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[Jestinos Mzezewa](#) * and Mulaifa Godfrey Tshabuse

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Article

Short-Term Effects of Combining Minimum Tillage and Manure Application on Water Retention Curve and Pore Size Distribution of a Ferralsol in Limpopo Province of South Africa

Jestinos Mzezewa * and Mulaifa Godfrey Tshabuse

University of Venda

* Correspondence: jestinos.mzezewa@gmail.com

Abstract

Little is known how the combination of minimum tillage and manure affects soil hydraulic properties. The aim of this study was to investigate the effects of combining minimum tillage (MT) and cattle manure application on soil water retention curve (SWRC), van Genuchten (vG) equation parameters, soil pore size distribution (PSD) and soil bulk density. Manual form of MT was tested. The study was configured as split plot design with tillage (conventional (CT) and minimum (MT)) as main plots and manure application rate (0, 5, 10 t/ha) as subplots. Undisturbed soil samples were collected from 0-5-, 10-15-, and 20-30 cm depths and subjected to different matric potentials for the determination of SWRC. The SWRC was fitted to vG equation using the RETC code. Equivalent pore size diameters were estimated from capillary rise equation. Compared to CT, bulk density in MT was significantly lower at all depths. Manure effects were non-significant. None of the vG parameters were significant in the 0-5 cm whereas the α , n parameters and PSD were significantly influenced by the tillage \times manure interaction at 10-15- and 20-30 cm depths, but the results were inconsistent, highlighting the need for long-term experiments and higher manure rates.

Keywords: manual minimum tillage; pore size distribution; tillage \times manure interaction; water retention curve

1. Introduction

Climate change could result in soil moisture deficits, affecting the productivity of farms (Eze et al., 2020). To cope with unpredictable weather patterns, farmers must adapt to climate resilient agricultural management systems that largely depend on maintaining good soil structure and soil organic matter (SOM) content [1]. Soil functions such as water storage and movement depend on soil structure [2]. Furthermore, nutrient retention and transport, aeration, resistance to water and wind erosion, microbial activities and root growth are all functions of soil structure [3]. Conservation agriculture (CA) is one of such promising innovative soil management system that can improve soil structural properties and farm productivity, thus enabling farmers to produce enough food for themselves. CA is anchored on three pillars: minimum soil disturbance (minimum or zero tillage); maintenance of soil cover (30%) and diversity of crops including a legume in the rotation. However, smallholder farmers cannot sustain the required soil cover due to competing uses of crop stover as animal feed. Smallholder farmers in sub-Saharan Africa (SSA) adopted the manual form of CA where land preparation is accomplished by use of a hand hoes [4]. The benefits of hand-hoe type CA are not widely reported. CA has the potential to build soil organic matter (SOM) levels which are usually low in smallholder farming systems of SSA [4]. SOM can conserve soil moisture and improve farm

productivity [5] and additionally, can maintain soil physical, chemical and biological properties that are responsible for greater water retention and nutrients, and hence improved crop yields [6].

Incorporation of manure as a source of SOM is usually the first choice of improving soil fertility for smallholder farmers because manures are easily accessible and affordable. In addition, the beneficial effects of farmyard manure for improving soil nutrients and soil physical and hydrological characteristics, especially so for soils with low SOM are widely documented [7,8]. Moreover, manure can facilitate earthworm activities resulting in increased macropores [9]. However, there have been little efforts to include manure application in CA systems because of the difficulties in minimizing soil disturbance and mixing. Nevertheless, manure application still plays a vital role as a soil cover, enhancing water retention and reducing soil erosion [10]. As component of SOM, soil organic carbon (SOC) acts as cementing agent and increasing water stable aggregates hence influencing soil pore size distribution [11]. Recently, [7] combined in-field rainwater (IRWH), a form of CA in South Africa, and manure application to determine their synergistic effects. The results indicated that the main effects of IRWH tillage and manure application were positive on most soil quality indicators but the interaction of IRWH and manure application were largely not statistically significant on most parameters. Thus, more investigations are needed to ascertain the synergistic effect of CA and manure application.

Shifting from conventional form of agriculture to CA practice is likely to impact key soil structural properties. Changes in soil quality are often indicated by examining the changes in dry soil bulk density, specific classes of pore size distribution (PSD), and changes in the water retention curve (WRC). The latter is achieved through the analysis of the van Genuchten [12] equation parameters [8,13,14]. The van Genuchten equation is a hugely popular, extensively tested and commonly used water retention curve function. Elevated bulk density is a good indicator of soil compaction and hence poor soil aeration. Soil water retention curve is a fundamental soil hydraulic property used to evaluate soil's water holding capacity that determines water movement and storage in soils, and its availability for plants [15]. It is defined as the relationship between volumetric water content (θ) and soil matric potential (h or Ψ). It is important for irrigation design and modeling. SWRC is affected by soil structural properties which are influenced by soil management, soil texture and pore size distribution [16,17]. Thus, changes in soil structure affect the SWRC and related ecosystem functions such as soil water storage and gas supply to the roots [13]. Pore size distribution determines gas and water movement and hence soil processes which are vital for crop growth and development [8].

Characterisation of the pore system is important in the investigations of the storage and movement of water and gas, nutrient availability for plant growth, infiltration and microbial activity [11]. Pore size distribution also determines the diversity of habitat for biota such as plant roots, soil fauna and microbial communities as well as the decomposition of organic matter [18]. Therefore, the change from conventional agriculture to CA is likely to be accompanied by changes in soil pore geometry and the associated functions of soil water storage and movement.

Due to the benefits observed elsewhere, CA is vigorously promoted to smallholder farmers in SSA in general [19] and South Africa in particular [20] to increase crop productivity and reduce farmers' vulnerability to drought. Crop yield improvements associated with CA have been reported in farmer's fields in Zambia [21] and Zimbabwe [22]. Results from long-term field trials in South Africa have often been inconclusive [23] whilst results from short-term trials indicated significant effects of tillage on some soil quality indicators [24]. Even though, there is still knowledge gap in the effects of CA on soil hydrological properties. Therefore, more systematic soil investigations are needed to evaluate CA's potential impact on soil hydrological properties and crop yields in South Africa. More so, there have been little attempts to quantify soil hydraulic properties which are thought to be responsible for the observed improved soil water and nutrient storage under the CA practice [5]. Changes in soil hydraulic properties, including soil water retention properties, need further investigation. The need to understand the changes on PSD following the introduction of CA practices are even greater because knowledge on PSD may unlock the mechanisms underpinning observed increase in water storage and availability associated with CA [25]. While the mechanical

form of CA received much attention, its manual counterpart, widely adopted by smallholder farmers in SSA, remains largely under studied.

