Canadian Journal of Soil Science

OPEN ACCESS | Research Article

Soil thermal properties: influence of no-till cover crops

Md Ariful Haque[a], **Seockmo Ku**[a], and **Samuel I. Haruna**[b]

[a]Department of Food Science and Technology, College of Agriculture and Life Sciences, Texas A&M University, College Station, TX 77843, USA; [b]School of Agriculture, College of Basic and Applied Sciences, Middle Tennessee State University, Murfreesboro, TN 37132, USA

Corresponding author: **Samuel I. Haruna** (email: Samuel.Haruna@mtsu.edu)

Abstract

Soil thermal properties, which determine heat transport, can influence soil health parameters and crop productivity. The objective of this study was to evaluate the 2-year effects of no-till cover crops (CCs) and no-till no cover crop (NC) on soil thermal properties (thermal conductivity (λ), volumetric heat capacity (C_V), and thermal diffusivity (*D*)). Two levels of CCs were used for this study: CC versus NC. The CCs included crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth.), winter peas (*Lathyrus hirsutus* L.), oats (*Avena sativa*), winter wheat (*Triticum aestivum* L.), triticale (*Triticale hexaploide* Lart.), flax (*Linum usitassimum* L.), and barley (*Hordeum vulgare* L.). Soil samples were collected at 0–10, 10–20, and 20–30 cm depths and their λ, C_V, and *D* were measured in the laboratory. Additionally, soil organic carbon, bulk density (BD), and volumetric water content (Θ) at saturation, −33 kPa, and −100 kPa soil water pressures were measured. Results showed that BD was 18% and 14% higher under CC compared with NC management during 2021 and 2022, respectively. Furthermore, Θ at all measured soil water pressures was slightly higher under CC compared with NC management during both years. As a result, λ and *D* were significantly higher under NC compared with CC management, while C_V was significantly higher under CC compared with NC management, during both years and at all measured soil water pressures. Generally, soil thermal properties were directly proportional to Θ, suggesting that Θ may be the most important factor influencing soil thermal properties.

Key words: cover crops, thermal conductivity, thermal diffusivity, soil organic carbon, volumetric heat capacity

Introduction

Heat transport within the soil plays a major role in the movement of moisture and nutrients, root growth and plant germination, gaseous interchange, prediction of microbial activity, greenhouse gas emissions, and organic matter decomposition (Abu-Hamdeh and Reeder 2000; Kang et al. 2003; Nkongolo et al. 2010; Hu et al. 2016; Ravazzani et al. 2016). In an increasingly more variable global climate, vadose zone heat transport will play an important determinant role in crop yield. Within the soil, heat transport can be estimated by measuring soil thermal conductivity (λ), volumetric heat capacity (C_V), and thermal diffusivity (*D*).

Thermal conductivity defines the relationship between heat flux per unit area and the thermal gradient of a material. It is influenced by the inherent λ of the various constituents of the soil matrix, among other factors. Researchers have reported a linear relationship between λ and soil bulk density (BD) (e.g., Abu-Hamdeh and Reeder 2000; Lu et al. 2014, 2016) and volumetric water content (Θ) (e.g., Adhikari et al. 2014; Haruna et al. 2017; Zaibon et al. 2019).

The C_V on the other hand is the change in heat content per unit bulk volume of soil per unit temperature change (Hilel 2012). In contrast to λ, C_V quantifies the ability of a unit bulk soil to buffer against rapid soil temperature change and is also a function of the proportion of the various soil constituents. Researchers have reported that Θ and soil organic carbon (SOC) are among the most important factors that influence C_V (Haruna 2019; Mitchell-Forsytk et al. 2021; Haruna et al. 2023).

Thermal diffusivity is the ability of a material to conduct heat relative to its heat buffering capacity per unit bulk volume of the material. While this is used as a mathematical convenience, *D* provides an estimate of heat dispersion within the vadose zone. While some researchers have previously reported significant influence of BD, SOC, and Θ on *D* (Haruna 2019; Zaibon et al. 2019; Haruna et al. 2023), Sindelar et al. (2019) reported that these soil properties (SOC, BD, and Θ) had no significant effect on *D*. Therefore, there is still a gap in current understanding of the role of soil properties on *D*.

The role of various management practices and landscape positions on soil thermal properties has been reported by several researchers. For example, Adhikari et al. (2014) reported that corn (*Zea mays*)–soybean (*Glycine max*) rotation significantly increased λ and *D* and lowered C_V as compared with prairies and conservation buffers. Further, Sindelar et al. (2019) reported that corn residue removal from soil surface significantly reduced λ and C_V due to increased soil water evaporation. In a study on the thermal properties of soils along a catena, Mitchell-Forsytk et al. (2021) reported that C_V

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

was 5% higher at the toeslope compared with the summit. This was attributed to the significantly higher Θ and SOC at the toeslope.

The inclusion of cover crops (CCs) in crop rotation cycles is beneficial for improving soil health parameters (Haruna et al. 2020). Besides improving soil health parameters, researchers have sought to understand their influence on soil thermal properties. While Haruna et al. (2017) reported that CCs can significantly improve the C_V, Sindelar et al. (2019) reported that CCs did not significantly influence C_V compared with no cover crop (NC) management. Further, CCs have been reported to significantly influence λ compared with NC management (Haruna et al. 2023). Conversely, Haruna (2019) and Sindelar et al. (2019) both reported no significant difference in λ between CC and NC managements. Therefore, more studies are needed to quantify the effects of CCs on soil thermal properties.

The objectives of this study were to (*i*) evaluate the effects of no-till (NT) CCs alone on soil thermal properties and (*ii*) quantify the interaction effects of CCs, sampling depths, and sampling year on soil thermal properties. It is hypothesized that (*i*) CCs alone will not significantly influence all measured soil thermal properties during 2 years, and (*ii*) treatment × depth interaction will significantly influence soil thermal properties, while treatment × year interaction will not significantly influence soil thermal properties.

Materials and methods

Site description

This study was conducted on a farmer's field in Murfreesboro, TN, USA (35.8176N, −86.3737W). The average elevation of the study site was 190 m above sea level, with a <2% slope. The soils at the study site were classified (USDA classification) as a Cumberland silt loam (fine, mixed, semiactive, thermic, and Rhodic Paleudalfs). Table 1 shows the particle size analysis for the study site. The average 30-year temperature data showed that the coldest and warmest months each year were January (−3.7 °C) and August (32.2 °C), respectively. During the same period, the highest and lowest precipitation occurs during May (139 mm) and October (85 mm), respectively. During 2021 and 2022, the mean atmospheric temperature was 15.3 and 15.4 °C, respectively, and the average precipitation during this time was 60 and 75 mm, respectively.

Management description

Prior to the establishment of this study in the Fall of 2020, the study site was under 5 years of CC management and 15 years of NT management. During the Fall of 2020, this study was established in a completely randomized block design (each plot measured 20.1 m × 7.4 m) with three replicates. There were two levels of CCs (CCs vs. NC), and the tillage management was NT. For this study, the CCs of choice included crimson clover (*Trifolium incarnatum* L.), hairy vetch (*Vicia villosa* Roth.), winter peas (*Lathyrus hirsutus* L.), oats (*Avena sativa*), winter wheat (*Triticum aestivum* L.), triticale (*Triticale hexaploide* Lart.), flax (*Linum usitassimum* L.), and barley (*Hordeum vulgare* L.). These CCs were chosen because of their suitability for the region and to reflect the current trends and practices of producers in this region. The NC fields were left fallow and weeds were managed by periodic (every 2 months) application of glyphosate.

