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# Influence of no-till cover crops on the physical and hydraulic properties of a Paleudult**

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A b s t r a c t. The influence of a single species cover crop on soil hydraulic properties during one growing season are well known. However, the influence of multi-year and multi-species cover crops on soil physical and hydraulic properties are not yet fully understood. The current study was set up using a completely randomized block design during 2021 and 2022, it investigated the effects of a multi-species cover crop (winter wheat (*Triticum aestivum* L.), crimson clover (*Trifolium incarnatum* L.), triticale (*Triticale hexaploide* Lart), hairy vetch (*Vicia villosa*), oats (*Avena sativa*), and cereal rye (*Secale cereale* L.)) on bulk density, soil organic carbon, saturated hydraulic conductivity, pore-size distribution, and volumetric water content at 0, -0.4, -1, -2.5, -5, -10, -20, -33, -100, and -1 500 kPa soil water pressures. The soil samples were collected in 10 cm increments from the soil surface down to 30 cm. After 2 years, the results showed that cover crop reduced bulk density by 17% as compared with no cover crop management. Further, the cover crop-induced increases in soil organic carbon as well as in macro- and mesoporosity led to 23, 25, and 28% increases in volumetric water content at 0, -33, and -100 kPa soil water pressures respectively, relative to no cover crop management. When comparing the two years of the study, under cover crop management alone, saturated hydraulic conductivity was higher in 2021 as compared to 2022, which suggests that cover crop-induced improvements in some hydraulic properties may not be proportional over time. In general, cover crops improved the measured soil hydraulic properties after 2 years and this has the potential to be beneficial for improving soil water storage.

K e y w o r d s: bulk density, cover crop, saturated hydraulic conductivity, soil organic carbon, water retention

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## INTRODUCTION

The increasing global human population, coupled with a decrease in arable land per capita is an agronomic challenge that needs to be overcome in order to feed the projected 9.2 billion humans by 2050 (Connor and Minguez, 2012; Grimblatt *et al.*, 2021). This challenge is being exacerbated by the increasing variability in the global climate. In order to meet this challenge, several soil management practices have been encouraged, with the aim of increasing crop productivity. These management practices include conservation tillage and the inclusion of cover crops (CCs) in crop rotation cycles, among others.

Conservation tillage, which requires that at least 30% of the residues of the previous crop are left on the soil surface to reduce soil loss and improve soil organic carbon (SOC) stocks (Lal *et al.*, 2003), involves reduced soil manipulation. For instance, it has been estimated that 24-40 Mt C $y^{-1}$ could be sequestered through the widespread adoption of conservation tillage in the US alone (Lal *et al.*, 2003). Globally, if all croplands are converted to conservation tillage, about 25 Gt C could be sequestered over the next half-century (Pacala and Socolow, 2004). Thus, the adoption of no-till (NT), a form of conservation tillage, has been increasing steadily due to its benefits to the ecosystem. For example, NT has been reported to increase SOC by 14% (Veum *et al.*, 2022), reduce bulk density (BD) by 13% (Blanco-Canqui *et al.*, 2009), and increase aggregate stability by 70% (Alvarez and Steinbach, 2009) at the top 10 cm soil depth as compared with conventional tillage. As such, this has led to increases in volumetric water content ($\Theta$) and also reduced soil losses (Hansen *et al.*, 2012) under NT as compared with conventional tillage.

Conversely, NT management can result in several challenges, especially when it is not used in conjunction with CCs. For example, when implemented on poorly aerated and drained clay soils, NT can reduce crop yields, especially during wet and cold growing seasons (Lal *et al.*, 2007). Further, without mechanical manipulation, NT systems may increase the soil bulk density and soil cone index (Jabro *et al.*, 2021) leading to nutrient and SOC stratification in the top 5 cm of the soil (Lupwayi *et al.*, 2006). As such, proper implementation under the right climatic conditions is important in order to minimize the challenges and realize the benefits of NT systems.

In addition to NT management, CCs have been reported to provide various ecosystem benefits. Due to their above- and belowground biomass, CCs have been reported to increase SOC at the 0-30 cm depth by 9% after 3 years (Villamil *et al.*, 2006), 7% after 15 years (Mazzoncini *et al.*, 2011), and 26% after 5 years (Haruna *et al.*, 2017) as compared with no cover crop (NC) management. This improvement in SOC content has been reported to increase the percentage of water stable aggregates (Liu *et al.*, 2005), as well as increasing water infiltration (Haruna *et al.*, 2022a) and reducing soil surface runoff (Zhu *et al.*, 1989). Additionally, the aboveground biomass of CCs can reduce surface soil crusting by intercepting raindrops and reducing splash detachment (Haramoto and Gallandt, 2005). All of these benefits have the potential to improve crop productivity and also soil and environmental sustainability.

The adoption of CCs can also help with climate regulation through C sequestration as compared with no NC. For example, Poeplau and Don (2015) reported that CCs can increase soil C storage at a mean rate of 0.32 Mg C $ha^{-1}$ $y^{-1}$ during the first 50-years of its implementation. Additionally, after 155 years of the practice, CCs have the potential to produce SOC saturation and increase the total soil C stock by 16.7 Mg $ha^{-1}$, and sequester 0.12 Pg C $y^{-1}$ globally (Poeplau and Don (2015). All of these benefits of conservation agriculture combined serve to enhance soil hydraulic properties.