Few studies in literature examined changes in PSD due to tillage practice. For instance, [26] investigated the effects of conventional tillage (CT), strip tillage (ST), and no-tillage (NT) in a clay loam's physical and hydraulic properties. Their results showed that none of the van Genuchten SWRC parameters, plant available water content, or PSD were significantly influenced by tillage type. Similarly, little or no significant variations in the SWRC were observed in their study. Furthermore, [27] reported that three tillage treatments (conventional deep ploughing (DP), cover cropping following shallow termination, no-tillage) and straw retention did not have a significant effect on soil bulk density. Meanwhile, they reported no significant effect on PSD due to the reduced tillage after 20 years of its implementation on a loam soil. Similarly, [28] reported that different tillage methods (deep and shallow ploughing, deep cultivation, shallow cultivation, no-tillage) did not affect PSD. There are no or limited documented studies on the interaction between tillage and manure application on SWRC and its vG equation parameters or PSD. Tillage and manure effects on soil properties are often studied separately. Further, very little is known on how soil hydraulic properties are influenced by the manual form of minimum tillage which is widely practiced in southern Africa. This knowledge paucity indicates a need for additional research to understand how manual tillage practices in combination with manure application influence soil hydraulic properties. Therefore, the aim of this study was to compare the performance of the manual form of minimum tillage and conventional tillage in combination with cattle manure on water retention characteristics, including vG parameters and PSD, as well as changes in soil bulk density following a 2- year implementation of minimum tillage in combination with manure application. It was hypothesized that there would be significant difference in vG equation parameters and PSD among treatment combinations.

2. Materials and Methods

2.1. Study Site and Experimental Design

The study was initiated during 2023/2024 and 2024/2025 cropping seasons. Data for the last season is presented. This study was located at the University of Venda Experimental Farm (22°58' S, 30°26' E, altitude 596 m), Thohoyandou in the Limpopo Province of South Africa. The soil texture was clay with approximate average sand, silt and clay content of 21, 7, and 72% for the 0–5 cm depth, 25, 4, and 71% for the 10–15 cm depth and 26, 5, 69% for the 20–30 cm depth, respectively. Other selected soil properties are shown in Table 1. Soil structure was moderate to fine sub angular blocky [29]. The soil was classified as Umbric Rhodic Ferralsols according to the World Reference Base for Soil Resources (WRB) [30] and Hutton form in South African classification system. The climate is semi-arid with hot summers and cool winters. Further site details regarding the climate were previously provided [29,31].

Table 1. Particle size distribution, pH and Electrical conductivity (EC) in 0 - 5 cm, 10 -15 cm and 20 - 25 cm depths at the study site.

Layer (cm)	Particle size distribution (%)			pH _(KCl)	EC (μS/cm)
	[†] Sand	Silt	Clay		
0 - 5	21.0	7.3	71.7	6.6	112.7
10 -15	25	4.0	71.0	6.1	158.6
20 - 30	26.3	4.7	69.0	5.7	178.4

[†]Sand = 2000-50, silt = 50-2 and clay = < 2 μm.

The experiment was configured as a split-plot arrangement in a randomized complete block design (RCBD) with tillage treatments as main plots and manure application rate as sub-plots. Tillage treatments were conventional tillage (CT) and minimum tillage (MT). Cattle manure was applied in the sub-plots at 0, 5 and 10 t/ha. Treatment combinations were: CT0 = CT + 0 t/ha; CT5 = CT + 5 t/ha,

and CT10 = CT + 10 t/ha. Similarly, MT0 = MT + 0 t/ha; MT5 = MT + 5 t/ha, MT10 = MT + 10 t/ha. Plot sizes were 5 x 4.5 m separated by 0.5 cm between plots. The plots were replicated four times. The research plots were established on land previously under fallow for nearly 3 years. The CT plots were established by ploughing using a tractor followed by disking and harrowing at the beginning of the experiment. Hand hoes were used in the subsequent seasons. The MT plots were created by clearing the land using a chemical weed killer commercially known as round-up (Glyphosate). After plot demarcation, hand hoes were used to make furrows of about 20 cm deep for planting for all plots. Cattle manure sourced from local community was weighed and applied in the furrows and incorporated before sunflower seed (*Helianthus annuus*), the test crop, was planted approximately 0.05 m deep in the furrow and furrows back filled. Weeding was done as needed using hand hoes in the CT plots. In the MT plots weeds were pulled by hands.

2.2. Soil Sample Collection and Analysis

Undisturbed soil cores were collected after harvest using stainless steel rings (100 cm³ volume) from depths of 0–5, 10–15, and 20–30 cm to determine water release curves in four replicates. Water retention was measured at 0, -1, -2.5, -10, -31.6, -63.1, and -100 cm matric potentials (h) using sandbox equipment (Eijkelkamp, Giesbeek, The Netherlands). Water content at -15,000 cm was determined by pedotransfer function (R²=0.8) [32]. This was necessitated by the breakdown of the compressor driving the pressure membrane apparatus. For this study, the water content at -100 and -15,000 cm was considered as field capacity (FC) and PWP, respectively. Wet soil mass was measured after equilibration at each matric potential. At the end of the run the samples were dried at 105° C for 24 h, and the gravimetric water content at each matric potential was calculated as the difference between wet mass and dry mass divided by the dry mass. Dry bulk density was calculated as the ratio of dry mass and sample volume. Then, the volumetric water content (cm³ cm⁻³) was calculated by multiplying the gravimetric water content and the dry bulk density.

The water retention was modeled using the van Genuchten equation [12] or vG equation (1). This is a widely applied water retention function in soil science and hydrology because it has few parameters, it is a smooth function and is continuous from saturation to dry conditions. Further, it is applicable across different soil types [12]. The vG equation was fitted using the RETC computer program [33]. The RETC program utilizes the non-linear least-squares optimization to determine parameters for soil hydraulic models.

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha|h|)^n]^m} \quad (1)$$

where θ is the volumetric water content (cm³ cm⁻³), θ_s is the saturated water content (cm³ cm⁻³), θ_r is the residual water content (cm³ cm⁻³), h is the matric potential (cm), α is the scaling parameter as an inverse matric potential at air entry (cm⁻¹), n is a fitting dimensionless parameter related to curve shape, porosity, and pore size distribution, and m is a constant defined in Equation (2) as follows:

$$m = \frac{1}{n} \quad (2)$$

In this study three pore size categories were defined according to their equivalent diameters [34]: (i) macropores or transmission pores with equivalent diameter greater than 1000 μ m that drains at matric potentials below 3 cm H₂O or pF 0.48; (ii) mesopores or storage pores with equivalent diameter between 10 and 1000 μ m that drains at matric potentials between 3 and 300 cm H₂O or between pF 0.48 and 2.48 (also called available moisture); (iii) micropores or residual pores with equivalent diameter < 10 μ m or pores that drain at greater than 300 cm H₂O or pF > 2.48. The equivalent pore diameters were estimated using equation 4. Each pore size class category has a special role as follows: Macropores, also known as drainage pores, hold water loosely, such that it freely drains under gravity and is unavailable to plants; storage pores or mesopores holds water strongly enough that it

does not drain away under gravity and is readily available to plants, and residual pores hold water so tightly that it is unavailable to plants [35].

The Young-Laplace capillary rise equation (3) was used to calculate the maximum equivalent diameter (D) of soil pores retaining water at potential (h) in water [14]:

$$D = \frac{4\sigma \cos(\omega)}{\rho_w g |h|} \quad (3)$$

where D is the equivalent pore radius (m), h is the matric potential (m), σ is the surface tension of water (72.75 mJ m⁻²), ω is the pore water contact angle (taken to be zero), ρ_w is the density of water (0.998 Mg m⁻³), and g is the gravitational acceleration (9.8 m s⁻²).

