land

MDPI

Article

Soil-Water Retention Curves and Pore-Size Distribution in a Clay Loam Under Different Tillage Systems

Jay Jabro [1,*], William Stevens [1], William Iversen [1], Upendra Sainju [1], Brett Allen [1], Sadikshya Dangi [1] and Chengci Chen [2]

[1] Northern Plains Agricultural Research Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Sidney, MT 59270, USA; bart.stevens@usda.gov (W.S.); bill.iversen@usda.gov (W.I.); upendra.sainju@usda.gov (U.S.); brett.allen@usda.gov (B.A.); sadikshya.dangi@usda.gov (S.D.)
[2] Eastern Ag Research Center, Montana State University, Sidney, MT 59270, USA; cchen@montana.edu
* Correspondence: jay.jabro@usda.gov

Abstract: Tillage practices significantly impact soil structure, pore-size distribution (PSD), and soil-water retention curves (SWRC). The SWRC, which represents the relationship between soil water content and soil water potential, is important for various studies involving plants, soil, environment, irrigation, drainage, modeling, and hydrology. In this study, the HYPROP method was used to measure SWRCs and estimate soil physical and hydraulic properties under conventional tillage (CT), strip tillage (ST), and no-tillage (NT) systems in clay loam soil. Undisturbed soil cores were collected from 0–15 cm and 15–30 cm depths within sugarbeet rows, with sampling replicated five times following a randomized block design. Soil-water retention curves were modeled using the van Genuchten (vG) model for each depth under each tillage system. The results showed that none of the soil parameters from the vG equation, plant-available soil water content, or pore-size distribution were significantly influenced by tillage type. This lack of significant difference may be attributed to considerable soil disturbance from sugarbeet root harvesting, freeze and thaw cycles between tillage and sampling, or soil displacement caused by beet root growth. However, small differences in soil parameters among the three tillage systems were noted at both soil depths, due to minor variations in soil porosity and pore-size distribution. Regardless of the tillage system, understanding SWRC is essential for insights into soil and water processes such as water flow, soil water storage, and water availability for plants.

Keywords: soil-water retention curve; van Genuchten equation; pore-size distribution; conventional tillage; strip tillage; no-tillage

Citation: Jabro, J.; Stevens, W.; Iversen, W.; Sainju, U.; Allen, B.; Dangi, S.; Chen, C. Soil-Water Retention Curves and Pore-Size Distribution in a Clay Loam Under Different Tillage Systems. *Land* **2024**, *13*, 1987. https://doi.org/10.3390/land13121987

Academic Editor: Amrakh I. Mamedov

Received: 16 October 2024
Revised: 9 November 2024
Accepted: 20 November 2024
Published: 22 November 2024

1. Introduction

Tillage management practices can significantly alter soil physical and hydraulic properties including soil-water retention curves (SWRC) and pore size distribution (PSD), due to soil disturbance [1–3]. Understanding SWRC and PSD is essential for numerous soil, plant, environmental, irrigation, drainage, and hydrological studies, as they are widely used to evaluate soil structure, water flow, soil water storage, and plant-available water capacity [2–5]. A soil-water retention curve, also known as soil-water release curve (SWRC) or soil-water characteristics curve (SWCC), represents a non-linear graphical relationship between volumetric water content and matric suction, which is the force holding water in the soil [2].

The effects of different tillage systems on soil physical and hydraulic properties remain uncertain, with findings from previous studies often showing inconsistencies under different soil types, cropping systems, and environmental conditions. Some researchers have reported no significant differences in soil physical properties among various tillage practices, while others have found the opposite [1–3,6–11].

Pena-Sancho et al. [1] studied the effects of conventional tillage, reduced tillage, and no-tillage systems on SWRCs and their related parameters derived from the van Genuchten equation [12]. Their study, conducted in fine loamy soil under semi-arid conditions, indicated that tillage significantly affected the shape of the SWRC, whereas soil depth did not. Further, they concluded that tillage increased the scaling parameter (α) while having no effect on the fitting parameter (n).

Castellini et al. [9] investigated the effects of tillage on physical and hydraulic properties, including SWRC, in two different textured soils under winter wheat. They reported differences in soil-water properties between tillage systems in both soils.

