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RESEARCH ARTICLE

Effects of cover crops on soil hydraulic properties during commodity crop growing season

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Abstract
Cover crops (CCs) can improve soil hydraulic properties prior to termination, but their effects on soil hydraulic properties during the growing season are less known. The objective of this study was to investigate the influence of no-till CC on the soil hydraulic properties during the commodity crop growing season in Murfreesboro, USA. The CCs 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.). The cash crop grown was corn (*Zea mays*). Soil samples were collected using a cylindrical core (55 mm inside diameter, 60 mm long) at 0–10, 10–20, and 20–30 cm depths during April (prior to CC termination), May, June and July. Results showed that soil bulk density (Db) was 23%, 12%, 11% and 10% higher under no cover crop (NCC) compared with CC management during April – July, respectively. This suggests a lower rate of soil consolidation under CC management even after several rainfall events. Four months after CC termination, macroporosity and total porosity were 306 and 50% higher, respectively, under CC compared with NCC management. Therefore, saturated hydraulic conductivity (K_{sat}) during July was two times higher under CC management compared with NCC management and this can affect increase water infiltration and conservation during the growing season. Due to CC root-induced improvement in macroporosity, CCs had 64% higher volumetric water content (θ) at saturation during July compared with NCC management. Cover crops can improve soil hydraulic properties and these benefits can persist for up to four months after termination.

KEYWORDS
bulk density, pore size distribution, saturated hydraulic conductivity, soil organic carbon, water retention

1 | INTRODUCTION

The inclusion of cover crops (CCs) into crop rotation cycles has been encouraged due to their ability to protect and improve soil physical conditions between periods of crop production (Schnepf & Cox, 2006). They are also valued for their ability to increase water infiltration into soils (Bodner et al., 2008), reduce soil erosion (Kasper et al., 2001), increase water retention and conservation (Daigh et al., 2014; Haruna, Anderson, et al., 2018), and improve soil organic carbon (SOC) (Mazzoncini et al., 2011; Olsen et al., 2014). Therefore, CCs have the potential to improve soil and water conservation, and environmental sustainability.

Soil hydraulic properties play a significant role in water movement, retention and environmental sustainability. These properties are dynamic and are influenced by natural and human-induced factors (Adeli et al., 2020; Nascante et al. 2015). Natural factors, for example particle size distribution, can affect water retention at lower soil water pressures (<−100 kPa) (Azooz & Arshad, 2001). Anthropogenic factors such as the inclusion of CC into crop rotation cycles can remarkably impact various soil hydraulic properties by improving SOC. Olsen et al. (2014) and Haruna (2019) reported that CCs increased SOC by 30% and 36%, respectively, compared with NCC in a silt loam soil due to decomposition of belowground biomass. Researchers Haruna et al. (2017), Demir et al. (2019), and Nascante et al. (2015) have reported that CC roots reduced soil bulk density (D_b) by 3%, 7% and 14%, respectively, compared with no cover crop (NCC). This was attributed to two mechanisms: increases in soil porosity due to CC root penetration, and the increase in SOC due to the decomposition of CC roots.

The living roots of CCs can also influence soil hydraulic properties by transpiring excessive water out of the soil. In a study on the effects of CCs on water infiltration, Chalise et al. (2018) reported that CCs reduced antecedent soil water content, and this led to increased soil water infiltration as compared with NCC management. More recently, Haruna et al. (2022) demonstrated that the pore spaces left behind by CC roots significantly increased cumulative water infiltration by 68% two months after their termination, as compared with NCC management. This increase in water infiltration can increase soil water content, for example Haruna et al. (2017) has reported that soils utilizing CC had 18 and 11% higher volumetric water content (θ) at saturation and −33 kPa pressures, respectively, compared with NCC management. Additionally, Villamil et al. (2006) reported that cereal rye (*Secale cereale*) and hairy vetch (*Vicia villosa* Roth.) increased soil porosity and these changes in pore size distribution are reflected in significant increases in transmission pores. Additionally, Rankoth et al. (2019) evaluated the effects of CC on soil moisture and sapflow of corn (*Zea mays*) with and without CC and found that, at 10, 20 and 30 cm depths, CC plots had 14%, 12% and 4%, respectively, greater soil water content compared with NCC plots. These authors concluded that plots under CC management maintained greater soil moisture conditions and provided more moisture to the commodity crops for a longer period compared with NCC plots. Therefore, CCs have been demonstrated to improve water retention and conservation, and overall improvement in crop productivity compared with NCC management (Delgado et al., 2021).

Furthermore, studies (Bodner et al., 2008; Villamil et al., 2006) have shown varying results of CCs on saturated hydraulic conductivity (K_{sat}). These researchers have reported that CCs had no significant effect on K_{sat}, despite an increase in pore heterogeneity. Conversely, Carof et al. (2007), Liesch et al. (2011) and Drury et al. (2014) reported significantly higher K_{sat} values under CC compared with NCC management, and this increase was attributed to the roots of CCs. The CC-induced increases in K_{sat} have been reported to reduce runoff from intense rainfall by up to 17% (Yu et al., 2016) which can improve soil conservation and environmental sustainability. Due to some of these conflicting results, further studies are needed to improve current knowledge on how CCs impact soil hydraulic properties.

Although several researchers (e.g., Basche et al., 2016; Blanco-Canqui et al., 2011; Bodner et al., 2013; Cercioglu et al., 2018; Garcia et al., 2013; Haruna, Nkongolo, et al., 2018; Rorick & Kladivko, 2017), have studied the effects of CCs on soil hydraulic properties, most of these studies were conducted just prior to CC termination. There is a need to understand the effects of different species of CC or mixture on soil hydraulic properties, not just before their termination, but also during the cash crop growing season. This information is important in management decisions that can improve crop productivity and environmental sustainability. This study is novel because it will be one of the few studies to evaluate the impact of CC on soil hydraulic properties during the commodity crop growing season. This information will be useful to scientists, land managers and extension agents by providing a better understanding the possible benefits of cover crops post-termination. Therefore, the objective of this study is to evaluate the effects of different species of CC on D_b, K_{sat}, pore size distribution and water retention during April – July. Due to several rainfall events during the growing season, it is hypothesized that the effects of CCs on soil hydraulic properties will not be significant during June and July.

