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Tillage and cover crop effects on the hydro-physical properties of a hapludalf**

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A b s t r a c t. Tillage and cover crop (CC) management represent two of the most widely implemented anthropogenic practices that influence soil water movement and storage. This study assessed the effects of no-till with cover crop (NT-CC), no-till with no cover crop (NT-NC), tillage with cover crop (Till-CC), and tillage with no cover crop (Till-NC) management practices on select soil properties. The CCs included winter wheat (*Triticum aestivum*) and crimson clover (*Trifolium incarnatum*). During the first year, Till-NC management had greater bulk density values than other management practices. Further, NT-CC significantly improved soil organic carbon, the proportions of macropores (> 1 000 μm effective diameter) and coarse mesopores (60-1 000 μm effective diameter), and this led to increases in saturated hydraulic conductivity (K_{sat}), and volumetric water content at 0, -33, and -100 kPa soil water pressures than other management practices during the second year. Over both years, the K_{sat} was similar under NT-CC and reduced by 24% under Till-CC management, suggesting that tillage can reduce water flow under saturated conditions over time due to increased pore tortuosity, regardless of any effects of CC. In general, the study demonstrated that NT-CC improved measured soil hydro-physical properties and may be a more sustainable land management practice.

K e y w o r d s: pore size distribution, saturated hydraulic conductivity, soil organic carbon, water retention

1. INTRODUCTION

Land management practices are an important anthropogenic factor that influences soil health and cropping system sustainability (Duval *et al.*, 2016; Tesfahunegn, 2016). Consequently, several authors have reported on diverse effects of land management on microbial community health and diversity (Moghimian *et al.*, 2017; Mann *et al.*, 2019; Haruna *et al.*, 2025), crop productivity (Fernández *et al.*, 2017; Jug *et al.*, 2019; Adeux *et al.*, 2021; Dewi *et al.*, 2025), and soil degradation (Baumhardt *et al.*, 2015; García-González *et al.*, 2018; Parkhomenko *et al.*, 2019). Further, the implementation of various land management practices, often dictated by traditions/customs and financial incentives, have shaped several civilizations through their effects on crop productivity and environmental sustainability (Brevik *et al.*, 2018; Ellis, 2021). Currently, increased socio-economic pressures have led to intensification of management practices, with negative agronomic and environmental consequences. Since crop production is inevitable without one or more management practices, it is imperative that these practices are carefully evaluated for their effects on soil health parameters at the farm scale. Some of these important and widely adopted management practices include tillage and the inclusion of cover crops (CC) into crop rotation cycles.

The mechanical agitation of the soil can be beneficial for seedbed preparation (Benvenuti *et al.*, 2021), mechanical weed control (Alagbo *et al.*, 2022), and alleviating soil compaction (Mohammadshirazi *et al.*, 2016). Specifically, conventional tillage has been reported to lower soil bulk density (BD) by 15% at the 0-10 cm depth (Osunbitan *et al.*, 2005), increase porosity (macropores, mesopores, and

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total pores) by 10% at the 0-20 cm depth (Yang *et al.*, 2021), and increase saturated hydraulic conductivity (K_{sat}) by 50% at the 0-30 cm depth (Jabro *et al.*, 2023) than no-till (NT). Conversely, conventional tillage was also reported to increase BD by 6% at the 0-15 cm depth (Alleto and Coquet, 2009), lower the proportion of non-capillary pores (macropores [> 1 000 μm effective diameter]) by 13% at the 0-30 cm depth (Schwen *et al.*, 2011), and lower K_{sat} values by 87% at the 0-10 cm depth (Zhang *et al.*, 2011) compared to NT management.

The differences between the results of these studies can be attributed to several factors, including soil type and climatic conditions. More importantly, differences could have resulted from the timing of the sample collection. Although tillage can improve soil properties right after implementation, it has been demonstrated that natural soil consolidation over time can worsen these properties (Haruna *et al.*, 2018). In fact, Sandin *et al.* (2017) reported that, one month post tillage, the proportion of macropores (> 1 000 μm effective diameter) was significantly lower under harrowing than NT management. Consequently, this led to significantly lower K_{sat} values under tillage than NT management.

Besides tillage, producers include CCs into crop rotation cycles for several agroecological benefits such as nutrient cycling (Ashworth *et al.*, 2020), biological weed control (Mennan *et al.*, 2020), and soil loss reduction (García-González *et al.*, 2018). Categorically, due to their above and belowground biomass addition to the soil, CCs have been reported to significantly increase soil organic carbon (SOC) by 30% at the 0-15 cm depth (Olsen *et al.*, 2014), lower BD by 24% at the 0-5 cm depth (Nascante *et al.*, 2015), increase macroporosity by 33% at the 0-10 cm depth (Cercioglu *et al.*, 2018), and increase K_{sat} by 41% at the 5-10 cm depth (Liesch *et al.*, 2011) than no cover crop (NC) management. Contrarily, Kasper and Singer (2011), Nouri *et al.* (2019), Haruna and Nkongolo (2015a), and Bodner *et al.* (2013) reported that SOC, BD, macroporosity, and K_{sat}, respectively, were similar between CC and NC management practices.

This lack of consensus could have resulted due to differences in the CCs used. Different CCs have different root morphology and C:N ratios, both of which can influence the soil hydro-physical properties that can accrue from their usage. Another possible reason could be the amount of CCs used. Compared with single species CCs, multi-species CCs tend to significantly improve soil hydraulic and physical properties (Chu *et al.*, 2017). Therefore, multi-species CCs may be more beneficial in crop rotation cycles.

As adumbrated in the foregoing, tillage and CC management practices have resulted in conflicting effects on soil hydro-physical properties, and this warrants further studies to improve current understanding. More importantly, these management practices are often incorporated on the same fields for several years. Therefore, it is important to assess the effects of both tillage and CC management practices on soil hydro-physical properties over time. This study is novel because it simultaneously quantifies the interactive effects of tillage and cover crops on soil hydro-physical properties on an annual basis and tracks their temporal evolution over the initial two years following establishment. The objectives of this study included: a) evaluating the effects of tillage and cover crops on soil hydro-physical properties each year, and b) assessing changes in soil hydro-physical properties over 2 years due to tillage and cover crop management practices. It is hypothesized that: a) tillage and cover crops will have no effect on measured soil hydro-physical properties due to the limited time since research establishment, and b) over time, the effects of tillage and cover crops on soil properties will not be significant.

2. MATERIALS AND METHODS

2.1. Site description

This study was conducted at the Middle Tennessee State University Experiential Research Farms located in Murfreesboro, Tennessee, USA (35.8922 N, 86.2841 W) (Fig. 1). The average elevation of the field was 181 m above sea level, with 2% slopes. The USDA soil classification at the site was Armour series (Fine-silty, mixed, active, thermic Ultic Hapludalfs) (Soil Survey Staff, NRCS, USDA 2012). The particle size distribution of soils at the study site is shown in Table 1. The climatic classification of the site is Humid Subtropical (Köppen, 1936). Over the past three decades, the average annual precipitation was 1 357 mm with the months of October (85 mm) and May (139 mm) being the driest and wettest months, respectively. During this same period, the average atmospheric temperature was 14.6°C, with August (32.3°C) and January (-3.7°C) being the warmest and coldest months, respectively.

2.2. Management description

The experimental design for this study was a split-split plot block design, with two levels of tillage (Till *vs*. NT) and two levels of CCs (CCs *vs*. NC). The total field size was 5 ha, divided into 12 plots, with each plot measuring 211 × 29 m. The treatment sequence included tillage with cover crops (Till-CC), tillage with no cover crop (Till-NC), no tillage with cover crops (NT-CC), and no tillage with no cover crop (NT-NC). Each treatment was replicated 3 times.

Prior to the establishment of the research plots in 2020, the field was under corn (*Zea mays*) monocropping, often planted in April and harvested in September each year. The tillage management was no-till. For this study, the CC of choice were winter wheat (*Triticum aestivum*) and crimson clover (*Trifolium incarnatum*), planted in October (2020 and 2021) in the Till-CC and NT-CC fields at the following rates: 5.9 kg ha^{-1} for crimson clover and 22.4 kg ha^{-1} for winter wheat. These rates were based on the recommendation of the University of Tennessee Cooperative Extension.