Bahmani [11] found that water retention capacity was greater in tilled soils than in untilled soils due to the higher bulk volume of pores in the top layer of tilled soils caused by tillage.

Recently, Jabro and Stevens [2,3] reported that the SWRC parameters α, n, the water content at saturation (θ_s) of the van Genuchten equation, soil pore-size distribution, bulk density and plant available water content were significantly affected by tillage type at two depths in a sandy loam soil under corn. They also noted that soil bulk density had a considerable impact on the α parameter.

In another recent long-term study, Talukder et al. [11] evaluated soil hydraulic properties under different tillage practices. Their results revealed significant effects of tillage on the van Genuchten equation's water content at saturation (θ_s) and fitting parameter (n), soil water retention and pore volume in a silt loam soil. They also reported that both θ_s and n parameters were significantly greater in intensive tillage compared to no-tillage, while α parameter and residual water content values (θ_r) were not affected by type of tillage.

Most recently, Pecan et al. [13] evaluated estimated parameters of the van Genuchten model across two growing seasons and two tillage systems. They reported that the shape of the curves depended more on the environmental conditions than on the tillage system. They also reported greater variability in the α parameter during the season under conventional tillage compared to no-tillage, with lower values in tilled soils.

To our knowledge, few studies have assessed the impact of various tillage practices on soil-water characteristic curves, their parameters, and pore-size distribution in the Northern Great Plains region of the United States. Moreover, the contradictory results of previous studies indicate a need for further research to understand how various tillage practices influence SWRC and soil physical and hydraulic properties. Thus, the objectives of this study were to determine the effects of conventional tillage (CT), strip tillage (ST), and no-tillage (NT) practices on van Genuchten's model (vG) estimated parameters of soil-water retention curves (SWRC) and pore-size distribution (PSD) at 0–15 cm and 15–30 cm depths within irrigated sugarbeet planting rows in clay loam soil.

The HYPROP system (Hydraulic Property Analyzer, Meter Group Inc., Pullman, WA, USA) was used to measure SWRCs [14]. This automated and efficient laboratory technique is based on the evaporation method and has been widely used to measure SWRCs and estimate soil parameters using different models [15–17].

We hypothesized that the estimated parameters of SWRC and pore-size distribution would vary significantly among the three tillage systems in clay loam soil under sugarbeet cultivation.

2. Materials and Methods

2.1. Field Study Description

The study was conducted at the Montana State University Eastern Agricultural Research Center (EARC) located in Sidney, MT, USA (47.7255° N, 104.1514° W, elevation 590 m) within a 6-year cropping system study established in 2018.

Meteorological data were collected from the weather station located near the field plots. The 30-year average annual precipitation is approximately 360 mm, the majority of which takes place during the crop growing season from April to September. Total precipitation was 310 mm in 2018–2019. Mean daily air temperature at the site varied from 29 °C in July

2018 to −30 °C in January 2019. All plots were irrigated with a self-propelled overhead linear move sprinkler irrigation system.

The soil series at the experimental site is Savage clay loam (fine, smectitic, frigid Vertic Argiustolls). The average sand, silt, and clay were 18.4, 35.1 and 46.5%, respectively for the 0–15 cm depth and 18.5, 34.7, and 46.8%, respectively for the 15–30 cm depth. Research main plots (14.7 m wide × 30.5 m long) for the original cropping system study of a 3-year sugarbeet-dry pea-spring wheat rotation and three tillage treatments were arranged in a balanced randomized complete block design with five replicates (Figure 1).

Figure 1. Scheme of the experimental site showing sugarbeet plots under conventional tillage (CT), strip tillage (ST) and no-tillage (NT) systems.

2.2. Tillage Operations

The three tillage management systems used in this study were conventional tillage (CT), strip-tillage (ST) where only a band of soil is tilled, and no-tillage (NT) or direct seeding. The CT treatment for the plots coming out of wheat and going into sugarbeet consisted of one pass with a tandem disk to a depth of 7 cm followed by two passes with a ripper to a depth of 30 cm. Tilled plots then received two passes with a cultipacker and finally two passes with a land plane on 14 September–19 October 2018. The ST operation was performed on 14 September 2018 to prepare for the next year's crop (spring 2019). The six-row strip tiller was set to a depth of 20 cm with a straight coulter in front of a semi-parabolic shank followed by two wavy coulters and a crows foot packer wheel (Schlagel TP 6524, Schlagel Mfg., Torrington, WY, USA) that tills 30-cm strips and leaves 30 cm of standing stubble between tilled rows.