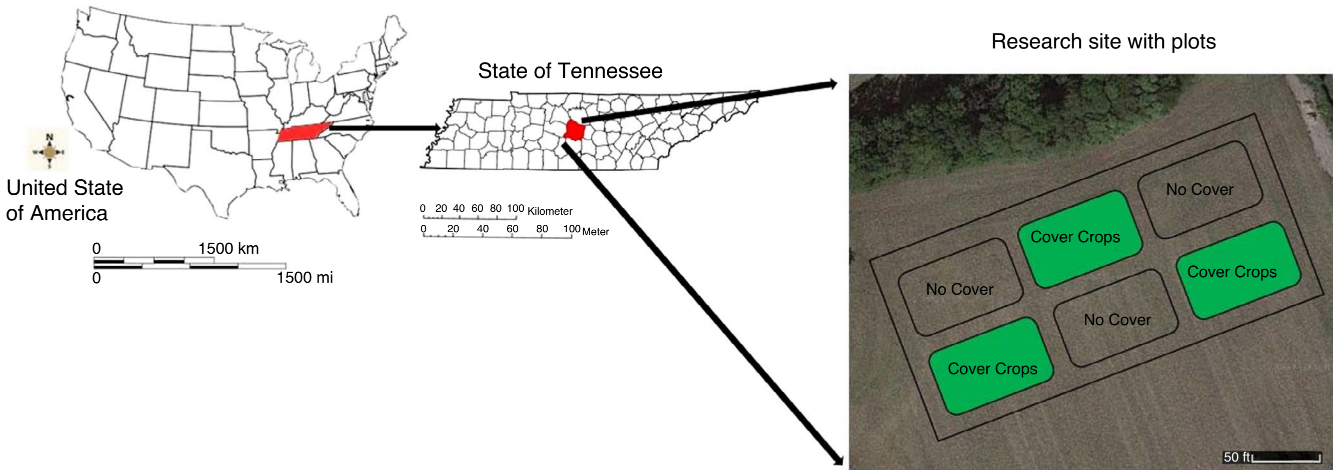

FIGURE 1 Research site in Tennessee showing research plots

2 | MATERIALS AND METHODS

2.1 | Site description

This 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) (Figure 1). The soil was classified by the USDA as a Cumberland silt loam (fine, mixed, semiactive, thermic Rhodic Paleudalfs). Particle size distribution analysis is shown in Table 1. The climate of the study area is Humid Subtropical (Koppen 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. During this study, cumulative precipitation during April, May, June and July were 60, 128, 56 and 142 mm, 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.

2.2 | Management description

The experimental design was a split-split plot design with a completely randomized whole plot with three replicates. The vegetative management treatments were two levels of CCs (CCs vs. NCC). Tillage management for the site was no-till. An 8-way CC mixture was used because of the uniqueness and diversity of their root morphology which can impact soil hydraulic properties (Haruna et al., 2017). Furthermore, this mix of CCs can provide other soil health benefits to the soil (Delgado et al., 2021) and it also reflects current trends in CC adoption by producers. These CCs consisted of hairy vetch, 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.). The grain crop (cash crop) grown was corn (*Zea mays* L.), planted in April and harvested in September.

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

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

Prior to the establishment of this study in 2020, the field was under 5 years of CC management and over 15 years of no-till practice. 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 total rates as recommended by University of Tennessee Cooperative Extension: 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 April 14, 2021, using 4.15 kg ha^{-1} acid equivalent of glyphosate [*N*-(phosphonomethyl) glycine]. Two passes of a 9.1 m CC roller were used a few hours after spraying the glyphosate to complete the termination of CCs. The corn was planted during April 16 using a

TABLE 2 Means ± standard errors and analysis of variance results of soil organic carbon (SOC), bulk density (D_b), and saturated hydraulic conductivity (K_{sat}) under different cover crop treatments during April, May, June, and July at three depths

	April			May		June		July	
	SOC	D_b	K_{sat}	D_b	K_{sat}	D_b	K_{sat}	D_b	K_{sat}
	g kg^{-1}	g cm^{-3}	mm h^{-1}	g cm^{-3}	mm h^{-1}	g cm^{-3}	mm h^{-1}	g cm^{-3}	mm h^{-1}
Treatment									
CC	18.93 ± 0.89 a	1.19 ± 0.04 b	34.62 ± 1.93 a	1.26 ± 0.03 b	31.24 ± 2.01 a	1.28 ± 0.03 b	30.82 ± 1.55 a	1.33 ± 0.01 b	27.57 ± 0.93 a
NCC	16.73 ± 0.63 b	1.41 ± 0.02 a	10.75 ± 1.07 b	1.41 ± 0.02 a	9.54 ± 0.89 b	1.42 ± 0.02 a	9.52 ± 0.87 b	1.46 ± 0.02 a	9.20 ± 0.50 b
Depth									
0–10	18.98 ± 0.88 a	1.21 ± 0.06 b	26.58 ± 5.73 a	1.26 ± 0.05 b	23.62 ± 5.33 a	1.27 ± 0.03 c	22.67 ± 4.92 a	1.35 ± 0.03 c	21.03 ± 4.06 a
10–20	17.87 ± 1.05 b	1.31 ± 0.05 a	22.99 ± 5.24 a	1.35 ± 0.03 a	20.84 ± 4.60 a	1.36 ± 0.03 b	20.77 ± 4.60 ab	1.40 ± 0.03 b	17.72 ± 3.79 b
20–30	16.65 ± 0.97 c	1.37 ± 0.04 a	18.49 ± 4.06 b	1.40 ± 0.03 a	16.73 ± 4.03 b	1.42 ± 0.03 a	17.08 ± 3.97 b	1.44 ± 0.03 a	16.41 ± 3.46 b
Analysis of variance $p > F$									
Tmt	0.021	0.010	0.011	0.033	0.011	0.008	0.007	0.010	0.002
Depth	0.002	0.006	0.007	0.001	0.009	<0.001	0.030	0.001	<0.001
Tmt*depth	0.514	0.609	0.134	0.218	0.126	0.171	0.267	0.532	0.123

Abbreviations: CC, cover crop; NCC, no cover crop; tmt, treatment; tmt*depth, treatment by depth interaction.

Mean comparisons were only made when p values for the main effects were ≤.05. Means with different letters within a column are significantly different at the .05 probability level.

