26 ± 0.03a	0.40 ± 0.01b	1.10 ± 0.01b	3.01 ± 0.02a	0.37 ± 0.03b	1.10 ± 0.01b	2.92 ± 0.08a	0.37 ± 0.01b
NC	1.53 ± 0.05a	2.83 ± 0.04b	0.54 ± 0.03a	1.28 ± 0.04a	2.68 ± 0.08b	0.48 ± 0.01a	1.27 ± 0.04a	2.66 ± 0.08b	0.47 ± 0.01a
Depth (cm)									
5	1.39 ± 0.02c	3.18 ± 0.02a	0.44 ± 0.01c	1.16 ± 0.01b	2.96 ± 0.03a	0.40 ± 0.01b	1.16 ± 0.01	2.96 ± 0.06	0.39 ± 0.01b
15	1.41 ± 0.04b	3.04 ± 0.03b	0.47 ± 0.02b	1.20 ± 0.02a	2.82 ± 0.03b	0.43 ± 0.02a	1.19 ± 0.01	2.69 ± 0.05	0.43 ± 0.02ab
25	1.44 ± 0.05a	2.91 ± 0.03c	0.50 ± 0.02a	1.21 ± 0.04a	2.75 ± 0.05b	0.45 ± 0.02a	1.20 ± 0.03	2.73 ± 0.09	0.45 ± 0.02a
ANOVA *P* > *F*									
Treatment	0.007	0.016	0.018	< 0.001	0.032	0.015	< 0.001	0.041	0.036
Depth	0.002	0.001	0.001	0.001	0.016	0.007	0.002	0.047	0.020
Tmt*depth	0.001	0.167	0.009	0.962	0.234	0.195	0.963	0.234	0.095
2022									
CC	1.36 ± 0.02b	3.28 ± 0.05a	0.42 ± 0.01b	1.21 ± 0.02b	3.13 ± 0.05a	0.39 ± 0.01b	1.18 ± 0.02b	3.04 ± 0.05a	0.39 ± 0.01b
NC	1.58 ± 0.05a	2.80 ± 0.09b	0.57 ± 0.09a	1.44 ± 0.04a	2.74 ± 0.09b	0.53 ± 0.04a	1.42 ± 0.04a	2.65 ± 0.08b	0.53 ± 0.03a
Depth (cm)									
5	1.35 ± 0.04b	3.19 ± 0.04a	0.43 ± 0.02c	1.21 ± 0.05b	3.09 ± 0.03a	0.39 ± 0.02c	1.19 ± 0.05b	3.00 ± 0.04a	0.39 ± 0.03c
15	1.49 ± 0.05a	3.02 ± 0.09ab	0.50 ± 0.03b	1.35 ± 0.05a	2.95 ± 0.04a	0.46 ± 0.03b	1.32 ± 0.05a	2.87 ± 0.05b	0.47 ± 0.03b
25	1.56 ± 0.06a	2.91 ± 0.09b	0.55 ± 0.04a	1.42 ± 0.06a	2.77 ± 0.09b	0.53 ± 0.05a	1.40 ± 0.06a	2.68 ± 0.09b	0.52 ± 0.05a
ANOVA *P* > *F*									
Treatment	0.019	0.0314	0.041	0.017	0.002	0.037	0.017	0.040	0.044
Depth	0.002	0.034	< 0.001	0.002	0.003	0.001	0.002	0.003	0.001
Tmt*depth	0.485	0.310	0.008	0.499	0.027	0.012	0.488	0.027	0.011
2021 Vs 2022									
Depth (cm)									
5	1.28 ± 0.01b	3.34 ± 0.05a	0.38 ± 0.01a	1.10 ± 0.01b	3.13 ± 0.05	0.35 ± 0.01b	1.08 ± 0.01c	3.08 ± 0.05	0.35 ± 0.01b
15	1.35 ± 0.02a	3.29 ± 0.04ab	0.41 ± 0.01ab	1.17 ± 0.03a	3.06 ± 0.05	0.38 ± 0.01a	1.16 ± 0.02b	2.88 ± 0.12	0.40 ± 0.01a
25	1.37 ± 0.03a	3.18 ± 0.03b	0.43 ± 0.01c	1.20 ± 0.03a	3.03 ± 0.06	0.40 ± 0.01a	1.19 ± 003a	2.98 ± 0.05	0.40 ± 0.01a
ANOVA *P* > *F*									
Year	0.315	0.208	0.340	0.049	0.001	0.095	0.130	0.287	0.392
Depths	< 0.001	0.097	0.003	< 0.001	0.483	0.002	< 0.001	0.294	0.020
Year*Depth	0.002	0.942	0.046	0.061	0.997	0.153	0.081	0.495	0.406

Means with different letters for a soil property are significantly different at the 0.05 probability level.
[¶] Mean ± S.E.
*interaction.
Tmt, treatment; CC, cover crops; NC, no cover crop.