Soil hydraulic properties are important for improving crop productivity and environmental sustainability. These properties (water retention curve, saturated hydraulic conductivity ($K_{sat}$), pore-size distribution) are important in understanding water movement and retention within the vadose zone and are influenced by pedologic and anthropogenic factors (Adeli *et al.*, 2020). Pedologic factors like parent material-induced soil texture have been reported to significantly influence water retention at lower soil water pressures (< – 100 kPa) and also $K_{sat}$ by influencing the matric potential of the soil (Azooz and Arshad, 2001). Anthropogenic factors such as including CCs into the cropping systems have been reported to influence various soil hydraulic properties. For example, Haruna *et al.* (2018) reported that cereal rye (*Secale cereale*) CCs improved the proportion of macropores (> 1000 μm effective diameter) by 30% at the 0-20 cm depth as compared with NC. Conversely, Carof *et al.* (2007) reported that red fescue (*Festuca rubra*) CC reduced the proportion of macropores by 67% at the 10-20 cm depth as compared with NC. Further, while the higher proportion of macropores was reported to increase $K_{sat}$ by 33% (Haruna *et al.*, 2018), Villamil *et al.* (2006) reported no significant effect of CCs on $K_{sat}$ at the 3-10 cm depth. Additionally, Hubbard *et al.* (2013) reported an 18% increase in $\Theta$ at -33 kPa soil water pressure at the 0-7.6 cm depth, while Villamil *et al.* (2006) reported no significant difference between CC and NC management. Speculatively, some of these conflicting results may be due to: 1) differences in soil types and climatic conditions, 2) differences in the CC species used, 3) time of sampling, and 4) time of CC termination. Due to these conflicting results, and the scarcity of studies on how multi-species CCs affect the hydraulic properties of the soil (Haruna *et al.*, 2020), more studies are required to further our understanding of the influence of CCs on soil hydraulic properties, particularly the influence of a multi-species CC.

This study was conducted to: 1) evaluate the effects of multi-species CCs on soil SOC, BD, $K_{sat}$, water retention, and pore-size distribution, as compared with NC; 2) compare the effects of no-till with cover crops (NT CCs) alone on the aforementioned physical and hydraulic properties, and SOC over 2 years; and 3) assess the interaction effects of CCs and soil depth, and sample year and soil depth on soil physical and hydraulic properties and SOC. It is hypothesized that: 1) the various roots and biomass of the CCs coupled with the NT systems will improve the evaluated soil properties, 2) because the same species of CCs were used on the same fields during both years examined, the CCs alone will not significantly influence the measured soil properties, and 3) the treatment by depth interaction will be more important compared with sample year by sample depth interaction for soil properties.

## MATERIALS AND METHODS

This study was conducted in a farmer's field in Coffee County, Tennessee, USA (35.330 N, 86.012 W). The site was at an average elevation of 310 m above sea level with 0-2% slopes. The USDA classifies the soil as a Holston sandy loam (Fine-loamy, siliceous, semiactive, thermic Typics). Whereas it is an Acrisols under the WRB classification system. The particle-size distribution relative to soil depth is shown in Table 1. The study area's climate is humid subtropical (Koppen Climate Classification). The average 40-year precipitation is 1 422 mm, with December (122 mm) and August (51 mm) receiving the highest and lowest amount of precipitation, respectively. The cumulative precipitation during the CC growing season was 31 and 29 mm during 2021 and 2022, respectively. The average

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

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

40 year temperature at the study site is 15°C, with July (31°C) and January (-1°C) being the warmest and coldest months, respectively.

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

The field was under 20 years of CC management and 25 years of NT management prior to the establishment of the current research in 2020. After the harvest of the cash crop in 2020, the research plots were delineated. Each plot was 20.1 m long and 7.4 m wide. During October of 2020 and 2021, the CCs were overseeded and later drilled into the soil at the following rates: 22.4 kg ha$^{-1}$ for winter wheat, 5.9 kg ha$^{-1}$ for crimson clover, 22.4 kg ha$^{-1}$ for triticale, 5.6 kg ha$^{-1}$ for hairy vetch, 29.1 kg ha$^{-1}$ for oats, and 17.8 kg ha$^{-1}$ for cereal rye. These seeding rates were based on the recommendations of the University of Tennessee Cooperative Extension. The CCs were terminated in April of each year using 4.15 kg ha$^{-1}$ acid equivalent of glyphosate (*N*-[phosphonomethyl] glycine). About 3 h after spraying, a 9 m CC roller was used to complete the CC termination. All plots were rain-fed during this study.

Soil samples were collected prior to CC termination using a cylindrical core with a diameter of 5.5 cm and a height of 6 cm, they were collected at three depths during 2021 and 2022; 0-10, 10-20, and 20-30 cm. During each year, a total of 18 (2 treatments x 3 depths x 3 replicates) soil samples were collected from the center of each plot. Each sample was trimmed, placed in pre-labelled plastic bags and stored in a refrigerator at 4°C until the time of analysis.

Prior to analysis, the soil samples were removed from their plastic bags, a cheesecloth was placed on the bottom of the cores using rubber bands, they were placed in a tub and saturated with water (electrical conductivity of 0.3 dS m$^{-1}$ at 20°C) from below until there was no tension on the soil surface. The saturated hydraulic conductivity was measured using the constant head method (Reynolds and Elrick, 2002). For soil with $K_{sat}$ values <0.1 cm h$^{-1}$, the falling head method was used. Intact cores were used for water retention measurement on ceramic plates at 0, -0.4, -1, -2.5, -5, -10, and -20, kPa soil water pressures. The samples were equilibrated to 35°C in a drying oven, and split into two halves. One half was broken-up, saturated and used for additional water retention measurements at -33, -100, and -1 500 kPa soil water pressures (Dane and Hopmans, 2002). The second half was ground and passed through a 2 mm diameter sieve. Particle-size distribution analysis was conducted on the <2 mm particles using the pipette method (Gee and Or, 2002). Soil BD was determined using the first half of the samples by using the air-dried sample weight adjusted for the oven-dry weight at a measured $\Theta$ (Grossman and Reinsch, 2002). The SOC was determined on the second half of each soil sample in a Skalar SNC (Skalar Analytical B.V., The Netherlands) analyzer, using the combustion method (Loss-on-Ignition at 1 200°C) (Schulte and Hopkins, 1996).