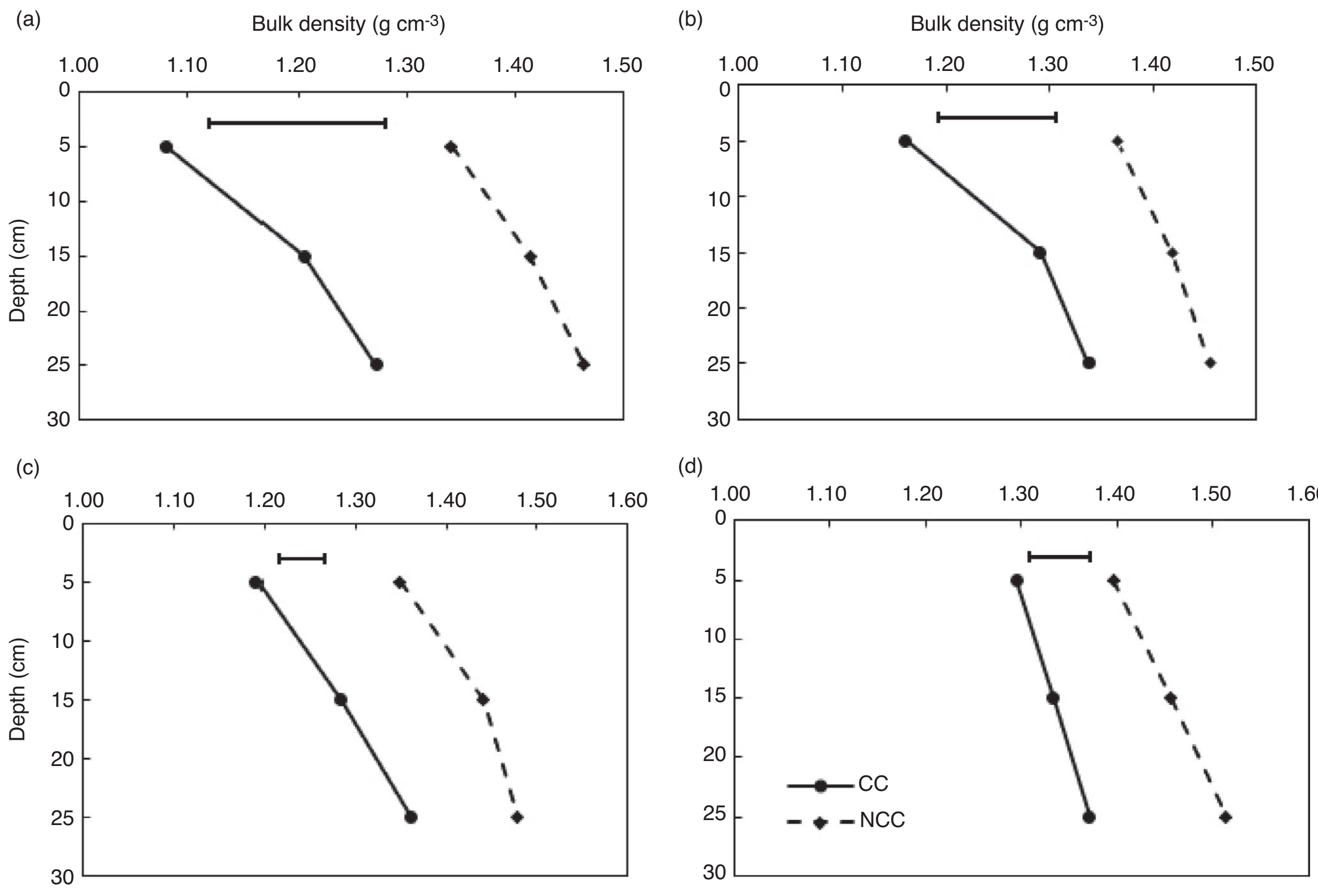

FIGURE 2 Soil bulk density as a function of depth during (a) April, (b) May, (c), June, and (d) July between cover crop (CC) and no cover crop (NCC) management. Horizontal bars represent least significant difference at .05 probability level

51 cm row planter. All plots were rainfed and under no-till management during this research.

2.3 | Soil sampling and analysis

Using historical precipitation patterns for the region as a guide, several rainfall events were anticipated during April, May, June and July. Therefore, it was expected that any benefits on soil hydraulic properties from CCs during the growing season will not be remarkable during June and July. Thus, soil samples were collected during the aforementioned months only. Soil samples were collected each month using a sampler with a cylindrical core measuring 55 mm inside diameter by 60 mm long from nontrafficked rows just before CCs were terminated (April 13), and again on May 17, June 14 and July 12 at 0–10, 10–20 and 20–30 cm depths. During each sampling period, a total of 18 soil samples were collected (2 treatments × 3 depths × 3 replicates). A total of 72 soil samples were collected for this study (2 treatments × 3 depths × 3 replicates × 4 months). Each soil sample was trimmed, placed in plastic bags and stored in a refrigerator at 4°C prior to analysis.

After removing the soil cores from the refrigerator, they were taken out of the plastic bags, weighed, and cheesecloth was gently placed at the bottom of each core and secured by rubber bands. They were placed in a tub and saturated for 24 h by gently raising the water level. The electrical conductivity of the water was 0.3 dS m^{-1} at 20°C. The constant head method was used to evaluate K_{sat} (Reynolds & Elrick, 2002). The falling head method was used for soils with K_{sat} values <0.1 cm h^{-1}.

After the K_{sat} measurement, water retention was measured on the same cores at 0.0, −0.4, −1.0, −2.5, −5.0, −10.0 and −20.0 kPa pressures on ceramic plates in a pressure chamber. The samples were then dried at 35°C for 48 h, removed from the sampling cylinder and split into two halves: one half was used to obtain soil aggregates and the other half was ground and passed through a 2-mm diameter sieve. The soil aggregates were used with pressure plates at −33 and −100 kPa pressures while the <2 mm samples were used with pressure plates at −1500 kPa pressure (Dane & Hopmans, 2002). Soil D_b was determined using the air-dried weight adjusted for oven-dry weight with a measured θ (Grossman & Reinsch, 2002). Soil organic carbon (SOC) was determined using the combustion

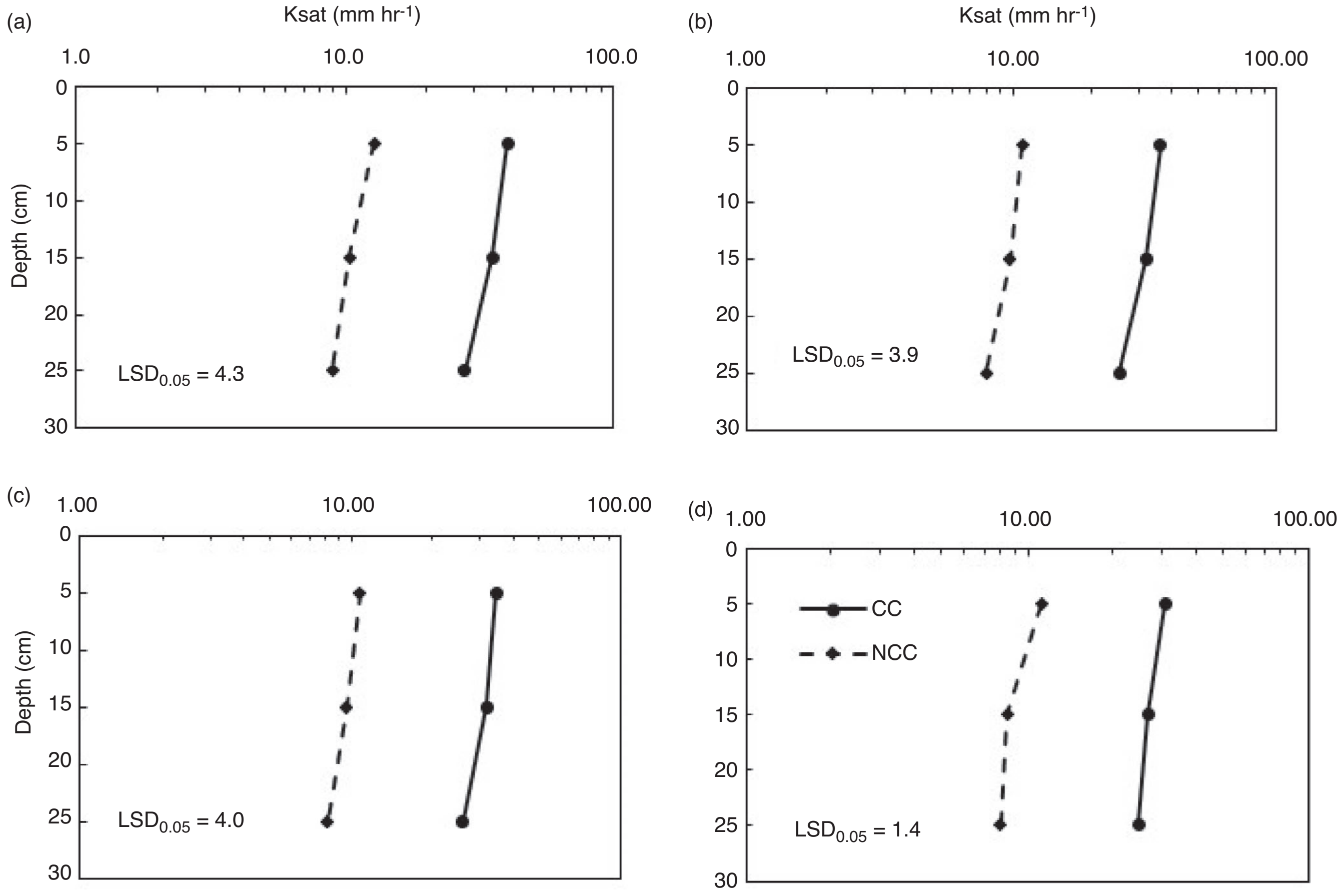

FIGURE 3 Saturated hydraulic conductivity (K_{sat}) as a function of depth during (a) April, (b) May, (c), June, and (d) July between cover crop (CC) and no cover crop (NCC) management. Due to log scale, least significant difference values are included

method (Loss-on-Ignition at 1200°C) (Schulte & Hopkins, 1996). Water retention curve was plotted as θ vs pressure.