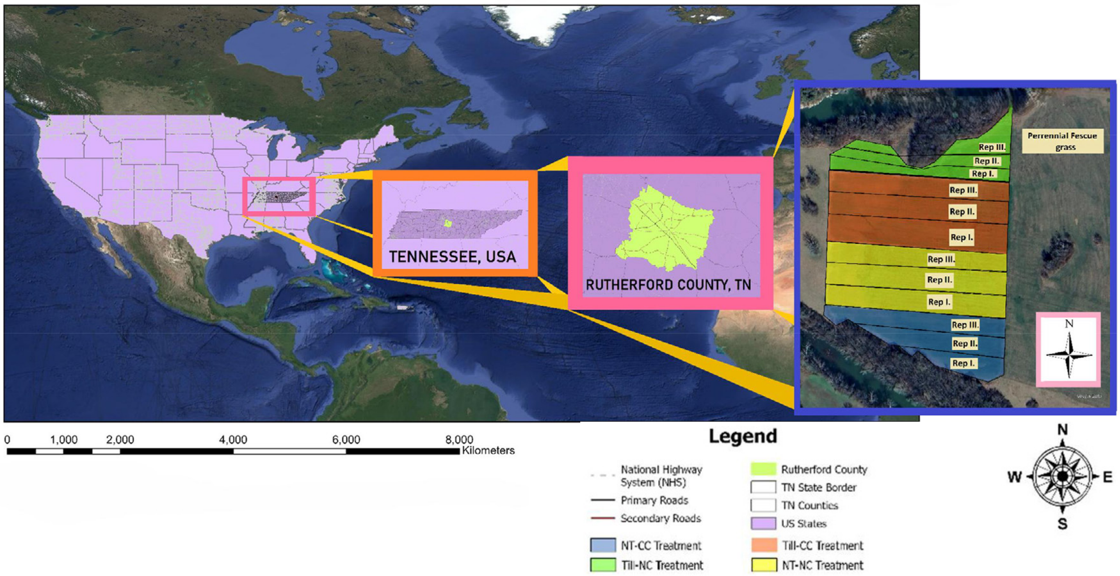

Fig. 1. Study site with the treatments highlighted.

Table 1. Particle size distribution as a function of depth for the study site (Armour series)

Depth (cm)	Clay	Silt	Sand
		(%)	
0-10	15.83	31.25	52.92
10-20	19.58	73.33	7.08
20-30	17.08	30.00	52.92

The CCs were allowed to grow during the winter months and terminated in April (2021 and 2022) using 4.15 kg ha^{-1} acid equivalent of glyphosate [*N*-(phosphonomethyl) glycine].

After CC termination, the Till-CC and Till-NC plots were tilled using a disc plow (Deere and Company, Moline, IL, USA) up to 15 cm depth. Prior to planting, a CP Series Frontier cultipacker (Deere and Company, Moline, IL, USA) was used to smoothen the seedbed. For the no-till plots (NT-CC and NT-NC), commodity crop (corn) seeds were drilled in. Corn was planted on all plots using a 51 cm row planter. Weeds were managed in the NT and NC treatments using glyphosate.

2.3. Soil sampling and analysis

Using a cylindrical core (5.5 cm inside diameter, and 6 cm long), soil samples were collected 1-2 days prior to CC termination from non-trafficked areas of each plot. The soil samples were collected at 0-10 cm, 10-20 cm, and 20-30 cm soil depths. A total of 36 soil samples were collected each year (4 treatments × 3 replicates × 3 soil depths). Using a soil spatula, each soil sample was trimmed, placed in pre-labeled plastic bags, and transported to the laboratory where they were stored in a refrigerator at 4°C before analysis.

After removal from the refrigerator, cheese cloth was placed at the bottom of each soil core and secured using rubber bands. The soils were then placed in a tub and saturated for about 48 h by gently raising the water level in the tub. The electrical conductivity of the water used was 0.3 dS m^{-1} at 20°C. The constant head method (Reynolds and Elrick, 2002) was used to determine the saturated hydraulic conductivity (K_{sat}). For samples with K_{sat} values < 0.1 cm h^{-1}, the falling head method was used for K_{sat} determination (Reynolds and Elrick, 2002). Water retention was measured using the methods of Dane and Hopmans (2002). Briefly, after K_{sat} measurements, soil water retention (at 0 [determined at saturation], -0.4, -1.0, -2.5, -5.0, -10.0, and -20.0 kPa pressures) was measured on the core samples using ceramic plates in a pressure chamber. Soil core samples were then broken into three aggregates and were used for water retention measurements at -33, -100, and -1 500.0 kPa pressures, respectively. This was done to ensure consistency across samples (standardization), since this reduces variability while maintaining internal pore structure (Dane and Hopmans, 2002). The aggregates were placed in a plastic container (5.5 cm inner diameter and 1.0 cm tall), placed on ceramic plates (appropriate for each pressure) and water retention at -33, -100, and -1 500 kPa pressures in a pressure chamber.

The van Genuchten (1980) (vG) function describes the water retention curve, and these parameters were estimated from measured soil water retention data using Eq. (1) below:

$$\theta = \theta_r + (\theta_S - \theta_r)[1 + (-\alpha h)^n]^{(1/n-1)}, \quad (1)$$

where: θ (cm^3 cm^{-3}) denotes the volumetric water content, θ_S and θ_r are the saturated and residual water contents, respectively, and h (cm) denotes the hydraulic head. The vG α (kPa^{-1}) and n parameters are the fitted parameters. The θ_S parameter was estimated based on saturation weight recalculation. The other parameters (θ_r, α, n, and m) were estimated using regression form equation 1 above. Soil water retention data were fitted using the van Genuchten equation through nonlinear regression, minimizing the sum of squared differences between observed and modeled volumetric water contents. Parameter estimation (θ_s, θ_r, α, and n) was performed using the Levenberg-Marquardt algorithm, with the constraint $m = 1 - 1/n$ to reduce model dimensionality. To ensure physically meaningful solutions and improve numerical stability, parameter bounds were imposed ($0 < \theta_r < \theta_s < 1$, $\alpha > 0$, $n > 1$), and matric potential values were analyzed on a logarithmic scale. To mitigate convergence to local minima inherent in nonlinear optimization, a multi-start approach was employed using multiple initial parameter estimates spanning plausible ranges, and the best-fit solution was selected based on the lowest residual sum of squares. Model performance was evaluated using standard goodness-of-fit metrics and visual inspection of residuals.

The residuals between the measured and predicted water retention values were used to calculate the root mean square error (*RMSE*) using Eq. (2) below:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{n}[z(Xi) - (Xi)]^2}, \tag{2}$$

where: N represents the number of samples, and $Z(X_i)$ and $\check{Z}(X_i)$ denote the observed and predicted values, respectively.

The core method was used for soil BD determination (Grossman and Reinsch, 2002). Particle size distribution was determined using the pipette method (Gee and Or, 2002). Soil organic carbon (SOC) was determined using the dry combustion method (at 1 200ºC) (Nelson and Sommers, 1996).

Using the capillary rise equation, pore size distribution was determined from the water retention data using the method of Jury *et al.* (1991). Macroporosity was calculated by subtracting the water content at -0.4 kPa from the water content at saturation. Coarse mesoporosity was calculated by subtracting the water content at -5 kPa from the water content at -0.4 kPa. Fine mesoporosity was determined by subtracting the water content at -33 kPa from the water content at -5 kPa, and microporosity was equal to the water content at -33 kPa (Zaibon *et al.*, 2016). The pore sizes were characterized as macropores (> 1 000 μm effective diameter), coarse mesopores (60-1 000 μm effective diameter), fine mesopores (10-60 μm effective diameter), and micropores (<10 μm effective diameter) (Zaibon *et al.*, 2016). Total pores were determined to be the θ at saturation (this was verified by summing all the pore sizes). Please note that these sizes (*e.g.* effective diameter) are representative pore diameters calculated using capillary rise equation to describe how easily fluid can move through a porous medium, rather than the actual geometric size of every individual pore.