The water retention data was used to calculate the effective pore sizes using the capillary rise equation (Jury *et al.*, 1991). Pore sizes were classified as macropores (> 1000 μm effective diameter), coarse mesopores (60-1 000 μm effective diameter), fine mesopores (10-60 μm effective diameter) and micropores (< 10 μm effective diameter) (Anderson *et al.*, 1990). The soil water content at saturation was used to determine the total porosity and this was verified by summing all of the pore sizes together.

A normality test was conducted on SOC, BD, $K_{sat}$, pore-size distribution, and $\Theta$ at 0, -33, -100, and -1 500 kPa soil water pressures using the Anderson-Darling test at the 0.05 probability level in SAS ver. 9.4 (SAS Institute, 2015). All data followed a Gaussian distribution. A 2-way ANOVA was conducted on the soil properties using the PROC GLM procedure in order to determine the main effects of treatment and depth and the interaction effects of the treatment*depth during each year. Also, an ANOVA was conducted on the individual CC samples that were collected during 2021 and 2022 in order to determine the CC and year*depth interaction effects on the soil hydraulic properties. Significant differences were determined at the 0.05 probability level.

## RESULTS

The means (with SE) and the ANOVA results of SOC and BD during 2021 and 2022, and those for the CCs alone during both years are shown in Table 2. The results showed that the treatment and depth of sampling significantly affected BD during both years. Averaged over all depths, BD was found to be 13 and 14% lower under CC management as compared with NC management during 2021 and

**Table 2.** Soil organic carbon (SOC), bulk density (BD), saturated hydraulic conductivity ($K_{sat}$) and volumetric water content at selected soil water pressures as influenced by cover crop management, soil depth, and year

| 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 | | | | | | | |
| CC | 16.95±1.16[¶] | 1.17±0.05b | 41.20±1.98a | 0.510±0.02a | 0.110±0.02a | 0.102±0.02a | 0.095±0.02 |
| NC | 15.86±1.01 | 1.35±0.04a | 26.83±1.68b | 0.395±0.02b | 0.059±0.01b | 0.051±0.01b | 0.049±0.01 |
| Depth (cm) | | | | | | | |
| 5 | 19.82±1.19a | 1.18±0.19b | 37.10±3.86a | 0.507±0.03a | 0.114±0.02a | 0.104±0.02a | 0.097±0.02a |
| 15 | 15.05±0.87b | 1.24±0.15ab | 35.25±3.60ab | 0.463±0.04a | 0.089±0.02ab | 0.085±0.02ab | 0.079±0.02ab |
| 25 | 14.34±0.61b | 1.36±0.08a | 29.69±2.85b | 0.387±0.03b | 0.044±0.01b | 0.044±0.01b | 0.039±0.01b |
| ANOVA P > F | | | | | | | |
| Treatment | 0.064 | 0.006 | <0.001 | 0.003 | 0.022 | 0.018 | 0.073 |
| Depth | 0.011 | 0.042 | 0.042 | 0.009 | 0.046 | 0.041 | 0.051 |
| Treatment*depth | 0.958 | 0.483 | 0.581 | 0.993 | 0.304 | 0.334 | 0.343 |
| 2022 | | | | | | | |
| CC | 18.34±0.34a | 1.19±0.02b | 36.75±2.40a | 0.490±0.01a | 0.119±0.01a | 0.114±0.01a | 0.103±0.01 |
| NC | 16.05±0.84b | 1.39±0.04a | 25.32±2.40b | 0.398±0.02b | 0.095±0.01b | 0.089±0.01b | 0.075±0.01 |
| Depth (cm) | | | | | | | |
| 5 | 18.60±0.38a | 1.18±0.03b | 37.69±3.51a | 0.472±0.03a | 0.111±0.02 | 0.105±0.02 | 0.095±0.02 |
| 15 | 17.39±0.52ab | 1.31±0.06a | 30.37±2.98b | 0.440±0.06b | 0.106±0.01 | 0.100±0.01 | 0.089±0.01 |
| 25 | 15.61±1.15b | 1.37±0.05a | 25.05±2.76b | 0.421±0.05c | 0.105±0.01 | 0.099±0.01 | 0.082±0.01 |
| ANOVA P > F | | | | | | | |
| Treatment | 0.018 | 0.032 | 0.018 | 0.016 | 0.038 | 0.043 | 0.061 |
| Depth | 0.038 | 0.003 | 0.010 | <0.001 | 0.746 | 0.724 | 0.610 |
| Treatment*depth | 0.370 | 0.147 | 0.720 | 0.020 | 0.074 | 0.080 | 0.379 |
| 2021 *vs*. 2022 | | | | | | | |
| Depth (cm) | | | | | | | |
| 5 | 19.69±0.92a | 1.08±0.05b | 45.05±1.68a | 0.534±0.02a | 0.142±0.01a | 0.135±0.01a | 0.125±0.01a |
| 15 | 17.17±0.95ab | 1.16±0.04ab | 39.54±1.95a | 0.505±0.02ab | 0.118±0.02ab | 0.113±0.01ab | 0.103±0.01ab |
| 25 | 16.08±0.80b | 1.29±0.02a | 32.34±2.00b | 0.460±0.01b | 0.083±0.02b | 0.077±0.02b | 0.069±-0.02ab |
| ANOVA P > F | | | | | | | |
| Year | 0.052 | 0.655 | 0.155 | 0.526 | 0.724 | 0.637 | 0.736 |
| Depths | 0.044 | 0.024 | 0.002 | 0.039 | 0.037 | 0.042 | 0.049 |
| Year*Depth | 0.226 | 0.035 | 0.459 | 0.025 | 0.025 | 0.046 | 0.286 |