From the water retention data, pore size distribution was calculated using the capillary rise equation to estimate the effective pore classes (Jury et al., 1991). Pore sizes were divided into macropores (>1000 μm effective diam.), coarse mesopores (1000–60 μm effective diam.), fine mesopores (10–60 μm effective diam.), and micropores (<10 μm effective diameter) (Anderson et al., 1990; Zaibon et al., 2016).

2.4 | Statistical analysis

The experiment was laid out in a split-split plot design with three completely randomized whole plot design. The whole plot factor included vegetative management treatments (CCs and NCC), four months (April, May, June and July) was a split-plot factor, and soil depths (0–10, 10–20, and 20–30 cm) were the split-split plot factor. A test of normality was conducted within each treatment, month, and soil depth. All data were normally distributed at $p = .05$. An analysis of variance (ANOVA) was performed on soil properties using the PROC GLM procedure in SAS ver. 9.4 (SAS Institute, 2015) statistical package to evaluate the effects of CC and soil depth on soil hydraulic properties as compared with NCC management for four months (April, May, June and July) in 2021. Statistical differences were evaluated using the PROC MEANS procedure from SAS with Duncan's test of means at an alpha level of .05.

3 | RESULTS

3.1 | Soil organic carbon, bulk density, and saturated hydraulic conductivity

The ANOVA and standard error (*SE*) for SOC, D_b, and K_{sat} are shown in Table 2. During the sample periods, these properties were significantly ($p \le .05$) affected by treatment and depth. Averaged over all depths, D_b was 23%, 12%, 11%, and 10% higher during April, May, June and July respectively, under NCC compared with CC management (Figure 2). During the same periods and averaged over all depths, K_{sat} was 222%, 228%, 224% and 200% higher, respectively, under CC compared with NCC management

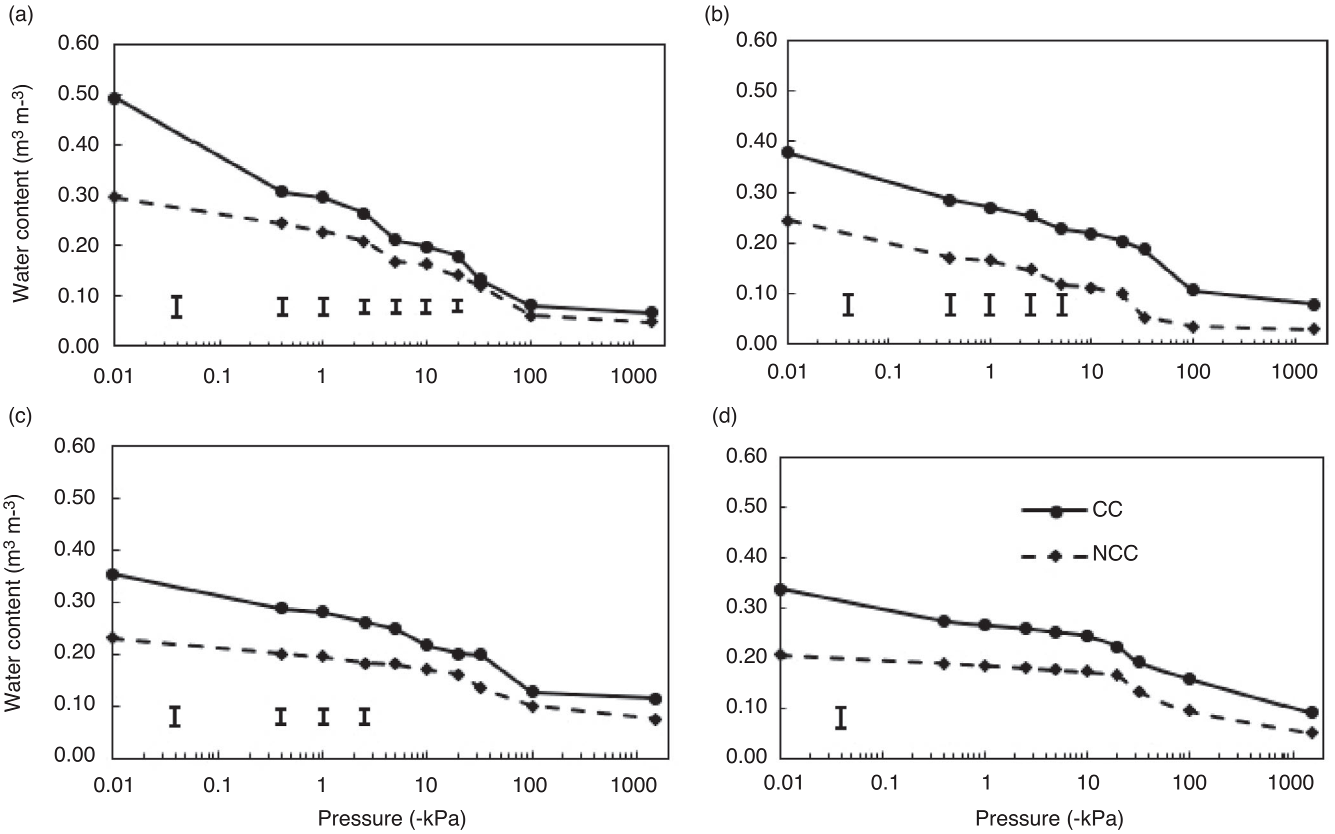

FIGURE 4 Cover crop (CC) and no cover crop (NCC) management effects on soil water retention during (a) April, (b) May, (c), June, and (d) July. Vertical bars represent least significant difference at .05 probability level

(Figure 3). Soil organic carbon, and K_{sat} were significantly higher at the 0–10 cm depth and decreased with increasing soil depth, while D_b was significantly lower at the same depth and increased with increasing soil depth.

3.2 | Soil water retention

Soil water retention results are shown in Figure 4. During April and averaged over all depths, θ under CC management at 0, −0.4, −1.0, −2.5, −5.0, −10.0 and −20.0 kPa soil water pressures was 67%, 25%, 34%, 27%, 24%, 21% and 19% higher, respectively, compared with NCC management. During May, CC plots had 55%, 66%, 65%, 71% and 91% higher θ at 0, −0.4, −1.0, −2.5 and −5.0 kPa soil water pressures respectively, compared with NCC management. Averaged over sampled depths during June, CC management increased θ at 0, −0.4, −1.0 and −2.5 kPa soil water pressures by 54%, 44%, 48% and 51%, respectively, compared with NCC management. Furthermore, results also showed that during July, θ was 64% higher, at saturation, under CC compared with NCC management. Averaged over both treatments, depth was significantly different ($p \leq .05$) only at higher pressures during the sample period. During April, θ was significantly higher at the top 10 cm and reduced with increasing soil depths at 0, −0.4, −1.0 and −2.5 kPa soil water pressures. During May, the difference among depths was only significant at 0 and −0.4 kPa soil water pressures. At all soil water pressures and during all sampling periods, θ was higher at the top 10 cm of the soil and reduced with increasing soil depth.