During October of 2021 and 2022, the CCs were first overseeded and later drilled-in at the following rates: 5.9 kg ha^{-1} for crimson clover, 5.6 kg ha^{-1} for hairy vetch, 14.6 kg ha^{-1} for winter peas, 29.1 kg ha^{-1} for oats, 22.4 kg ha^{-1} each for winter wheat and triticale, 50.4 kg ha^{-1} for flax, and 15.3 kg ha^{-1} for barley. The CCs were allowed to grow through the winter months and terminated in April of each year using 4.15 kg ha^{-1} acid equivalent of glyphosate. A few hours after spraying, a 9.1 m roller crimper was used to complete the CC termination. The cash crop (corn) was planted shortly after CC termination using a 51 cm row planter. All plots were rainfed.

Soil sampling and analysis

Soil samples were collected 1–2 days prior to CC termination using a cylindrical core with a total volume of 143 cm^3 from non-trafficked areas in each plot. The samples were trimmed using a soil spatula, covered with plastic lids, placed in pre-labelled plastic bags, and stored in the refrigerator at <4 °C before analysis.

After removing the soils from the refrigerator and plastic storage bags, a cheese cloth was placed at the bottom of each soil sample using rubber bands and placed in a tub. The soils were saturated for at least 24 h by gently raising the level of water in the tub. The electrical conductivity of the water was 0.3 dS m^{-1} at 20 °C. The samples were then weighed and equilibrated to −33 and −100 kPa soil water pressures on ceramic plates using a pressure chamber (Dane and Hopmans 2002). After equilibration, the soil samples were weighed, and BD data were used to determine Θ at each pressure.

A KD2 Pro heat-pulse sensor (Decagon devices, Pullman, WA) was used to determine the λ, C_V, and D at each soil water pressure (0, −33, and −100 kPa). The accuracy of the heat-pulse sensor was determined using performance verification standards prior to measurement. At each soil water pressure, the probe was inserted vertically into the soil core (being careful to avoid prior insertion holes and core walls) and the thermal properties (λ, C_V, and D) were recorded.

After Θ and thermal properties measurement, the soil samples were oven-dried for 24 h. Soil BD was determined using the core method (Grossman and Reinsch 2002). The oven-dried sample was ground and passed through a 2 mm sieve. The pipette method (Gee and Or 2002) was used to determine particle size analysis using 20 g of the <2 mm soil sample. Another 250 mg of the <2 mm particles was used to determine

Table 2. Means (±SE) for soil organic carbon (SOC), bulk density (BD), and volumetric water content at selected soil water pressures.

Treatment	SOC (g kg^{-1})	BD (g cm^{-3})	Volumetric water content (cm^3 cm^{-3}) 0 kPa	−33 kPa	−100 kPa	−1500 kPa
2021						
CC	16.71 ± 0.32	1.19 ± 0.04b	0.492 ± 0.03a	0.084 ± 0.02	0.082 ± 0.02	0.067 ± 0.02
NC	16.27 ± 0.55	1.41 ± 0.02a	0.295 ± 0.01b	0.070 ± 0.01	0.062 ± 0.01	0.049 ± 0.01
Depth (cm)						
0–10	17.03 ± 0.49a	1.21 ± 0.06b	0.457 ± 0.05a	0.100 ± 0.03	0.094 ± 0.02	0.080 ± 0.02
10–20	16.54 ± 0.56ab	1.31 ± 0.05a	0.381 ± 0.04b	0.073 ± 0.02	0.069 ± 0.02	0.054 ± 0.02
20–30	15.89 ± 0.53b	1.37 ± 0.04a	0.344 ± 0.04b	0.059 ± 0.02	0.052 ± 0.02	0.040 ± 0.02
ANOVA $p > F$						
Treatment	0.179	0.010	<0.001	0.184	0.175	0.162
Depth	0.035	0.006	0.014	0.442	0.502	0.497
Tmt × depth	0.933	0.609	0.524	0.922	0.921	0.946
2022						
CC	17.07 ± 0.36	1.24 ± 0.01b	0.477 ± 0.03a	0.094 ± 0.02	0.093 ± 0.02	0.087 ± 0.02
NC	16.27 ± 0.55	1.410.02a	0.288 ± 0.02b	0.061 ± 0.01	0.060 ± 0.01	0.054 ± 0.01
Depth (cm)						
0–10	17.44 ± 0.52a	1.30 ± 0.04	0.460 ± 0.05a	0.139 ± 0.01a	0.138 ± 0.01a	0.131 ± 0.01a
10–20	16.66 ± 0.56ab	1.32 ± 0.04	0.381 ± 0.05ab	0.049 ± 0.02b	0.048 ± 0.02b	0.043 ± 0.02b
20–30	15.91 ± 0.53b	1.35 ± 0.04	0.308 ± 0.05b	0.044 ± 0.01b	0.044 ± 0.01b	0.038 ± 0.01b
ANOVA $p > F$						
Treatment	0.061	0.002	0.007	0.084	0.099	0.084
Depth	0.008	0.151	0.018	0.004	0.004	0.004
Tmt × depth	0.647	0.876	0.827	0.763	0.736	0.753
2021 versus 2022						
Depth (cm)						
0–10	17.61 ± 0.34a	1.12 ± 0.05b	0.617 ± 0.06a	0.322 ± 0.08a	0.316 ± 0.07a	0.2740.05a
10–20	16.96 ± 0.31ab	1.20 ± 0.02ab	0.493 ± 0.04ab	0.249 ± 0.08ab	0.247 ± 0.08ab	0.201 ± 0.06b
20–30	16.11 ± 0.38b	1.25 ± 0.02b	0.410 ± 0.03b	0.189 ± 0.06b	0.186 ± 0.06b	0.156 ± 0.05b
ANOVA $p > F$						
Year	0.250	0.012	0.131	0.009	0.010	0.009
Depths	0.044	0.021	0.046	0.128	0.101	0.007
Year × depth	0.789	0.258	0.860	0.677	0.620	0.425

Note: Means followed by different letters for a soil property are significantly different at the 0.05 probability level. Tmt, treatment; CC, cover crops; NC, no cover crop; ANOVA, Analysis of variance.

SOC by the combustion method (loss-on-ignition at 1200 °C) in a Skalar SNC analyzer (Skalar Analytical B.V., the Netherlands).

Statistical analysis

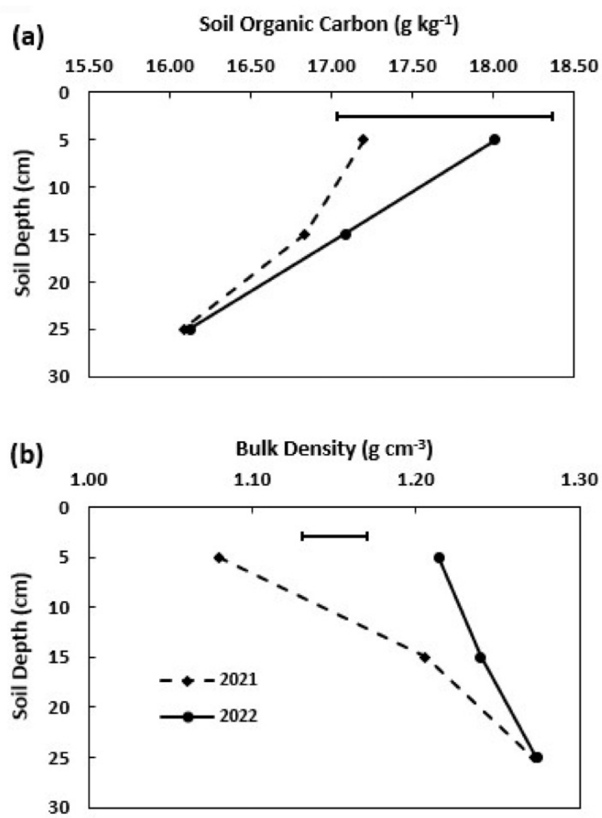
The vegetative management (CCs vs. NC) was the whole plot factor in the split–split plot experimental design, 2 years (2021 and 2022) was the split-plot factor, and the soil depth (0–10, 10–20, and 20–30 cm) was the split–split-plot factor. A normality test (Anderson–Darling) showed that the data (BD, SOC, Θ at 0, −33, and −100 kPa, λ, C_V, and D) followed a Gaussian distribution at $p = 0.05$. The main and interaction effects of CCs and soil depth on soil physical and thermal properties during 2021 and 2022 were analyzed through Analysis of variance (ANOVA) using the PROC GLM procedure in SAS ver. 9.4 (SAS Institute 2015) statistical package during each year. Additionally, to determine the CC and year × depth interaction effects on soil physical and thermal properties, an ANOVA was conducted on individual CC samples collected during 2021 and 2022. Statistical differences were evaluated at an alpha level of 0.05.