2.3. Soil Sampling and Preparation

Intact soil cores (8 cm in diameter and 5 cm in height) were obtained from 0–15 cm and 15–30 cm depths in sugarbeet planting rows at one sample per plot in the spring of 2019 (Figure 1).

Soil cores were saturated by the capillary action. Two mini-tensiometers were placed at two different depths within the saturated soil core that was attached to the HYPROP assembly. Soil-water retention curves were processed by the evaporation method using a HYPROP apparatus [2,14]. The apparatus automatically provided continuous measurements of soil water content and matric suction over time due to evaporation. Detailed information relating to soil sampling, sample preparation and procedures were provided by Jabro and Stevens [2,3] and Schindler et al. [14].

2.4. The Van Genuchten Equation's Parameters and Pore Size Distribution Estimation

The van Genuchten (vG) equation [12] is generally used to define the soil-water retention curve (SWRC) function in unsaturated soils. The vG equation is stated as:

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

where θ is the water content (cm^3 cm^{-3}), h is the pressure head (cm), θ_s is the water content at saturation (cm^3 cm^{-3}), θ_r is the residual water content (cm^3 cm^{-3}), α is the scaling parameter as an inverse pressure head at air-entry (cm^{-1}), and n is a fitting dimensionless parameter, related to curve shape, porosity, and pore size distribution.

Differentiating Equation (1) with respect to h provides a change in slope of SWRC as:

$$\frac{d\theta}{dh} = \frac{\theta_s - \theta_r}{\left[1+(\alpha|h|)^n\right]^{1-\frac{1}{n}}}\left[\frac{1-\frac{1}{n}}{1+(\alpha|h|)^n}\right](\alpha|h|)^n\frac{n}{h} \quad (2)$$

where $\frac{d\theta}{dh}$ is the slope of the SWRC, usually termed the specific water capacity (C(h)) according to Hillel [18]. It is stated as the ratio at which soil water content changes with changes in soil suction [2].

The C(h) for any given h value was estimated using Equation (2). This method has been widely used for estimating pore-size distribution in various porous media [3,7,19–23]. Soil physical and hydraulic parameters of Equation (1) are given in Table 1.

Table 1. Analysis of variance for estimated parameters of soil-water retention curves based on the van Genuchten equation. Significant effects at $p \leq 0.05$.

	Analysis of Variance, p > F							
Source	**α §**	**n §**	**θ_r §**	**θ_s §**	**Bulk Density**	**θ_{33} §**	**θ_{1500} §**	**PAWC § (θ_{33}–θ_{1500})**
Tillage (T)	0.7557	0.9476	0.7631	0.1511	0.1796	0.6042	0.7221	0.3683
Depth (D)	0.2679	0.1004	0.6997	0.0077	0.0005	0.0866	0.1904	0.5943
T × D	0.2937	0.3006	0.3886	0.1326	0.2639	0.8713	0.7973	0.1921

§ The α is an inverse pressure head at air-entry, n is a parameter related to pore size distribution, θ_r is residual water content, θ_s is water content at saturation, θ_{33} and θ_{1500} are volumetric water contents at 33 and 1500 kPa suctions, respectively, and PAWC (θ_{33}–θ_{1500}) is plant available water capacity for a clay loam.

The effective diameter of soil pores retaining water at soil water potential or suction was calculated using the simplified capillarity equation [3] as:

$$D \approx \frac{3000}{h} \quad (3)$$

where D is the soil pore diameter (µm), and h is the pressure head or suction in cm or hPa.

Criteria proposed by Luxmoore [24] that divided soil pore spaces into three classes based on the pore diameter used in this study include: (1) micro-pores are small pores that have a $D < 10$ µm, which can lose water for $h > 300$ hPa; (2) meso-pores are medium size pores with D between 10 and 1000 µm, which can lose water for h between 300 and 3 hPa, and (3) macro-pores are large pores with a $D > 1000$ µm, which lose water for $h < 3$ hPa [3,23].

