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SOIL RESEARCH

Influence of no-till cover crop management on soil thermal properties

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ABSTRACT

Context. Soil thermal properties influence soil health parameters and can help determine crop productivity with changing global atmospheric climate. **Aim.** This study investigated the influence of no-till (NT) and cover crop (CC) management on soil thermal properties. **Methods.** The study site was managed with NT. The CCs used included hairy vetch (*Vicia villosa* Roth.), crimson clover (*Trifolium incarnatum* L.), winter wheat (*Triticum aestivum* L.), winter peas (*Lathyrus hirsutus* L.), oats (*Avena sativa*), triticale (*Triticale hexaploide* Lart.), barley (*Hordeum vulgare* L.) and flax (*Linum usitatissimum* L.). Soil samples were collected at 0–10, 10–20, and 20–30 cm depths just prior to CCs being planted and also collected just before CCs were terminated. Treatments included NT CC and NT no cover crop (NC). Soil thermal properties (thermal conductivity [λ], volumetric heat capacity [C_V], and thermal diffusivity [D]) were measured at 0, −33, and −100 kPa soil water pressures. **Key Results.** C_V at saturation was 13% higher under CC management compared with NC management. Averaged over all depths just before CC termination, λ and D at saturation were 21 and 35% higher, respectively, under NC management compared with CC management probably due to closer contact between soil particles. **Conclusions.** Results from this study suggest CCs with NT management may be able to resist extreme soil temperature changes which could improve soil health and crop productivity in these systems. **Implications.** NT and CC could improve crop productivity in the future but more *in situ* studies of soil thermal properties under these systems are needed.

Keywords: bulk density, cover crops, no-till, soil organic carbon, thermal conductivity, thermal diffusivity, volumetric heat capacity, volumetric water content.

Introduction

Soil health and crop productivity are directly related to and influenced by various land management practices such as mechanical soil manipulation and crop rotation, among others. Tillage has been reported to reduce soil bulk density (D_b) at the 0–7.5 and 7.5–15 cm depths by 14 and 12%, respectively, (Singh and Malhi 2006), increase moisture content by 21% (Rashidi and Keshavarzpour 2011), and significantly improve total porosity, field measured saturated hydraulic conductivity and water use efficiency (Iqbal *et al.* 2008), compared with no-till (NT) management. However, these benefits were reported right after tillage. More recently, tillage has been reported to increase D_b, reduce macroporosity, reduce saturated hydraulic conductivity and reduce volumetric water content (θ) over time (Peña-Sancho *et al.* 2016; Blanco-Canqui and Ruis 2018; Haruna *et al.* 2018). This suggests that NT management can improve soil quality parameters and the overall health of soils in the long term (Nunes *et al.* 2018).

Besides tillage practices, crop rotations, especially the inclusion of cover crops (CCs) into crop production cycles, can influence soil quality parameters. For example, while crop residue removal significantly reduced fine particulate organic matter, Wegner *et al.* (2018) reported that CCs restored the fine particulate organic matter to previous levels, while also increasing fungal:bacterial ratios. Similarly, Thapa *et al.* (2021) reported that oat (*Avena sativa* L.), canola (*Brassica napus* L.), forage radish (*Raphanus sativus* L.), and barley (*Hordeum vulgare* L.) CCs increased fungal abundance and soil enzyme activities by 12–14% compared with no cover crop (NC) management. Further, Chalise *et al.* (2019) reported that CCs reduced D_b, increased soil water infiltration, increased soybean (*Glycine max* L.) yield by 14% and improved overall soil quality compared with NC.

Soil thermal properties influence water movement and availability, microbial activity and seed germination (Shukla 2014). They (soil thermal properties) can be analysed by measuring soil thermal conductivity (λ), volumetric heat capacity (C_V) and thermal diffusivity (D). These thermal properties determine the effective transport of heat (and can reduce or increase temperature change over soil depth), and the ability of the soil to resist extreme changes in temperature and are influenced by several land management practices. For example, Abu-Hamdeh (2000) reported that chisel and rotary tillage significantly reduced λ compared with NT management in clay loam and loamy soils. This was attributed to lower D_b under the tillage management. Further, Dorota (2006) reported that conservation tillage significantly increased θ, and therefore also increased λ and C_V compared with conventional (moldboard plough to a depth of 30 cm) tillage. With more variable global climatic conditions, soil thermal properties may play a significant role in crop productivity. As such, an understanding of the effects of CC and NT management practice on soil thermal properties is imperative for improved soil health and quality.

Previous studies have reported on the influence of CCs on soil thermal properties (e.g. Haruna *et al.* 2017; Haruna 2019; Sindelar *et al.* 2019). However, these studies evaluated the influence of CCs on thermal properties just before CCs were terminated. The current study evaluated the influence of CCs on soil thermal properties before CCs were planted and just before they were terminated, thus providing a deeper understanding of the possible temporal influence of CCs on soil thermal properties. It is hypothesised that CCs will improve soil thermal properties right before termination compared with soil thermal properties before planting.