Results

Soil organic carbon and physical properties

Table 2 shows the treatment and depth means (±SE) and ANOVA of SOC, BD, and Θ at saturation, −33 kPa, −100 kPa, and −1500 kPa soil water pressures during 2021 and 2022. Further, the ANOVA for these properties under CC management alone for both years is also presented. Results showed that the depth-averaged SOC was slightly higher under CC compared with NC management during both years. Results also showed that during 2021, the depth-averaged BD

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



was 18% higher under NC compared with CC management, while the depth-averaged Θ at saturation was 67% higher under CC compared with NC management. During 2022, the depth-averaged BD was 14% higher under NC compared with CC management, while the depth-averaged Θ at saturation was 66% higher under CC compared with NC management. Although not significant, the depth-averaged Θ at −33 and −100 kPa soil water pressures were numerically higher under CC compared with NC management during both years.

During both years of this study, the treatment-averaged BD significantly increased with increasing soil depth. Conversely, the treatment-averaged SOC and other soil physical properties reduced with increasing soil depth during both years. A comparison of CC plots alone showed that SOC was numerically higher in 2022 compared with 2021 (Fig. 1*a*). During this same period and management, BD was significantly higher during 2022 compared with 2021 (Fig. 1*b*), while Θ at −33, −100, and −1500 kPa soil water pressures were significantly higher in 2021 compared with 2022 (Table 2).

Soil thermal properties

The treatment and depth means (±SE) and ANOVA of λ, C_V, and *D* at saturation, −33 kPa, and −100 kPa soil water pressures during 2021 and 2022 are shown in Table 3. Additionally, Table 3 also shows the ANOVA for these properties under CC management alone during both years. Also, Figs. 2–4 show the effects of sampling year (under CC management alone) at different depths (*a*–*c*) and different soil matric potentials (*d*–*f*) for λ, C_V, and *D*. Results showed that during 2021, the depth-averaged λ was 21% (at saturation), 14% (at −33 kPa soil water pressures), and 14% (at −100 kPa soil water pressures) higher under NC compared with CC management. During 2022, the depth-averaged λ at saturation, −33 kPa, and −100 kPa soil water pressures was 20%, 11%, and 10% higher, respectively, under NC compared with CC management. During both years, the treatment-averaged λ increased with increasing soil depth. A comparison of CC plots alone showed that the depth-averaged λ was 5% and 3% higher at −33 and −100 kPa soil water pressures, respectively, in 2022 compared with 2021 (Table 3) (Fig. 2).

Averaged over all depths in 2021, C_V was 13% (at saturation), 6% (at −33 kPa soil water pressures), and 6% (at −100 kPa soil water pressures) higher under CC compared with NC management. During 2022, the depth-averaged C_V was 12%, 10%, and 10% higher at 0, −33, and −100 kPa soil water pressures, respectively, under CC compared with NC management. Averaged over all treatments in 2021, C_V numerically reduced with increasing soil depths at all matric potentials measured. This trend was similar but significant during 2022. When CC plots alone were compared between both years, the depth-averaged C_V was 3% higher in 2021 compared with 2022 at saturation. Conversely, the depth-averaged C_V was 2% and 2% higher at −33 and −100 kPa soil water pressures, respectively, in 2022 compared with 2021 (Table 3; Fig. 3).

During 2021, the depth-averaged *D* was 35% (at saturation), 22% (at −33 kPa soil water pressures), and 22% (at −100 kPa soil water pressures) higher under NC compared with CC management. Averaged over all soil depths in 2022, *D* was 34%, 26%, and 26% higher at 0, −33, and −100 kPa soil water pressures, respectively. Further, the treatment-averaged *D* increased numerically (in 2021) and significantly (in 2022) with increasing soil depths at all soil water pressures measured. A comparison of CC plots alone showed that the depth-averaged *D* was significantly higher in 2021 compared with 2022 at −33 and −100 kPa soil water pressures (Table 3; Fig. 4).

Discussions

Soil organic carbon and physical properties

As an important soil health parameter, SOC provides several benefits within the ecosystem, including C sequestration (Guoju et al. 2020), serving as a source of energy for soil organisms (Wolters 2000), and providing a large surface area for nutrient retention and improved crop productivity (Kochiieru et al. 2022), among others. The slightly higher SOC under CC compared with NC during both years can be attributed to (*i*) the breakdown of aboveground CC biomass by microorganisms (Hamonts et al. 2017), (*ii*) breakdown and addition of belowground CC biomass (Gougoulias et al. 2014), and (*iii*) deposition of the remains of the soil organisms involved in the breakdown of CC residues (Nair and Ngouajio 2012). There-