4. Discussions

4.1. Soil physical properties

An important ecosystem and soil health benefit of CCs is their ability to increase SOC accumulation, while also reducing the loss of SOC stock, chiefly by their contribution to above and belowground biomass and moderating soil temperatures (Poeplau and Don, 2015; Blanco-Canqui et al., 2011). Although not significantly different, the slightly higher SOC under CC management during 2021 (which was the first year after research implementation) shows the effects of microbial activity on residue turnover. With little above and belowground biomass addition, microbial activity under the NC management probably resulted in a slight depletion of previously accumulated SOC within the soil, compared with the CC management with more biomass. With limited residue input under NC compared with CC management, the magnitude of difference in SOC between both management practice is expected to be proportional with time, as the results show in 2022. Further, the numerically higher SOC values during 2022 compared with 2021 under CC management alone further demonstrates that continued use of CCs can increase SOC stocks through the preservation of SOC stocks and the addition of more biomass. Also, with a decrease in the amount of biomass relative to an increase in soil depth, SOC significantly reduced with increasing soil depths during both years of study.

The significantly lower BD values under CC compared with NC management was attributed to several mechanisms. First, since SOC is less dense than soil particles, higher SOC values under CC management will inversely influence soil BD values. Second, active root growth and the associated rhizosphere depositions of belowground biomass can increase soil porosity and aggregation and lower soil BD under CC compared with NC management. Finally, a reduction in the kinetic energy of raindrops due to aboveground biomass under CC management can better preserve soil structure, pore integrity, reduce soil particle consolidation, and ultimately soil BD compared with NC management. Due to the weight of overburden soil and lower SOC, BD increased with increasing soil depth.

Besides increasing SOC and reducing soil BD, plant roots can also increase the proportion of different soil pore sizes within the soil. For