Materials and methods

Site description

The current study was conducted at a rainfed farmer's field located in Murfreesboro, Tennessee, USA (35°8167′N, 86°3737′W; average elevation 190 m above sea level). The soil was classified by the USDA as a Cumberland silt loam (fine, mixed, semiactive, thermic Rhodic Paleudalfs). Particle size distribution analysis is in Table 1. The climate of the study area is Humid Subtropical (Köppen (1936) Climate Classification). The average 30-year precipitation was 1357 mm, with the months of May (139 mm) and October (85 mm) recording the highest and lowest precipitation, respectively. The mean annual temperature over the last three decades was 14.6°C, with the months of January (−3.7°C) and August (32.3°C) being the coldest and warmest, respectively.

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

Depth (cm)	Silt (%)	Sand (%)	Clay (%)
0–10	64.17	23.33	12.50
10–20	62.50	21.67	15.83
20–30	60.83	20.83	18.33

Management description

The experimental design included three replicated plots in a completely randomised design, with two levels of CCs (CCs vs NC). Management for the site was NT. A suite of several CCs was used, including, hairy vetch (*Vicia villosa* Roth.), crimson clover (*Trifolium incarnatum* L.), winter wheat (*Triticum aestivum* L.), winter peas (*Lathyrus hirsutus* L.), oats (*Avena sativa* L.), triticale (*Triticale hexaploide* Lart.), barley (*Hordeum vulgare* L.) and flax (*Linum usitatissimum* L.). The main grain crop (cash crop) grown was corn (*Zea mays* L.), planted in April and harvested in September in each growing season.

Prior to the establishment of this study in 2020, the field was under 5 years of CC management and over 15 years of NT management. After the harvest of the corn in September of 2020, the research plots were delineated. Each plot measured 20.1 m in length and 7.4 m in width. For this study, CCs were first overseeded and then drilled in during October 2020 at the following rates: 5.6 kg ha^{-1} for hairy vetch, 5.9 kg ha^{-1} for crimson clover, 22.4 kg ha^{-1} for winter wheat, 14.6 kg ha^{-1} for winter peas, 29.1 kg ha^{-1} for oats, 22.4 kg ha^{-1} for triticale, 15.3 kg ha^{-1} for barley, and 50.4 kg ha^{-1} for flax. The CCs were allowed to grow during the winter months and terminated during 14 April 2021 using glyphosate [*N*-(phosphonomethyl) glycine]. Two passes of a 9 m roller crimper were used a few hours after spraying the glyphosate to complete the termination of CCs.

Soil sampling analysis

Soil samples were collected using a sampler with a cylindrical core measuring 55 mm inside diameter by 60 mm long from non-trafficked rows before CCs were planted (in October 2020) and just before CCs were terminated (in April 2021) at three depths: 0–10, 10–20 and 20–30 cm. During the April sample collection, soil samples were collected from areas within the soil with active plant roots. Thus, CCs were trimmed to the soil surface using standard hedge shears, the soil cores were then placed directly above the plant roots and soil samples were collected. This was done to understand the effects of belowground biomass on soil physical and thermal properties. During each sampling period, a total of 18 soil samples were collected (two treatments × three depths × three replicates). After the samples were collected, excess soil was removed using a soil test spatula, labelled, secured with plastic caps at both ends and placed in plastic bags. They were stored in a refrigerator at 4°C until analysis.

After removing the soil cores from the refrigerator, they were removed from the plastic bags and the caps were removed. Cheesecloth was gently placed at the bottom of each core and secured by rubber bands. They were placed in a tub and saturated from the bottom up for about 24 h. The electrical conductivity of the water was 0.3 dS m^{-1} at 20°C. After saturation, the samples were weighed, placed on pressure plates, and equilibrated to −33, and −100 kPa pressure (Dane and Hopmans 2002). The soils were weighed after equilibration at each pressure and θ was determined at each of those pressures. Please note that θ at 0, −33 and −100 kPa are represented as θ_0, θ_{-33}, and θ_{-100}, respectively.

Thermal properties were measured using a KD2 (Decagon Devices, Pullman, WA) dual-probe heat-pulse sensor. Several researchers (e.g. Campbell *et al.* 1991; Bristow *et al.* 1993; Kluitenberg *et al.* 1995; Dahiya *et al.* 2007; Zaibon *et al.* 2019) have used a similar probe. Before measurement, the probe was calibrated and its accuracy was verified using performance verification standards. At each pressure (0, −33 and −100 kPa), the probe was vertically inserted into the soil and thermal properties were recorded. While inserting the probe, care was taken to avoid core walls and previous insertion locations.