Canadian Science Publishing

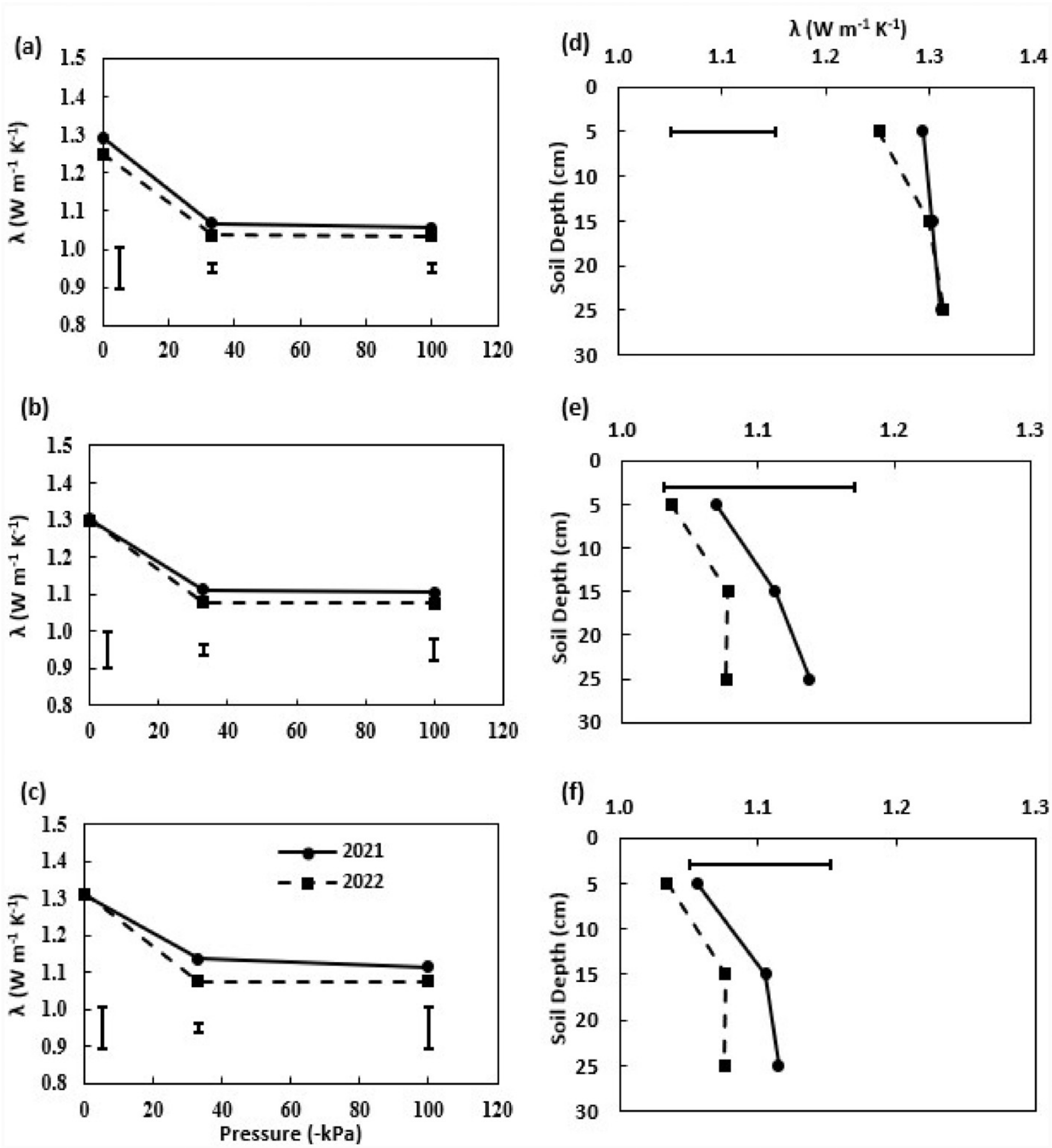
Table 3. Means (±SE) of thermal conductivity (λ), volumetric heat capacity (C_V), and thermal diffusivity (D) at selected soil water pressures during 2021 and 2022.

	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 ± 0.01b	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 ± 0.02a
Depth (cm)									
0–10	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 ± 0.06
10–20	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 ± 0.06
20–30	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 ± 0.06
ANOVA $p > F$									
Treatment	<0.001	0.004	0.001	0.003	0.007	0.003	0.002	0.002	<0.001
Depth	0.022	0.201	0.153	0.001	0.714	0.051	<0.001	0.834	0.059
Tmt × depth	0.780	0.811	0.973	0.380	0.892	0.725	0.123	0.966	0.780
2022									
CC	1.29 ± 0.02b	3.18 ± 0.02a	0.41 ± 0.01b	1.06 ± 0.02b	3.08 ± 0.03a	0.35 ± 0.01a	1.06 ± 0.02b	3.07 ± 0.03a	0.35 ± 0.01b
NC	1.55 ± 0.03a	2.84 ± 0.05b	0.55 ± 0.02a	1.18 ± 0.03a	2.80 ± 0.03b	0.44 ± 0.01b	1.17 ± 0.03a	2.79 ± 0.03b	0.44 ± 0.05a
Depth (cm)									
0–10	1.36 ± 0.05b	3.09 ± 0.07a	0.44 ± 0.03b	1.08 ± 0.03b	3.05 ± 0.03a	0.36 ± 0.01b	1.08 ± 0.03b	3.05 ± 0.05a	0.36 ± 0.01b
10–20	1.43 ± 0.07a	3.01 ± 0.06ab	0.48 ± 0.03ab	1.12 ± 0.02ab	2.89 ± 0.06b	0.39 ± 0.02ab	1.12 ± 0.02b	2.89 ± 0.07b	0.39 ± 0.02ab
20–30	1.47 ± 0.08a	2.93 ± 0.08b	0.51 ± 0.04a	1.16 ± 0.05b	2.87 ± 0.05b	0.43 ± 0.06a	1.15 ± 0.04b	2.87 ± 0.08b	0.43 ± 0.06a
ANOVA $p > F$									
Treatment	0.011	0.006	0.013	0.043	0.006	0.054	0.033	0.007	0.046
Depth	0.349	0.011	0.047	0.048	0.044	0.047	0.037	0.037	0.045
Tmt × depth	0.809	0.593	0.613	0.582	0.988	0.788	0.983	0.986	0.810
2021 versus 2022									
Depth (cm)									
0–10	1.27 ± 0.02	3.32 ± 0.03a	0.38 ± 0.01b	1.05 ± 0.02b	3.12 ± 0.03a	0.34 ± 0.01b	1.05 ± 0.01	3.10 ± 0.04a	0.34 ± 0.01b
10–20	1.30 ± 0.02	3.23 ± 0.03b	0.40 ± 0.01ab	1.10 ± 0.02ab	3.04 ± 0.02b	0.36 ± 0.01a	1.09 ± 0.02	3.03 ± 0.02ab	0.36 ± 0.01a
20–30	1.31 ± 0.02	3.16 ± 0.03b	0.42 ± 0.01a	1.11 ± 0.02b	2.99 ± 0.02b	0.37 ± 0.01a	1.10 ± 0.02	2.99 ± 0.02b	0.37 ± 0.01a
ANOVA $p > F$									
Year	0.417	0.019	0.181	0.043	0.049	0.023	0.029	0.038	0.032
Depths	0.499	0.007	0.046	0.048	0.002	0.005	0.112	0.010	0.008
Year × depth	0.773	0.805	0.842	0.817	0.117	0.802	0.933	0.053	0.690

Note: Means followed by different letters for a soil property are significantly different at the 0.05 probability level. Tmt, treatment; CC, cover crops; NC, no cover crop; ANOVA, Analysis of variance.

Can. J. Soil Sci. **104**: 246–256 (2024) | dx.doi.org/10.1139/CJSS-2023-0095

Fig. 2. Soil thermal conductivity (λ) for cover crops during 2021 and 2022 at (*a*) 0–10 cm, (*b*) 10–20 cm, and (*c*) 20–30 cm depths and at (*d*) 0 kPa, (*e*) −33 kPa, and (*f*) −100 kPa soil water pressures. Least square difference (at $p < 0.05$) among the study years is indicated by bars.