Since pore spaces could be filled with either water or air, the proportion of pores filled with water and those filled with air was calculated. This was done to provide better insight and to determine if management practices can influence the proportion of air- and water-filled pore spaces. Using the methods of Haruna and Nkongolo (2015b), the air-filled pore spaces (AFPS) were determined as the difference between volumetric water content (θ) at -10 kPa soil water pressures and total pores. Additionally, the water-filled pore spaces were calculated as the difference between total pore spaces and AFPS.

2.4. Statistical analysis

In order to conduct the statistical analysis, experimental design and the data distribution were taken into consideration. The experiment was laid out using a split-split plot design. The whole plot factor included the tillage treatment (Till *vs*. NT), the split-plot factor was the CC treatment (CC and NC), and the soil depths (0-10, 10-20, and 20-30 cm) were the split-split plot factor. In accordance with the experimental design, analysis of variance (ANOVA) was selected to determine the treatment, depth, and year effects on measured soil properties. The Anderson-Darling normality test was utilized to determine if the data followed a uniform distribution. The normality test showed that all data followed a normal distribution ($p = 0.05$). The ANOVA for the main treatment and depth effects during both years was conducted in SAS version 9.4 (SAS institute, 2015) using the PROC MIXED procedure. This was important for evaluating the first hypothesis. Single degree of freedom contrasts for tillage and CCs were divided into 'NT vs. Till', 'NC vs. CC', and 'CC vs. Till'. For the soil depth data analysis, the Tukey's HSD post-hoc analysis was used for comparison. Additionally, ANOVA was conducted on soil samples collected during both years to determine any temporal effects of the various management practices on measured soil properties. This was essential in evaluating the second hypothesis. Statistical significance was evaluated at the $p \leq 0.05$ probability level.

3. RESULTS

3.1. Soil organic carbon, bulk density, saturated hydraulic conductivity, and soil water retention

The means with standard error and ANOVA of SOC, BD, K_{sat}, and θ at 0, -33, -100, and -1 500 kPa soil water pressures for all treatments and depths during 2021 and 2022 are displayed in Table 2. During 2021, the treatment effect was significant for BD, K_{sat}, and θ at 0, -33, -100, and -1 500 kPa soil water pressures. The results showed that the

Table 2. Means (with standard error) of soil organic carbon (SOC), soil bulk density (BD), saturated hydraulic conductivity (K_{sat}), and volumetric water content at 0, -33, -100, and -1500 kPa soil water pressures

Treatment	SOC (g kg^{-1})	BD (g cm^{-3})	K_{sat} (mm h^{-1})	Volumetric water content (cm^3 cm^{-3})			
				0 kPa	-33 kPa	-100 kPa	-1 500 kPa
			2021				
NT-CC	43.33±3.38	1.15±0.03b	40.64±2.07a	0.49±0.01a	0.16±0.01a	0.13±0.01a	0.09±0.01a
NT-NC	41.66±1.66	1.31±0.01a	29.97±3.24c	0.45±0.02ab	0.14±0.01b	0.11±0.01bc	0.05±0.01c
Till-CC	42.41±2.54	1.18±0.01b	38.41±1.48ab	0.48±0.01ab	0.14±0.01a	0.12±0.01ab	0.08±0.01b
Till-NC	43.85±4.50	1.27±0.02a	32.17±1.27bc	0.44±0.02b	0.10±0.01b	0.09±0.01c	0.05±0.01bc
Depth (cm)							
0-10	50.65±7.45a	1.18±0.10b	38.83±6.45a	0.49±0.04a	0.15±0.03a	0.13±0.03a	0.08±0.03a
10-20	41.77±5.96b	1.24±0.08a	35.12±7.04ab	0.47±0.04ab	0.14±0.03ab	0.12±0.03ab	0.07±0.03ab
20-30	36.02±7.75b	1.27±0.07a	31.95±8.21b	0.45±0.05b	0.12±0.04b	0.10±0.03b	0.05±0.03b
ANOVA p > F							
Depth	0.001	0.002	0.046	0.039	0.033	0.036	0.020
Treatment	0.942	<0.001	0.006	0.045	0.003	0.003	0.006
Tmt*depth	0.984	0.987	0.991	0.992	0.971	0.870	0.961
NT vs Till	0.570	0.079	0.326	0.821	0.329	0.666	0.331
CC vs NC	0.815	0.815	0.993	0.411	0.020	0.094	0.806
CC vs Till	0.968	<0.001	0.001	0.016	0.003	0.001	0.001
			2022				
NT-CC	43.94±1.47a	1.16±0.02c	43.56±1.87a	0.45±0.02a	0.13±0.01a	0.09±0.01a	0.07±0.01a
NT-NC	39.21±2.80b	1.32±0.02ab	28.80±2.51b	0.36±0.01c	0.10±0.01b	0.07±0.01b	0.04±0.01b
Till-CC	41.22±1.78ab	1.31±0.03b	31.04±1.58b	0.39±0.02b	0.13±0.01a	0.10±0.01a	0.07±0.01a
Till-NC	32.22±1.99c	1.37±0.02a	20.41±1.42c	0.34±0.01c	0.07±0.01c	0.05±0.01c	0.02±0.01b
Depth (cm)							
0-10	45.20±4.97a	1.24±0.10b	34.67±9.58a	0.40±0.08a	0.11±0.04	0.09±0.03a	0.06±0.03a
10-20	38.36±5.89b	1.28±0.09b	30.80±9.53ab	0.38±0.06ab	0.10±0.03	0.08±0.02ab	0.05±0.03ab
20-30	33.89±6.61c	1.34±0.10a	27.38±8.34b	0.36±0.06b	0.10±0.03	0.07±0.02b	0.04±0.02b
ANOVA p > F							
Depth	<0.001	0.002	0.013	0.046	0.505	0.012	0.049
Treatment	<0.001	<0.001	<0.001	0.001	0.001	<0.001	0.001
Tmt*depth	0.930	0.995	0.999	0.966	0.990	0.902	0.889
NT vs Till	0.141	0.016	0.264	0.061	0.071	0.054	0.311
CC vs NC	0.002	<0.001	<0.001	0.118	0.174	0.199	0.387
CC vs Till	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
			2021 vs. 2022				
ANOVA p > F							
NT-CC	0.838	0.434	0.003	0.068	0.028	0.027	0.046
NT-NC	0.233	0.245	0.161	0.004	0.001	0.001	0.472
Till-CC	0.530	0.002	0.002	0.001	0.128	0.013	0.020
Till-NC	0.011	0.021	0.001	0.001	0.067	0.059	0.083

NT-CC – no tillage with cover crop, NT-NC – no tillage with no cover crop, Till-CC – tillage with cover crop, Till-NC – tillage with no cover crop, Tmt*depth – treatment by depth interaction. Mean comparison was made when *p* values for the main effects were ≤ 0.05. Means with different letters within treatment and soil depth means for a soil property are significantly different at the 0.05 probability level.

values for K_{sat}, and θ at 0, -33, -100, and -1 500 kPa soil water pressures were significantly greater under NT-CC than other management practices evaluated. Admittedly, the Till-CC values were similar to those of NT-CC for these properties; however, they were numerically lower under Till-CC than under NT-CC management. Conversely, the BD values were significantly greater under NT-NC than other management practices. Interestingly, the K_{sat} and θ values at 0, -33, -100, and -1 500 kPa soil water pressures were significantly greater under CC than tillage management. Additionally, besides BD, all other treatment-averaged properties significantly reduced with increasing soil depth. Soil BD followed an inverse relationship.

During 2022, the SOC, BD, K_{sat} and water retention results responded similarly to various management practices as they did during 2021. However, the magnitude of differences between management practices for soil properties was greater in 2022 than 2021. For example, while SOC was numerically greater under NT-CC than other management practices during 2021, this difference was significant ($p < 0.001$, r = 89) during 2022. Further, SOC and K_{sat} were significantly greater under CC than NC management, while BD was significantly greater under NC than CC management (Table 2).