After the thermal properties and θ_0, θ_{-33} and θ_{-100} were measured, the soil was oven-dried at 105°C and D_b was determined using the core method (Grossman and Reinsch 2002). The soil was then ground and passed through a 2 mm sieve. Twenty grams of the <2 mm particles were used for soil texture determination using the pipette method (Gee and Or 2002, pp. 272–277). Another 10 g of the <2 mm aggregates was used for soil organic carbon (SOC) (including root biomass) determination using the combustion method (Schulte and Hopkins 1996).

Statistical analysis

Test of normally was conducted for D_b, SOC, θ_0, θ_{-33} and θ_{-100}, and thermal properties using the Anderson–Darling test at $P = 0.05$ in SAS ver. 9.4 (SAS Institute, Carey, NC; SAS Institute 2015). Normality tests showed that the data followed a Gaussian distribution. ANOVA was conducted using the general linear procedure. ANOVA was also conducted to determine the treatment × depth interaction on soil physical and thermal properties measured. Additionally, ANOVA was conducted on CC samples alone collected during October and April to determine the effects of CCs on soil properties. Statistical differences were declared at $P \leq 0.05$.

Results

Soil physical properties

Table 2 shows the SOC, D_b, θ_0, θ_{-33} and θ_{-100} means (with s.e.) averaged over the sampled depths and the ANOVA between treatments before CCs were planted (October), terminated (April), and for CCs alone between October and April. Please note that due to the method of soil sampling, the SOC contained a lot of root biomass. There was no significant difference in SOC, D_b, θ_0, θ_{-33} and θ_{-100} values between treatments during October. As expected, SOC values were significantly higher at the 0–10 cm depth and decreased with an increase in soil depth. Conversely, D_b values were significantly lower at the 0–10 cm depth and increased with an increase in soil depth. Consequently, θ_0, θ_{-33} and θ_{-100} values were highest at the 0–10 cm depth and reduced with an increase in soil depth.

Just before CCs were terminated in April, SOC was about 14% higher under CC management compared with NC management, averaged over all depths. Soil D_b was 18% higher under NC management compared with CC management. Averaged over all depths, soil θ was 35, 52 and 50% higher under CC management compared with NC management at 0, −33 and −100 kPa pressures, respectively. Soil organic carbon, D_b, θ_0, θ_{-33} and θ_{-100} followed a similar trend with depth as they did before CCs were planted (Table 2).

In order to fully understand the influence of CCs on soil physical properties, comparison was made between soil physical properties under CC management alone during October and April. Soil organic carbon, D_b, θ_0, θ_{-33}, θ_{-100} and θ_{-1500} was significantly different under CC management alone between October and April. For example, SOC (including plant root biomass) was 8% higher during April compared with October. Soil D_b was 11% higher during October compared with April. Accordingly, θ_0, θ_{-33} and θ_{-100}, were 35, 37 and 38% higher, respectively, during October compared with April. Soil physical properties followed a similar trend with soil depth as they did during April (Table 2).

Soil thermal properties

Table 3 shows the means (with s.e.) averaged over the sampled depths and the ANOVA for soil thermal properties at different soil water pressures between treatments during October and April and for CCs alone during October and April. During October, there were no significant differences in soil thermal properties between CC and NC management at all measured soil water pressures. At saturation, λ values increased with an increase in soil depth. Although not

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

Treatment	SOC (g kg^{-1})	D_b (g cm^{-3})	Volumetric water content (cm^3 cm^{-3})		
			0 kPa	−33 kPa	−100 kPa
October 2020					
CC	14.78 ± 0.66[A]	1.27 ± 0.03	0.40 ± 0.04	0.30 ± 0.04	0.26 ± 0.04
NC	14.67 ± 0.59	1.27 ± 0.04	0.37 ± 0.04	0.28 ± 0.04	0.24 ± 0.08
Depth (cm)					
5	16.17 ± 0.37a	1.16 ± 0.03b	0.50 ± 0.04a	0.41 ± 0.04a	0.37 ± 0.04a
15	14.83 ± 0.60ab	1.28 ± 0.03a	0.37 ± 0.03b	0.28 ± 0.02b	0.24 ± 0.02b
25	13.17 ± 0.72b	1.36 ± 0.04a	0.29 ± 0.03b	0.18 ± 0.03c	0.14 ± 0.03c
ANOVA $P > F$					
Treatment	0.667	0.965	0.167	0.181	0.265
Depth	0.007	0.011	0.007	0.001	0.002
Treatment × depth	0.871	0.750	0.933	0.882	0.8714
April 2021					
CC	15.89.00 ± 1.30a	1.14 ± 0.04b	0.54 ± 0.05a	0.41 ± 0.04a	0.36 ± 0.04a
NC	14.00 ± 0.50b	1.34 ± 0.03a	0.40 ± 0.02b	0.27 ± 0.04b	0.24 ± 0.06b
Depth (cm)					
5	16.50 ± 5.12a	1.17 ± 0.06b	0.56 ± 0.07a	0.43 ± 0.05a	0.38 ± 0.05a
15	14.83 ± 4.05a	1.25 ± 0.05ab	0.43 ± 0.05b	0.33 ± 0.05ab	0.28 ± 0.05ab
25	13.50 ± 1.88b	1.31 ± 0.04a	0.41 ± 0.03b	0.27 ± 0.05b	0.23 ± 0.04b
ANOVA $P >$ F					
Treatment	0.014	<0.001	0.027	0.017	0.033
Depth	0.003	0.003	0.040	0.029	0.029
Treatment × depth	0.840	0.274	0.475	0.621	0.557
October 2020 and April 2021 means (CC only)					
Depth (cm)					
5	16.83 ± 3.54a	1.11 ± 0.05b	0.58 ± 0.07a	0.44 ± 0.06a	0.40 ± 0.06a
15	15.50 ± 3.44a	1.22 ± 0.03ab	0.45 ± 0.04ab	0.37 ± 0.04ab	0.32 ± 0.04ab
25	13.67 ± 1.73b	1.29 ± 0.04a	0.37 ± 0.04b	0.26 ± 0.04b	0.22 ± 0.04b
ANOVA $P >$ F (October 2020 vs April 2021 for CC only)					
Months	0.009	0.012	0.012	0.035	0.039
Depths	0.007	0.029	0.044	0.016	0.031
Month × depth	0.973	0.925	0.947	0.881	0.877