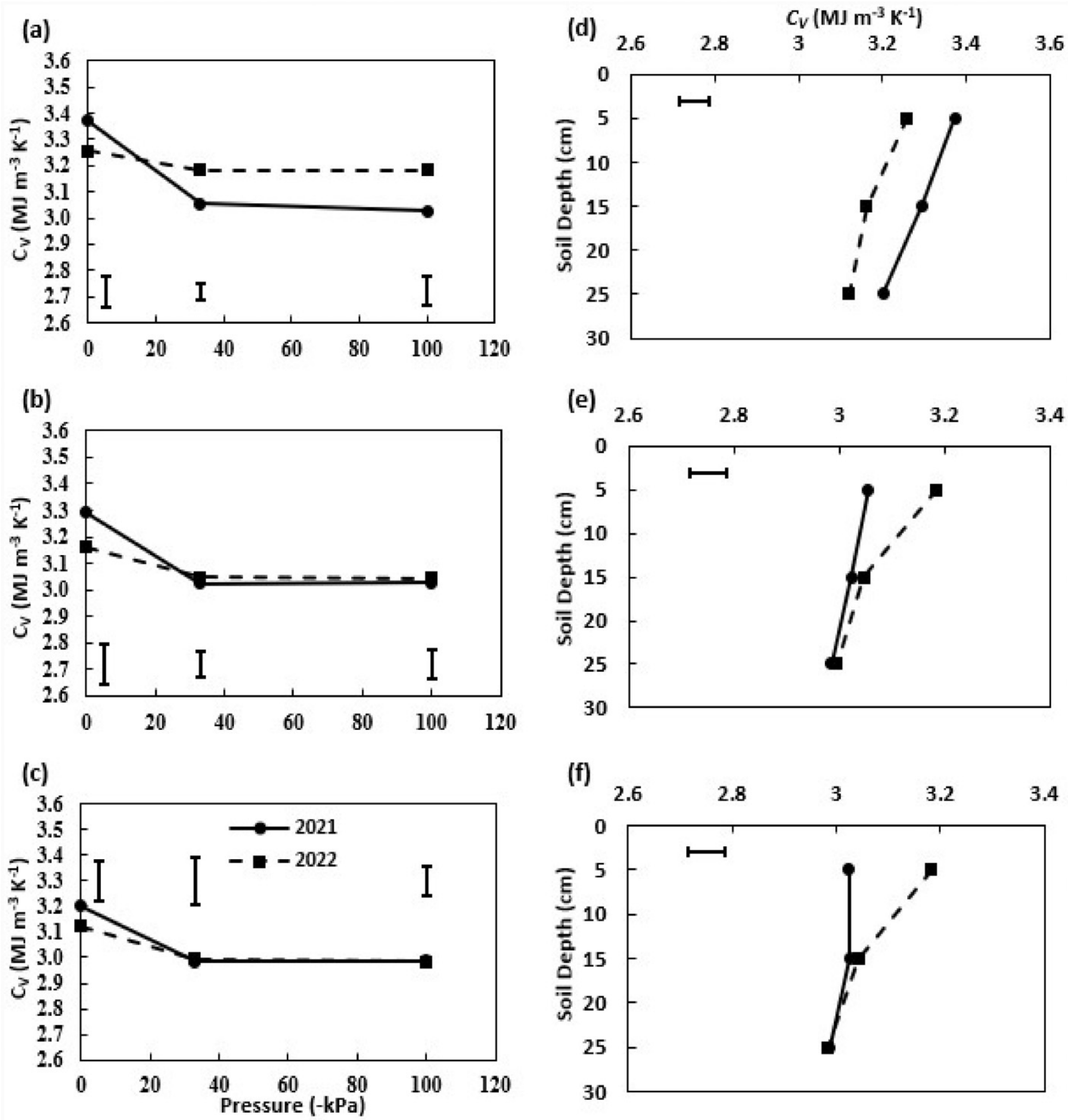


fore, results of the current study showed that CC management can improve SOC, and this has the potential to improve soil health compared with NC management.

While other researchers have reported significant differences in SOC content between CC and NC management (Mazzoncini et al. 2011; Olsen et al. 2014; Haruna et al. 2017), the differences in the current study were only numerical. This could be due to the timing of the studies (previous studies were longer than 2 years). Therefore, it can be concluded that it takes more than 2 years after establishment for CC management to significantly increase SOC stocks.

The slight increase in SOC under CC management alone during 2022 compared with 2021 was probably due to the addition of the second year CC biomass to the remainder of the first year CC biomass (since it takes more than 1 year for the complete breakdown and decomposition of CC residues). The general decrease in SOC with increasing soil depth during this study can be attributed to a decrease in

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

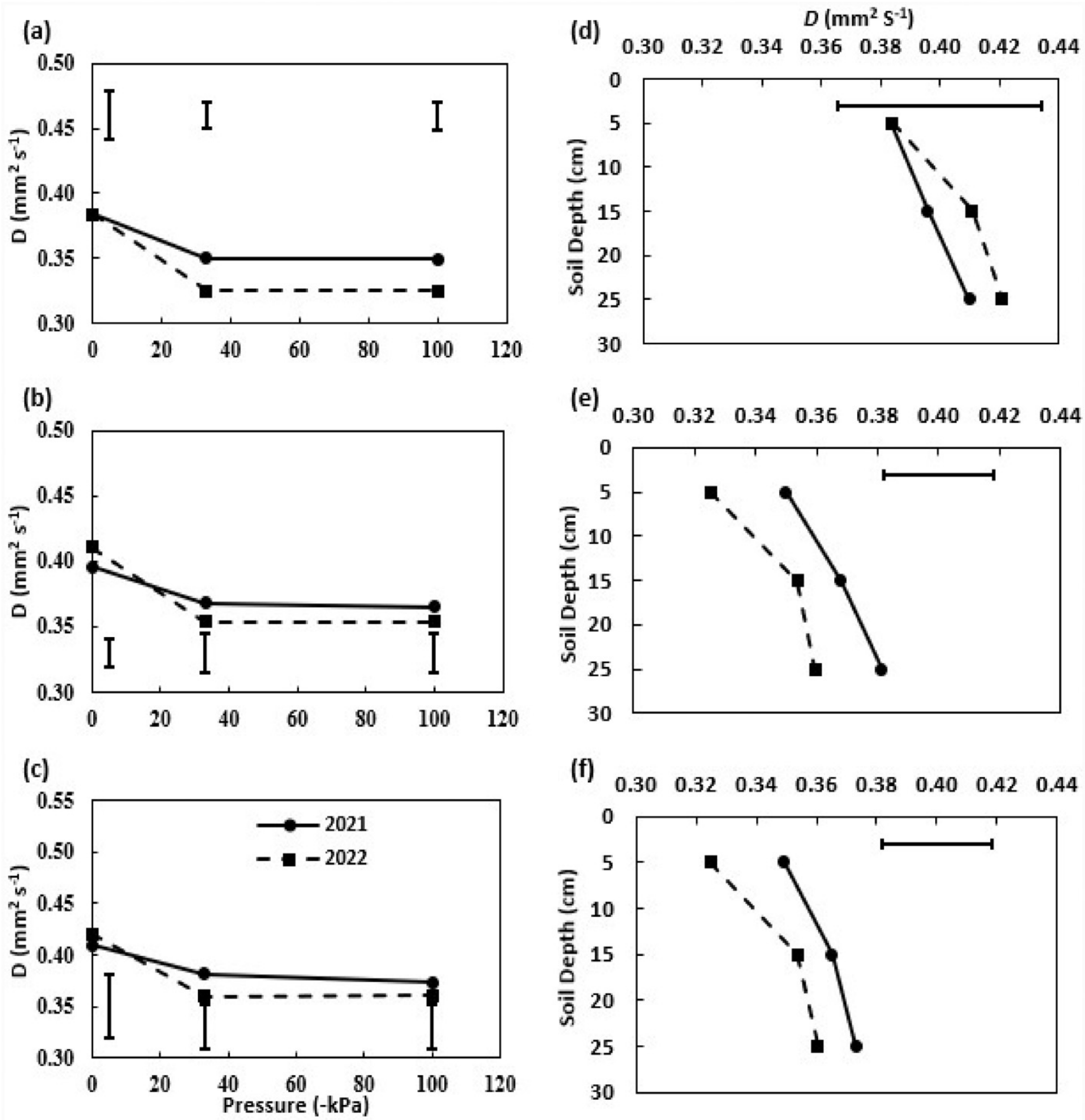


the amount of belowground CC biomass with increasing soil depth.