2.5. Statistical Analyses

Tillage treatment effects on vG parameters of SWRC were evaluated using a mixed model [25]. Tillage treatment and depth were considered as fixed effects and replication as a random effect. The least significant differences (LSD) at $p \leq 0.05$ were used to compare among tillage treatments means. Further, one-way analysis of variance [25] was used to test and compare the significance of differences in the slope (PSD) of the curves among the three tillage systems.

3. Results and Discussion

3.1. Soil-Water Retention Curves and Estimated Parameters of the vG's Equation

Laboratory-measured and van Genuchten (vG) equation estimated SWRCs for CT, ST, and NT at 0–15 cm and 15–30 cm depths are shown in Figures 2–4, respectively.

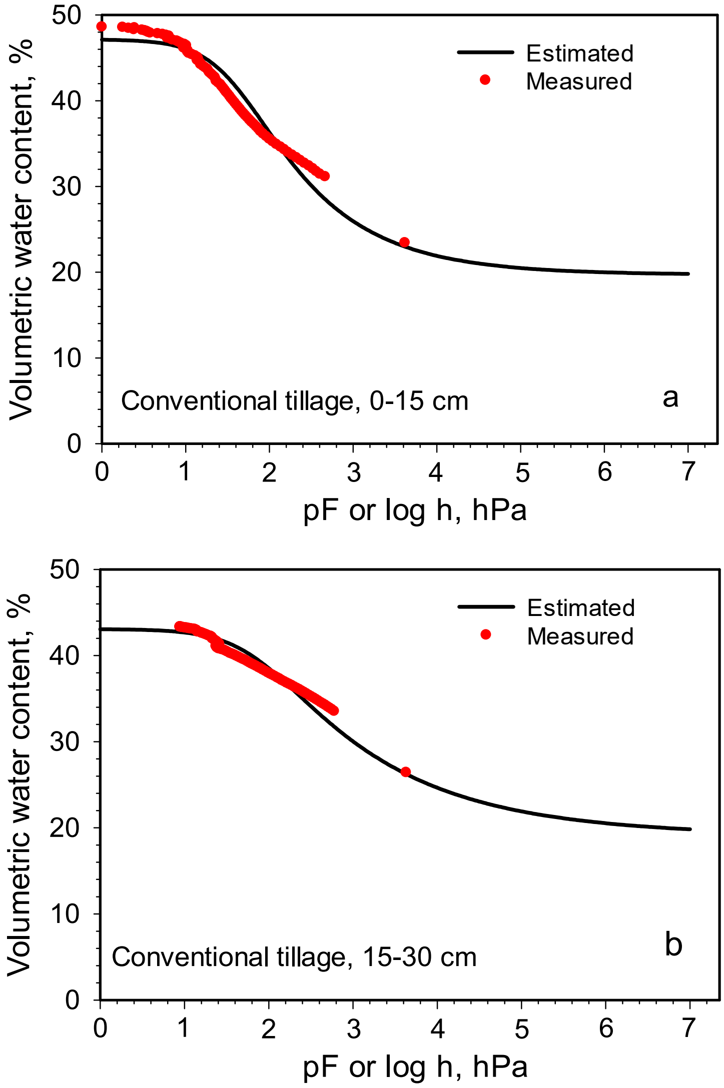

Figure 2. Measured and estimated soil-water retention curves for conventional tillage (CT), (**a**) at 0–15 cm soil depth and (**b**) at 15–30 cm soil depth.