Means with different letters within a column are significantly different at the 0.05 probability level. Means without letter groupings are not significantly different at the 0.05 probability level. [¶]Mean ± S.E. *interaction, CC – cover crops, NC – no cover crop.

2022, respectively. During both years, the treatment averaged BD was found to be significantly lower at the 0-10 cm depth and increased with increasing soil depth (Table 2). Although not significant, the depth averaged SOC was numerically higher under CC as compared with NC during 2021. During 2022, the SOC was 14% higher under CC as compared with NC management. Averaged over both treatments, SOC was significantly higher at the 0-10 cm depth and decreased with increasing soil depth over the course of the two years of the study. A comparison of these properties under CC management alone between 2021 and 2022 showed that BD was higher in 2022 as compared with 2021 at the 0-10 and 10-20 cm depths. At the 20-30 cm depth, BD was higher in 2021 as compared with 2022 (Fig. 1a). During 2021 and 2022, both SOC and BD were significantly influenced by soil depth with SOC decreasing and BD increasing with increasing soil depth (Fig. 1b, a).

The saturated hydraulic conductivity results are shown in Table 2 and Fig. 1c. Averaged over all depths, $K_{sat}$ was 54 and 45% higher under CC as compared to NC management during 2021 and 2022, respectively. During both years of the study, the treatment averaged $K_{sat}$ was highest at the

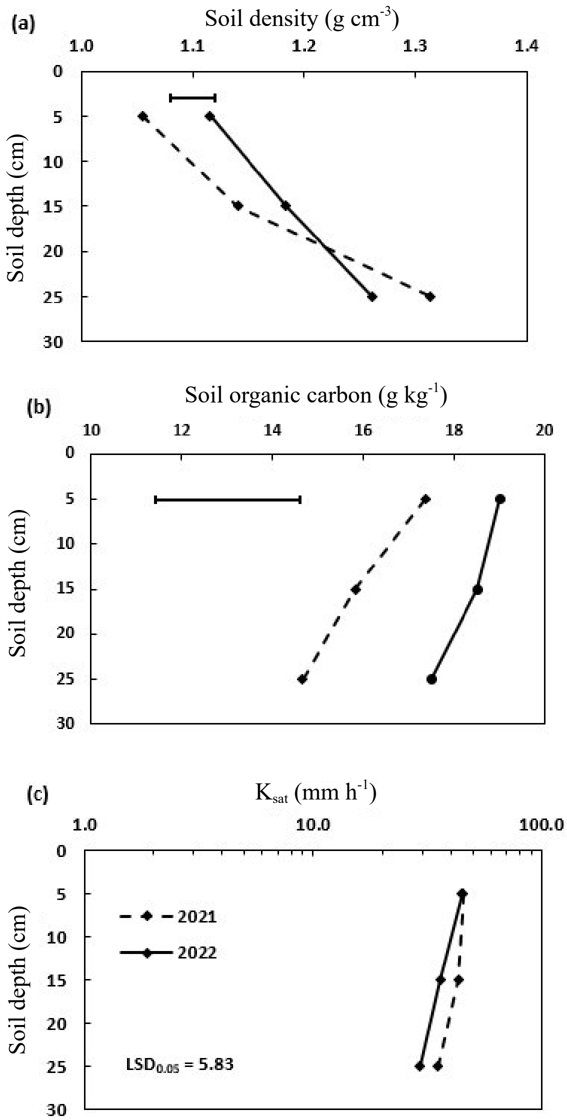


**Fig. 1.** Soil properties: a) soil bulk density, b) soil organic carbon, and c) saturated hydraulic conductivity ($K_{sat}$), relative to soil depth for cover crops during 2021 and 2022. Bars represent the least square difference at $p \leq 0.05$ for soil bulk density and soil organic carbon between the years. Due to the logarithmic scale, the least square difference value is indicated for $K_{sat}$.

0-10 cm depth and decreased significantly with increasing soil depth (Table 2). Although not significant, when the CC $K_{sat}$ values were compared between both years, this soil property was numerically higher in 2021 as compared with 2022 (Fig. 1c).

Table 2 shows the mean (with SE) and ANOVA of $\Theta$ at 0, -33, -100, and -1500 kPa soil water pressures during 2021 and 2022 and for CCs alone during both years. The results showed a significant treatment effect for $\Theta$ at 0, -33, and -100 kPa soil water pressures during both years of the study. Averaged over all of the sampled depths, $\Theta$ values at 0, -33, and -100 kPa soil water pressures were 29, 83, and 100% higher, respectively, under CC as compared with NC management in 2021. During 2022, the depth averaged $\Theta$ at 0, -33, and -100 kPa soil water pressures were 23, 25, and 28% higher under CC as compared with NC management. During the two years of the study and at all water pressures measured, $\Theta$ numerically decreased with increasing soil depth. Although not significant, the $\Theta$ values at saturation was numerically higher in 2021 as compared with 2022 under CC management alone. However, at lower soil water pressures, this trend was reversed. The year*depth interaction showed that the $\Theta$ at saturation, -0.4, -1.0, and -2.5 kPa soil water pressures were significantly higher in 2021 as compared with 2022 at the 0-10 and 10-20 cm depths (Fig. 2a, b). Conversely, at the 20-30 cm depth, the $\Theta$ values at saturation, -0.4, -1.0, and -2.5 soil water pressures were significantly higher in 2022 as compared with 2021 (Fig. 2c).