3.3 | Pore size distributions

Pore size distribution results are shown in Figures 5-9. Just before CC termination and averaged over all depths, macroporosity, microporosity and total porosity were 265, 19% and 66% higher, respectively, under CC compared with NCC management. During May, CC plots had 91%, 82% and 54% higher fine mesoporosity, microporosity and total porosity, respectively, compared with NCC plots. Similar results were obtained in June; however, the differences between both managements were smaller (41%, 22% and 51% higher under CC compared with NCC management). Pore size difference between CC and NCC managements during July was comparable to results obtained during April (macroporosity, fine mesoporosity, microporosity and total porosity during July were 306, 32%, 24% and 50% higher, respectively under CC as compared with

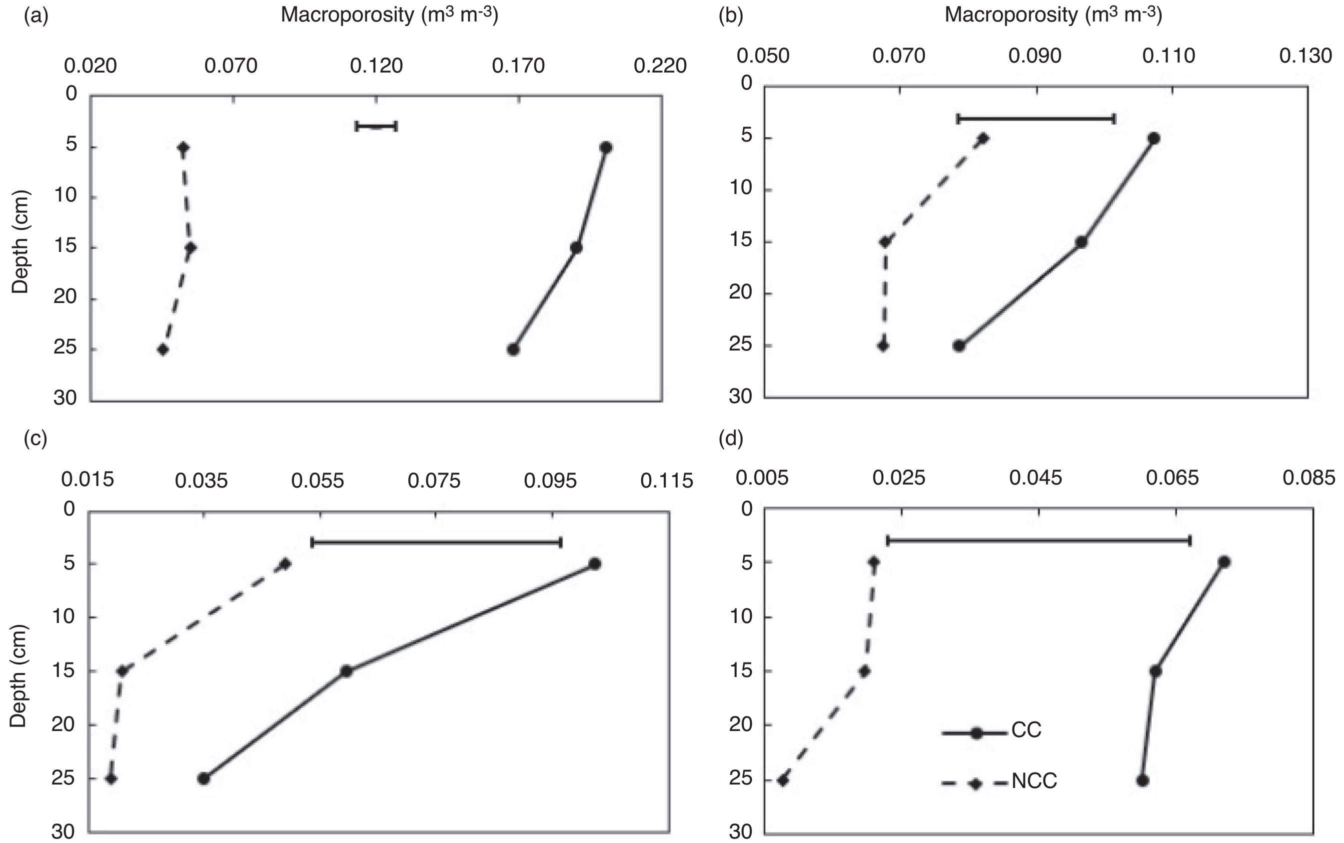

FIGURE 5 Macroporosity (>1000 μm effective diameter) as a function of depth during (a) April, (b) May, (c), June, and (d) July between cover crop (CC) and no cover crop (NCC) management. Horizontal bars represent least significant difference at .05 probability level

NCC management). Pore sizes decreased with increasing soil depth (Figures 5-9). Generally, pore sizes decreased for both management practices during April – July; however, the pore sizes under NCC management showed the greatest decrease during this period.

4 | DISCUSSION

4.1 | Soil organic carbon, bulk density, and saturated hydraulic conductivity

As an indicator of soil health, SOC plays an important role in crop production. Soil organic carbon has been reported to improve nutrient availability (Li et al., 2020), microbial activity (Lagomarsino et al., 2012), volumetric heat capacity (Haruna, 2019; Haruna et al., 2017) and soil hydraulic properties (Blanco-Canqui et al., 2011; Cercioglu et al., 2018; Haruna et al., 2020). Therefore, management practices that improve SOC are desirable for healthy agroecosystems. The numerically higher SOC values under CC compared with NCC management was attributed to the above-and-belowground biomass, as well as root exudates of the various CCs. As the roots of the CCs used in this study are concentrated in the top 15 cm and reduces with increasing soil depth (Bodner et al., 2019; Yu et al., 2016), SOC was effectively higher at the 0–10 cm depth and reduced with increasing soil depth. Due to the lower mass-to-volume ratio of SOC and the roots of CCs, D_b was significantly lower under CC management compared with NCC management during April – July. The significantly lower D_b under CC management was attributed to CC residues left on the soil surface and the roots of the terminated CCs. These residues take longer than 3 months to totally decompose (Drost et al., 2020; Jahanzad et al., 2016) (they were visible during July sampling) and can reduce soil consolidation from the impact of raindrops and runoff.