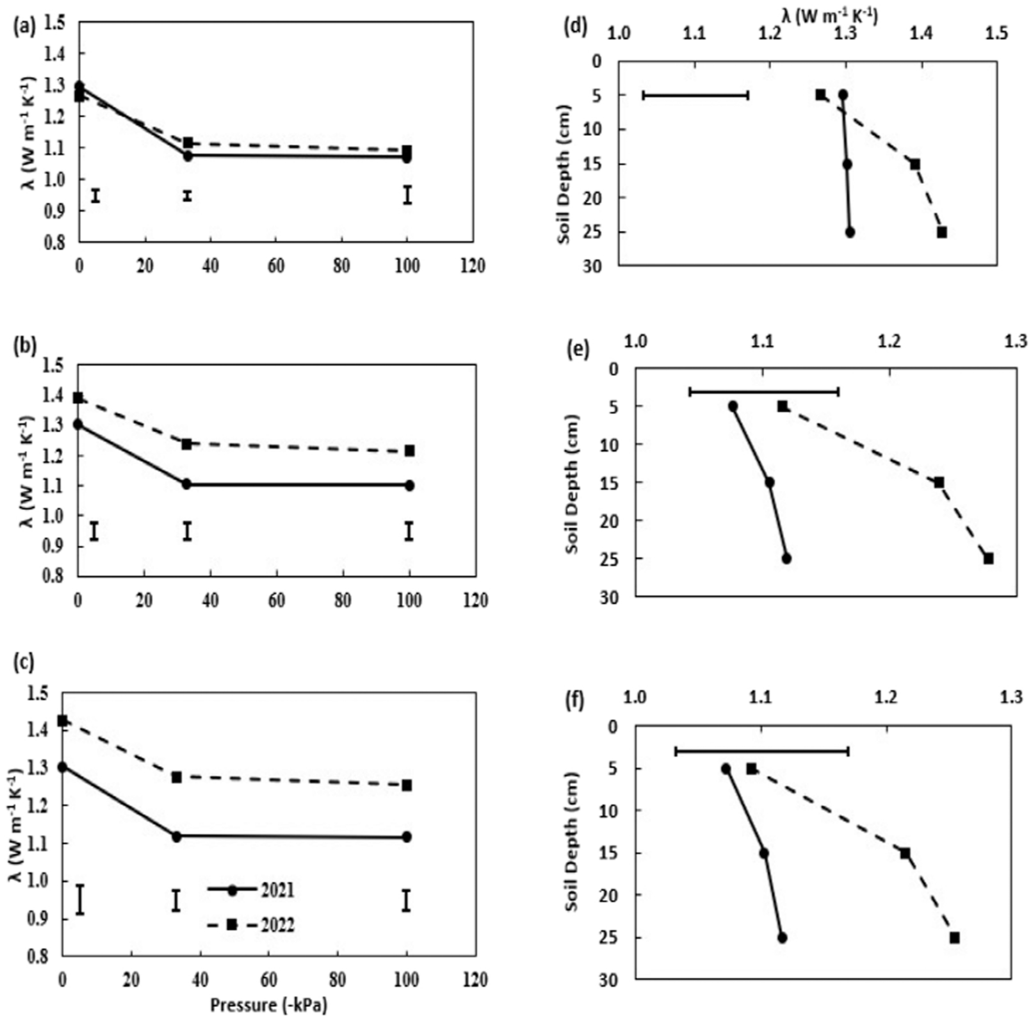

Fig. 2. Thermal conductivity (λ) for cover crops during 2021 and 2022 at (a) 0–10, (b) 10–20, and (c) 20–30 cm depths and at (d) 0, (e) − 33, and (f) – 100 kPa soil water pressures. Bar indicated the least square difference at $P < 0.05$ for λ among the years.

example, Haruna et al. (2022) reported a 265% higher macroporosity (< 1000 μm diameter) and a 91% higher fine mesoporosity (10 – 60 μm diameter), while Haruna et al. (2018) reported a 30% higher coarse mesoporosity (10 – 1000 μm diameter) under CC compared with NC management during the first month after CC termination. Further, Villamil et al. (2006) reported a significantly higher proportion of interconnected pores under CC management compared with NC. As such, the significantly higher Θ under CC compared with NC management during 2021 and 2022 at 0, − 33, and − 100 kPa soil water pressures was attributed to; 1) CC root-induced increases in macropores, coarse and fine mesopores that causes water drainage at these soil water pressures, 2) SOC-induced improvement in soil aggregation (Blanco-Canqui and Lal, 2004) which increases water drainage, especially at higher soil water pressures, and 3) CC root-induced pore continuity which reduces soil pore tortuosity and can further increase water drainage at the aforementioned soil water pressures (Table 2). As expected, Θ reduced with increasing soil depth during both years and when CC management alone was compared probably due to increasing BD and reducing SOC with increasing soil depth.

4.2. Soil thermal properties

Factors that influence λ include soil texture, arrangement of and contact between soil solids, proportion of P_r, as well as the contact between liquids and solids. As the proximity between soil particles increases, heat is transferred quickly over a temperature gradient (Haruna and Anderson, 2022). The higher λ under NC compared with CC during both years at all measured soil water pressures can be attributed to the closer contact between soil particles under NC management as depicted by higher BD values. This suggests that NC management can lead to a rapid heat change within the soil with the attendant consequences of increasing and sustaining soil water evaporation over longer periods of time compared with CC management. Additionally, the lack of surface residue may also exacerbate the rapid soil warming during the late spring seasons. This can be detrimental to crop growth during drier growing seasons.

Interestingly, there was a non-linear relationship between λ and Θ below saturation, similar to the study by Abu-Hamdeh (2003) and Lu et al. (2014). The regression analysis suggests that while P_r was the most crucial factor that influenced λ at saturation (equation [3]), Θ was the most important factor influencing λ at − 33 and − 100 kPa soil water pressures (equations [6] and [9]) for both management systems. This result disproved the second hypothesis that Θ will be the most important factor influencing soil thermal properties at all soil water pressures measured. Some mechanisms may be responsible for this. At saturation, the mechanical forces of attraction between soil water and plant roots (adhesion) creates a 'thermal bridge' that enhances thermal conductivity over a gradient. Second, plant root exudates are denser than soil solution and their secretion is affected by available water (Williams and de Vries, 2019). These exudates (e.g. mucigels) can further increase