Pore-size distribution and total pore means (with SE) and ANOVA during 2021 and 2022 and for CCs alone during both years are shown in Table 3. In 2021, the depth averaged macropores, micropores and total pores were 29, 72, and 27% higher, respectively, under CC as compared with NC management. Although not significant, the depth averaged coarse and fine mesopores were numerically higher under CC as compared with NC management. When averaged over all sampled depths in 2022, CCs improved the macropores by 38% relative to NC management. During both years of the study and averaged over both treatments, all pore sizes and total pores reduced with increasing soil depth (although this was not significant in all cases). A comparison of soil pores under CC management alone between 2021 and 2022 showed that the year*depth interaction was significant for coarse and fine mesopores. The coarse mesopores were higher in 2021 at the 0-10 and 10-20 cm depths and this was also the case in 2022 at the 20-30 cm depth (Fig. 3b). At the 0-10 cm depth, fine mesopores were higher in 2021 as compared with 2022. This trend was reversed at the 10-20 and 20-30 cm depths (Fig. 3c). Further, the micropores significantly (27%) higher in 2022 as compared to 2021 at all of the measured depths (Fig. 3d).

## DISCUSSION

Soil organic carbon is an important soil health parameter, and it plays a major role in enhancing crop productivity and environmental sustainability (Dabney *et al.*, 2001; Deb *et al.*, 2015; Haruna and Nkongolo, 2020). The major source of SOC within the soil is from both the above and belowground biomass (Lal, 2003). Cover crops can contribute to SOC in two ways: 1) the decomposition of their residues left on the soil surface, and 2) the decomposition of their roots belowground (Haruna *et al.*, 2020). While the former can potentially lead to SOC stratification in the top 10 cm of the soil, especially under no-till management, the latter can reduce the severity of this phenomenon and lead to a greater distribution of SOC with soil depth. While

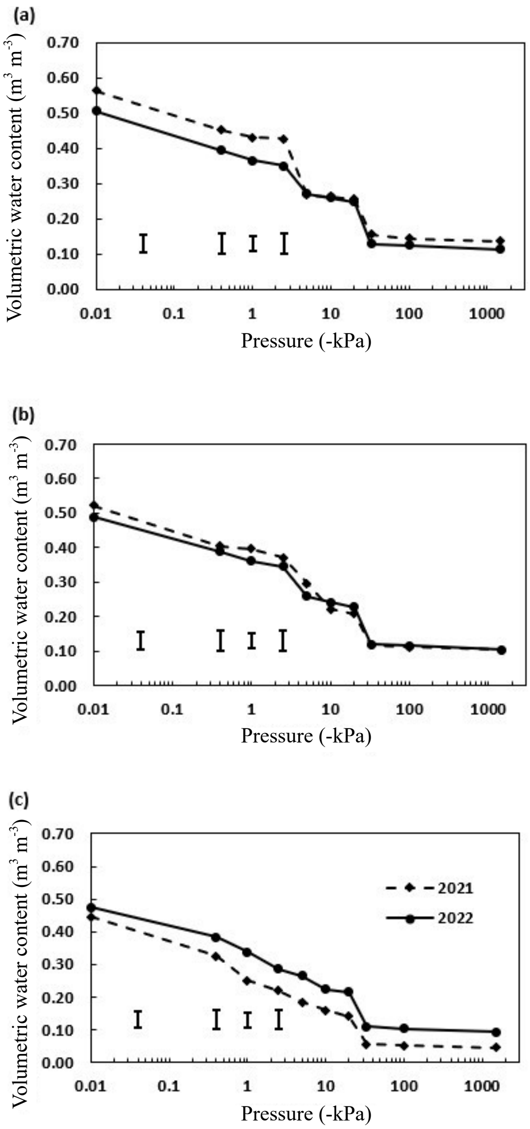


**Fig. 2.** Soil water retention under cover crop management at: a) 0-10, b) 10-20, and c) 20-30 cm depth during 2021 and 2022. Bars indicate the least square difference at $p \leq 0.05$ at all depths during both years of the study.

SOC was not significantly different between management in 2021, it was significantly higher under CC management in 2022 suggesting that, with little new above and below-ground biomass addition under NC, the microbial activity under NC management probably led to a slight depletion in SOC stock within the soil. As fewer residues are returned to the soil under NC management and more are returned to it under CC management over the succeeding years, the differences in SOC between these practices are expected to increase. This is supported by the current results that show a slight increase in SOC under CC management alone during 2022 as compared with 2021. This increase in SOC under CC management was in agreement with the first hypothesis. As expected, SOC decreased with increasing soil depth, this was probably due to a decrease in the amount of plant roots and their density with increasing soil depth. Bodner *et al.* (2019) reported similar findings. In general, the results from the current study show that the difference in SOC between the CC and NC management systems becomes more significant over time as compared with the first year of the implementation of CC.