After substituting the constants into Equation (3), the equivalent pore diameter (D, μm) at Corresponding matric potentials is approximated as in Equation (4):

$$D \approx \frac{3000}{|h|} \quad (4)$$

where h is the matric potential (cm)

2.3. Statistical Analysis

All data were tested for normality with the Shapiro-Wilks test. The data was normally distributed at $p > 0.05$. The effects of tillage methods, manure application rates and their interactions were analyzed separately per soil depth using 2-way ANOVA, IBM SPSS version 29 (IBM, Corp., Armonk, NY, USA). The means between treatments were separated using least significant difference (LSD) at $p < 0.05$. Where there was significant interaction between tillage method and manure application rate, pairwise comparisons using Benferroni ($P < 0.05$) were performed to identify significant differences between tillage levels at each level of manure application rate.

3. Results

3.1. Statistical Analysis

The results of two-way analysis of variance (ANOVA) for tillage, manure application rate, and their interaction are given in Table 2. Mean values of the studied parameters and their LSD multiple-range comparisons are given in Tables A.1-A.6. The results of the analysis (Table 2) highlight that tillage and manure application rates, and their combinations effects varied differently across all depths. However, there was no significant variation ($p > 0.05$) of θ_r and θ_s across all depths.

3.2. Soil water-Retention Curves

The vG equation (Equation 1) was fitted to the measured WRCs for soils under two tillage treatments in combination with three manure applications for each soil depth. The measured and estimated SWRCs for CT and MT in combinations with 0, 5 and 10 t/ha cattle manure applications at 0-5 cm, 10-15 cm and 20-30 cm depths are shown in Figures 1-2. There were small differences in the SWRCs due to treatment combinations at all depths.

Table 2. Analysis of variance summary for fitted vG parameters and different porosity attributes, and bulk density (Db) at different soil depths. $P > 0.05$ is not significant.

Parameter	0 – 5 cm		10 – 15 cm		20-30 cm		
	F-value	p-value	F-value	p-value	F-value	P-value	
θ_s (cm ³ /cm ³)	+T	0.537	0.473	0.393	0.538	1.358	0.259
	MR	2.016	0.162	0.567	0.236	1.032	0.376

	T x	0.143	0.868	1.108	0.352	1.166	0.334
	MR						
α (cm^{-1})	T	0.181	0.676	4.880	0.040	2.493	0.132
	MR	2.630	0.100	4.132	0.033	0.066	0.365
n (-)	T x	0.009	0.991	11.436	<0.001	0.595	0.562
	MR						
Macropores (cm^3/cm^3)	T	3.750	0.069	0.152	0.702	26.088	<0.001
	MR	2.304	0.129	0.442	0.263	12.035	<0.001
Mesopores (cm^3/cm^3)	T x	1.173	0.332	6.882	0.006	9.682	0.001
	MR						
Micropores (cm^3/cm^3)	T	48.020	<0.001	6.090	0.030	46.547	<0.001
	MR	387.11	<0.001	527.24	<0.001	183.791	<0.001
Db (g/cm^3)	T x	140.36	<0.001	644.18	<0.001	1325.06	<0.001
	MR	1		3		8	
	T	156.47	<0.001	6.908	0.001	323.629	<0.001
	MR	4		0			
	T x	51.343	<0.001	330.00	<0.001	300.236	<0.001
	MR			7			
	T	9.031	0.011	0.984	0.341	96.466	<0.001
	MR	10.125	0.003	137.43	<0.001	2.723	0.106
	T x	9.875	0.003	243.89	<0.001	35.255	<0.001
	MR			2			
	T	23.933	<0.001	7.686	0.013	5.222	0.035
	MR	0.245	0.785	0.244	0.786	1.001	0.387
	T x	0.04	0.961	0.292	0.750	0.252	0.780
	MR						

†T= tillage; ‡MR=manure rate.

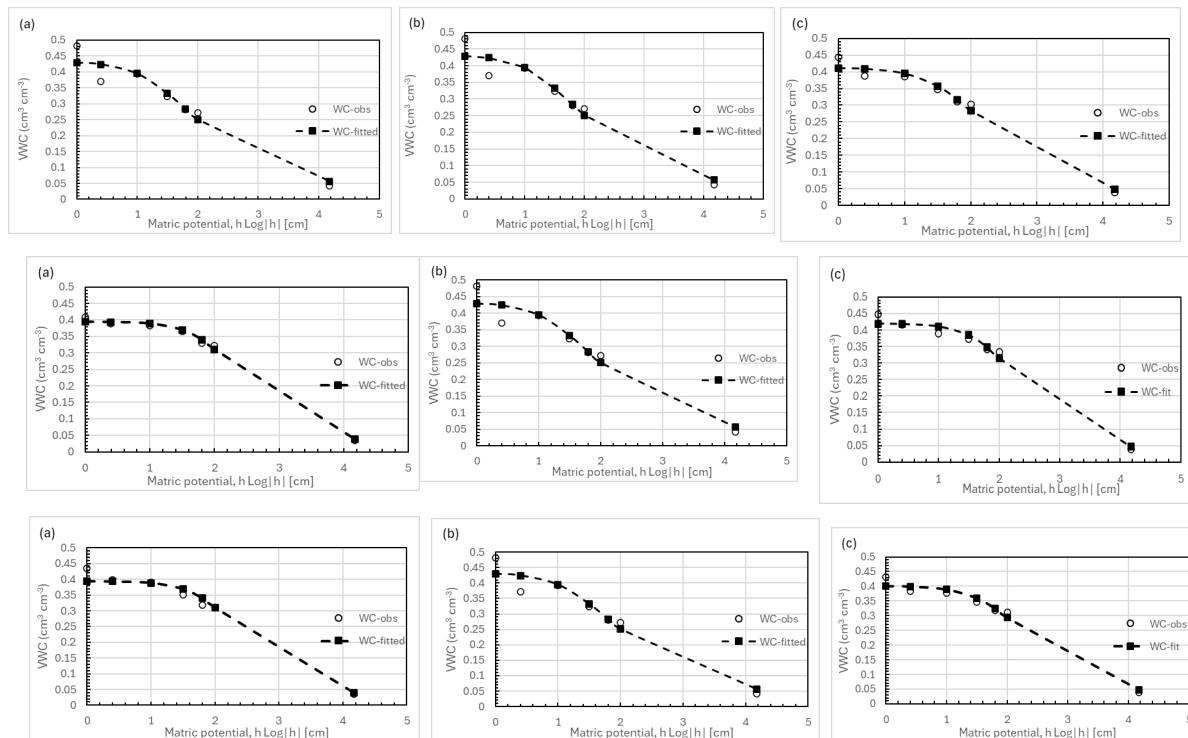


Figure 1. Observed (WC-obs.) and vG model fitted (WC-fit.) WRCs for tillage – manure treatment combinations. **Upper panel:** (a) CT0 (b) CT5, and (c) CT10 at 0-5 cm depth. **Middle panel:** (a) CT0, (b) CT5, and (c) CT10 at 10-15 cm depth. **Lower panel:** (a) CT0, (b) CT5, and (c) CT10 at 20-30 cm depth. Each data point represents an average of 4 replications.