In order to evaluate the temporal effects of management practices on soil properties, treatment effects were compared between both years. The results showed that θ at -33, -100, and -1 500 kPa soil water pressures were 23, 44, and 29% greater, respectively, during 2021 than during 2022. Further, the θ values at 0, -33, and -100 kPa soil water pressures were 25, 40, and 57% greater, respectively, during 2021 than 2022 under NT-NC management. Under Till-CC, K_{sat}, θ at 0, -100, and -1 500 kPa soil water pressures were 24, 23, 20, and 14% greater, respectively, during 2021 than 2022, while BD was 11% greater during 2022 than 2021. For Till-NC management, SOC, K_{sat}, and θ at saturation were 36, 58, and 29% greater, respectively, during 2021 than 2022. Conversely, BD was 8% greater during 2022 than 2021 under Till-NC management (Table 2, Figs 2 and 3).

3.2. van Genuchten parameters

For this study, the van Genuchten (vG) function was used to determine and verify the shape of the water characteristic curve. This function (vG) provided a good fit with measured data ($R^2 > 0.87$, $RMSE < 0.04$). Figure 4 shows examples of the vG function fitted to measured data at 0-10, 10-20, and 20-30 cm soil depths for NT-CC during 2022. Table 3 shows the means and ANOVA for the vG α, θ_S, and n parameters during 2021 and 2022 as influenced by treatment and soil depths. During 2021, the depth-averaged vG α and θ_S parameter values were significantly greater under NT-CC than other management practices. Also, the vG α parameter was significantly greater under NT than tillage management, while the vG θ_S parameter was greater, significantly, under CC than NC management. The treatment-averaged θ_S values were significantly greater at the top 10 cm depth and decreased with increasing soil depth.

During 2022, the vG α and θ_S parameters were significantly greater under NT-CC management, while the vG n parameter value was greater under NT-NC than other management practices. Furthermore, the vG α and θ_S parameters were greater under CC than tillage management, but the vG n parameter was greater under tillage than CC management. Also, the results showed that the vG θ_S parameter was greater under CC than NC management. Additionally, all vG parameters decreased with increasing soil depth (Table 3).

A comparison of all management practices during both years showed that, under NT-CC management, the vG n parameter was 83% greater in 2021 than in 2022. Under NT-NC management, the vG α and θ_S parameters were 225 and 32% greater, respectively during 2021 than 2022, while the n parameter was 283% greater during 2022 than 2021. For Till-CC management, the vG α parameter was 346% greater during 2022 than 2021. At the same time, the vG θ_S parameter was 14% greater during 2021 than 2022. Under Till-NC management, the vG θ_S parameter was 41% greater during 2021 than 2022, while being 183% greater during 2022 than during 2021 (Table 3).

3.3. Pore size distribution, air- and water-filled pore spaces

The depth-averaged and treatment-averaged mean and ANOVA results for pore size distribution, AFPS, WFPS, and total pores are shown in Table 4. During 2021, the depth-averaged coarse mesopores and AFPS were significantly greater under Till-NC management, while the proportions of fine mesopores, micropores, WFPS, and total pores were greater under Till-NC than other management practices. Further, the proportions of coarse mesopores, fine mesopores, and micropores were greater under tillage than NT management. The results also showed that the proportion of AFPS was greater under NC than CC while that of WFPS was greater under CC than NC management. While the proportion of coarse mesopores was greater under tillage than CC management, the proportions of fine mesopores, micropores, WFPS, and total pores were greater under CC than tillage management. Generally, all pore sizes analyzed, including AFPS and WFPS, decreased with increasing soil depth (Table 4).

During 2022, the depth-averaged proportions of macropores, coarse mesopores, AFPS, WFPS, and total pores were significantly greater under NT-CC than other management practices. In contrast, the proportion of micropores was greater under NT-NC than other management practices. A comparison between tillage and NT showed that macropores were greater under tillage than NT, while AFPS and total pores were greater under NT than tillage management.

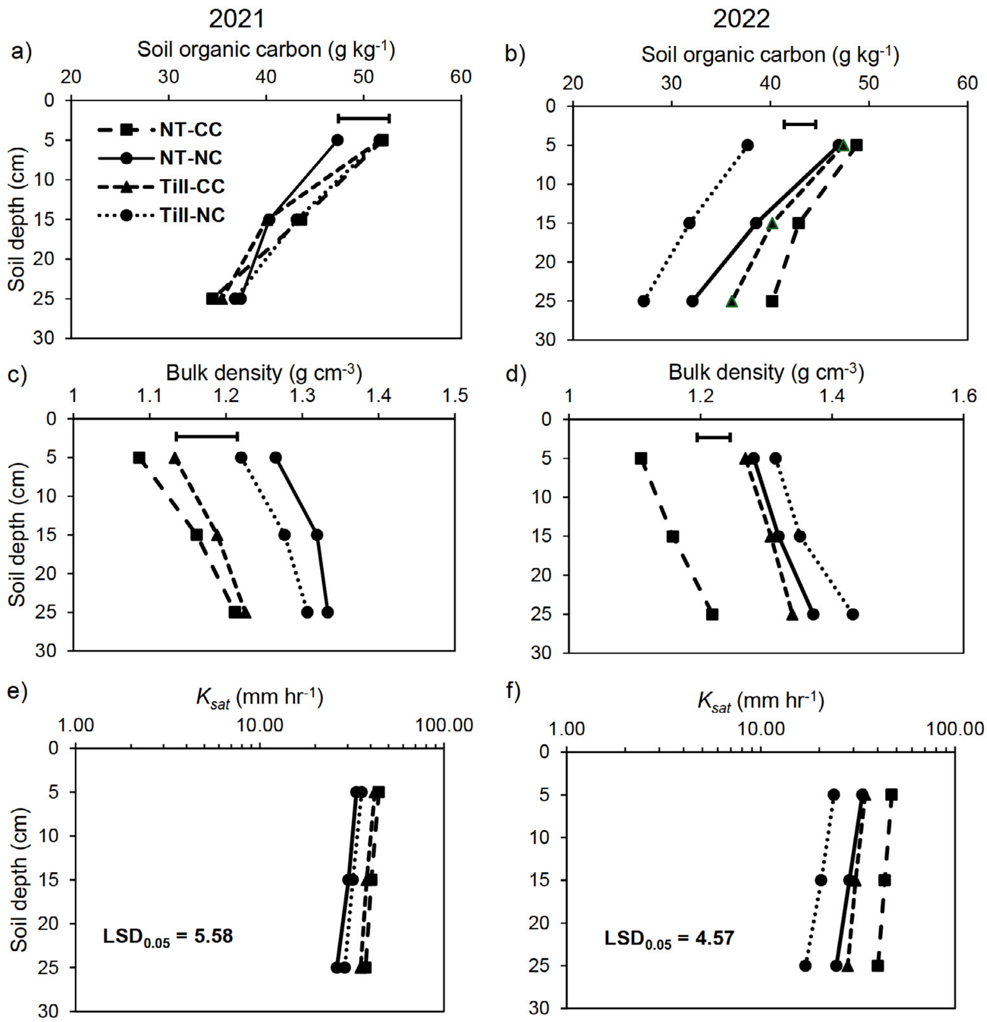

Fig. 2. Soil properties relative to soil depth under no-till with cover crop (NT-CC), no-till with no cover crop (NT-NC), tillage with cover crop (Till-CC) and tillage with no cover crop (Till-NC) treatments during 2021 and 2022. The bars show the least square difference (LSD) at $p \leq 0.05$ for soil organic carbon and bulk density. Due to the logarithmic scale used, the LSD for saturated hydraulic conductivity (Ksat) is indicated. Please note that LSD represents the best-fit line for the data points. Thus, smaller LSD values mean the model fits the data well.

Further, the proportions of macropores, coarse mesopores, and WFPS were greater under CC than tillage management (Table 4, Fig. 5).

Between 2021 and 2022, significant differences for measured pore sizes (except coarse mesopores), AFPS, and WFPS were also observed for many treatments. For example, the proportions of macropores under NT-NC and Till-CC were 100 and 13% greater, respectively, during 2021 than 2022. While the proportions of AFPS and WFPS under Till-NC remained fairly consistent, they decreased by 12 and 17%, respectively, from 2021 to 2022 under NT-NC management. Similarly, the proportions of AFPS and WFPS for NT-CC were reduced by 16% between 2021 and 2022. Overall, total porosity was also significantly different for all treatments except NT-CC. For example, NT-NC and Till-NC yielded a 15 and 13% reduction in total pores, respectively, between 2021 and 2022.