In addition to SOC, soil BD can also influence crop productivity through its impact on root growth (Ola *et al.*, 2018). The significantly lower BD values under CC as compared with NC management in the current study were attributed to several mechanisms. First, since SOC is less dense than soil particles, the higher SOC values under CC management will inversely influence soil BD values. This not only increases soil microbial activity, but it also enhances root growth as well as water and nutrient uptake as reported by Yang *et al.* (2004) and Blanco-Canqui *et al.* (2009). Second, active root growth and the associated rhizosphere depositions of belowground biomass can increase soil porosity and aggregation and also lower soil BD under CC as compared with NC management (significant amounts of plant roots were visible under CC management during soil sampling). This is in agreement with the first hypothesis. Third, CCs have been reported to increase microbial activity (Salmerón *et al.*, 2019), whose casting and pores can increase organic matter content and porosity, respectively, and also they can further lower soil BD. Finally, a reduction in the kinetic energy of raindrops due to aboveground biomass under CC management can better preserve soil structure, pore integrity, soil particle consolidation, and ultimately soil BD as compared with NC management. Due to the weight of overburden soil and lower SOC, BD increased with increasing soil depth. The year*depth interaction results show that, even though CC residues may limit natural soil consolidation during a particular year, this benefit may not be consistent in successive years, especially at the top 20 cm of soil.

The current study demonstrated decisively that the inclusion of multi-species CCs into crop rotation cycles can improve root penetration as early as the first year of implementation and this improvement is expected to become increasingly evident over several years. Conversely, Reichert *et al.* (2019) reported no significant differences in soil BD between NC and CC management. One of the reasons for this contrast could be because these authors (Reichert *et al.*, 2019) utilized only one CC species (Oats) while this study utilized a suite of 6 CC mixes. The different morphology and architecture of these CC roots can help to reduce soil BD as compared to a single species (Bodner *et al.*, 2019). Therefore, in management practices where a rapid reduction in bulk density is required, a mixture of CCs may be more suitable as compared to a single CC species. With few studies to date concerning the influence of multi-species CCs on soil hydraulic properties (*e.g.*, Barker *et al.*, 2018; Singh *et al.*, 2022; Simon *et al.*, 2022;

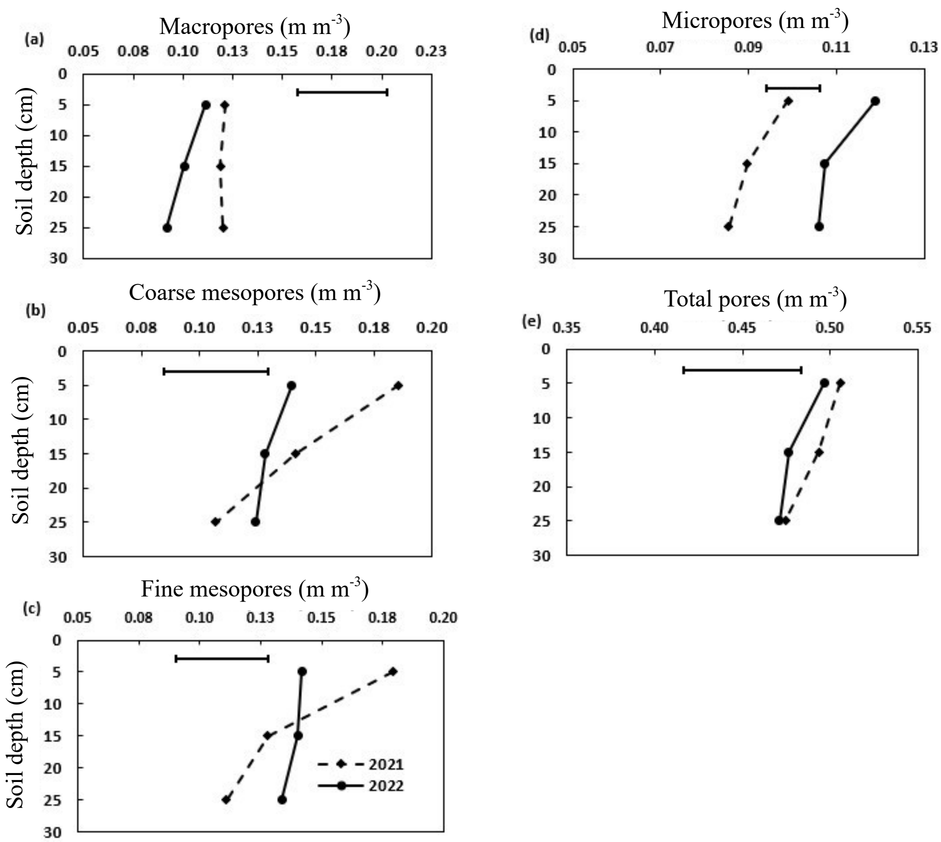


**Fig. 3.** Proportion of various pore sizes and total pores relative to soil depth under cover crop management during 2021 and 2022: a) macropores (>1000 μm effective diameter, b) coarse mesopores (60-1 000 μm effective diameter), c) fine mesopores (10-60 μm effective diameter), d) micropores (<10 μm effective diameter), and e) total pores. Bars indicate the least square difference at $p \leq 0.05$ at all depths during both years of the study.

Haruna *et al.*, 2022b), the current study could be helpful in agronomic decision making that have environmental implications.