Another soil health parameter is BD, and it is an indicator of soil compaction (Haruna et al. 2020). The significantly lower BD values under CC compared with NC management was probably due to (*i*) the slightly higher SOC under CC management, (*ii*) the belowground biomass of CCs, and (*iii*) the aboveground biomass of CCs. The first mechanism is supported by the fact that SOC is less dense (per volume) than soil minerals (Brady et al. 2008); therefore, higher SOC will reduce the overall ratio of dry soil mass-to-volume. The second mechanism is supported by studies that have demonstrated that CC plant roots can alleviate soil compaction by lowering soil BD (Chen and Weil 2010; Çerçioğlu et al. 2018; Ogilvie et al. 2021). The aboveground biomass of CCs can lower the kinetic energy of raindrops, and this can reduce natural soil consolidation, further leading to lower BD under CC management.

Interestingly, BD values were significantly higher in 2022 compared with 2021. This was attributed to the mechanical traffic of the CC planting equipment. Compared with 2021, the CC plots in 2022 had one more passage of the planting

Fig. 4. Soil thermal diffusivity (*D*) for cover crops during 2021 and 2022 at (*a*) 0–10 cm, (*b*) 10–20 cm, and (*c*) 20–30 cm depths and at (*d*) 0 kPa, (*e*) −33 kPa, and (*f*)−100 kPa soil water pressures. Least square difference (at $p < 0.05$) among the study years is indicated by bars.



equipment. While the roots of CCs can alleviate some of this compaction compared with NC, when compared with CCs from the previous year, this compaction can be obvious as reported in this study. The increase in BD with increasing soil depth can be attributed to the weight of the overburden soil, a reduction in the amount and density of plant roots, and the less SOC with increasing soil depth.

The significantly higher Θ at saturation and the numerically higher Θ at −33 and −100 kPa under CC management compared with NC management during both years were attributed to several reasons. First, the biopores generated (by decaying CC roots and soil organisms) under CC systems can increase the proportion of macro- and mesopores that drain at these pressures (Abdollahi et al. 2014). This therefore suggests that NT with CC systems can increase the proportion of non-capillary pores within the soil. Second, higher SOC under CC management can improve the stability of these biopores (Du et al. 2017), and this can result in higher water drainage at higher pressures. Finally, aboveground biomass of CCs can reduce splash detachment, and this can further preserve the integrity of these pores, leading to higher water drainage under this management system. The decrease in Θ with increasing soil depth was attributed to higher BD values with increasing soil depth.

Earlier studies by Villamil et al. (2006), Blanco-Canqui et al. (2011), and Rorick and Kladivko (2017) all reported that

CCs had no significant effect on soil water retention (at these pressures) compared with NC management. Although these studies were conducted on similar soils (silt loams), these studies used a single CC species for their study. Conversely, the current study used a suit of eight different CCs. Therefore, the contrast between the previous studies and the current study could be due to the diversity of the biomass (above- and belowground) of the CCs used in this study.

Soil thermal properties

The transfer of heat over a temperature gradient between adjoining areas determines how well the body transfers heat. Therefore, λ is inversely related to the distance between individual particles within the body/material. The significantly higher λ values under NC management compared with CC management during both years were attributed to the closer proximity between soil particles under NC management. Since the value λ of soil minerals (2.90 W M^{-1} K^{-1}) is greater than those of SOC (0.25 W M^{-1} K^{-1}), water (0.57 W M^{-1} K^{-1}), and air (0.025 W M^{-1} K^{-1}) (Bristow 2002), management practices that increase the proximity and proportion of soil minerals will increase λ. This agreed with BD results. Therefore, as BD increased with increasing soil depth, λ also increased for both management practices (Figs. 2*a*–2*c*).

Results of this study showed that λ was highest at saturation compared with other soil water pressures measured. This was probably due to the higher Θ in the soil at saturation compared with other soil water pressures. This can create a water bridge between individual soil particles, leading to higher λ at saturation. Further, results also showed that, regardless of the management practice, λ decreased with decreasing soil water pressures (Figs. 2*d*–2*f*), with the greatest decrease in λ occurring between saturation and −33 kPa soil water pressure. This was probably due to the increased water drainage between these potentials. As water drains out of the soil, the pores are replaced with air (which has a lower λ value), and this reduces λ within the soil. In a study on a sandy loam soil, Haruna et al. (2023) reported that, while plant root was the most important factor affecting λ at saturation, Θ was the most important factor influencing λ at lower soil water pressures. This further demonstrates a different mechanism by which CCs can influence λ. Under CC management alone, the higher λ during 2022 compared with 2021 was attributed to higher BD during 2022. This disproved the first hypothesis of this study, demonstrating that CCs can have some effects on λ regardless of time after establishment.

By increasing the λ of soils, NC management can be beneficial in very cold climatic conditions and regions as it can potentially lengthen the growing season and increase seed germination. However, while this might be beneficial in the near term for seed germination, it might be detrimental in the long-term for C storage and overall soil health in these soils. This is because, with the high amount of C stored in cold soils globally (1014 ± 185 Pg C; Mishra et al. 2021), higher λ increases the vulnerability of the stored C through mineralization. This can further lead to increased atmospheric C and potentially more variability in global climate (Ping et al. 2015). Further, higher λ and lack of surface residues under NC management can lead to increased water evaporation from the soil during the spring season. This can potentially reduce soil water content and water availability for the subsequent cash crop.

In warm climate conditions, higher λ under NC management can increase soil temperature rapidly, and to deeper depth. This can lead to supra-optimal soil temperature for seed germination (Watt and Bloomberg 2012) and has been reported to reduce the growth and germination of seeds (especially summer annuals) under such conditions (Egly 2017). Further, the higher λ, coupled with less residues, can further increase surface water evaporation and reduce the moisture availability for the cash crop.

The C_V determines the ability of a material to buffer against rapid heat change per unit volume, and is influenced by the composition of the material. Generally, the value C_V of water (4.18 MJ M^{-3} K^{-1}) is significantly higher than that of SOC (2.50 MJ M^{-3} K^{-1}), soil minerals (1.94 MJ M^{-3} K^{-1}), and air (0.0012 MJ M^{-3} K^{-1}) (Bristow 2002). The higher C_V under CC at all measured soil water pressures compared with NC management was attributed to higher Θ and SOC under CC management. This was also in concert with current results that showed that as water is replaced by air at lower soil water pressures, C_V also reduced. Conversely, Mendis et al. (2022) reported that CCs had no significant effect on C_V due to lack of biomass accumulation resulting from low CC establishment. Further, as SOC and Θ decreased with increasing soil depth, C_V also decreased correspondingly.

The role of SOC on C_V is interesting because it can help buffer against quick heat change within the soil. Besides their inherent heat capacity values, SOC can increase water retention due to their colloidal characteristics, and this can further increase the buffering capacity of the soil. Therefore, besides C sequestration, SOC can also act as heat storage within the soil ecosystem.

Results from the current study showed that CCs can improve the ability of the soil to buffer against rapid heat change. In colder climatic regions, higher heat buffering can shorten the growing season by delaying seed germination. This can limit the profitability of crop production systems under these conditions. In warmer climatic regions, the higher C_V and residues under CC management can lengthen the growing season by delaying the onset of increased soil temperatures and this can improve crop productivity. Further, higher heat buffering capacity and surface residues can reduce surface evaporation and increase soil water movement (Çerçioğlu et al. 2019) and storage (Charlise et al. 2019).

Thermal diffusivity compares the ability of the soil to transfer heat by conduction with its ability to buffer against rapid temperature change. Due to the higher BD and λ, NC management had significantly higher *D* at all measured soil water pressures compared with CC management. Results also showed that maximum *D* occurs at 20–30 cm depth (Figs. 4*a*–4*c*), and this was probably due to higher BD values at this depth. This disproved the second hypothesis. This study further showed that, at all soil water pressures measured, CC management buffers more heat than it transfers by conduction compared with NC management. This can be attributed to the higher proportion of Θ and SOC under this management.