4. DISCUSSION

4.1. Soil organic carbon, bulk density, saturated hydraulic conductivity, volumetric water content

Soil organic carbon is an important dynamic soil property because of its direct relationship to C sequestration, and also because it is an indicator for soil health and erosion susceptibility (Haruna and Anderson, 2023; Hancock *et al.*, 2025). Considering these factors, accumulation of SOC through best management practices is beneficial, not only at the farm scale, but also on the regional and global scale. In assessing four treatments, the current study observed initially great SOC values under Till-NC management during the first year (2021); however, this same treatment significantly lowered SOC values during the second year. Contrarily, the NT-CC treatment maintained high amounts of SOC throughout the two-year study. Breil

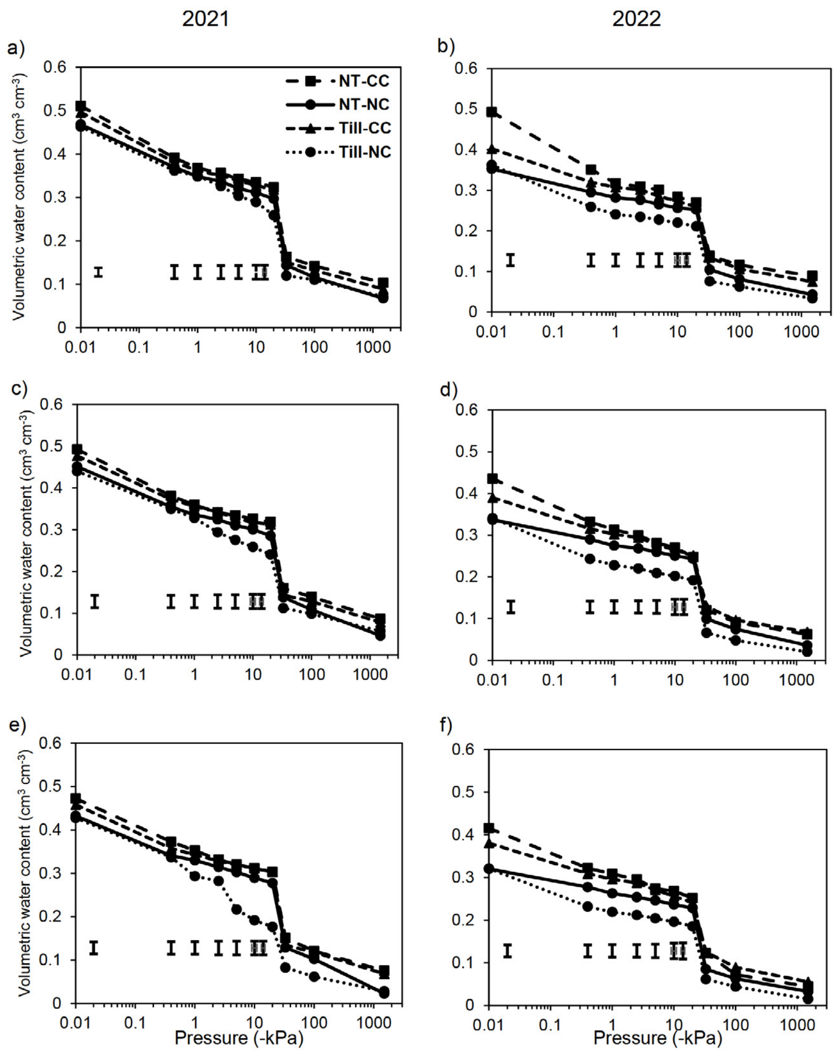

Fig. 3. Soil water retention under no-till with cover crop (NT-CC), no-till with no cover crop (NT-NC), tillage with cover crop (Till-CC) and tillage with no cover crop (Till-NC) treatments during 2021 and 2022; a) and b) 0-10 cm, c) and d) 10-20 cm, and e) and f) represents 20-30 cm soil depths. Bars represent least square differences (LSD) at $p \leq 0.05$ at each measured soil water pressure. Please note that -0.01 kPa pressures represent water content at saturation. Please note that LSD represents the best-fit line for the data points. Thus, smaller LSD values mean the model fits the data well.

et al. (2023) reported similar findings. This was probably due to several mechanisms. First, annual tillage can expose buried SOC content to microbial activity and, consequently, increased SOC breakdown and CO_2 emission. In fact, tillage has been reported to significantly reduce SOC and increase CO_2 emissions by 7 times more than NT management (Buragienė *et al.*, 2019).

Another possible mechanism for differences in SOC between management practices could be due to residue return under CC management. Prior to decomposition, the surface CC biomass may provide soil cover, buffering the soil against rainfall energy, as well as regulating soil temperature compared with NC management (Blanco-Canqui *et al.*, 2011). Additionally, according to Haruna *et al.* (2017), the lack of stable soil temperatures experienced under NC management can result in microbial activity that rapidly depletes OM and thereby decreases SOC. Further, Hu *et al.* (2024) demonstrated that the greatest changes in SOC were dominated by enzyme activity, the microbial community, and microbial necromass C, all of which can be influenced by CCs, specifically legumes compared to non-legumes. These observations support previous findings that CCs improve C sequestration and improve SOC stocks over time (Duval *et al.*, 2016; Novara *et al.*, 2019). However, it may take several years of implementation to notice these benefits, and the length of time may depend on the composition of the residues and other abiotic factors.

As noticed in this study, the decrease in SOC with an increase in depth is expected and likely due to the decrease in OM and root residue with increasing depth. In general, the current results suggest that tillage may immediately benefit SOC accumulation in the soil but may not persist

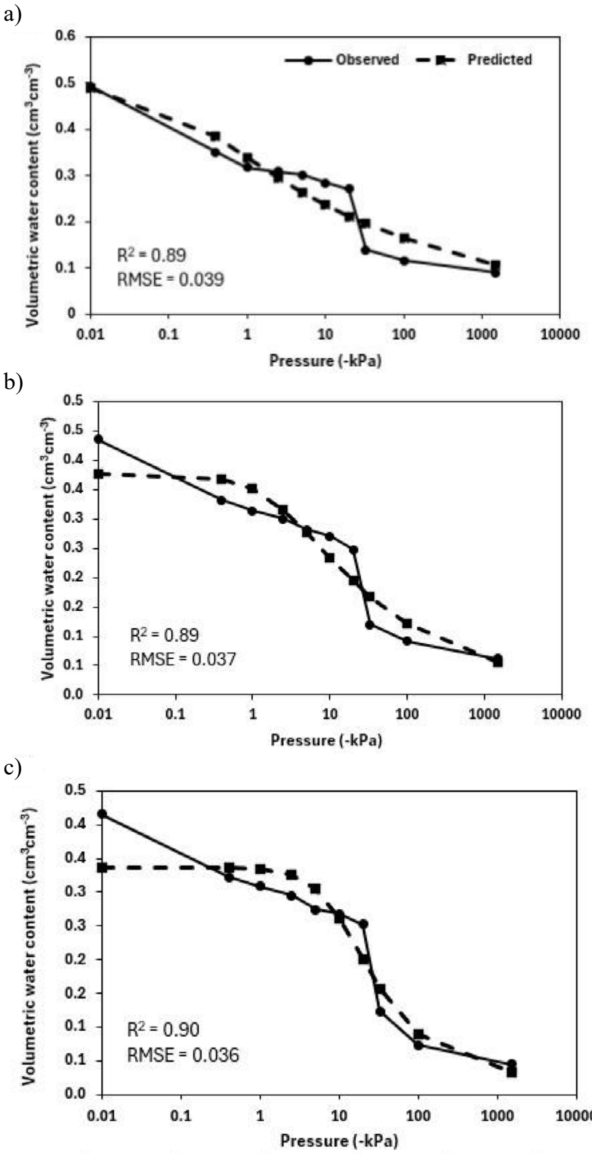

Fig. 4. Estimated van Genuchten parameters fitted to observed data for a select management (No-tillage with cover crop) at: a) 0-10 cm, b) 10-20 cm, and c) 20-30 cm soil depths during 2022.

with time (over a 2-year period). Additionally, the significant interaction between CC *vs*. NC demonstrates the potential benefits of CC over time.