Saturated hydraulic conductivity estimates water movement under saturated conditions when subjected to a hydraulic gradient and it is influenced by soil structure, pore size distributions and especially pore connectivity (Shuckla, 2014). Higher proportions of larger pores (>60 μm effective diameter), SOC-induced improvement in soil structure, and lower D_b probably led to the higher K_{sat} values under CC management compared with NCC management during the sampling periods (Figure 3). As K_{sat} is very sensitive to compaction and is directly related to soil pore spaces, results of this study showed that CCs (especially when their residues are also left on the soil surface) can better resist

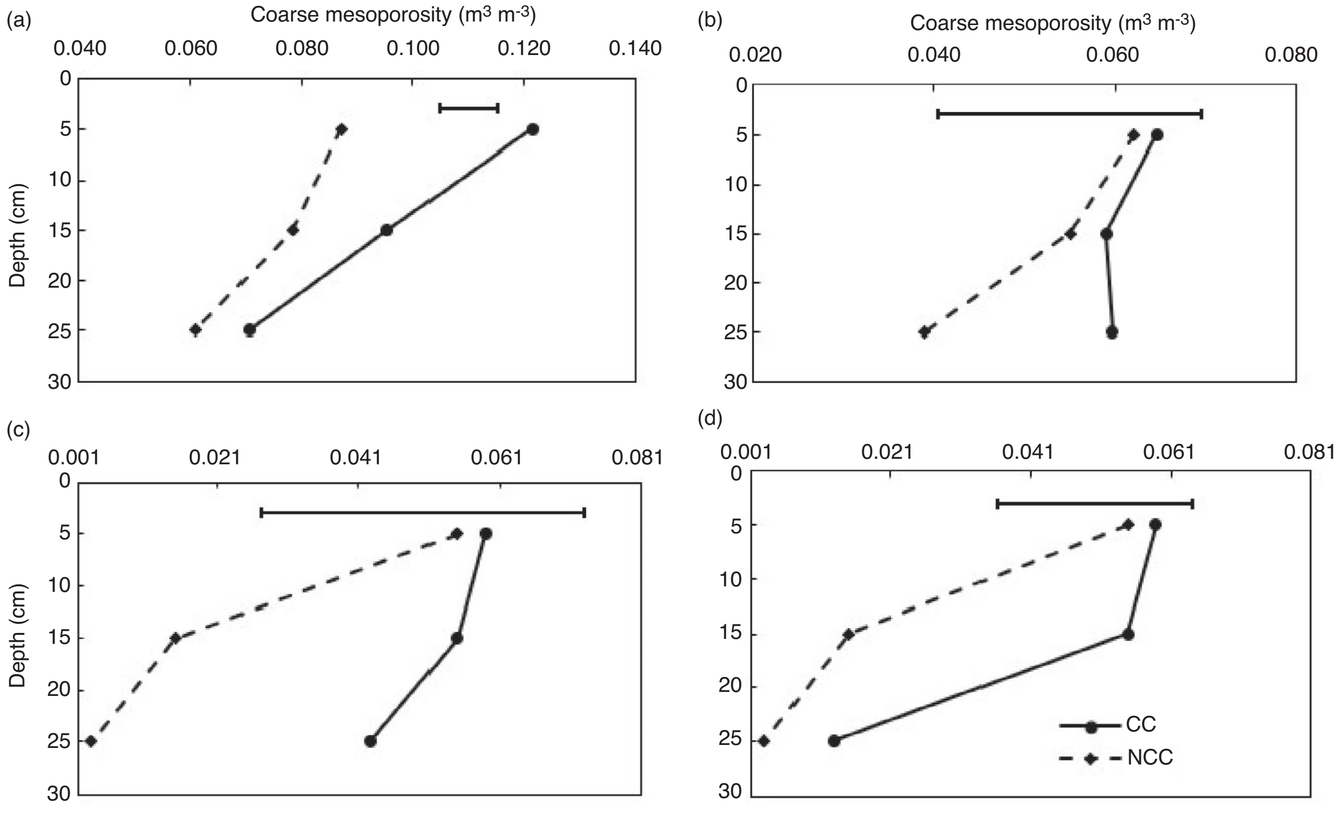

FIGURE 6 Coarse mesoporosity (1000–60 μm effective diameter) as a function of depth during (a) April, (b) May, (c), June, and (d) July between cover crop (CC) and no cover crop (NCC) management. Horizontal bars represent least significant difference at .05 probability level

raindrop-induced soil compaction compared with NCC and agreed with the findings of Blanco-Canqui et al. (2011). These authors (Blanco-Canqui et al., 2011) reported that CCs reduced D_b of the top 10 cm of soil by 4% relative to NCC. Higher K_{sat} value has a positive outcome on water infiltration (Haruna, Nkongolo, et al., 2018) and allows soils to transmit a given flux at a lower water content. Consequently, results from this study showed that for a given rate of water application, the water content behind the wetting front of soils under CC management is lower compared to soils under NCC management. This decrease in soil water moves the wetting front deeper into the soil under CC management. Thus, improved K_{sat} under CC management suggests that CCs can enhance soil water recharge and storage and reduce surface runoff. This reduced surface runoff can lower soil loss and improve soil and water conservation. Expectedly, K_{sat} reduced with increasing soil depth which agreed with D_b results (Table 2).

4.2 | Soil water retention

The soil water retention curve is important in simulating soil water movement and in evaluating soil water availability and capacity (Dane & Hopmans, 2002). As such, this soil characteristic can be an important tool for improving crop productivity under an increasingly variable climatic condition (Haruna et al., 2017). It can also be an indication of potential surface runoff (Yu et al., 2016). Results of this study showed that significant differences between CC and NCC management in water retention was limited to higher pressures (especially during June and July) (Figure 4). Repeated wetting and drying over time may have reduced the uniformity of interconnected pores, changed pore structure, and entrapped more air within soil pores, all of which can reduce soil water retention.

Results further showed that θ reduced at all pressures during April – July, suggesting an overall reduction in water retention overtime. Therefore, CC management might temporarily improve water drainage during the first 2 months after termination and this can be beneficial in water-logged environments by reducing surface runoff. This mechanism has been reported to improve infiltration parameters and cumulative infiltration under CC compared with NCC management (Haruna et al., 2022). Additionally, the lower water retention noticed under NCC management suggests that CCs can improve water and nutrient availability and transport (especially during the early vegetative stages of most cash crops). Effects on crop productivity may become more noticeable during drier growing seasons.