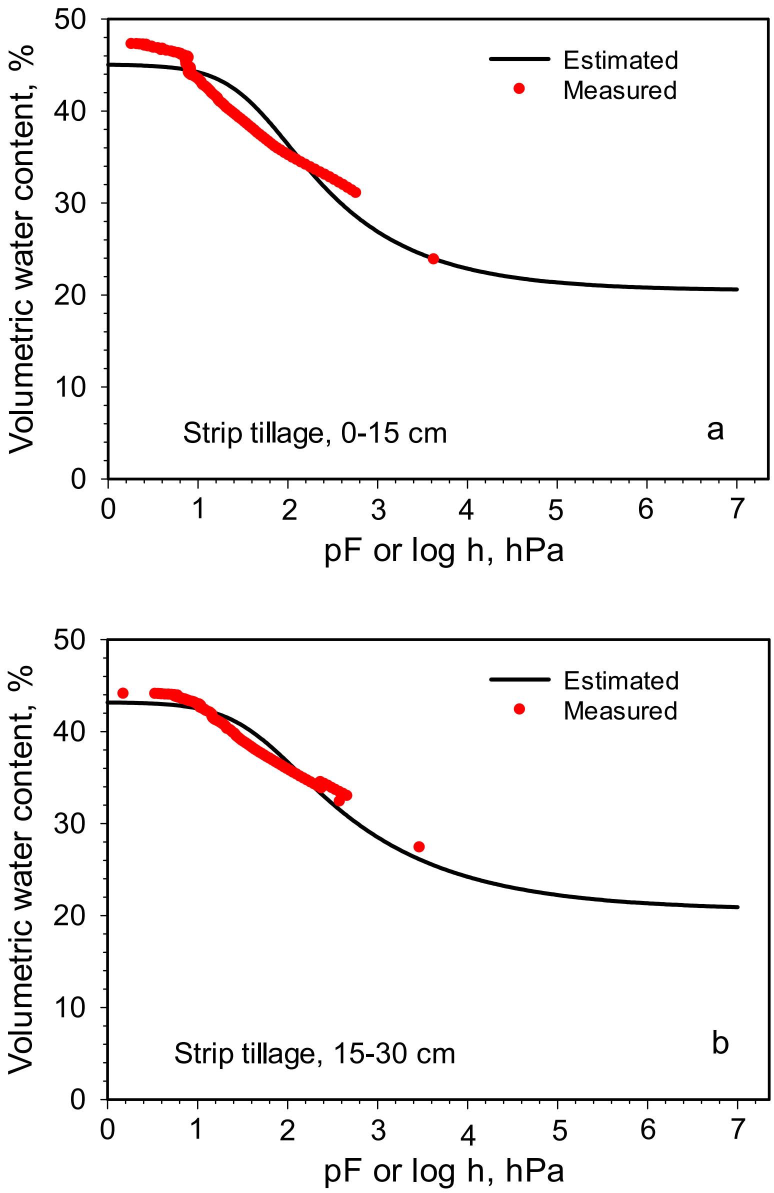

Figure 3. Measured and estimated soil-water retention curves for strip tillage (ST), (**a**) at 0–15 cm soil depth and (**b**) at 15–30 cm soil depth.

The measured SWRCs were modeled using the vG equation (Equation (1)) for soils under three tillage treatments for each depth.

Results indicated that small differences existed in measured SWRCs, which could be associated with the spatial variability in soil properties (i.e., particle size distribution, total porosity, organic matter content) among replications within each tillage system at both depths across the field.

Statistical analysis for estimated parameters of soil-water retention curves based on Equation (1) are given in Table 1.

Estimated parameters of SWRCs based on Equation (1) were not significantly affected by tillage at 0–15 cm and 15–30 cm depths or when averaged across both depths, except for the θ_s parameter, which was 5.4% larger at 0–15 cm than at 15–30 cm (Table 2).