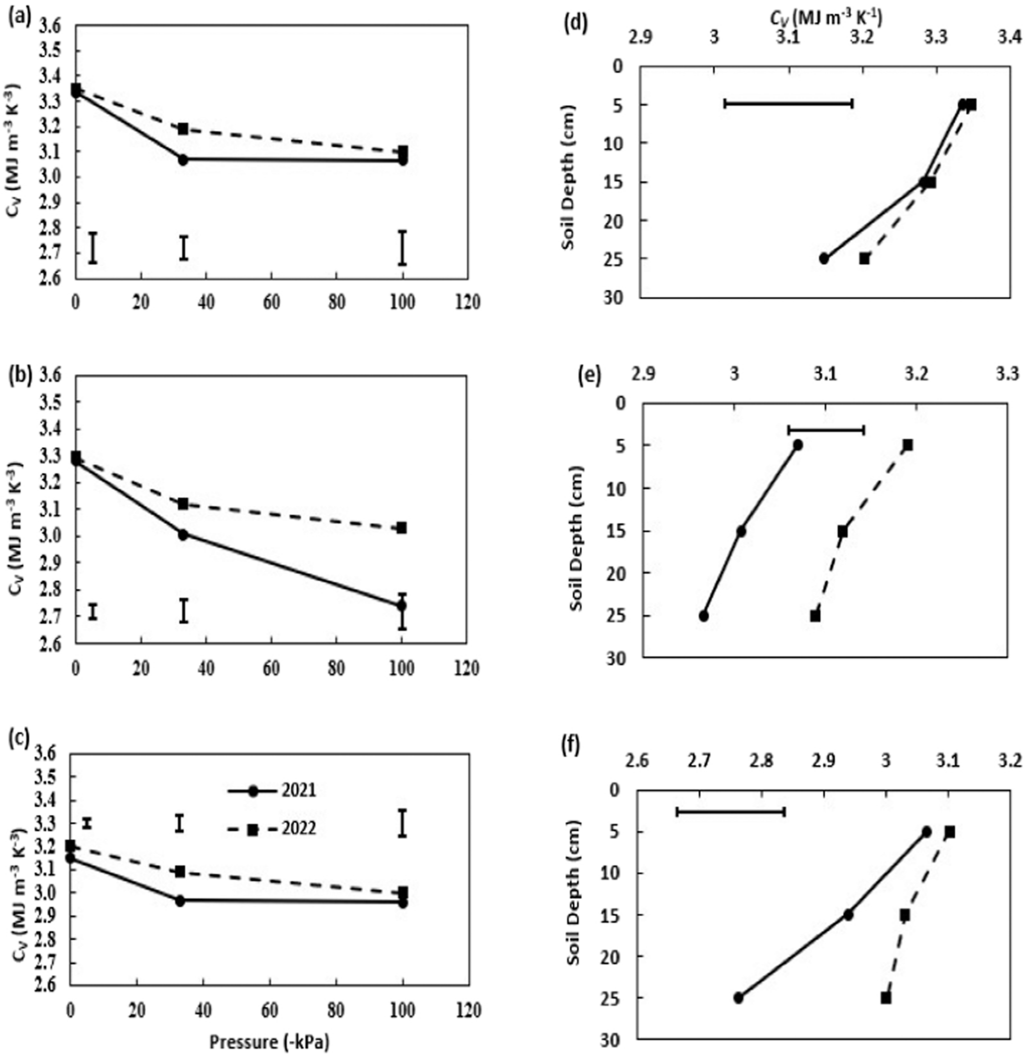

Fig. 3. Volumetric heat capacity (C_V) for cover crops during 2021 and 2022 at (a) 0–10, (b) 10–20, and (c) 20–30 cm depths and at (d) 0, (e) − 33, and (f) – 100 kPa soil water pressures. Bar indicated the least square difference at $P < 0.05$ for C_V among the years.

thermal conductivity of soils due to the linear relationship between λ and denser materials (Van Donk and Tollner, 2000; Zhang et al., 2020).

Below saturation, plant roots close their stomates and downregulate the secretion of exudates (Henry et al., 2019). Further, as the soil dries out, the ratio of soil water to soil air reduces. Since BD generally does not change significantly at different soil water pressures and the λ of water (0.57 W m^{-1} K^{-1}) is higher than that of air (0.025 W m^{-1} K^{-1}) (Bristow, 2002), this variability in Θ becomes more important below saturation and leads to a general decrease in λ with decreasing soil water pressures. Also, due to rapid drainage of water between 0 and − 33 kPa soil water pressures, λ also decreased significantly between these pressures for both treatments (Fig. 2). Since the variability in Θ with soil depth was not as significant as the variability in BD with soil depth (Table 2), increases in λ with increasing soil depth was attributed to increasing proximity between soil particles with increasing soil depth.

When the λ of CC management alone was compared for both years, the λ was higher in 2022 compared with 2021 at all depths (Fig. 2a-c) and pressures (Fig. 2d-f) probably due to a slightly higher BD, Θ, and SOC in 2022 (Table 2).