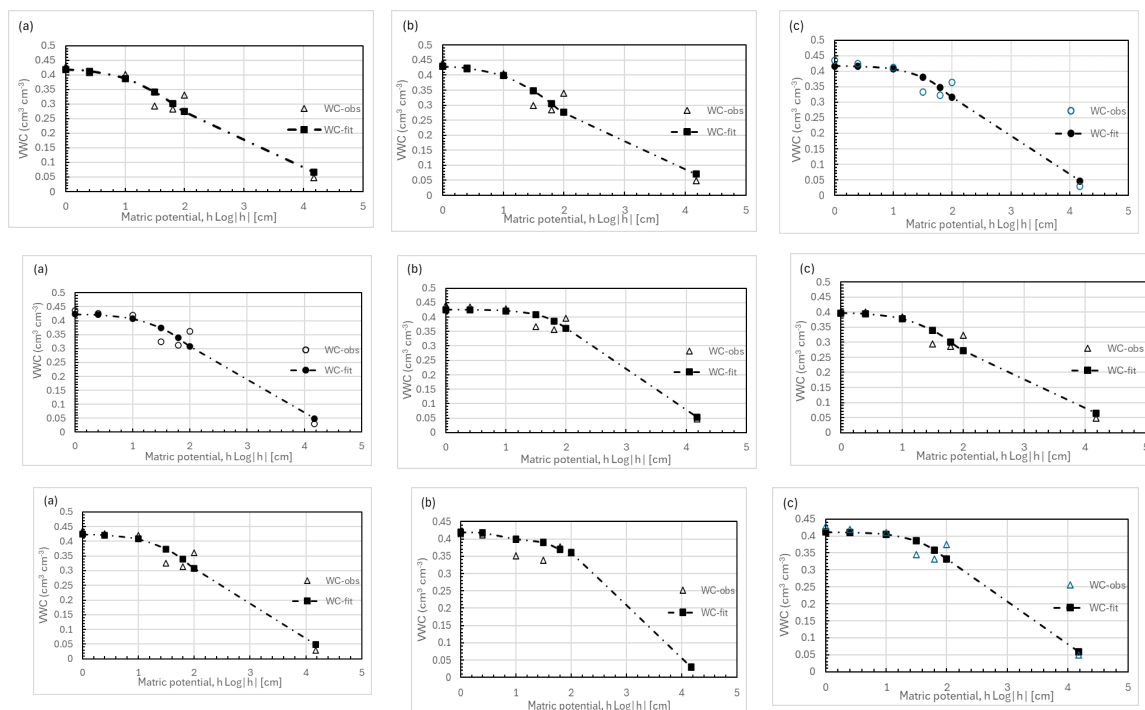


Figure 2. Observed (WC-obs.) and vG model fitted (WC-fit.) WRCs for treatment combinations. **Upper panel:** (a) MT0 (b) MT5, and (c) MT10 at 0-5 cm depth. **Middle panel:** (a) MT0, (b) MT5, and (c) MT10 at 10-15 cm depth. **Lower panel:** (a) MT0, (b) MT5, and (c) MT10 at 20-30 cm depth. Each data point represents an average of 4 replications.

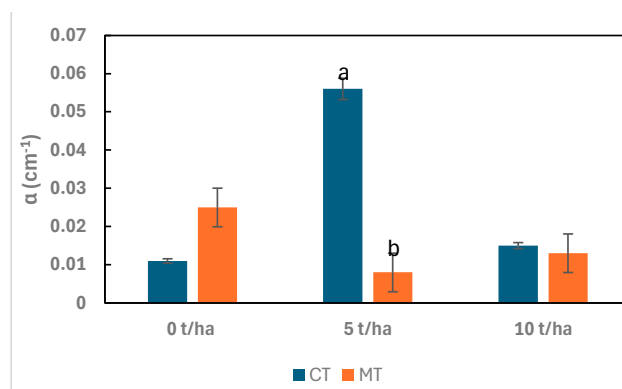


Figure 3. Tillage and manure application rate interaction on vG fitted α parameters at 10 - 15 cm depth. Bars represent standard error, and different letters indicate significant differences between treatments within each depth ($p < 0.05$).

3.3. vG Parameters

There was no significant variation of α parameter at 0-5 cm depth, but significant variations were observed due to tillage ($p = 0.04$), manure application rate ($p = 0.033$) and the interaction between tillage and manure ($p < 0.001$) at the 10-15 cm depth (Table 2). The means of estimated vG parameters for across all depths are shown in Tables S1-S3. The fitted residual water content (θ_r) was nearly zero for all treatments and soil depths. Though non-significant, θ_s ranged from 39.5% to 42.2% in all depths for all treatments.

The interactive effects of tillage and manure α parameters are shown in Figure 3, where α value of CT treatment was nearly 85% more than the MT at 5 t/ha at the 10-15 cm depth. There were no significant differences between tillage treatments at the other application rates. Similarly, α parameter was not significantly influenced by the treatments at the 20-30 cm depth (Table A.3).

The parameter n was not significantly affected by treatments at 0-5 cm depth but was significantly affected by tillage x manure application rate interaction ($p = 0.006$) at 10-15 cm depth where n in MT treatment was significantly greater than CT treatment at 5 t/ha manure application rate (Figure 4). The highest average significant n parameter value was 1.435 in the MT treatment compared to 1.302 in CT treatment. A similar trend was observed on parameter n at 20-30 cm depth where n was nearly 3.4 times higher in MT than the CT treatment. At this depth, the average significant n parameter of 4.442 was observed in MT treatment versus 1.302 in CT. No significant differences between tillage treatments were observed at both the control and 10 t/ha at both soil depths (Figure 4).

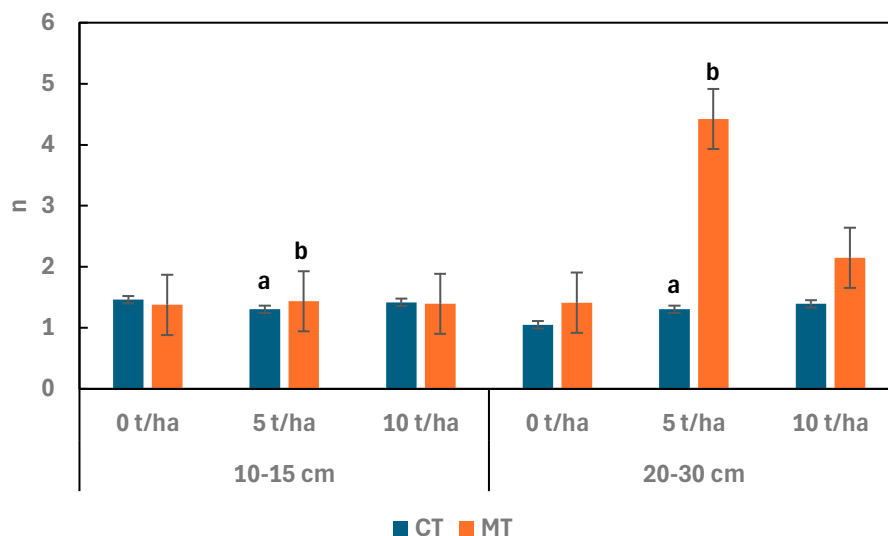


Figure 4. Tillage and manure application rate interaction effect on vG fitted n parameter at 10-15 cm and 20 - 30 cm depth. Bars represent standard error, and different letters indicate significant differences between treatments within each soil depth ($p < 0.05$).