Means with different letters for a soil property are significantly different at the 0.05 probability level. Please note that SOC values included plant root biomass.

[A] Mean ± s.e.

CC, cover crops; NC, no cover crop.

significant, this trend was noticed at other measured soil water pressures. Between saturation and −100 kPa soil water pressures, C_V was significantly higher at the 0–10 cm depth and decreased with an increase in soil depth. Thermal diffusivity followed a similar trend as λ, being significantly higher at the 20–30 cm depth at all measured soil water matric potentials.

During April, λ values were about 21, 14 and 14% higher under NC compared with CC management at 0, −33 and −100 kPa soil water pressures, respectively (averaged over all sampled depths). During the same sampling regime, C_V values were about 13, 6 and 6% higher under CC compared with NC management at 0, −33, and −100 kPa soil water pressures, respectively. Thermal diffusivity was 35, 22 and 22% higher under NC compared with CC management at 0, −33 and −100 kPa soil water pressures, respectively (Table 3). Further, soil thermal properties followed a similar trend with soil depth during April as they did during October. However, the magnitude of difference was higher at saturation during April compared with October.

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

Treatment	**0 kPa**			**−33 kPa**			**−100 kPa**		
	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})**
October 2020									
CC	1.36 ± 0.03[A]	2.91 ± 0.03	0.47 ± 0.01	1.24 ± 0.02	2.81 ± 0.03	0.44 ± 0.01	1.23 ± 0.02	2.80 ± 0.03	0.44 ± 0.01
NC	1.35 ± 0.05	2.93 ± 0.04	0.46 ± 0.05	1.22 ± 0.01	2.80 ± 0.03	0.44 ± 0.05	1.22 ± 0.01	2.80 ± 0.03	0.44 ± 0.05
Depth (cm)									
5	1.26 ± 0.02b	2.98 ± 0.02a	0.42 ± 0.01b	1.18 ± 0.02	2.86 ± 0.04a	0.41 ± 0.01b	1.18 ± 0.02	2.86 ± 0.04a	0.41 ± 0.01b
15	1.38 ± 0.03a	2.94 ± 0.01a	0.47 ± 0.01a	1.23 ± 0.02	2.82 ± 0.02ab	0.44 ± 0.01ab	1.23 ± 0.02	2.81 ± 0.02ab	0.44 ± 0.01ab
25	1.43 ± 0.03a	2.84 ± 0.03b	0.50 ± 0.01a	1.28 ± 0.03	2.74 ± 0.03b	0.47 ± 0.01a	1.27 ± 0.03	2.73 ± 0.03b	0.47 ± 0.01a
ANOVA $P > F$									
Treatment	0.7029	0.2102	0.3543	0.7243	0.7575	0.7455	0.7279	0.7505	0.7684
Depth	0.0073	0.0074	0.0064	0.1673	0.0485	0.0204	0.1646	0.0480	0.0208
Treatment x depth	0.7486	0.8930	0.9111	0.4606	0.6595	0.6344	0.4475	0.6702	0.6202
April 2021									
CC	1.30 ± 0.01b	3.29 ± 0.03a	0.40 ± 0.01b	1.11 ± 0.01b	3.02 ± 0.01a	0.37 ± 0.01b	1.09 ± 0.01b	3.01 ± 0.01a	0.36 ± 0.01b
NC	1.57 ± 0.02a	2.90 ± 0.03b	0.54 ± 0.04a	1.26 ± 0.02a	2.84 ± 0.05b	0.45 ± 0.05a	1.24 ± 0.01a	2.83 ± 0.04b	0.44 ± 0.015a
Depth (cm)									
5	1.42 ± 0.06b	3.15 ± 0.09	0.46 ± 0.03	1.15 ± 0.04b	2.95 ± 0.06	0.39 ± 0.02	1.14 ± 0.03c	2.93 ± 0.06	0.39 ± 0.02
15	1.44 ± 0.06a	3.11 ± 0.08	0.47 ± 0.03	1.19 ± 0.03a	2.93 ± 0.06	0.41 ± 0.02	1.18 ± 0.03b	2.93 ± 0.06	0.40 ± 0.02
25	1.44 ± 0.06a	3.02 ± 0.09	0.48 ± 0.03	1.21 ± 0.03a	2.91 ± 0.05	0.42 ± 0.02	1.19 ± 0.03a	2.91 ± 0.06	0.41 ± 0.02
ANOVA $P > F$									
Treatment	<0.0001	0.0043	0.0001	0.0027	0.0067	0.0026	0.0021	0.0018	0.0007
Depth	0.0217	0.2006	0.1529	0.0005	0.7143	0.0514	<0.0001	0.8338	0.0926
Treatment × depth	0.7800	0.8111	0.9732	0.3802	0.8918	0.7249	0.1234	0.9663	0.9179
October 2020 and April 2021 means (CC only)									
Depth (cm)									
5	1.29 ± 0.02b	3.18 ± 0.08a	0.41 ± 0.01b	1.13 ± 0.03	2.96 ± 0.04a	0.38 ± 0.01b	1.12 ± 0.03	2.94 ± 0.04a	0.38 ± 0.01b
15	1.33 ± 0.02ab	3.11 ± 0.08ab	0.43 ± 0.02ab	1.19 ± 0.03	2.93 ± 0.04a	0.41 ± 0.02a	1.18 ± 0.03	2.93 ± 0.04a	0.41 ± 0.02a
25	1.37 ± 0.03a	5.02 ± 0.08b	0.46 ± 0.02a	1.20 ± 0.04	2.85 ± 0.06b	0.42 ± 0.02a	1.18 ± 0.04	2.85 ± 0.06b	0.42 ± 0.02a
ANOVA $P > F$ (October 2020 vs April 2021 for CC only)									
Months	0.0364	0.0006	0.0396	0.0074	0.0171	0.0041	0.0030	0.0277	0.0071
Depths	0.0477	0.0121	0.0187	0.0957	0.0150	0.0016	0.0946	0.0487	0.0037
Month × depth	0.1195	0.9412	0.2875	0.8167	0.3780	0.6215	0.9029	0.2897	0.4217