Another important soil quality indicator is bulk density, which can affect the ability of plant roots to penetrate the soil, as well as alter fluid movement through the surface and soil profile. The mechanical agitation of the soil tends to aerate the soil, lowering the dry soil mass to volume ratio, especially right after tillage, as reported by Osunbitan *et al.* (2005) and Tian *et al.* (2022). However, this benefit of tillage may not persist and can be short-term, as noticed during the second year under tillage management. This was probably due to the natural consolidation of soil particles due to kinetic energy transfer from raindrops, especially under Till-NC management.

Regarding CC management, the decreased bulk density may be attributed to many factors: 1) belowground root activities of the CCs in alleviating soil compaction (Jabro *et al.*, 2021); 2) an increase in SOC which reduces the soil mass to volume ratio (Robinson *et al.*, 2022); and 3) the aboveground biomass accumulation which protects the soil surface from the kinetic energy of raindrops and, therefore, prevents consolidation and clay particle flocculation due to rainfall (Céspedes-Payret *et al.*, 2017). Given that NT-CC resulted in the lowest BD values during both years, this suggests that a combination of NT and CCs may alleviate compaction and enhance soil structure, as well as improve root penetration and fluid movement.

It is important to note that NT systems alone (without CCs) have been reported to have increased BD due to lack of surface cover (Reinert *et al.*, 2008). However, the current result shows that inclusion of CCs in NT systems can provide the bio-tillage effect necessary to lower soil BD. This disproved the first hypothesis that tillage and cover crops will have no effect on soil BD due to the limited time since establishment. In general, the CC vs. Till contrast for BD during 2022 was interesting. It showed that CC may provide a more lasting soil quality benefit by lowering BD prior to planting the subsequent commodity crop. Although tillage prior to planting can also provide similar benefits, the lower BD derived from tillage does not last as long as those derived from CC (Haruna *et al.*, 2018, 2023).

Besides BD, the K_{sat} of a soil is instrumental in predicting and describing water movement and is one of the most important hydro-physical properties necessary for plant growth and environmental sustainability. Variabilities observed in K_{sat} are often due to pore size distribution, pore continuity and geometry, BD, particle size distribution, and land management (Shukla, 2014; Baiamonte *et al.*, 2017). The significantly greater K_{sat} values under NT-CC during both study years were attributed to several mechanisms. First, NT management has been reported to reduce soil pore tortuosity (Haruna and Nkongolo, 2015b) and increase the proportion and connectivity of non-capillary pores (Schlüter *et al.*, 2018; Talukder *et al.*, 2022) compared with conventional tillage. Second, the roots of CCs can lower BD, with the resultant effect of improving water flow under saturated conditions (De Baets *et al.*, 2011; Haruna *et al.*, 2017; Cercioglu *et al.*, 2019). Third, the aboveground biomass from CCs can also protect the soil surface from rainfall energy that may cause surface crusting or consolidation (Brant *et al.*, 2017). Finally, CCs have been reported to increase water transpiration (Peters and Haruna, 2024), leading to an initial reduction in water content. However, under saturated conditions, this effect moves the wetting front deeper into the soil, leading to enhanced soil water recharge and storage. Therefore, it can be argued that a combination of little mechanical disturbance with the inclusion of CCs can improve ground water recharge and lower surface runoff. This was also demonstrated to improve over

Table 3. Treatment effects on saturated water content (θ_S) and fitted van Genuchten parameters (α and n) with respect to soil depth during 2021 and 2022

Treatment	α (cm^{-1})	θ_S (cm^3 cm^{-3})	n	R^2	*RMSE*
			2021		
NT-CC	1.85a	0.44a	2.95	0.88	0.04
NT-NC	0.13b	0.37b	1.56	0.90	0.04
Till-CC	0.61b	0.40ab	2.59	0.87	0.04
Till-NC	1.00ab	0.38b	1.44	0.90	0.04
Depth (cm)					
0-10	1.08	0.42a	1.87	0.88	0.04
10-20	0.99	0.40ab	2.23	0.89	0.04
20-30	0.63	0.38b	2.30	0.90	0.04
ANOVA p > F					
Depth	0.571	0.049	0.845	-	-
Treatment	0.022	0.021	0.289	-	-
Tmt*depth	0.681	0.993	0.983	-	-
NT vs Till	0.009	0.088	0.856	-	-
CC vs NC	0.623	0.297	0.712	-	-
CC vs Till	0.084	0.012	0.063	-	-
			2022		
NT-CC	4.72a	0.40a	1.61c	0.90	0.03
NT-NC	0.04b	0.28c	5.98a	0.94	0.02
Till-CC	2.72ab	0.35b	2.64bc	0.92	0.02
Till-NC	0.81ab	0.27c	4.08ab	0.87	0.04
Depth (cm)					
0-20	4.56a	0.35a	3.95	0.90	0.03
10-20	0.96b	0.32ab	3.61	0.90	0.03
20-30	0.70b	0.30b	3.18	0.91	0.03
ANOVA p > F					
Depth	0.047	0.031	0.749	-	-
Treatment	0.010	<0.001	0.006	-	-
Tmt*depth	0.119	0.547	0.968	-	-
NT vs Till	0.327	0.263	0.090	-	-
CC vs NC	0.661	0.049	0.603	-	-
CC vs Till	0.026	<0.001	0.002	-	-
			2021 vs. 2022		
ANOVA p > F				-	-
NT-CC	0.515	0.207	0.011	-	-
NT-NC	0.034	0.001	0.007	-	-
Till-CC	0.016	0.006	0.944	-	-
Till-NC	0.811	0.001	0.039	-	-

NT-CC – no tillage with cover crop, NT-NC – no tillage with no cover crop, Till-CC = tillage with cover crop, Till-NC – tillage with no cover crop, Tmt*depth – treatment by depth interaction. Mean comparison was made when p values for the main effects were ≤ 0.05. Means with different letters within treatment and soil depth means for a soil property are significantly different at the 0.05 probability level.

Table 4. Pore size distribution, air filled pore spaces, water filled pore spaces, and total pores as affected by treatment during 2021 and 2022