The use of a multi-species CC can also extend beyond lowering soil BD to improvements in the hydraulic conductivity of the soil under saturated conditions. This occurs because, when subjected to a hydraulic gradient, water movement under saturated conditions is influenced by soil structure, soil BD, pore-size distribution, and pore continuity (Shukla, 2014). The significantly higher $K_{sat}$ values under CC as compared with NC management during both years of the study were attributed to several factors. First, the plant root and microbial activity generated biopores can facilitate water movement under saturated conditions by increasing the proportion of macropores and coarse mesopores which facilitates the movement of water by gravitational forces. Second, the SOC-induced improvement in soil structure (Grosbellet *et al.*, 2011) and the reduction in BD can further help to maintain the integrity of these biopores, reduce soil pore tortuosity, and consequently improve $K_{sat}$. Third, the aboveground biomass of CCs can reduce splash-detachment (Brant *et al.*, 2017) and also reduce surface soil crust formation, further helping to maintain soil porosity and therefore $K_{sat}$. Finally, by reducing the thermal variability in soils under saturated conditions (Haruna *et al.*, 2017; Sindelar *et al.*, 2019), CCs can influence the surface tension and viscosity of the moving water (Gao and Shao, 2015) by influencing the soil water temperature and consequently its flow, thereby improving $K_{sat}$ as compared with NC management.

As expected, $K_{sat}$ decreased significantly with increasing soil depth, this was probably due to an increase in BD and a reduction in the proportion of biopores relative to increasing soil depth. This was in concert with the results of Seguel *et al.* (2020). Additionally, a slightly higher BD during 2022 was probably responsible for the slightly lower $K_{sat}$ value, especially at the 10-20 and 20-30 cm depths, as compared to 2021 under CC management alone. This result corroborates the second hypothesis.

The $K_{sat}$ of the soil is an important hydrological parameter that provides an understanding of soil-water-plant interactions, water and solute movement and retention within the soil. As such, for a given water application rate, management practices which produce significantly higher $K_{sat}$ values can decrease the water content behind the wetting front of soils, resulting in a more rapid water flow. The results from this study show that CC management can increase the rate of soil water percolation deeper

**Table 3.** Pore-size distribution as influenced by cover crop management, soil depth, and year

| Treatment | Macropores (> 1 000 µm) | Coarse mesopores (60 – 1 000 µm) | Fine mesopores (10 – 60 µm) | Micropores (< 10 µm) | Total pores |
|---|---|---|---|---|---|
| | ($m^3 m^{-3}$) | | | | |
| 2021 | | | | | |
| CC | 0.116±0.01a | 0.145±0.01¶ | 0.139±0.01 | 0.091±0.01a | 0.491±0.01a |
| NC | 0.090±0.01b | 0.122±0.01 | 0.124±0.01 | 0.053±0.01b | 0.388±0.01b |
| Depth (cm) | | | | | |
| 5 | 0.114±0.01a | 0.142±0.02 | 0.137±0.01 | 0.093±0.01a | 0.487±0.01a |
| 15 | 0.113±0.01a | 0.131±0.02 | 0.130±0.02 | 0.074±0.01a | 0.447±0.03a |
| 25 | 0.082±0.02b | 0.126±0.01 | 0.128±0.01 | 0.049±0.02b | 0.385±0.04b |
| ANOVA P > F | | | | | |
| Treatment | 0.042 | 0.069 | 0.765 | 0.049 | 0.038 |
| Depth | 0.002 | 0.505 | 0.817 | 0.006 | 0.002 |
| Treatment*depth | 0.001 | 0.002 | 0.074 | 0.061 | 0.068 |
| 2022 | | | | | |
| CC | 0.101±0.01a | 0.131±0.01 | 0.139±0.01 | 0.111±0.01 | 0.481±0.01 |
| NC | 0.073±0.01b | 0.101±0.01 | 0.130±0.01 | 0.091±0.01 | 0.394±0.02 |
| Depth (cm) | | | | | |
| 5 | 0.104±0.01a | 0.123±0.01 | 0.140±0.01 | 0.116±0.01a | 0.483±0.01a |
| 15 | 0.081±0.01b | 0.113±0.02 | 0.136±0.01 | 0.094±0.01b | 0.423±0.02b |
| 25 | 0.076±0.01b | 0.111±0.02 | 0.127±0.01 | 0.092±0.01b | 0.407±0.03b |
| ANOVA P > F | | | | | |
| Treatment | 0.045 | 0.190 | 0.081 | 0.043 | 0.048 |
| Depth | 0.003 | 0.729 | 0.495 | <0.001 | 0.002 |
| Treatment*depth | 0.180 | 0.281 | 0.922 | <0.001 | 0.005 |
| 2021 *vs.* 2022 | | | | | |
| Depth (cm) | | | | | |
| 5 | 0.111±0.01 | 0.155±0.01a | 0.159±0.01a | 0.109±0.01a | 0.501±0.06 |
| 15 | 0.110±0.01 | 0.141±0.01ab | 0.131±0.01b | 0.099±0.01b | 0.485±0.06 |
| 25 | 0.106±0.01 | 0.118±0.01b | 0.126±0.01b | 0.096±0.01b | 0.473±0.06 |
| ANOVA P > F | | | | | |
| Year | 0.067 | 0.278 | 0.971 | 0.002 | 0.126 |
| Depths | 0.740 | 0.074 | 0.001 | 0.001 | 0.223 |
| Year*depth | 0.129 | 0.046 | 0.002 | 0.862 | 0.902 |

Means with different letters within a column are significantly different at the 0.05 probability level. Means without letter groupings are not significantly different at the 0.05 probability level. ¶Mean ± S.E, *interaction, CC – cover crops, NC – no cover crop.

into the soil profile, enhance soil water storage and thereby reduce soil surface runoff as compared with NC management. These processes can lead to improvements in nutrient transportation, crop productivity, and environmental sustainability as a result of CC usage.