3.5. Soil Pore Size Distribution

3.5.1. Macropores

There were significant variations of pore size distribution at 0-5 cm depth due to tillage, manure application rate and their interaction (Table 2). As shown in Figure 5, the effect of tillage on macropore (>1000 μm diameter) volume varied depending on manure application rate. There was no significant difference between CT and MT at 0 t/ha but manuring application rate at 5 t/ha significantly increased macropore volume in MT (0.034 cm^3/cm^3) compared to the CT (0.019 cm^3/cm^3) treatment. In contrast, the trend was reversed at a manure application rate of 10 t/ha although with a decreased pore volume magnitude compared to 5 t/ha manure application rate. Similarly, macropore volume distribution at the 10–15 cm soil depth was significantly influenced by both tillage and manure application rate and by their interaction (Table 2). Compared to the MT treatment, the CT treatment had significantly more macropores at 0 and 10 t/ha of manure application, but the MT surpassed the CT at 5 t/ha, like the 0-5 cm depth (Figure 5). A pattern observed at 0-5 cm depth was repeated at 20-30 cm depth (Figure 5).

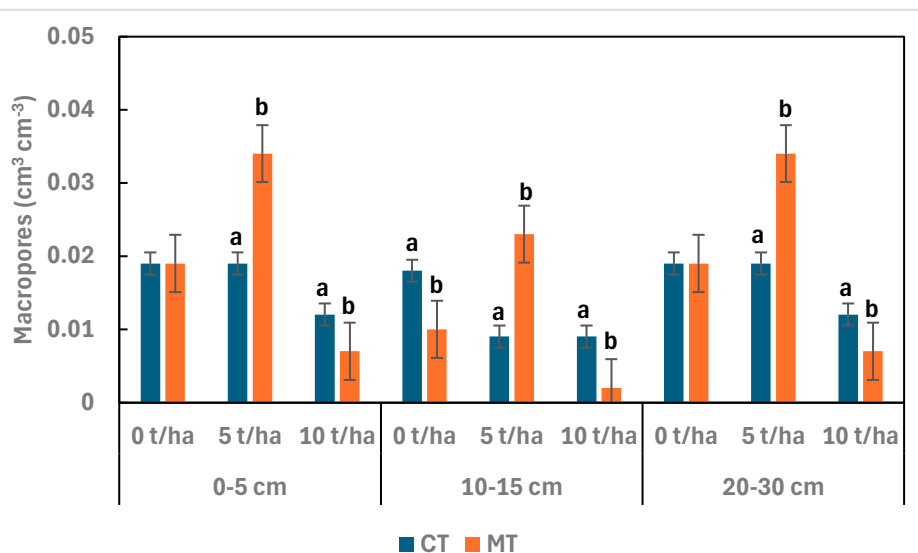


Figure 5. Effect of interaction between tillage and manure application rate on macropores at 0-5 cm and, 10-15 cm and 20-30 cm soil depth. Different letters indicate significant difference between treatments ($p < 0.05$).

3.5.2. Mesopores

The mesopores were significantly affected by the interaction between tillage and manure application at all soil depths ($P < 0.001$) (Table 2). The mesopore volume (10-1000 μm diameter) were significantly greater in CT than MT at 0 t/ha manuring rate at 0-5 cm depth (Figure 6). This pattern was repeated at 5 t/ha manure application rate although the difference between tillage treatments was non-significant. Increasing the manure application rate by 10 t/ha significantly increased mesopore volume in CT compared with MT. The most significant difference in mesopore volumes between the CT and MT was observed at a manure application rate of 10 t/ha where the mesopore volume was 11-fold higher in CT than in MT treatment. At 10-15 cm depth, the effect of adding manure was inconsistent in affecting the mesopores (Figure 6). The MT treatment had greater mesopore volume than the CT at 0 t/ha but this was reversed at 5 t/ha manure application rate. The effect of manure application was also not consistent at 20-30 cm depth where the mesopore volume in CT was less than MT at 0 t/ha but consistently higher than MT except at 5 and 10 t/ha manuring rate (Figure 6).

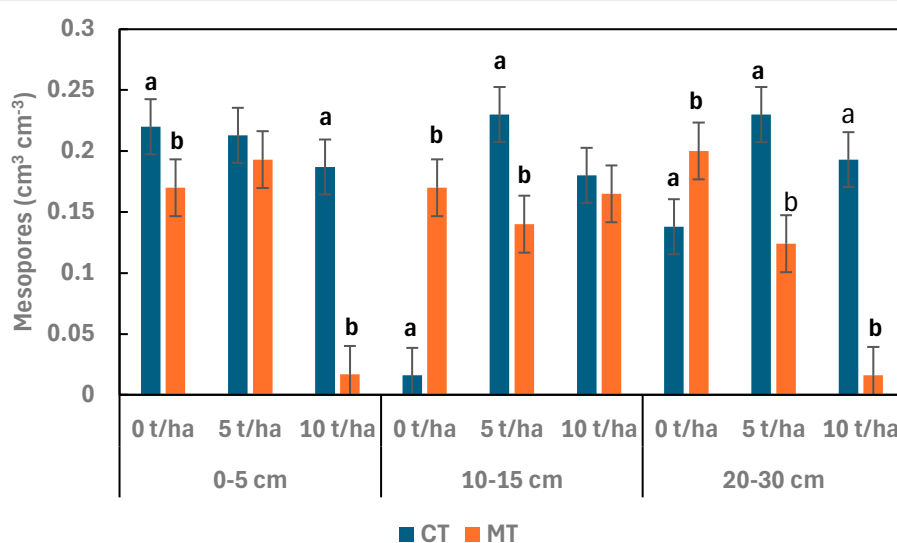


Figure 6. Effect of interaction between tillage and manure application rate on mesopores at 0-5 cm and, 10-15 cm and 20-30 cm soil depth. Different letters indicate significant difference between treatments ($p < 0.05$).

3.5.3. Micropores

The micropore (< 10 μm diameter) volume was significantly influenced by the interaction between tillage methods and manure application rate at all soil depths ($P < 0.001$) (Table 2). A significant tillage \times manure application rate was observed at 5 t/ha where micropore volume was greater in MT than CT at 0-5 cm depth (Figure 7). There was no significant difference in micropore volumes between the two tillage systems at 0 and 10 t/ha manuring rate cm depth. A similar pattern was observed at 10-15 cm depth although the micropore volumes in CT were significantly higher than the MT (Figure 7). At 20-30 cm depth a pattern observed at 0-5 cm depth was repeated (Figure 7).

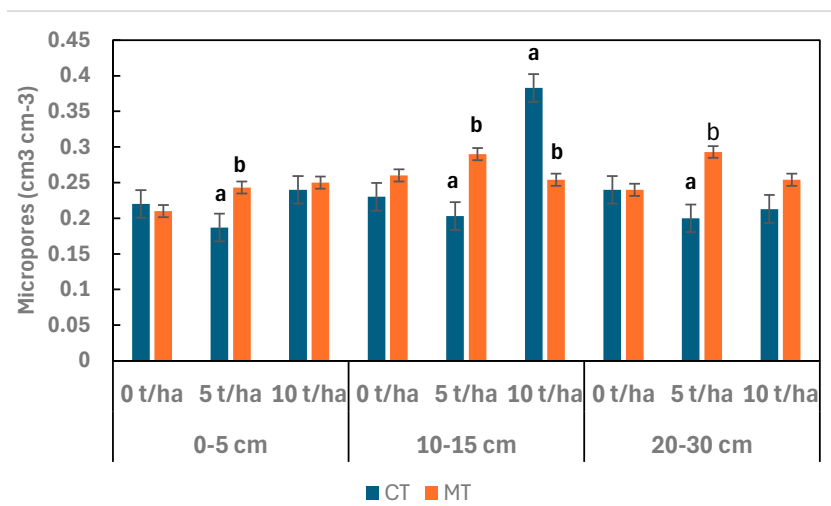


Figure 7. Tillage and manure application rate interaction effect on micropores at 0-5 cm, 10-15 cm and 20-30 cm depth. Bars represent standard error, and different letters indicate significant differences between treatments within each depth ($p < 0.05$).