Means with different letters for a soil property are significantly different at the 0.05 probability level.

[A] Mean ± s.e.

CC, cover crops; NC, no cover crop.

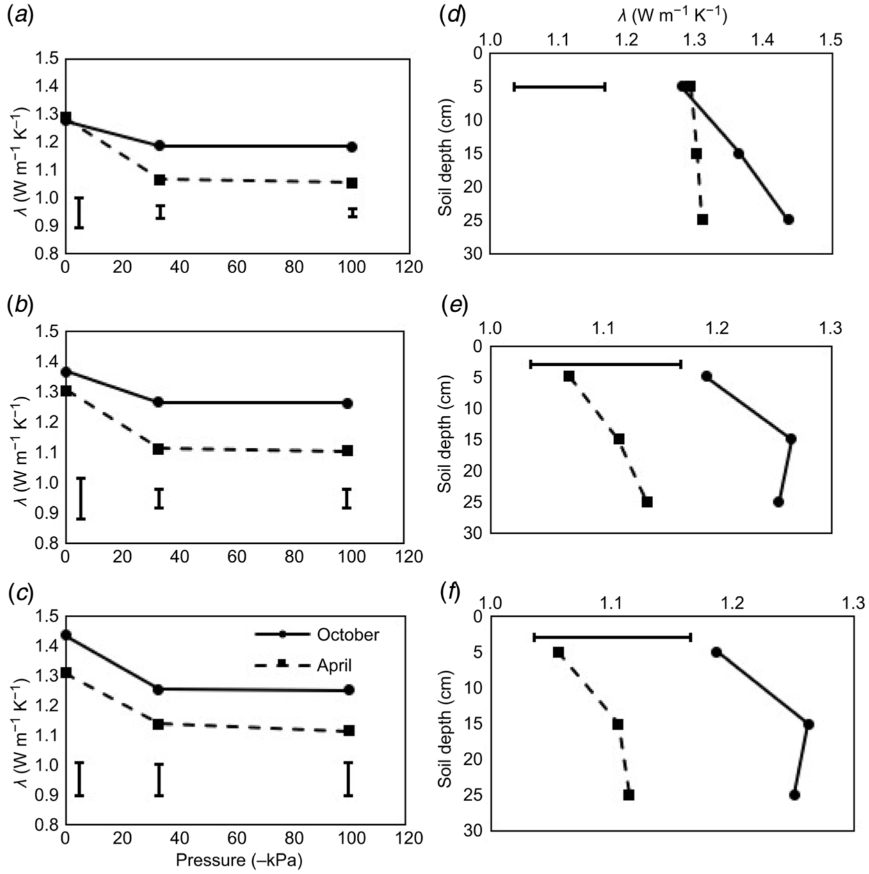

Fig. 1. Thermal conductivity (λ) for cover crops during October and April at (*a*) 0–10 cm, (*b*) 10–20 cm and (*c*) 20–30 cm depths and at three soil water matric potentials (*d*) 0, (*e*) −33 and (*f*) −100 kPa. Bar indicates the least squares difference (l.s.d.) at $P < 0.05$ for λ among the months.