Equally important for crop productivity and environmental sustainability is the amount of water retained in the soil under various matric potentials. Water retention is important with reference to scheduling irrigation, simulating solute transport and water flow, and in evaluating soil water availability (Dane and Hopmans, 2002). Soil water retention is influenced by the soil structure and texture, the former is influenced mainly by anthropogenic processes and the latter is influenced by pedological processes. In general terms, water retention is directly related to and significantly influenced by the soil structure between 0 and -100 kPa soil water pressure, while the soil texture determines water retention at soil water pressures lower than -100 kPa (Otalvaro *et al.*, 2016). Therefore, the effects of soil management practices on water retention are better evaluated between saturation and -100 kPa soil water pressures.

When multi-species CCs are included in crop rotation cycles, the results from the current study showed that the living roots of these crops can generate biopores which are responsible for water retention for up to 5 days after rainfall or irrigation. Additionally, when these CC roots and residues decay, they can improve SOC (as demonstrated by the results of the current study) and further, improvements in SOC have been related to an improvement in the soil structure by previous authors (*e.g.*, Acin-Carrera *et al.*, 2013; Hu *et al.*, 2014). This mechanism also leads to an improvement in water retention under CC management.

The roots of CCs can hold the soils in place and reduce soil particle transport, thereby helping to reduce the rearrangement of soil particles (Ogilvie *et al.*, 2021). Although not significant, the numerically higher $\Theta$ at -1500 kPa soil water pressures under CC management in both years suggests that this management practice can reduce soil particle movement and redistribution, and as a consequence lead to slightly more water availability under drier conditions.

As expected, increasing BD probably resulted in reduced water retention with increasing soil depth at all soil water pressures measured during both years of the study. The current results also showed that the slope of the water retention curve was slightly lower in 2022 as compared with 2021 and this was attributed to a higher BD value in 2022 as compared with 2021. This is because the slope of the water retention curve is inversely related to soil BD (Camron, 1978). Therefore, as BD increases and soil water pressure decreases, the decrease in $\Theta$ remains relatively constant. This suggests that management decisions for improving soil water availability should be based on their influence on BD.

The significant interaction between the sample year and depth for $\Theta$ at all measured soil water pressures disproved the third hypothesis. This demonstrates that the adoption of a suite of CCs beyond the first year can potentially improve water retention at various depths. Taken together, the results of the current study showed that CCs can improve solute and water flow within the vadose zone, and can also potentially decrease the need for and delay the timingof irrigation schedules in humid regions without compromising crop productivity. This would have the multiplier effect of further conserving water resources, which is important for improving crop productivity in a changing global atmospheric climate.

Limiting the need for water irrigation in the cropping systems of humid environments can be achieved by reducing surface water runoff. As such, management practices that improve the pore-size distribution in the soil are invaluable. The higher proportion of pores of various sizes under CC as compared to NC management during both years of the study was attributed to; 1) lower BD under CC management, 2) higher SOC under CC management which can improve the soil structure, 3) higher root density and diversity due to the different species of CCs, and microbially generated biopores (which were visible during soil sampling), and 4) an aboveground biomass-induced reduction in the kinetic energy of raindrops which resulted in soil particle consolidation. Further, the decreasing CC root density (Bodner *et al.*, 2019) and increasing BD with increasing soil depth were probably responsible for the lower proportion of pores with increasing soil depth during both years of the study. The depth*year interaction results show that the proportion of coarse mesopores and fine mesopores were higher at the 0-10 cm depth during 2021 as compared with 2022. This suggests that the benefits of CCs on these pore sizes at the 0-10 cm depth are greater during the first years of their inclusion as compared to subsequent years.

Soil water drainage under gravity is mainly facilitated by non-capillary pores (macropores and coarse mesopores) (Amer, 2012). The results from the current study showed that by improving the proportion of these non-capillary pores, CC management can enhance crop productivity in very wet growing seasons by lengthening the growing season, increasing microbial activity, and as a consequence, nutrient mineralization. Further, their ability to transpire water out of the soil (Haruna *et al.*, 2022a) can also improve crop productivity in water-logged environments.

Conversely, capillary pores (micropores) are responsible for water movement and availability under dry conditions (Amer, 2012). By increasing the proportion of capillary pores, CC management can also enhance water availability, and possibly crop productivity, during drier years. This is especially important in a rapidly warming global climate with increasing potential for soil water evaporation.

In general terms, while the current study demonstrated that CC management practices can improve soil hydraulic properties over the 2 years of the study, climatic and pedologic factors can limit these effects. For example, a lower SOC caused by a water-deficiency induced reduction in plant residues and a coarser-sized soil particles sizes can inversely affect soil structure formation. Under these conditions, any improvements in soil hydraulic properties may be caused by climatic and pedologic, rather than anthropogenic factors.

## CONCLUSIONS

1. The results of the current study also demonstrated that a multi-species cover crop mix can limit the need for water irrigation in humid environments, further helping to conserve available water.

2. The benefits of multi-year studies include an evaluation of the temporal variability of management practices on the sustainability of the current cropping systems. In this vein, the benefits of cover crops are directly proportional to the number of years that have passed after implementation, but longer-term studies are required to further verify the results of the current study.

2. After 2 years, the current study demonstrated that no-till cover crops can improve soil functioning by gradually increasing soil organic carbon by 14% as compared with no cover crop (and thereby sequestering $CO_2$) through residues returned to the soil.

3. In addition to improvements in soil organic carbon stocks, cover crop root-induced improvements in capillary (72% higher) and non-capillary (29% higher) pores as compared with no cover crop led to increased water storage and retention.

4. Finally, a multi-species mix of cover crops is desirable, not just for their hydraulic benefits to the soil, but also other potential soil quality benefits.

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