3.6. Bulk Density

Tillage significantly ($p < 0.001$) affected soil bulk density at 0- 5 cm depth (Figure 8). Compared to the CT treatment, the bulk density in MT was nearly 20% lower than the CT. There were no significant effects of manure application rate nor tillage \times manure rate interaction at all depths (Table 2). Similarly, bulk density was affected by tillage ($p = 0.013$) at 10 – 15 cm depth where CT was nearly 1% higher than the MT treatment. Similar results were obtained at 20 – 30 cm depth. The highest bulk density of 1.0 g/cm^3 was observed in CT in the 10-15 and 20-30 cm depths while the lowest of 0.81 g/cm^3 was recorded in the MT treatment in 0-5 cm depth.

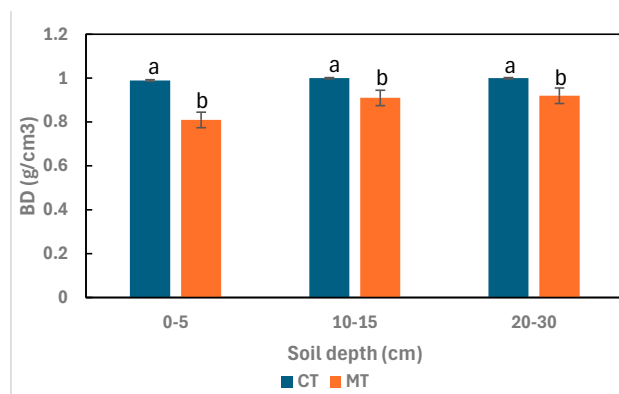


Figure 8. Effect of tillage on bulk density (BD) at 0-5, 10-15 and 20-30 cm depth. Vertical bars are standard error bars. Different letters indicate significant differences between treatments per column ($p < 0.05$).

4. Discussion

4.1. Water Retention Curves and vG Parameters

Effects of land use and management on soil structure are often studied by assessing changes in the soil water retention curve (SWRC) and its van Genuchten equation parameters [8]. Our results showed that there were insignificant effects of tillage methods and manure applications on the SWRC at all soil depths, suggesting that soil water retention was mainly a function of inherent properties rather than management practices in the short-term, agreeing with [26] who observed same in SWRCs of conventional tillage, strip tillage and no-tillage in the 0-15 cm and 15-30 cm depths. They attributed the small differences to spatial variability of soil properties such as particle size distribution and soil organic matter.

The results of the present study showed that all fitted vG parameters were insignificantly affected by tillage, manure application and their interaction in the 0-5 cm depth (Table S1) while θ_r and θ_s did not differ significantly between treatments at all soil depths (Table A.1-A.3). The residual water content represents the maximum of water in a soil that will not contribute to liquid flow because of blockage of flow paths or strong adsorption onto the soil matrix while the θ_s is the maximum volumetric water content of the soil primarily depending on soil texture, bulk density and structure. However, according to [33], the fitted θ_r and θ_s parameters are viewed as empirical constants in soil water retention functions and hence without much physical meaning. Like the present study, [26] observed nonsignificant differences in all the parameters of the vG equation except the θ_s in the 0-15 and 15-30 cm depths of a clay loam soil and they attributed lack of tillage response to, *inter alia*, root extraction mechanisms of the radish plant roots that could have disturbed the soils. However, in the present study the test crop was sunflower whose root system differs totally from their test crop. Similarly, [36] reported no significant difference in θ_r among different land use systems and attributed this to the empirical nature of the parameter.

Parameter α was significantly influenced by the interaction of tillage and manure application at 5 t/ha manure loading rate where CT was much greater than MT treatment in the 10-15 cm depth (Table A.2 and Figure 3). The α (cm^{-1}) parameter is the inverse of air entry value (AEV) or air entry suction ($1/\alpha$). The AEV is the critical suction at which higher saturation levels start to decline, and air starts to enter the larger pores [37]. Higher α value in the CT corresponds to lower air entry value/suction or soils with high macro-porosity, indicating larger pore diameters which hold water loosely. The results could suggest that soil disturbance in the CT plots in addition to the manure application rate of 5 t/ha, created macro-porosity compared to the MT treatment. This result was not expected because the bulk density in CT was higher than MT, which implied more macro-porosity in MT. A plausible explanation could be that the manure application could have modified the pore structure by cementing soil aggregates thereby creating higher proportion of larger pores although the total porosity could be less in CT treatment. Nevertheless, our results concurred with previous studies that found that soils under conventional tillage have larger structural pores compared to untilled soils [14]. However, our results contradicted [26] who reported that an increase in bulk density led to a decrease in α value. However, they observed a weak relationship ($R^2=0.583$) between α parameter and bulk density. [38] also observed that the bulk density was not significantly correlated to the AEVs as previously thought.

Tillage and manure application or their interaction did not influence parameter n in the 0-5 cm depth. However, n was affected by the interaction between tillage and manure application in the 10-15 and 20-30 cm depths where n was significantly greater in MT than CT at 5 t/ha manure application rate (Figure 4). There was no significant difference in treatments at the lowest (control) and maximum manure application rates. Our results could suggest that there was synergy in the effects of tillage and manure applications which were more evident at 5 t/ha manure application rate and especially in deeper soil layers. The shape parameter n represents the rate at which soil desaturates as the matric potential decreases. The higher the n value indicates a more uniform pore size (steeper slope between AEV and residual water content) in the MT, while a low n value indicates a wider distribution of pore

sizes (shallower curve) in CT [33]. Previous studies [4,26] reported no significant effects of tillage on n parameter while [29] observed significant n only in the 0-10 cm layer under CT on Cambic Ferralsol. However, no relevant studies on the effects of manure or its interaction with tillage on fitted n parameter could be found in literature.