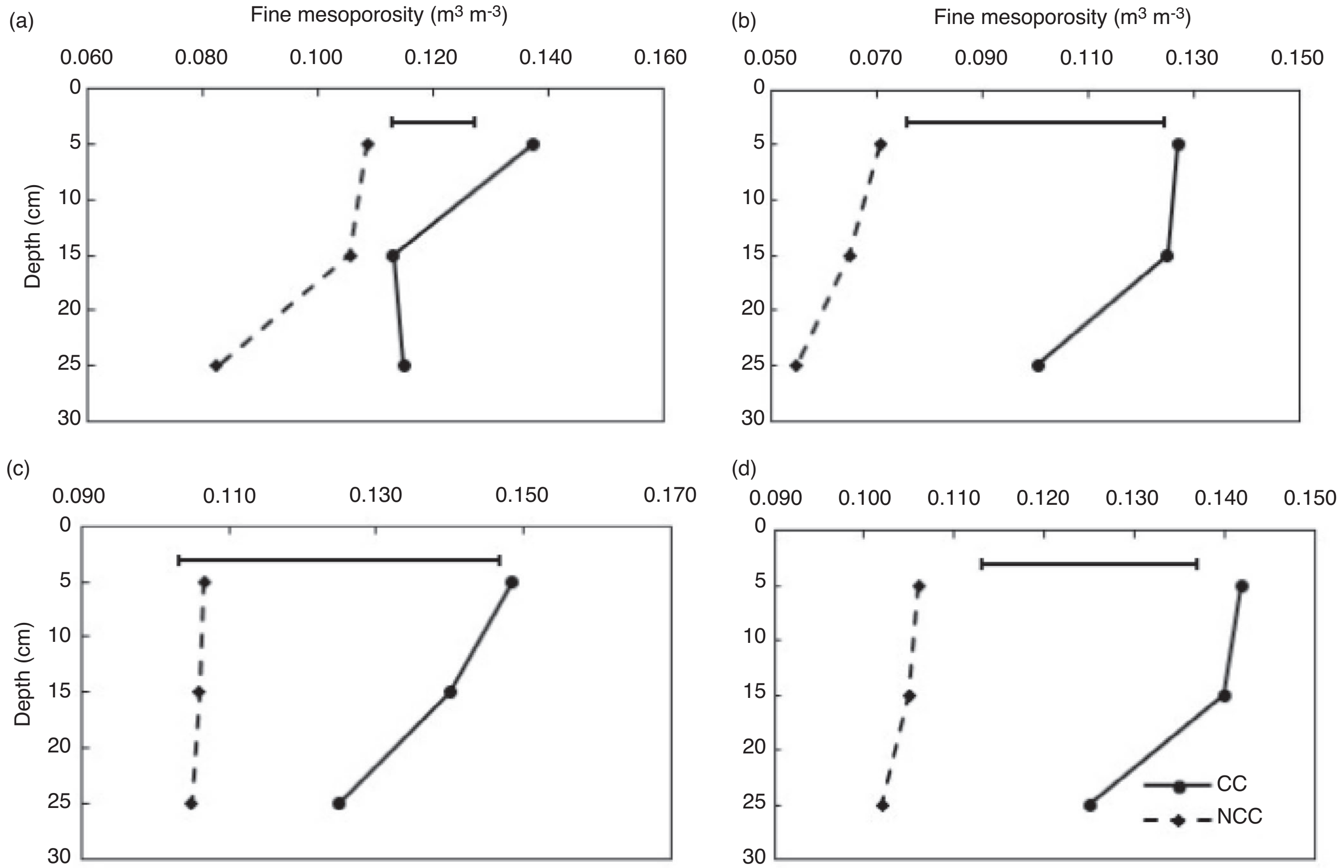

FIGURE 7 Fine mesoporosity (60–10 µm effective diameter) as a function of depth during (a) April, (b) May, (c), June, and (d) July between cover crop (CC) and no cover crop (NCC) management. Horizontal bars represent least significant difference at .05 probability level

The slope of the water retention curve has been reported to decrease with increasing D_b (Cameron, 1978), like the results of this study. Soil D_b was the highest during July, and this coincided with the lowest slope for the water retention curve (Figures 2 and 4). Therefore, as D_b increases, decreases in water content remains relatively constant over soil water pressures. In management decisions to improve soil water availability and crop productivity, significant consideration should also be placed on their D_b effects.

Results of this study showed that θ was only significantly different at higher soil water pressures during all 4 months. In fact, during July, θ was not significantly different among depths at any of the soil water pressures. One of the possible reasons for this could be the absence of CC roots. As CC roots are mostly concentrated in the top 15 cm of the soil (Bodner et al., 2019; Yu et al., 2016), microbial decomposition of roots (which increases overtime after CC termination) can weaken the integrity of biopores which makes them more susceptible to natural processes of soil consolidation (Juyal et al., 2021). As such, water retention, although numerically higher at the 0–10 cm depth, was statistically similar among depths overtime.

4.3 | Pore size distributions

Plant roots and biotic activity have been reported to improve macroporosity and coarse mesoporosity (Udawatta & Anderson, 2008; Udawatta et al., 2006), and these pore sizes are important for water infiltration, transport within the soil and overall soil conservation. During April, the roots of CCs were probably responsible for the significantly higher macroporosity and coarse mesoporosity, especially at the 0–10 and 10–20 cm depths (Figures 5a and 6a). During May, SOC-induced microbial activity, and decaying roots (which leaves behind pore spaces), probably resulted in the higher macroporosity under CC compared with NCC management, especially at the top two sampled depths (Figure 5b). The decrease in root density and biotic activity with increasing soil depth may have led to the reduction in these pores with an increase in soil depth. These pores may have also contributed to the drainage of water at soil water pressures between saturation and −5 kPa as noticed in the water retention curves results.

Fine mesoporosity and microporosity play an important role in water retention and availability within the soil. Higher number of fine mesoporosity and microporosity under CC management during April (Figures 7a and 8a)

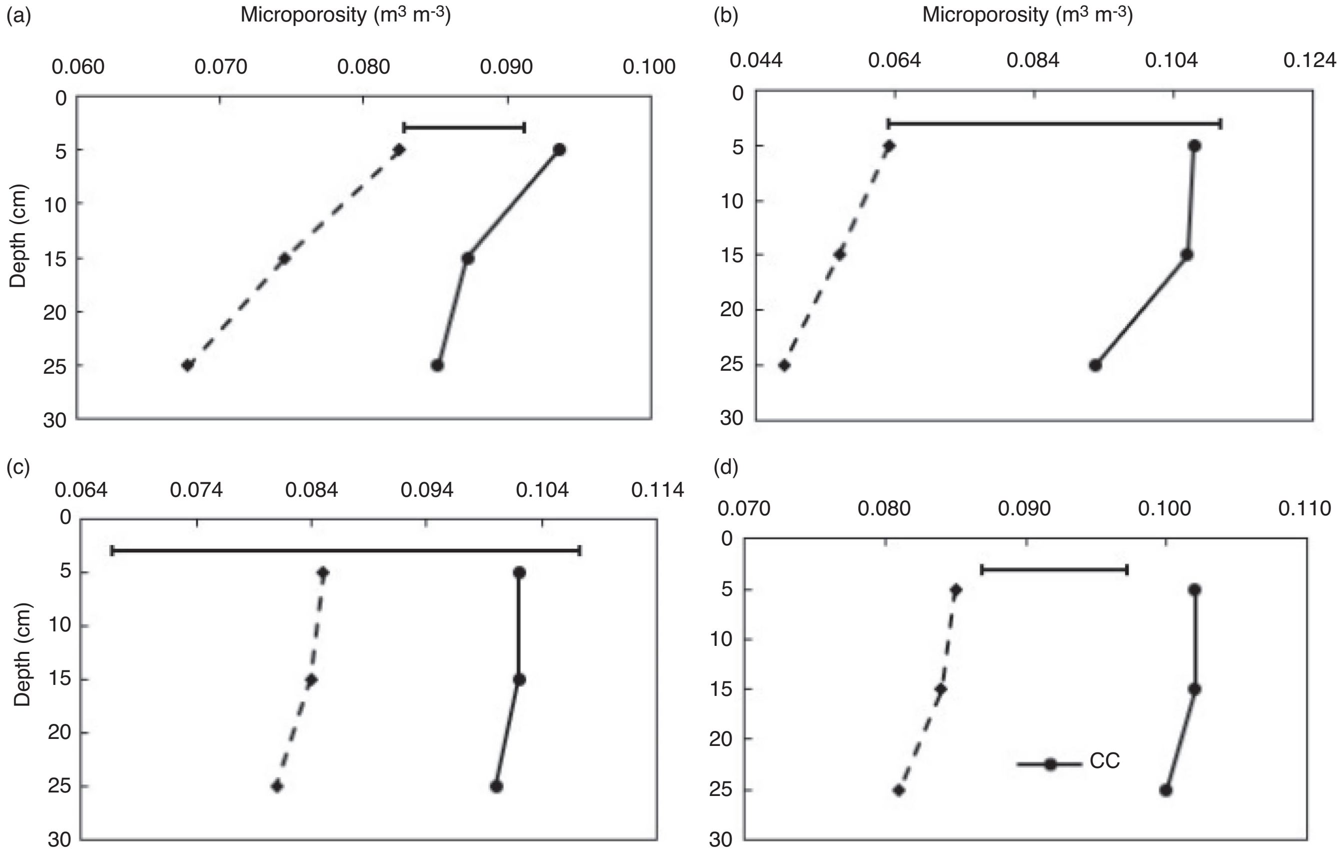

FIGURE 8 Microporosity (<10 µm effective diameter) as a function of depth during (a) April, (b) May, (c), June, and (d) July between cover crop (CC) and no cover crop (NCC) management. Horizontal bars represent least significant difference at .05 probability level