The C_V values of water and SOC is 4.18 MJ m^{-3} K^{-1} and 2.50 MJ m^{-3} K^{-1}, respectively, both of which are significantly higher than the C_V of soil minerals at 1.20 MJ m^{-3} K^{-1} (Bristow, 2002). Therefore, the C_V is directly related to Θ and SOC and inversely related to BD as shown in Eqs. (4), (7), and (10). Further, the colloidal surface of SOC can also retain soil water, further increasing Θ and C_V. Thus, the higher C_V under CC management compared with NC during both years was attributed to higher Θ and SOC under the CC management. Also, lower SOC and Θ, and higher BD with increasing soil depth was possibly responsible for lower C_V values with increasing soil depth (Tables 2 and 3).

Additionally, it has been demonstrated that plant roots can further increase the C_V of the soil (Steinberg et al., 2006). Results of the current study show that CCs can improve the C_V of the soil through several mechanisms; 1) the roots of the CCs can modify the dynamics of water content and distribution around the rhizosphere (Rabbi et al., 2018), 2) root hair extension can lead to the extraction of more water from deeper parts of the soil (Benough (2012)), and 3) root exudates secreted by root growth, like mucigels, (Brady and Weil, 2008) can further increase water content and retention around plant roots. Further, Moradi et al. (2011) reported that the rhizosphere hold more water than the root-free soil over different water potentials, even as the soil dries. This agrees with the results of Fu et al. (2020).

Processes like seed germination, plant root growth, and microbial activity are very sensitive to rapid soil temperature change (Onwuka and Mang, 2018). Therefore, in an increasingly more variable atmospheric climatic condition, results show that CCs can significantly increase the soil's heat buffering capacity, helping moderate and maintain processes like seed germination and microbial activity. Also, aboveground biomass of the CCs can help reduce the amount of solar radiation

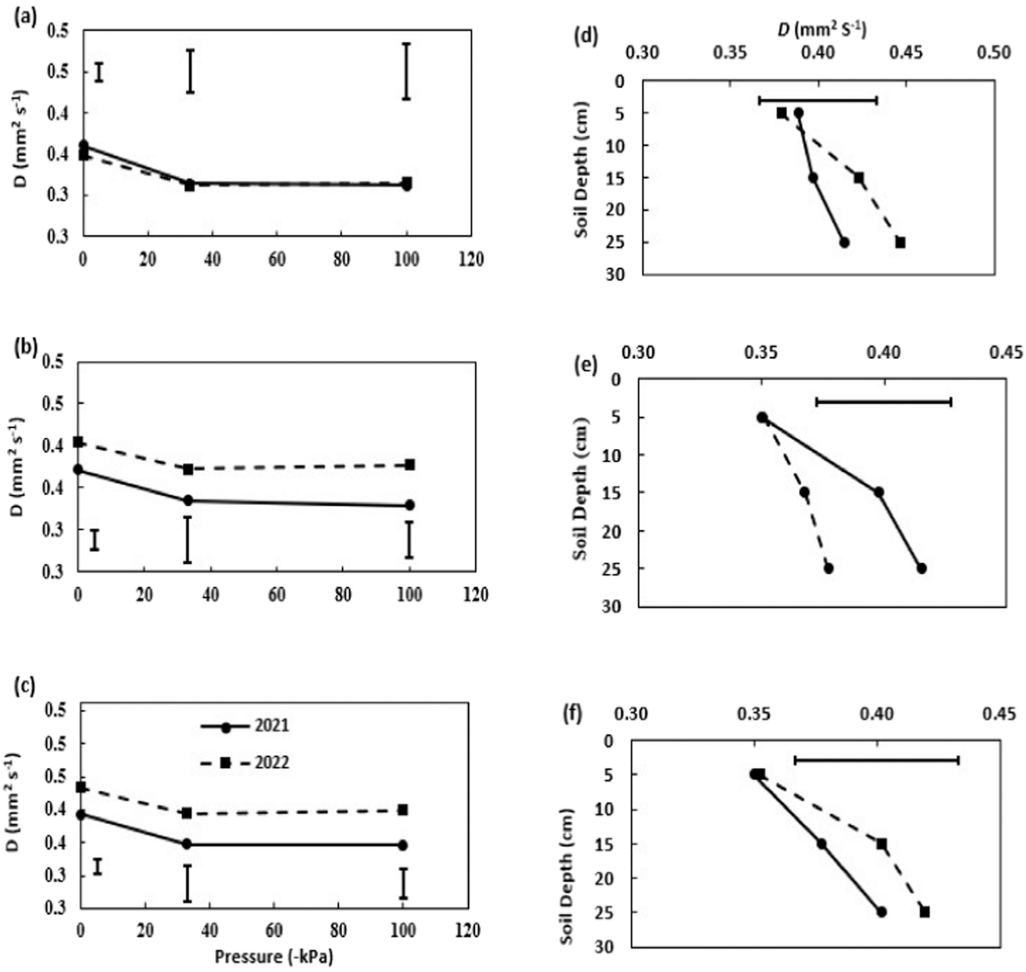

Fig. 4. Thermal diffusivity (D) for cover crops during 2021 and 2022 at (a) 0–10, (b) 10–20, and (c) 20–30 cm depths and at (d) 0, (e) − 33, and (f) – 100 kPa soil water pressures. Bar indicated the least square difference at $P < 0.05$ for D among the years.

reaching the soil surface, further helping to increase soil buffering capacity.