Treatment	Macropores (> 1 000 μm)	Coarse mesopores (60-1 000 μm)	Fine mesopores (10-60 μm)	Micropores (< 10 μm)	Air filled pores spaces	Water filled pore spaces	Total pores
	($m^3\ m^{-3}$)						
2021							
NT-CC	0.11±0.01	0.05±0.01b	0.17±0.01ab	0.16±0.01a	0.17±0.02b	0.32±0.01a	0.49±0.01ab
NT-NC	0.10±0.01	0.04±0.01b	0.17±0.01ab	0.15±0.01a	0.16±0.01b	0.30±0.01a	0.46±0.01b
Till-CC	0.09±0.01	0.04±0.01b	0.19±0.01a	0.17±0.01a	0.18±0.01ab	0.32±0.01a	0.50±0.01a
Till-NC	0.11±0.01	0.08±0.02a	0.16±0.01b	0.12±0.01b	0.21±0.02a	0.25±0.02b	0.46±0.02b
Depth (cm)							
0-10	0.11±0.02	0.06±0.01	0.18±0.01a	0.16±0.02	0.19±0.04	0.32±0.03a	0.49±0.03
10-20	0.10±0.02	0.05±0.02	0.17±0.01ab	0.15±0.02	0.18±0.04	0.30±0.04ab	0.48±0.04
20-30	0.10±0.02	0.05±0.05	0.17±0.03b	0.14±0.04	0.18±0.06	0.28±0.07b	0.46±0.05
ANOVA p > F							
Depth	0.467	0.510	0.045	0.217	0.794	0.047	0.204
Treatment	0.433	0.011	0.015	0.002	0.042	0.001	0.048
Tmt*depth	0.923	0.352	0.164	0.473	0.876	0.607	0.993
NT vs Till	0.899	0.016	0.018	0.005	0.290	0.079	0.562
CC vs NC	0.745	0.087	0.837	0.187	0.036	0.035	0.779
CC vs Till	0.112	0.048	0.018	0.003	0.419	0.001	0.014
2022							
NT-CC	0.11±0.01a	0.05±0.01a	0.16±0.01	0.13±0.01ab	0.18±0.02a	0.27±0.01a	0.45±0.02a
NT-NC	0.05±0.01d	0.03±0.01b	0.16±0.01	0.14±0.01a	0.14±0.01b	0.25±0.01a	0.39±0.01b
Till-CC	0.08±0.01c	0.04±0.01ab	0.15±0.01	0.12±0.01b	0.11±0.01b	0.26±0.02a	0.38±0.02b
Till-NC	0.10±0.01b	0.03±0.01b	0.15±0.01	0.13±0.01ab	0.12±0.01a	0.21±0.01b	0.40±0.01ab
Depth (cm)							
0-10	0.10±0.04a	0.04±0.02	0.16±0.02	0.13±0.02	0.17±0.05	0.26±0.05	0.42±0.05
10-20	0.08±0.03b	0.04±0.02	0.15±0.02	0.13±0.02	0.16±0.04	0.25±0.04	0.40±0.05
20-30	0.07±0.02b	0.04±0.02	0.15±0.02	0.13±0.02	0.15±0.04	0.24±0.04	0.39±0.05
ANOVA p > F							
Depth	0.006	0.852	0.807	0.731	0.580	0.540	0.243
Treatment	<0.001	0.044	0.504	0.048	0.001	0.012	0.035
Tmt*depth	0.355	0.871	0.892	0.962	0.918	0.894	0.847
NT vs Till	<0.001	0.325	0.783	0.561	0.001	0.270	0.021
CC vs NC	0.318	0.350	0.140	0.095	0.928	0.080	0.149
CC vs Till	0.003	0.046	0.995	0.127	0.136	0.006	0.191
2021 vs. 2022							
ANOVA p > F							
NT-CC	0.812	0.909	0.005	0.009	0.496	0.005	0.052
NT-NC	0.003	0.058	0.011	0.015	0.007	0.001	0.001
Till-CC	0.001	0.198	0.001	0.004	<0.001	0.001	<0.001
Till-NC	0.458	0.118	0.356	0.551	0.527	0.216	0.001

NT-CC – no tillage with cover crop, NT-NC – no tillage with no cover crop, Till-CC – tillage with cover crop, Till-NC – tillage with no cover crop, Tmt*depth – treatment by depth interaction. Mean comparison was made when p values for the main effects were ≤ 0.05. Means with different letters within a parameter and soil depth means for a soil property are significantly different at the 0.05 probability level.

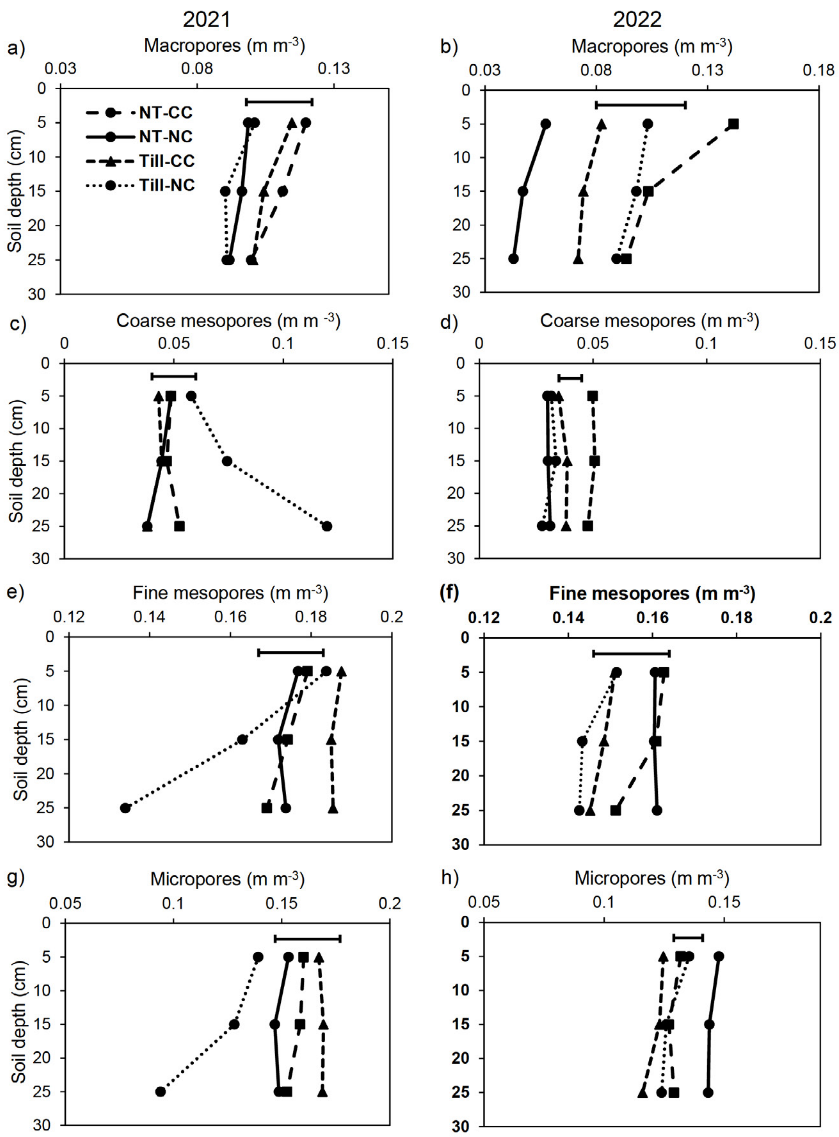

Fig. 5. Pore size distribution with respect to soil depth under no-till with cover crop (NT-CC), no-till with no cover crop (NT-NC), tillage with cover crop (Till-CC) and tillage with no cover crop (Till-NC) treatments during 2021 and 2022. The bars indicate least square differences (LSD) at $p \leq 0.05$ at all depths. LSD represents the best-fit line for the data points. Thus, smaller LSD values mean the model fits the data well.

time (Table 2), and this disproved the second hypothesis over time: the effects of tillage and cover crops on K_{sat} will not be significant because any changes would be transient. While these mechanisms agreed with the BD results, they were also supported by the contrast between CC and tillage (for both years) and between CC and NC (for 2022 only).

Conversely, Akiş and Lal (2022) reported that chisel plow tillage had greater K_{sat} values than NT management due to lower BD values under the chisel plow management. The reasons for the contrasting results could be due to the timing of soil sampling. Since the soil samples were collected just after tillage, the lower BD and K_{sat} values reported by Akiş and Lal (2022) could be due to mechanical agitation. Further, while the current study included CCs, the study by Akiş and Lal (2022) did not include CC with their tillage management. Therefore, it can be concluded that CCs can improve the hydraulic benefits of NT systems.

Generally, the lower K_{sat} values with increasing soil depth were attributed to the greater BD values and lower CC roots at these depths. The results for K_{sat} further confirm the potential benefits of the NT-CC treatment, as the significantly higher K_{sat} measurements were recorded under this treatment for both years. The difference in CC vs. NC and CC vs. Till management demonstrates further benefits that can be seen under CCs. These findings are supported by the study of Çerçioglu *et al.* (2019) describing a significant increase in K_{sat} under CC management, with the highest measurements recorded 5 years after CC implementation.

The increase in K_{sat} due to CCs may be attributed to an increase in SOC and reduction in BD observed under CC management that improves soil structure and aggregate stability. Further, CCs can increase belowground root biomass which can create larger continuous pores that facilitate water drainage (Haruna *et al.*, 2017). In addition, plant roots and root exudates stabilize soil pores and soil structure. Overall, CCs improve soil structure and help stabilize and maintain total porosity and pore size distribution while reducing tortuosity often seen with conventional tillage, which largely influences K_{sat} and explains the significantly higher values observed under CC treatments. The K_{sat} values for NT-CC were significantly higher in both years and increased between the years, suggesting that the long-term effects of NT-CC may continuously improve soil structure and stability with time. The treatment-averaged measurements for K_{sat} indicate that this property also decreases with increasing depth, which may be explained by the reduction in SOC and root biomass, as well as increases in BD in the subsurface horizons.