and May (Figures 7b and 8b) illustrate the potential of CCs in improving water availability during the critical vegetative growth periods of most cash crops. Total porosity at all depths were significantly higher under CC management (Figure 9) probably due to the roots of CCs and their residues left on the soil surface subsequently enhance soil health. These residues reduce the kinetic energy of raindrops (Haramoto & Gallandt, 2005) and this may have led to slower soil consolidation under CC management. This phenomenon also probably resulted in CC plots showing less degree of decrease in pore sizes over from April to July compared with NCC plots. These results agree with D_b results, and they show that CCs can improve the soil conditions necessary for water and gaseous interchange within the soil. The increases in the proportion of macropores under CC treatment can probably enhance soil hydraulic properties (e.g. K_{sat}, water holding capacity, and D_b) as compared with NCC management.

Similar to soil water retention curve results, most pore sizes were only significantly different during April (the only exception was macroporosity which was significantly different among depths during April, May and June). This was attributed to the compromised integrity of soil pores over time because of CC root decay (Bodner et al., 2010). To improve and maintain soil pore spaces overtime, CC specie selection should also include consideration of their root morphology and the overall C/N ratio of their biomass (Ramírez-García et al., 2015).

Results from this study showed that some hydraulic properties were not significantly different between treatments during June but were significantly different about one month later (e.g. Figures 7 and 8). This change was probably due to monthly precipitation distribution. Historically (and during this study), precipitation is lower during June compared with April, May and July. More rainfall during July may have led to more soil consolidation under NCC management (due to less residue cover) compared with CC management. Additionally, the benefits of CCs on soil hydraulic properties may persist for up to four months after their termination (as demonstrated by the current study), and this improvement can play an important role in crop productivity, especially under rainfed systems in a rapidly changing global climate. Finally, some results agreed with the hypothesis of the current study (e.g. soil water retention at lower pressures, coarse mesoporosity) while others disproved the hypothesis (e.g. K_{sat}, D_b). Further studies are thereby needed, especially through the entire growing season, to quantify the effects

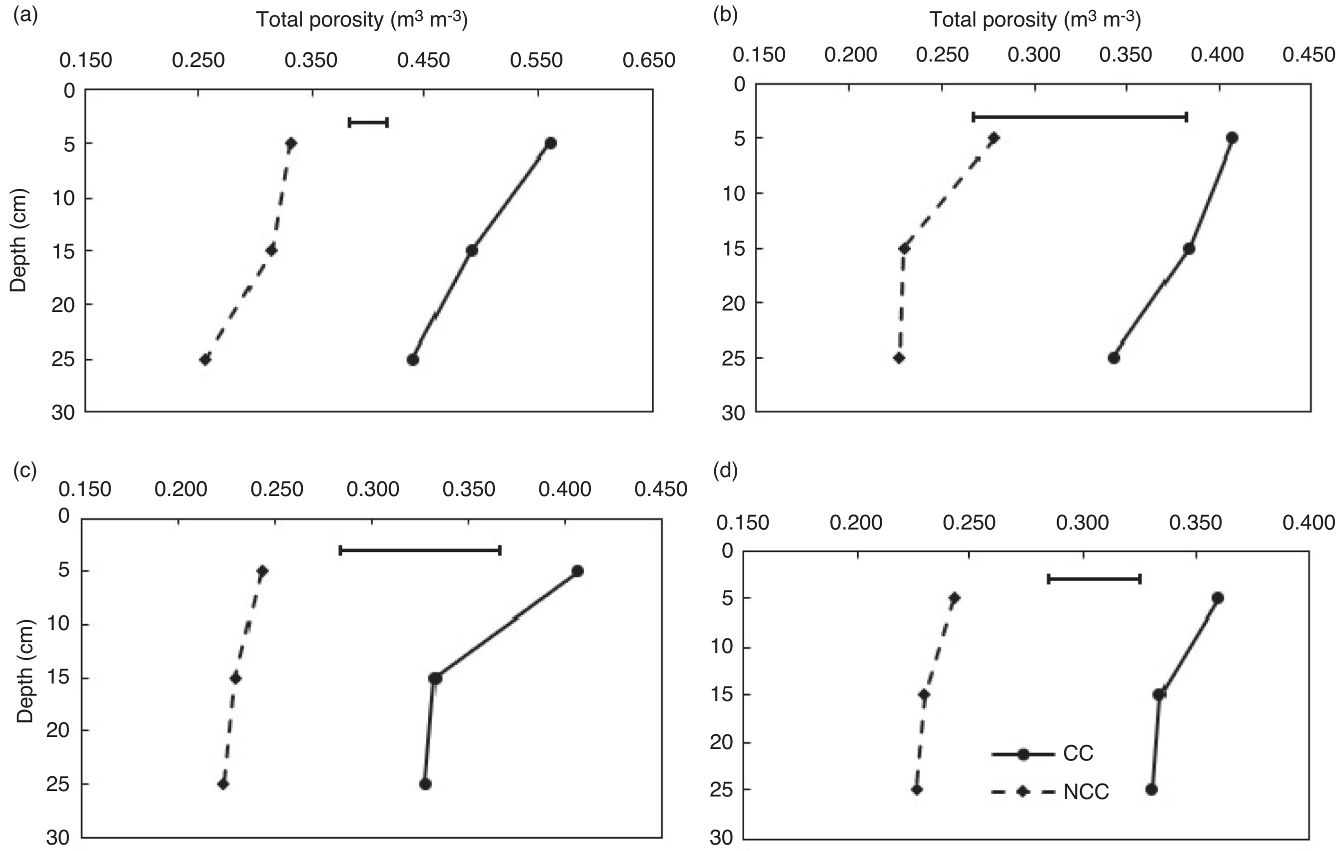

FIGURE 9 Total porosity as a function of depth during (a) April, (b) May, (c), June, and (d) July between cover crop (CC) and no cover crop (NCC) management. Horizontal bars represent least significant difference at .05 probability level

of CCs on soil properties during the later stages of grain crop growth.

5 | CONCLUSION

This study investigated the effects of multi species CCs on soil hydraulic properties during part of corn growing season in Middle Tennessee region of the United States. Soil organic carbon was numerically higher under CC compared with NCC management and this effect may have led to significantly lower D_b during April-July. The K_{sat} under CC management was about two times higher compared with NCC management 4 months after CC termination and this shows that CC management can improve soil water transport at low water content. Findings of soil water retention showed that CCs can significantly improve plant available water, especially during the critical growing periods, making water available to grain crops for longer periods. During the study period, CC management remarkably improved the proportion of various pore sizes, and this can be beneficial for water infiltration and storage. Effectively, this study demonstrated that CCs could reduce surface runoffs by increasing soil water storage and this can increase soil and water conservation. Therefore, the benefits of CCs on soil hydraulic properties and environmental sustainability can persist for up to 4 months after their termination and represent an important option for improving crop productivity. More studies are needed, particularly through the entire growing season, to quantify the influence of CCs on soil hydraulic properties during the later stages of grain crop growth.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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