The rapid decrease in C_V between 0 and − 33 kPa soil water pressures and a steadier decrease between − 33 and − 100 kPa soil water pressures was attributed to the water drainage at these matric potentials. This suggests that Θ is the major factor influencing C_V in soil systems, as demonstrated by its high heat capacity and the regression equations.

Under CC management alone, C_V was higher in 2022 compared with 2021 at all depths (Fig. 3a-c) and measured soil water pressures (Fig. 3d-f) due to higher Θ at these depths and soil water pressures and also SOC at these depths in 2022 (Table 2 and Fig. 1b). This disproved the first and third hypotheses of this study. Since organic matter decomposition is mostly directly related to soil temperatures, CC management can help reduce CO_2 emissions from the soil while also helping to further maintain SOC stocks. This benefit of CCs translates beyond the soil and can be an important management practice in combatting climate variability.

Thermal diffusivity is the ratio of λ to C_V, determines how quickly a material reacts to changes in temperature, and is somewhat related to the thermal inertia of the material (Speight, 2019). Therefore, D is directly related to BD and inversely related to Θ (equations [5], [8], and [11]). Not surprisingly, the D under NC was higher compared with CC management in both years due to higher BD under NC management (Table 2). As water drains out of the soil at lower soil water pressures, D reduces for both management practices and during both years. This was attributed to the fact that Θ influences C_V more than λ, thereby lowering the ratio of λ to C_V at these water pressures (Table 3 and Fig. 4a-f). The numerically higher D values in 2022 compared with 2021, under CC management alone, at all pressures and depths can be attributed to the numerically higher BD in 2022.

Since D provides information about the balance between heat conduction and storage (Dante, 2016), results from the current study show that NC management can increase heat transfer within the soil. While this might be beneficial in lengthening the growing season in very cold regions, it can be detrimental in warmer climates. Therefore, in a changing global climate, NC management, by facilitating rapid heat transfer, can lead to further emissions of CO_2 and depletion of SOC stocks within the soil.

In general, CCs, living or dead, influences the energy partitioning on the soil surface. The leaves of living CCs and the residues of terminated CCs can reduce the amount of solar radiation reaching the soil surface (Haruna, 2019). During cold periods, these leaves and residues can reduce the amount of heat radiated back to the atmosphere. In both cases, CCs can further help buffer against significant heat change within the soil. Conversely, if CCs are grown in drier climatic conditions or terminated late in the spring period, there benefits can be reversed. Transpiration of soil moisture by these CCs may allow the soil surface to heat and cool more readily by reducing the soil C_V. Therefore, the use of CCs for soil heat management should be dependent on climatic conditions, in association with other economic considerations.

Despite the interesting results of the current study, there are some limitations that can lead to further understanding of the influence of CCs on soil thermal properties. This study was limited to one climatic zone and soil type. Future studies should explore how CCs influence soil thermal properties over different climatic conditions. Further, in situ studies are needed to better quantify the effects of CC Pr on soil thermal properties. These will help bridge some of the gaps in current understanding of CC effects on soil thermal properties.

5. Conclusion

The effects of no-till CC management on soil thermal properties during 2 years were evaluated on a Paleudult. During both years, CC management significantly reduced soil BD and Θ at saturation, − 33, and − 100 kPa soil water pressures compared with NC management. Consequently, λ was lower while C_V was higher under CC relative to NC management. At saturation, CC plant roots was the most important factor influencing λ. At − 33 and − 100 kPa soil water pressures, Θ was the most important factor influencing λ. At all soil matric potentials, Θ influenced C_V the most. By significantly increasing the C_V of the soil, CCs can help buffer against extreme heat change within the soil compared with NC. Since soil temperature is extremely important for microbial activity, seed germination, root growth and survival, including CCs into crop rotation cycles can help maintain and possibly improve crop productivity in a rapidly changing global climate.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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References

Abu-Hamdeh, N.H., 2000. Effects of tillage treatments on soil thermal conductivity for some Jordanian clay loam and loam soils. Soil Tillage Res. 56, 145–151. https://doi.org/10.1016/S0167-1987(00)00129-X.