While K_{sat} provides information about water movement specific to non-capillary pores, the soil water retention data can provide more in-depth information about water movement and storage as dictated by all active pores. Further, the soil water retention curve can also provide useful information on water availability and capacity, along with the potential for surface runoff (Yu *et al.*, 2016). According to Otalvaro *et al.* (2016), the greatest influence of soil structure on water retention often occurs between saturation and -100 kPa, while soil texture is more responsible for retained water at pressures < -100 kPa soil water pressures. At each soil depth, the results showed that differences in θ occurred at higher pressures (Fig. 3). As such, differences in θ at these pressures were attributed to treatment-induced changes to soil structure (Otalvaro *et al.*, 2016). Therefore, NT-CC significantly improved soil water retention at higher soil water pressures due to: 1) CC root activity, 2) soil structure stabilization by SOC, and 3) CC-induced reduction in rainfall impact on soil surface (Dabney *et al.*, 2001; Hatfield, 2015), which can maintain soil structure integrity.

Averaged over all soil depths, the treatment effects on soil water retention extend beyond the higher pressures (Table 2). The NT-CC management still retained more θ at < -100 kPa soil water pressures. This supports earlier speculations on the effects of CCs in lowering the kinetic energy of raindrops. Additionally, the CC vs. Till interaction was significant for both years at all water pressures. This signifies the importance of CC implementation and underlines the impact of tillage on volumetric water content. While CCs can help restore soil structure and porosity to improve water retention, conventional tillage appears to yield significantly reduced θ content at all measured soil water pressures.

Regardless of management practice and soil depth, θ at all measured soil water pressures were lower in 2022 than in 2021. The repeated wetting and drying over time may have changed soil pore structure (Fomin *et al.*, 2023), decreased the uniformity of interconnected pores (Pires, 2023), and entrapped more air within the pores (Princ *et al.*, 2024). Taken together, these mechanisms may have lowered soil water retention over time. Therefore, in predicting soil water storage over time, the mechanisms mentioned in the forgoing should be considered.

4.2. van Genuchten parameters

The vG α parameter is a numerical parameter which corresponds to the matric potential axis of the soil water retention curve (van Lier and Pinheiro, 2018). Further, it is inversely related to the air-entry suction. Consequently, the greater vG α parameter under NT-CC than other managements during both years shows that this management (NT-CC) can increase water retention at measured soil water pressures. This agreed with the water retention results. During 2021, the greater vG α parameter under NT than Till management suggests greater water retention and less tortuous pores under NT, as speculated above. During 2022, CC had a greater vG α parameter than Till probably due to the activity of CC roots.

The vG θ_S parameter measures the maximum amount of water that a soil can hold. As apparent in Table 3, the depth-averaged measurements were significant for both 2021 and 2022, with NT-CC representing the highest vG θ_S parameter measured during either year. Additionally important was the interaction observed between CC vs. Till (both years) and CC vs. NC (2022). The significance of the CC vs. Till treatment interaction is further evidenced with the vG θ_S parameter data, as Till-NC was notably lower than NT-CC throughout the study. This was also attributed to CC root activity (responsible for increasing the vG θ_S parameter under NT-CC management) and greater soil consolidation and BD (responsible for lowering the vG θ_S parameter under Till-NC management). Furthermore, enhanced tortuosity observed in tilled plots may also explain these results. These findings mirror previously discussed results and may also explain higher water retention and K_{sat} values reported under CC management. Overall, the vG parameters confirmed the effects of management practices on soil water retention observed from laboratory measurements.

4.3. Pore size distribution, air- and water-filled pore spaces

Pore size distribution and total porosity have major effects on the other soil properties previously discussed such as BD, K_{sat}, and water retention. While all pore sizes are crucial to soil water movement and storage, the proportions of macropores, coarse mesopores, and micropores are of particular interest. This is because macropores and coarse mesopores often dictate drainage by gravity, and micropores relate to water retention, dictated by matric potentials. During 2021, NT-CC and Till-CC had greater total pores, which was attributed to the greater proportion of capillary pores under this management. This may have contributed to the significantly greater proportion of WFPS under these managements, and this agrees with water retention data. Although the Till-NC management had greater coarse mesopores, these pores were filled with air, demonstrating the effect of gravity on these non-capillary pores. The CC vs. Till and CC vs. NC contrasts showed that the pores generated by CCs, regardless of their sizes, were often filled with water compared with those generated by NC and Till. This was attributed to the ability of CCs to reduce surface evaporation of water, as reported by Peters and Haruna (2024).

In a study by Tan *et al.* (2025), no-till management reduced macroporosity and total porosity at the top 30 cm soil depth, compared with rotary tillage and subsoiling after 4 years. Contrarily, after two years, the current study showed that the proportions of both macropores and coarse mesopores were greater under NT-CC than other managements probably due to: 1) less soil disturbance under NT management, 2) the root activity of CCs, 3) lower BD values under NT-CC management, and 4) the greater SOC values under NT-CC, which may have stabilized the pores generated by the aforementioned mechanisms (Blanco-Canqui and Lal, 2008). Interestingly, the NT-CC management also had a greater proportion of AFPS and WFPS. This was attributed to the influence of these management practices on the proportion of pores attributable to fast and slow drainage.

It should be noted that, while Till-NC had a greater proportion of AFPS during 2021, NT-CC had greater proportions of AFPS and WFPS during 2022. This could either be due to: 1) the effects of tillage-induced tortuosity that was magnified during the earlier years of tillage and CC establishment, or 2) the roots of CCs, once established for more than one year, created more continuous pores leading to more water drainage and retention, or 3) both. In any case, the inclusion of CC with NT management seems to improve water movement and storage, and possibly gaseous interchange. This also agrees with the results of the vG parameters where NT-CC had greater α and θ_S parameters.

As expected, the proportions of pore sizes reduced over time and with increasing soil depth. This may also have contributed to the lower water retention under all management practices over time and with increasing soil depth. Generally speaking, CCs can improve pore size distribution, increase total porosity, and retain higher WFPS, which has strong impacts on soil health.

From an agroecological point of view, current results showed that NT-CC may be a more sustainable management practice than the other practices studied. This is because NT-CC reduces soil disturbance, increases soil cover, and biomass return. These attributes led to lower soil BD, greater SOC values, and improved water retention. Additionally, increases in macroporosity under NT-CC systems contribute to better water penetration and infiltration (Page *et al.*, 2019). While most of the soil properties evaluated decreased over time, the decrease was less under NT-CC than other management practices, further suggesting the benefit of this management in sustainable agriculture.

Although this study provided interesting results on the coupled influence of CCs and tillage management practices on soil hydraulic properties, it was limited to one geographic region. Future studies should explore the effects of these management practices on several regions, soil types, and climatic conditions. This will provide more insight on any effect of these variables on soil properties and will better inform management decision making.

5. CONCLUSIONS

This study evaluated the effects of tillage and cover crop on select soil hydro-physical properties in a rain-fed silt loam soil during 2 years. The results showed that, after 2 years, NT-CC improved SOC and lowered BD because of the limited disturbance of no-till management, and the effects of above- and belowground CC biomass. Consequently, K_{sat} and water retention were significantly greater under NT-CC than any other management practice evaluated. Further, NT-CC improved the proportions of capillary and non-capillary pores after 2 years, suggesting that CCs can enhance the ability of NT management to improve water drainage and storage at different soil water pressures. While Till-NC improved AFPS during the first year, NT-CC improved both AFPS and WFPS during the second year, suggesting a more lasting agronomic and environmental benefit. In general, the soil hydro-physical properties evaluated responded more positively to NT-CC than other management practices during the 2 year study period.

Authors contributions: O.M.P. interpreted the results and wrote the original draft of the manuscript, S.I.H. designed the study, acquired funding, and critically revised the manuscript. All authors gave final approval of the manuscript.

Competing interest. The authors declare that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this study.

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Data availability. The data that support the findings of this study are available from the corresponding author upon reasonable request.

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