Interestingly, while BD plays an important role in soil thermal properties, that role may be limited by water content. As shown in Figs. 2*d*–2*f*, 3*d*–3*f*, and 4*d*–4*f*, the role of BD on soil thermal properties was more evident at saturation, suggesting that Θ is one of the most important soil properties that influences soil thermal properties. Therefore, management practices, like the inclusion of CCs in crop rotation cycles, that improve water retention and storage may be more beneficial for preventing rapid soil temperature change. This may be due to (1) the aboveground biomass of CCs can delay or prevent solar radiation from reaching the soil surface, and (2) by increasing SOC, CCs can also increase heat storage.

Although this study demonstrated that a multi-species CC can improve soil storage, there is still a gap in current understanding if these benefits can also accrue under a single specie CC management. Further studies are needed to evaluate the effects of a single specie versus multi-species CC on soil thermal properties, both in situ and ex situ. This will provide an option in the toolkit of producers in a changing global climate.

Conclusions

The current study evaluated the effects of NT CC management on soil thermal properties during 2 years on a farmers' field in Middle Tennessee, USA. Results showed that CC management significantly lowered BD and slightly increased SOC and Θ (at 0, −33, and −100 kPa soil water pressures) compared with NC management during both years. As a result, λ was significantly higher under NC compared with CC management at 0, −33, and −100 kPa soil water pressures. Further, due to the higher Θ values, C_V was significantly higher under CC compared with NC management, suggesting that CC management can help stabilize soil temperatures. Therefore, since soil temperatures determine seed germination, plant growth, and microbial activity, CCs may have the potential to improve soil health and crop productivity in a changing global climate.

Acknowledgements

The authors are grateful to Mr. Wil Hutchinson and the staff of Hutchinson Farms for permission to conduct this study on their farm.

Article information

History dates

Received: 12 September 2023
Accepted: 5 February 2024
Accepted manuscript online: 5 March 2024
Version of record online: 8 April 2024

Notes

This paper is part of a Collection entitled "Conservation tillage: Effect on soil properties and crop productivity". https://cdnsciencepub.com/topic/cjss-conservationtillage

Copyright

Data availability

Data generated or analyzed during this study are available from the corresponding author upon reasonable request.

Author information

Author ORCIDs

Md Ariful Haque https://orcid.org/0000-0002-7224-4237
Seockmo Ku https://orcid.org/0000-0003-2661-5073
Samuel I. Haruna https://orcid.org/0000-0001-7302-9435

Author contributions

Conceptualization: SIH
Data curation: SIH
Formal analysis: MAH, SK
Funding acquisition: SIH
Investigation: SIH
Methodology: SIH
Project administration: SIH
Writing – original draft: SIH
Writing – review & editing: MAH, SK

Competing interests

The authors declare that they have no conflict of interest.

Funding information

This study was supported by a grant awarded to SIH by the Southern Region Sustainable Agriculture Research and Education (funding number: LS24-391).

References

Abdollahi, L., Munkholm, L.J., and Garbout, A. 2014. Tillage system and cover crop effects on soil quality: II. Pore characteristics. Soil Sci. Soc. Am. J. **78**(1): 271–279. doi:10.2136/sssaj2013.07.0302.

Abu-Hamdeh, N.H., and Reeder, R.C. 2000. Soil thermal conductivity effects of density, moisture, salt concentration, and organic matter. Soil Sci. Soc. Am. J. **64**(4): 1285–1290. doi:10.2136/sssaj2000.6441285x.

Adhikari, P., Udawatta, R.P., and Anderson, S.H. 2014. Soil thermal properties under prairies, conservation buffers, and corn–soybean land use systems. Soil Sci. Soc. Am. J. **78**(6): 1977–1986. doi:10.2136/sssaj2014.02.0074.

Blanco-Canqui, H., Mikha, M.M., Presley, D.R., and Claassen, M.M. 2011. Addition of cover crops enhances no-till potential for improving soil physical properties. Soil Sci. Soc. Am. J. **75**(4): 1471–1482. doi:10.2136/sssaj2010.0430.

Brady, N.C., Weil, R.R., and Weil, R.R. 2008. The nature and properties of soils. Vol. 13. Prentice Hall, Upper Saddle River, NJ.pp. 150–156.

Bristow, K.L. 2002. Thermal conductivity. *In* Methods of soil analysis. Part 4. SSSA Book Ser. 5. *Edited by* J.H. Dane and G.C. Topp. SSSA, Madison, WI. pp. 1209–1226. doi:10.2136/sssabookser5.4.c50.

Çerçioğlu, M., Anderson, S.H., Udawatta, R.P., and Haruna, S.I. 2018. Effects of cover crop and biofuel crop management on computed tomography-measured pore parameters. Geoderma, **319**: 80–88. doi:10.1016/j.geoderma.2018.01.005.

Çerçioğlu, M., Anderson, S.H., Udawatta, R.P., and Alagele, S. 2019. Effect of cover crop management on soil hydraulic properties. Geoderma, **343**: 247–253. doi:10.1016/j.geoderma.2019.02.027.

Chalise, K.S., Singh, S., Wegner, B.R., Kumar, S., Pérez-Gutiérrez, J.D., Osborne, S.L., and Rohila, J.S. 2019. Cover crops and returning residue impact on soil organic carbon, bulk density, penetration resistance, water retention, infiltration, and soybean yield. Agron. J. **111**(1): 99–108. doi:10.13031/trans.12700.

Chen, G., and Weil, R.R. 2010. Penetration of cover crop roots through compacted soils. Plant Soil, **331**: 31–43. doi:10.1007/s11104-009-0223-7.

Dane, J.H., and Hopmans, J.W. 2002. Water retention and storage. *In* Methods of soil analysis, part 4 —physical methods, book Ser 5. *Edited by* J.H. Dane and G.C. Topp. Soil Science Society of America, Madison, WI.

Du, Z., Han, X., Wang, Y., Gu, R., Li, Y., Wang, D., and Guo, L. 2017. Changes in soil organic carbon concentration, chemical composition, and aggregate stability as influenced by tillage systems in the semi-arid and semi-humid area of North China. Can. J. Soil Sci. **98**(1): 91–102. doi:10.1139/cjss-2017-0045.

Egley, G.H. 2017. Seed germination in soil: dormancy cycles. *In* Seed development and germination. *Edited by* J. Kigel. Taylor and Francis Group, New York. pp. 529–543.

Gee, G.W., and Or, D. 2002. Particle-size analysis. *In* Methods of soil analysis: part 4. Physical methods. *Edited by* J.H. Dane and G.C. Topp. Soil Science Society of America, Madison, WI. pp. 272–278.

Gougoulias, C., Clark, J.M., and Shaw, L.J. 2014. The role of soil microbes in the global carbon cycle: tracking the below-ground microbial processing of plant-derived carbon for manipulating carbon dynamics in agricultural systems. J. Sci. Food Agric. **94**(12): 2362–2371. doi:10.1002/jsfa.6577.

Grossman, R.B., and Reinsch, T.G. 2002. Bulk density and linear extensibility. *In* Methods of soil analysis. Part 4—physical methods. Book Ser. Vol. 5. *Edited by* J.H. Dane and G.C. Topp. Soil Science Society of America, Madison, WI. pp. 201–228.