Abu-Hamdeh, N.H., 2003. Thermal properties of soils as affected by density and water content. Biosyst. Eng. 86, 97–102. https://doi.org/10.1016/S1537-5110(03)00112-0.

Benough, A.G., 2012. Water dynamics of the root zone: rhizosphere biophysics and its control on soil hydrology. Vadose Zone J. 11:vzj2011- 0111. https://doi.org/10.2136/vzj2011.0111.

Blanco-Canqui, H., Lal, R., 2004. Mechanisms of carbon sequestration in soil aggregates. Crit. Rev. Plant Sci. 23, 481–504. https://doi.org/10.1080/07352680490886842.

Blanco-Canqui, H., Ruis, S.J., 2020. Cover crop impact on soil physical properties: a review. Soil Sci. Soc. Am. J. 84, 1527–1576. https://doi.org/10.1002/saj2.20129.

Blanco-Canqui, H., Mikha, M.M., Presley, D.R., Claasen, M.M., 2011. Addition of cover crops enhances no-till potential for improving soil physical properties. Soil Sci. Soc. Am. J. 75, 1471–1482. https://doi.org/10.2136/sssaj2010.0430.

Brady, N.C., Weil, R.R., 2008. The Nature and Properties of Soils. In: Pp, Vol. 13. Prentice Hall, Upper Saddle River, NJ, USA, pp. 468–469.

Bristow, K.L., 2002. Thermal conductivity. In: Dane, J.H., Topp, G.C. (Eds.), Methods of soil analysis: part 4. Soil Science Society of America book series 5, Madison, pp. 1209–1226.

Dane, J.H., Hopmans, J.W., 2002. Water retention and storage. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis, Part 4- Physical Methods. Book Ser 5. Soil Science Society of America, Madison, WI, pp. 680–688.

Dante, R.C., 2016. Metals. In: Dante, R.C. (Ed.), Handbook of Friction Materials and their Applications. Woodhead Publishing, Sawston, UK, pp. 123–134.

Fu, Y., Lu, Y., Heitman, J., Ren, T., 2020. Root-induced changes in soil thermal and dielectric properties should not be ignored. Geoderma 370, 114352. https://doi.org/10.1016/j.geoderma.2020.114352.

Henry, C., John, G.P., Pan, R., Bartlett, M.K., Fletcher, R.L., Scoffoni, C., Sack, L., 2019. A stomatal safety-efficiency trade-off constrains responses to leaf dehydration. Nat. Commun. 10, 1–9. https://doi.org/10.1038/s41467-019-11006-1.

Ju, Z., Ren, T., Hu, C., 2011. Soil thermal conductivity as influenced by aggregation at intermediate water contents. Soil Sci. Soc. Am. J. 75, 26–29. https://doi.org/10.2136/sssaj2010.0050N.

Lu, Y., Lu, S., Horton, R., Ren, T., 2014. An empirical model for estimating soil thermal conductivity from texture, water content, and bulk density. Soil Sci. Soc. Am. J. 78, 1859–1868. https://doi.org/10.2136/sssaj2014.05.0218.

Mendis, S.S., Udawatta, R., Anderson, S.H., Ansari, J., Saleda, M., 2022. Effects of cover crops on soil thermal properties of a corn cropping system. Soil Sci. Soc. Am. J. https://doi.org/10.1002/saj2.20409.

Moradi, A.B., Carminati, A., Vetterlein, D., Vontobel, P., Lehmann, E., Weller, U., Hopmans, J.W., Vogel, H., Oswald, S.E., 2011. Three-dimensional visualization and quantification of water content in the rhizosphere. N. Phytol. 192, 653–663. https://doi.org/10.1111/j.1469-8137.2011.03826.x.

Onwuka, B., Mang, B., 2018. Effects of soil temperature on some soil properties and plant growth. Advances in plants and agriculture. Research 8, 34–37.

Poeplau, C., Don, A., 2015. Carbon sequestration in Agricultural soils via cultivation of cover crops: a meta-analysis. Agric., Ecosyst., Environ. 200, 33–41. https://doi.org/10.1016/j.agee.2014.10.024.

Potter, K.N., Cruse, R.M., Horton, R., 1985. Tillage effects on soil thermal properties. Soil Sci. Soc. Am. J. 49, 968–973.

SAS Institute, 2015. Base SAS 9.4 Procedures Guide. SAS Institute, Carey, NC, USA.

Gee, G.W., Or, D. 2002. Particle size analysis. In: J.H. Dane, & G.C. Topp (Eds). Methods of Soil Analysis. Part 4: Physical Methods. SSSA Book Series 5. Madison, WI. Pp. 255–293.