Results showed that laboratory measured soil thermal properties were significantly influenced by CCs. For example, averaged over all sampled depths, λ values were 5, 12 and 13% higher in October compared with April at 0, −33 and −100 kPa soil water pressures, respectively (Fig. 1). Additionally, averaged over all depths, C_V values were 13, 7 and 8% higher in April compared with October at 0, −33 and −100 kPa soil water pressures, respectively (Fig. 2). Averaged over all depths, *D* values were 18, 19 and 22% higher in October compared with April at 0, −33 and −100 kPa soil water pressures, respectively (Fig. 3). Soil thermal properties followed a similar trend with soil depth as they did during April.

Discussion

Soil physical properties

As expected, soil physical properties measured were not significantly different before CCs were planted probably because this was the end of the regular growing season and the beginning of the treatments. Due to higher above and belowground biomass from the cash crops, SOC was higher and D_b was lower at the 0–10 cm depth. Since higher SOC and lower D_b results in higher porosity (Evrendilek *et al.* 2004; Haruna and Nkongolo, 2015; Cercioglu *et al.* 2018), θ_0, θ_{-33} and θ_{-100} were also highest at the 0–10 cm depth.

One of the important ecosystems and soil health benefits of CCs is their ability to increase SOC (Haruna *et al.* 2020). This increase in SOC chiefly results from belowground biomass (Mishra *et al.* 2003). As such, Kuo *et al.* (1997), Villamil *et al.* (2006), Olsen *et al.* (2014), and Haruna (2019) reported 7, 9, 30 and 36% higher SOC values under CC compared with NC managements. The higher difference in SOC between CC and NC management in the current study, just before CC termination, compared to previous studies is probably due to the biomass included during sample collection and the multi-species CCs used in the current study as opposed to two or three different species of CCs. The various CCs increase belowground biomass significantly, which may have led to the higher SOC values. Consequently, the growth and several rhizosphere depositions of the belowground biomass probably significantly reduced D_b. Soil organic carbon decreased with an increase in soil depth probably due to a reduction in belowground biomass with an increase in soil depth. Lower SOC with an increase in soil depth and also the weight of the overburden soil probably led to an increase in D_b as soil depth increased.

Soil organic carbon and living roots have been reported in improve soil structure and porosity (Fuentes *et al.* 2004).