4.2. Soil Pore Size Distribution

It is known that long-term (> 10 years) manure application particularly at higher rate influence soil macro-porosity [9] by binding soil particles into stable aggregates [5,10]. Our results show that soil pores size distributions were consistently influenced by the interactions between tillage and manure application rate at all depths. Overall, the results showed that macropore volumes were higher in MT treatments than CT at all soil depths particularly at 5 t/ha manuring rate where the highest macropore volume of 3.4% (v/v) was recorded in MT treatment, contrary to [47] who observed a greater proportion of large pores under CT than NT although their plots were unmanured. The mesopore volumes tended to be greater in CT than MT at all soil depths but the effects seemed to be amplified at 5 t/ha manuring rate where CT recorded the highest of 23% (v/v) mesopore volume. On average, the micropore volumes seemed to be evenly distributed between the tillage systems regardless of soil depth and manure application rate. However, a lot of inconsistencies were observed across the pore size categories and soil depths. There could be various reasons for the inconsistencies. Firstly, manure effects are usually most pronounced in the surface layer (0-15 cm) due to direct application and increased aerobic decomposition, regardless of tillage. Lack of consistency at shallow depth could indicate uneven manure incorporation by tillage tools, masking its impact on transient soil properties like bulk density and aggregate stability that have direct impact on soil pore sizes. Another reason for lack of consistency could be that the low rates of manure applied in this study were not sufficient to modulate the effects of tillage particularly in low organic matter soils such as those on the study site (Tables A.1-A.3). On the other hand, high rates (10 t/ha) might not improve aggregate stability fast enough, due to the short duration of the experiment, to affect macro-porosity, leading to inconsistent results. However, the effects of manure on soil pore size distribution depend on soil texture and crop grown. In the previous studies, manure increased the porosity of pores <30 μm in the two fine-textured sites and increased the porosity of pores > 30 μm for wheat and maize plots in the sandy loam site (Fu et al., 2022). It is worth noting that the interactive effects of tillage and manure application on soil pore size distribution is hardly reported in literature. Most studies evaluated the effects of tillage or land use alone or manure alone albeit very few for the latter [9]. For instance, [14] reported that soil meso- and macro-pore volumes were greater under CT than NT at 0-15 cm and 15-30 cm depths, while micro-pore volume was lower in CT than NT at both depths. [27] reported that reduced tillage methods had insignificantly fewer mesopores compared to conventional deep ploughing. Meanwhile, [5] observed that the transmission pores were higher in all CA plots excluding those with cowpeas only at 10-20 cm depth, but the effects were also site- specific, making generalisation impossible. Soil pore size distribution is always changing and therefore, the results of this study highlight the need for long-term studies to effectively evaluate the influence of tillage and organic matter amendments. It must be noted that the CT and MT reported in literature are mostly tractor based yet our study was manual based, making comparisons very difficult.

4.3. Bulk Density Changes

While soil bulk density reflects soil compaction to some degree depending on tillage practices, it fluctuates throughout the seasons, making it an unstable parameter [27]. Our results show that soil bulk density was generally low with CT treatments slightly lower and MT much lower than the expected bulk density range of 1.1-1.3 g/cm³ in such soil types [39]. Our results suggest that minimum tillage reduced soil bulk density whilst conventional tillage elevated soil bulk density (Figure 8). The increase in bulk density in CT plots was attributed to soil disturbance that could have destroyed soil aggregates whilst low bulk density in MT was attributed to reduced soil disturbance as previously reported albeit in long term studies [40]. The results were consistent with the observed soil organic

carbon content in the present study (Tables S1-S3). In contrast, [41], reported a greater bulk density in MT than CT in the upper soil layers (5-10- and 15-20 cm) of a loamy soil. Similarly, [42] observed that surface soil bulk density decreased under increased degree of loosening such as in CT. Conversely, [43] reported statistically similar bulk density in CT (1.3 g/cm³) and MT (1.23 g/cm³) during 2018/2019 cropping season on this site. They reported similar results during 2019/2020 cropping season, akin to the results of [7]. Similarly, [27] observed that bulk density decreased insignificantly in the reduced tillage and no-tillage treatments in the 5–10 cm, 15–20 cm and 30–35 cm layers of a loam soil. Lack of significant results were also reported between conventional tillage, strip tillage and no-tillage on a clay loam soil at 0-30 cm depth [26]. Other studies observed inconsistent results on bulk density between maize CA-no-till plus residue mulch and conventional tillage in 0-10 cm depth on sites with different particle size distribution after 2 years of trial establishment [44]. They attributed lack of consistence on the effect of CA on most soil hydraulic properties on the short duration of studies and the influence of site-specific characteristics such as soil texture. Bulk density inconsistencies among tillage practices have been reported previously [46]).

Lack of significant differences in bulk density due to manure application at all soil depths could also be attributed partly to low manure application rates and short duration of the study that could be ineffective in altering soil bulk density, like [7] who observed similar results on clay and sandy loam using cattle manure rate between 20 to 35 t/ha in a 2-year study. Conversely, studies elsewhere indicated that long-term (24 to 126 years) manure application reduced soil bulk density by an average of 3-6% for three sites with silty clay, silt loam and sandy loam. However, increasing manure rates in their study resulted in no further improvements in bulk density for the sandy loam and loamy sand. They attributed the low bulk density in manured plots to soil enrichment by soil organic carbon that acted as binding agent, creating more soil pores thus reducing bulk density [9]. It must be noted that the afore mentioned study used farmyard manure loading rate ranging between 10 to 20 t/ha dry matter every 2 years, thus making their study significantly different from the current study in terms of total manure loading and the duration of the experiment.

5. Conclusions

The present study was carried out to evaluate the effects of tillage methods, manure application rate and their interaction on soil water retention curve, van Genuchten equation parameters and bulk density of a clay Ferralsol. After 2 years of field study, the results showed that minimum tillage (MT) reduced bulk density relative to the conventional tillage (CT) at all soil depths. Higher bulk density in CT compared to MT was attributed to soil disturbance that could have destroyed soil organic matter associated with soil aggregates by exposing them to aerobic oxidation. The results also indicated small differences in soil water retention curves, suggesting that SWRC responded more to inherent soil properties rather than to soil management. There was no effect of manure application on most measured variables, suggesting that future studies must focus on higher manure loading rates. No significant variations of residual water content (θ_r) and saturated volumetric water content (θ_s) were observed at all soil depths. Fitted parameters α and n varied significantly between treatment due to the interactive effects of tillage and manure application particularly at 10-15 cm and 20-30 cm depths indicating variation in the general shape of the fitted curves according to treatment combinations but the response of tillage methods to manure application rate were not consistent. Similarly, the variations of soil pore size distribution were affected by the interactions between tillage and manure application rates, but the response of tillage treatments to levels of manure application were highly inconsistent. The lack of consistency of our results further highlights the need for long-term studies to evaluate the synergy between conservation tillage and manure application on soil hydraulic properties. Despite the limitations of the study, which include short duration (2 years) study, single site and one crop type, the results offer valuable insights into the potential of integrating conservation agriculture and manure application.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, SWRC raw data.

Author Contributions: Conceptualization, Jestinos Mzezewa; methodology, Jestinos Mzezewa; software, Jestinos Mzezewa and Mulaifa Godfrey Tshabuse; validation, Jestinos Mzezewa; formal analysis, Jestinos Mzezewa and Mulaifa Godfrey Tshabuse; investigation, Mulaifa Godfrey Tshabuse; resources, Mulaifa Godfrey Tshabuse.; data curation, Jestinos Mzezewa.; writing—original draft preparation, Jestinos Mzezewa.; writing—review and editing, Mulaifa Godfrey Tshabuse; visualization, Jestinos Mzezewa and Mulaifa Godfrey Tshabuse.; supervision, Jestinos Mzezewa.; project administration, Mulaifa Godfrey Tshabuse.; funding acquisition, Jestinos Mzezewa. All authors have read and agreed to the published version of the manuscript." Please turn to the [CRediT taxonomy](#) for the term explanation. Authorship must be limited to those who have contributed substantially to the work reported.

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Appendix A

Appendix A.1

Table A1. Fitted van Genuchten parameters, bulk density (g/cm³) and soil organic carbon (%) as influenced by tillage and manure application rate at 0-5 cm depth. θ_r is the residual water content (cm³ cm⁻³), θ_s is the saturated water content (cm³ cm⁻³); α is the scaling parameter as an inverse matric potential at air entry (cm⁻¹), and n is a fitting dimensionless parameter related to curve shape, porosity, and pore size distribution. The parameters were fitted using the RETC program.