Grossman, R.B., & Reinsch, T.G. (2002). Bulk density and linear extensibility. In: J.H. Dane, & G.C. Topp (Eds.), Methods of soil analysis. Part 4-physical methods. Book Ser. Vol. 5. SSSA, 201–228.

Haruna, S.I., 2019. Influence of winter wheat on soil thermal properties of a Peleudalf. Int. Agrophysics 33, 389–395. https://doi.org/10.31545/intagr/110850.

Haruna, S.I., Anderson, S.H., 2022. Influence of no-till cover crop on soil thermal properties. Soil Res. 60, 580–589. https://doi.org/10.1071/SR21197.

Haruna, S.I., Anderson, S.H., Nkongolo, N.V., Reinbott, T., Zaibon, S., 2017. Soil thermal properties influenced by perennial biofuel and cover crop management. Soil Sci. Soc. Am. J. 81, 1146–1156. https://doi.org/10.2136/sssaj2016.10.0345.

Haruna, S.I., Anderson, S.H., Nkongolo, N.V., Zaibon, S., 2018. Soil hydraulic properties: influence of tillage and cover crops. Pedosphere 28, 430–442. https://doi.org/10.1016/S1002-0160(17)60387-4.

Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S., Gao, Y., 2020. Improving soil physical properties through the use of cover crops: a review. Agrosystems. Geosci. Environ. 3, e20105 https://doi.org/10.1002/agg2.20105.

Haruna, S.I., Ritchey, E., Mosley, C., Ku, S., 2022. Effects of cover crops on soil hydraulic properties during commodity growing season. Soil Use Manag. https://doi.org/10.1111/sum.12803.

Rabbi, S.M.F., Tighe, M.K., Flavel, R.J., Kaiser, B.N., Guppy, C.N., Zhang, X., Young, I.M., 2018. Plant roots redesign the rhizosphere to alter the three-dimensional physical architecture and water dynamics. N. Phytol. 219, 542–550. https://doi.org/10.1111/nph.15213.

Schulte, E.E., Hopkins, B.G., 1996. Estimation of soil organic matter by weight loss-on ignition. In: Magdoff, F.R., Tabatabai, M.R., Hanlon Jr., E.A. (Eds.), Soil organic matter: Analysis and interpretation. SSSA, pp. 21–32.

Sindelar, M., Blanco-Canqui, H., Jin, V.L., Ferguson, R., 2019. Do cover crops and corn residue removal affect soil thermal properties? Soil Sci. Soc. Am. J. 83, 448–457. https://doi.org/10.2136/sssaj2018.06.0239.

Speight, J.G., 2019. Unconventional gas. In: Speight, J.G. (Ed.), (ED.) Natural Gas: A Basic Handbook, Second ed. Elsevier, The Netherlands, pp. 59–98.

Steinberg, S.L., Klutenberg, G.J., Tanzeema, S., 2006. Roots affect the accuracy of dual-probe heat-pulse method for measuring water content in plant growth media. HortScience 41, 970E–971E. https://doi.org/10.1111/nph.15213.

Van Donk, S.J., Tollner, E.W., 2000. Apparent thermal conductivity of mulch materials exposed to forced convection. Trans. ASAE 43, 1117–11127. https://doi.org/10.13031/2013.3004.

Villamil, M.B., Bollero, G.A., Darmody, R.G., Simmons, F.W., Bullock, D.G., 2006. No-till corn/soybean systems including winter cover crops: effects on soil properties. Soil Sci. Soc. Am. J. 70, 1936–1944. https://doi.org/10.2136/sssaj2005.0350.

Williams, A., de Vries, F.T., 2019. Plant root exudation under drought: implications for ecosystem functioning. N. Phytol. 225, 1899–1905. https://doi.org/10.1111/nph.16223.

Yang, J., 2005. Theory of thermal conductivity. In: Tritt, T.M. (Ed.), Thermal Conductivity: Theory, Properties, and Applications. Springer Science and Business Media, pp. 1–20.

Zhang, W., Gao, W., Whalley, W.R., Ren, T., 2020. Physical properties of a sandy soil as affected by incubation with synthetic root exudate: strength, thermal and hydraulic conductivity, and evaporation. Eur. J. Soil Sci. 72, 782–792. https://doi.org/10.1111/ejss.13007.

Zhou, Z.C., Shangguan, Z.P., 2005. Soil anti-scouribility enhanced by plant roots. J. Integr. Plant Biol. 47, 676–682. https://doi.org/10.1111/j.1744-7909.2005.00067.x.