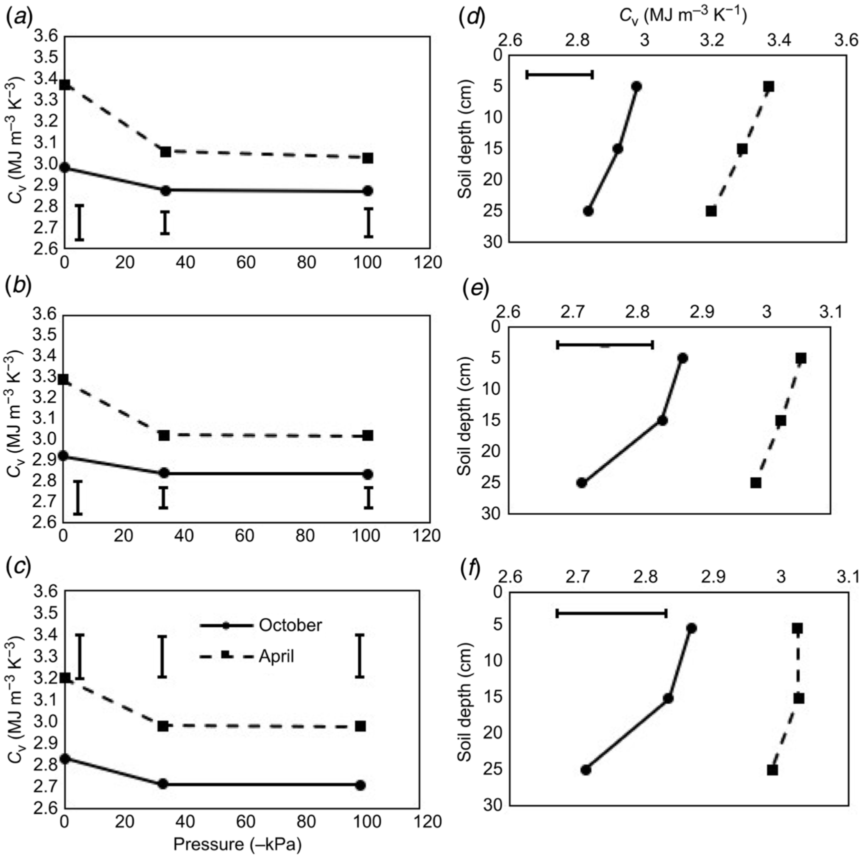

Fig. 2. Volumetric heat capacity (C_V) for cover crops during October and April at (*a*) 0–10 cm, (*b*) 10–20 cm, and (*c*) 20–30 cm depths and at three soil water matric potentials (*d*) 0, (*e*) −33 and (*f*) −100 kPa. Bar indicates the least squares difference (l.s.d.) at $P \leq 0.05$ for C_V among the months.

In fact, Haruna *et al.* (2018) reported that 2 weeks after termination, cereal rye (*Secale cereal* L.) CC increased macropores by 30% compared with NC at the 0–20 cm depth. Further, Villamil *et al.* (2006) reported that CCs can significantly improve the volume of interconnected pores compared with NC. SOC-induced improvements in soil structure, porosity and pore connectivity may have resulted in the higher water drainage under CC management compared with NC management between 0 and −33 kPa pressure just before CC termination (Table 2). The significantly higher θ_0, θ_{-33} and θ_{-100} under CC management compared with NC management suggests that CCs may lead to more macropores (>1000 μm in diameter) and mesopores (10–1000 μm in diameter), pore sizes that drain at these soil water pressures. The significant reduction in θ_0, θ_{-33} and θ_{-100} with an increase in soil depth was in concert with SOC and D_b results.

By comparing soil properties under CC management during October and April (rather than a comparison between CCs and NC before CC termination alone), the current study provides an important insight into the benefits CCs provide when they are actively growing. Since soil properties were statistically similar between CC and NC management during October, variations in the magnitude of difference in soil properties between CC and NC management during April and in CCs alone during October and April can be attributed to actively growing CCs. For example, SOC was 14% higher under CC management compared with NC management during April; however, the difference in SOC, under CC management alone, between October and April was 8%. Since most of this significant difference in SOC resulted from the inclusion of root biomass in the samples, it suggests that the growth of CC roots can improve soil health parameters over time. Soil D_b results agreed with SOC results, demonstrating that CC roots can alleviate soil compaction.

Soil thermal properties

Thermal conductivity is dependent on the proportions of different soil fractions, the contact between solids, as well as between solids and liquids, and the size and arrangement of soil solids. The increase in λ values with an increase in soil depth at saturation during October can be attributed to the distance between individual soil particles and water content. As the distance between soil particles decrease with an increase in soil depth, heat is transferred more rapidly across a temperature gradient. Conversely, C_V is influenced by θ and SOC. Noting the C_V values of water (4.18 MJ m^{-3} K^{-1}) and SOC (2.50 MJ m^{-3} K^{-1}) are both significantly higher than that of clay minerals (1.20 MJ m^{-3} K^{-1}) (Bristow 2002), higher θ and SOC usually leads to higher soil C_V. The higher SOC and θ_0, θ_{-33}