Treatment	Fitted parameter				Bulk density	SOC
	θ_r	θ_s	α	n	g/cm ³	%
Tillage						
CT	0.0	0.425	0.047	1.325	0.99a	1.03a
MT	0.0	0.417	0.051	1.289	0.81b	2.61b
Manure rate						
0	0.0	0.426	0.057	1.298	0.88	1.65
5	0.0	0.431	0.058	1.289	0.89	1.94
10	0.0	0.405	0.03	1.335	0.91	1.86
P value						
Tillage	ns	0.473ns	0.676ns	0.069ns	<0.001***	***

Manure rate	ns	0.162ns	0.100ns	0.129ns	0.785ns	ns
Tillage*Manure rate	ns	0.868ns	0.991ns	0.332ns	0.961ns	ns

Different lower-case letters indicate significant differences between treatments at $P < 0.05$. ns = not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.001$.

Table A2. Fitted van Genuchten parameters, bulk density (g/cm^3) and soil organic carbon (%) as influenced by tillage and manure application rate at 10 - 15 cm depth. θ_r is the residual water content ($\text{cm}^3 \text{cm}^{-3}$), θ_s is the saturated water content ($\text{cm}^3 \text{cm}^{-3}$); α is the scaling parameter as an inverse matric potential at air entry (cm^{-1}), and n is a fitting dimensionless parameter related to curve shape, porosity, and pore size distribution. The parameters were fitted using the RETC program.

Treatment	Fitted parameter				Bulk density g/cm^3	SOC %
	θ_r	θ_s	α	n		
Tillage						
CT	0.0	0.413	0.027a	1.392	1.00a	1.03a
MT	0.0	0.419	0.015b	1.401	0.91b	2.61b
Manure rate						
0	0.0	0.408	0.018ab	1.418	0.95	1.65
5	0.0	0.428	0.032a	1.368	0.94	1.94
10	0.0	0.413	0.014b	1.359	0.97	1.86
P value						
Tillage	ns	0.538ns	0.040*	0.702ns	0.013*	***
Manure rate	ns	0.236ns	0.033*	0.263ns	0.786ns	ns
Tillage*Manure rate	ns	0.352ns	<0.001***	0.006**	0.750ns	ns

Different lower-case letters indicate significant differences between treatments at $P < 0.05$. ns = not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.001$.

Table A3. Fitted van Genuchten parameters, bulk density (g/cm^3) and soil organic carbon (%) as influenced by tillage and manure application rate at 20 - 30 cm depth. θ_r is the residual water content ($\text{cm}^3 \text{cm}^{-3}$), θ_s is the saturated water content ($\text{cm}^3 \text{cm}^{-3}$); α is the scaling parameter as an inverse matric potential at air entry (cm^{-1}), and n is a fitting dimensionless parameter related to curve shape, porosity, and pore size distribution.

Treatment	Fitted parameter				Bulk density g/cm^3	SOC %
	θ_r	θ_s	α	n		
Tillage						
CT	0.0	0.380	0.066	1.247a	1.00a	1.18a
MT	0.0	0.421	0.014	2.661b	0.92b	2.57b
Manure rate						
0	0.0	0.367	0.073	1.229a	0.94	1.80
5	0.0	0.427	0.028	2.862b	0.99	1.79
10	0.0	0.409	0.018	1.771a	0.94	2.04
P value						
Tillage	ns	0.259ns	0.132	<0.001***	0.035*	***
Manure rate	ns	0.376ns	0.365	<0.001***	0.387ns	ns
Tillage*Manure rate	ns	0.334ns	0.562	0.001**	0.780ns	ns

Different lower-case letters indicate significant differences between treatments at $P < 0.05$. ns = not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.001$.

Table A4. Pore volumes of macro-, meso-, and micropores derived from water retention curve at 0 – 5 cm. Macropore volume was calculated as the difference between volumetric water contents at matric potentials between $h = 0$ (saturation) and $|h| < 3$ cm or $\log|h| < 0.48$ cm; meso pores were calculated as the difference between volumetric water contents at matric potentials of $|h| = 3 - 300$ cm or $\log|h| = 0.48 - 4.48$ cm; and micropore volume was calculated as the remainder from total porosity (θ_s).

Treatment	Macropores > 1000 μm	Mesopores 10 – 1000 μm	Micropores <10 μm
$\text{cm}^3 \text{cm}^{-3}$			
Tillage			
CT	0.017a	0.207a	0.216a
MT	0.020b	0.127b	0.234b
Manure rate			
0	0.009a	0.102a	0.215a
5	0.019b	0.195b	0.215a
10	0.027c	0.203b	0.245b
P value			
Tillage	<0.001***	<0.001***	0.011*
Manure rate	<0.001***	<0.001***	0.003**
Tillage*Manure rate	<0.001***	<0.001***	0.003**

Different lower-case letters indicate significant differences between treatments at $P < 0.05$. ns = not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.01$; *** = significant at $P < 0.001$.

Table A5. Pore volumes of macro-, meso-, and micropores derived from water retention curve at 10 – 15 cm. Macropore volume was calculated as the difference between volumetric water contents at matric potentials between $h = 0$ (saturation) and $|h| < 3$ cm or $\log|h| < 0.48$ cm; meso pores were calculated as the difference between volumetric water contents at matric potentials of $|h| = 3 - 300$ cm or $\log|h| = 0.48 - 4.48$ cm; and micropore volume was calculated as the remainder from total porosity (θ_s).

Treatment	Macropores >1000 μm	Mesopores 10 – 1000 μm	Micropores <10 μm
$\text{cm}^3 \text{cm}^{-3}$			
Tillage			
CT	0.012a	0.142a	0.272a
MT	0.011b	0.158b	0.268a
Manure rate			
0	0.006a	0.093a	0.245a
5	0.014b	0.172b	0.247a
10	0.016c	0.185c	0.318b
P value			
Tillage	0.030*	<0.001***	0.341ns
Manure rate	<0.001***	<0.001***	<0.001***
Tillage*Manure rate	<0.001***	<0.001***	<0.001***

Different lower-case letters indicate significant differences between treatments at $P < 0.05$. ns = not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.01$; *** = significant at $P < 0.001$.

Table A6. Pore volumes of macro-, meso-, and micropores derived from water retention curve at 20 – 30 cm depth. Macropore volume was calculated as the difference between volumetric water contents at matric potentials between $h = 0$ (saturation) and $|h| < 3$ cm or $\log|h| < 0.48$ cm; meso pores were calculated as the difference between volumetric water contents at matric potentials of $|h| = 3 - 300$ cm or $\log|h| = 0.48 - 4.48$ cm; and micropore volume was calculated as the remainder from total porosity (θ_s).

Treatment	Macropores >1000 μm	Mesopores 10 – 1000 μm	Micropores <10 μm
$\text{cm}^3 \text{cm}^{-3}$			
Tillage			
CT	0.012a	0.187a	0.218a
MT	0.010b	0.114b	0.262b
Manure rate			
0	0.009a	0.105a	0.240
5	0.010b	0.169b	0.247
10	0.014c	0.177b	0.237
P value			
Tillage	<0.001***	<0.001***	<0.001***
Manure rate	<0.001***	<0.001***	0.106ns
Tillage*Manure rate	<0.001***	<0.001***	<0.001***

Different lower-case letters indicate significant differences between treatments at $P < 0.05$. ns = not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.01$; *** = significant at $P < 0.001$.

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