Guoju, X., Yanbin, H., Qiang, Z., Jing, W., and Ming, L. 2020. Impact of cultivation on soil organic carbon and carbon sequestration potential in semiarid regions of China. Soil Use Manage. **36**(1): 83–92. doi:10.1111/sum.12540.

Hamonts, K., Bissett, A., Macdonald, B.C., Barton, P.S., Manning, A.D., and Young, A. 2017. Effects of ecological restoration on soil microbial diversity in a temperate grassy woodland. Appl. Soil Ecol. **117**: 117–128. doi:10.1016/j.apsoil.2017.04.005.

Haruna, S.I. 2019. Influence of winter wheat on soil thermal properties of a paleudalf. Int. Agrophys. **33**(3): 389–395. doi:10.31545/intagr/110850.

Haruna, S.I., Anderson, S.H., Nkongolo, N.V., Reinbott, T., and Zaibon, S. 2017. Soil thermal properties influenced by perennial biofuel and cover crop management. Soil Sci. Soc. Am. J. **81**(5): 1147–1156. doi:10.2136/sssaj2016.10.0345.

Haruna, S.I., Anderson, S.H., Udawatta, R.P., Gantzer, C.J., Phillips, N.C., Cui, S., and Gao, Y. 2020. Improving soil physical properties through the use of cover crops: a review. Agrosyst. Geosci. Environ. **3**(1): e20105. doi:10.1002/agg2.20105.

Haruna, S.I., Ward, Z.A., Cartwright, A.L., Wunner, A.A., Jackson, C.A., and Berry, C.R. 2023. No-till cover crop effects on the thermal properties of a Paleudult. Soil Till. Res. **231**: 105717. doi:10.1016/j.still.2023.105717.

Hilel, D. 2012. Applications of soil physics. Elsevier. pp. 204–208.

Hu, G., Zhao, L., Wu, X., Li, R., Wu, T., Xie, C., and Cheng, G. 2016. New Fourier-series-based analytical solution to the conduction–convection equation to calculate soil temperature, determine soil thermal properties, or estimate water flux. Int. J. Heat Mass Transf. **95**: 815–823. doi:10.1016/j.ijheatmasstransfer.2015.11.078.

Kang, S., Doh, S., Lee, D., Lee, D., Jin, V.L., and Kimball, J.S. 2003. Topographic and climatic controls on soil respiration in six temperate mixed-hardwood forest slopes. Korea. Glob. Chang. Biol. **9**(10): 1427–1437. doi:10.1046/j.1365-2486.2003.00668.x.

Kochiieru, M., Lamorski, K., Feizienė, D., Feiza, V., Šlepetienė, A., and Volungevičius, J. 2022. Land use and soil types affect macropore network, organic carbon and nutrient retention, Lithuania. Geoderma Reg. **28**: e00473. doi:10.1016/j.geodrs.2021.e00473.

Lu, Y., Lu, S., Horton, R., and Ren, T. 2014. An empirical model for estimating soil thermal conductivity from texture, water content, and bulk density. Soil Sci. Soc. Am. J. **78**(6): 1859–1868. doi:10.2136/sssaj2014.05.0218.

Lu, Y., Liu, X., Heitman, J., Horton, R., and Ren, T. 2016. Determining soil bulk density with thermo-time domain reflectometry: a thermal conductivity-based approach. Soil Sci. Soc. Am. J. **80**(1): 48–54. doi:10.2136/sssaj2015.08.0315.

Mazzoncini, M., Sapkota, T.B., Barberi, P., Antichi, D., and Risaliti, R. 2011. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil Till. Res. **114**(2): 165–174. doi:10.1016/j.still.2011.05.001.

Mendis, S.S., Udawatta, R., Anderson, S.H., Ansari, J., and Salceda, M. 2022. Effects of cover crops on soil thermal properties of a corn cropping system. Soil Sci. Soc. Am. J. **86**(5): 1194–1205. doi:10.1002/saj2.20409.

Mishra, U., Hugelius, G., Shelef, E., Yang, Y., Strauss, J., Lupachev, A., and Orr, A. 2021. Spatial heterogeneity and environmental predictors of permafrost region soil organic carbon stocks. Sci. Adv. **7**(9): eaaz5236. doi:10.1126/sciadv.aaz5236.

Mitchell-Forsytk, B., Haruna, S., and Downs, K. 2021. Variability of soil thermal properties along a catena in Middle Tennessee, U.S.A. Int. Agrophys. **35**(2): 209–219. doi:10.31545/intagr/140079.

Nair, A., and Ngouajio, M. 2012. Soil microbial biomass, functional microbial diversity, and nematode community structure as affected by cover crops and compost in an organic vegetable production system. Appl. Soil Ecol. **58**: 45–55. doi:10.1016/j.apsoil.2012.03.008.

Nkongolo, N.V., Johnson, S., Schmidt, K., and Eivazi, F. 2010. Greenhouse gases fluxes and soil thermal properties in a pasture in central Missouri. J. Environ. Sci. **22**(7): 1029–1039. doi:10.1016/S1001-0742(09)60214-X.

Ogilvie, C.M., Ashiq, W., Vasava, H.B., and Biswas, A. 2021. Quantifying root-soil interactions in cover crop systems: a review. Agriculture, **11**(3): 218. doi:10.3390/agriculture11030218.

Olson, K., Ebelhar, S.A., and Lang, J.M. 2014. Long-term effects of cover crops on crop yields, soil organic carbon stocks and sequestration. Open J. Soil Sci. **4**(8): 48993. doi:10.4236/ojss.2014.48030.

Ping, C.L., Jastrow, J.D., Jorgenson, M.T., Michaelson, G.J., and Shur, Y.L. 2015. Permafrost soils and carbon cycling. Soil, **1**(1): 147–171. doi:10.5194/soil-1-147-2015, 2015.

Ravazzani, G., Curti, D., Gattinoni, P., Della Valentina, S., Fiorucci, A., and Rosso, R. 2016. Assessing groundwater contribution to streamflow of a large alpine river with heat tracer methods and hydrological modelling. River Res. Appl. **32**: 871–884. doi:10.1002/rra.292.

Rorick, J.D., and Kladivko, E.J. 2017. Cereal rye cover crop effects on soil carbon and physical properties in southeastern Indiana. J. Soil Water Conserv. **72**(3): 260–265. doi:10.2489/jswc.72.3.260.

SAS Institute. 2015. Base SAS 9.4 procedures guide. SAS Institute.

Sindelar, M., Blanco-Canqui, H., Jin, V.L., and Ferguson, R. 2019. Do cover crops and corn residue removal affect soil thermal properties? Soil Sci. Soc. Am. J. **83**(2): 448–457. doi:10.2136/sssaj2018.06.0239.

Villamil, M.B., Bollero, G.A., Darmody, R.G., Simmons, F.W., and Bullock, D.G. 2006. No-till corn/soybean systems including winter cover crops: effects on soil properties. Soil Sci. Soc. Am. J. **70**(6): 1936–1944. doi:10.2136/sssaj2005.0350.

Watt, M.S., and Bloomberg, M. 2012. Key features of the seed germination response to high temperatures. New Phytol. **196**(2): 332–336. Available from https://www.jstor.org/stable/newphytologist.196.2.332. doi:10.1111/j.1469-8137.2012.04280.x.

Wolters, V. 2000. Invertebrate control of soil organic matter stability. Biol. Fertil. Soils, **31**: 1–19. doi:10.1007/s003740050618.

Zaibon, S., Anderson, S.H., Veum, K.S., and Haruna, S.I. 2019. Soil thermal properties affected by topsoil thickness in switchgrass and row crop management systems. Geoderma, **350**: 93–100. doi:10.1016/j.geoderma.2019.05.005.