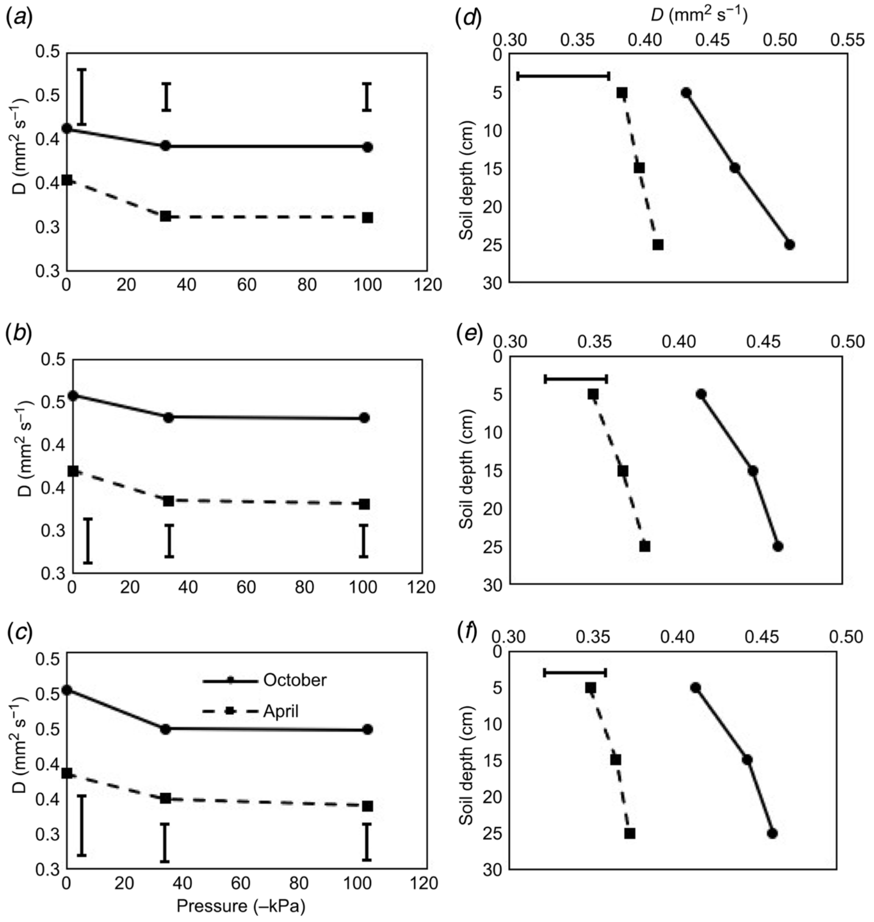

Fig. 3. Thermal diffusivity (D) for cover crops during October and April at (a) 0–10 cm, (b) 10–20 cm, and (c) 20–30 cm depths and at three soil water matric potentials (d) 0, (e) −33 and (f) −100 kPa. Bar indicates the least squares difference (l.s.d.) at $P \leq 0.05$ for D among the months.

θ_{-100} at the 0–10 cm depth was presumably responsible for the higher C_V between saturation and –100 kPa pressure at this depth. Since D is a ratio of λ to C_V, factors that increase λ and reduce C_V generally tend to increase D. Therefore, D was significantly higher at the 20–30 cm depths during October.

It has been reported that the λ of water (0.57 W m^{-1} K^{-1}) is much greater than that of air (0.025 W m^{-1} K^{-1}) (Bristow 2002). Further, results from the current study show greater water drainage at different soil water pressures under CC management compared with NC management during April (Table 3). As water drains out of the soil with decreasing soil water matric potentials, those pore spaces are immediately filled with air. Therefore, λ was significantly higher at all water pressures measured under NC management compared with CC management during April. Since CC management resulted in higher SOC and θ_0, θ_{-33} θ_{-100} compared with NC management, the higher C_V under CC management compared with NC before CCs during April was attributed to θ and SOC. Additionally, C_V decreased from saturation to –33 kPa soil water pressure, mirroring a similar decrease in θ at these pressures. Due to an increase in λ and a decrease in C_V under NC compared with CC management at 0, –33 and −100 kPa soil water pressures, D was significantly higher under NC management at the soil water pressures.

A comparison of soil thermal properties under CC management during October and April shows that CCs significantly reduced λ, especially at 0 and –33 kPa soil water pressures (Fig. 1). CCs also improved C_V (Fig. 2). These results suggest that, under laboratory conditions, CCs can buffer against extreme heat change within the soil. As such, CCs can help maintain soil temperature for a longer time by increasing SOC and conserving more water. Generally, as the soil dries out after precipitation or irrigation schedule, the ability of the soil to buffer against extreme heat also reduces, almost proportionally. Additionally, the colloidal surfaces of SOC are able to hold more water in thin films. Therefore, management practices like CCs that improve water conservation (Daigh *et al.* 2014) and SOC may help keep soil temperatures more stable under increasingly less predictable precipitation events and more expensive irrigation systems. This may be more beneficial for root germination and microbial activity, especially in warmer climates where very drastic daily and seasonal soil temperatures have the potential to threaten crop productivity.

Results from the current study show that CCs may help conserve soil moisture and reduce thermal conductance. Living CCs and their biomass can also reduce the amount of solar energy reaching the soil surface, thereby further reducing thermal conductance. A more stable soil temperature favours increased microbial activity and an overall healthy soil ecosystem. Although the current study compared soil thermal properties before CCs were planted and just before they were terminated, there is still a gap in the understanding of the effects of CCs on soil thermal properties during the growing season. As such, future studies should consider evaluating the effects of CCs on laboratory and *in situ* measured soil thermal properties during the cash crop growing season.

Conclusions

The current study investigated the influence of NT cover crops on soil thermal properties of a Paleudalf in Middle Tennessee region, USA. Results showed that, averaged over all depths, CCs increased SOC and θ_0 values by 8 and 35%, respectively, during April compared with October. Further, D_b was 11% higher during October compared with April. Since the C_V of soils are highly dependent on SOC and θ, the C_V values under CC management, averaged over all depths, were 13, 7 and 8% higher in April compared with October at 0, −33 and −100 kPa soil water pressures, respectively. Due to higher D_b values, CCs increased λ and D values by 5 and 18%, respectively, at saturation, in October compared with April.

Cover crops have been reported to improve soil health parameters under NT management by reducing D_b and increasing SOC. Current results show that CCs can improve the ability of the soils under NT management to buffer against extreme heat change. This might be beneficial for several plant processes and microbial activity in a changing global climate.

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Data availability. Due to other ongoing research, the data used in this paper is not currently publicly available. However, the data is available upon request.

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