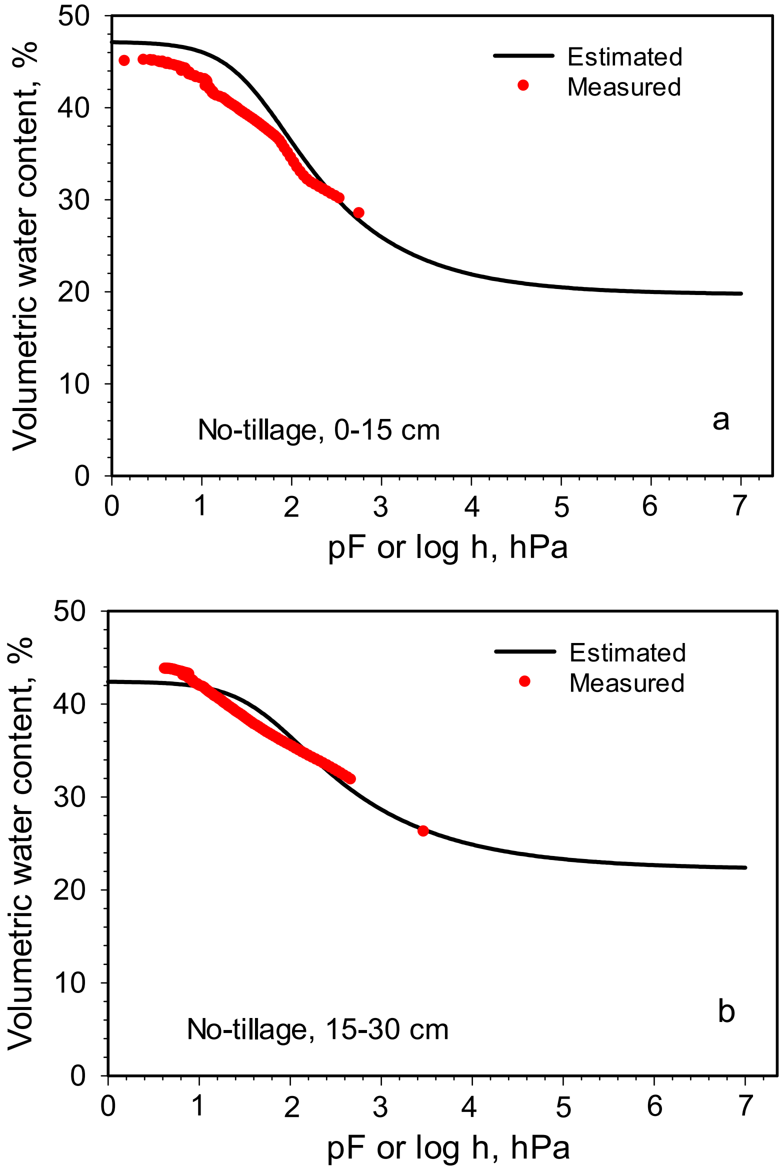

Figure 4. Measured and estimated soil-water retention curves for no-till (NT), (**a**) at 0–15 cm soil depth and (**b**) at 15–30 cm soil depth of a clay loam soil.

The lack of tillage effect could be due to several factors. Even though the puller wheels that lift the roots from the soil are typically set only 5 to 10 cm deep, the extraction of the root can disturb the surrounding soil. The growing roots also displace the surrounding soil as they expand in size though the growing season, similar to daikon radish, also referred to as tillage radish, that are bred to develop a large taproot to penetrate compacted soil layers and increase soil aeration and water infiltration [26]. A third factor that would have affected all 3 treatments is the freeze/thaw cycles that occurred between the harvest in the fall and the sampling in the spring [27]. Under these intensively disturbed soil conditions, SWRCs depend more on clay content in clay textured soils than on the tillage system. Pacan et al. [12] reported no significant difference in the n parameter between CT and NT systems in a clay loam soil, while the α parameter was greater under the NT than under the CT system.

Table 2. Estimated parameters of the soil-water retention curve for a clay loam at 0–15, 15–30, and 0–30 cm depths under conventional tillage (CT), strip tillage (ST), and no-till (NT) systems. Significant effects at $p \leq 0.05$.

Depth, cm	Tillage	α (hPa^{-1}) §	n §	θ_r (cm^3 cm^{-3}) §	θ_s (cm^3 cm^{-3}) §
0–15	CT	0.0298	1.6318	0.2398	0.4724
	ST	0.0279	1.5386	0.2416	0.4528
	NT	0.0217	1.5336	0.2186	0.4376
15–30	CT	0.0180	1.3706	0.2158	0.4332
	ST	0.0247	1.4376	0.2514	0.4318
	NT	0.0242	1.4718	0.2498	0.4280
			Average across two depths		
0–30	CT	0.0239	1.5012	0.2278	0.4528
	ST	0.0263	1.4881	0.2465	0.4421
	NT	0.0230	1.5027	0.2342	0.4328

§ The α is an inverse pressure head at air-entry (hPa^{-1}), n is an indicator of pore size distribution, θ_r is residual water content (cm^3 cm^{-3}), and θ_s is water content at saturation (cm^3 cm^{-3}). Each value is an average of 5 observations.

3.2. Effect of Soil Bulk Density on the α Parameter

Regression analysis revealed a significant quadratic relationship between measurements of soil bulk density obtained by the HYPROP system and the α parameter values estimated from the vG equation of the SWRC for three tillage treatments and two depths combined in a clay loam soil (Figure 5). These results indicated that an increase in soil bulk density led to a decrease in the α parameter and an increase in the air-entry value due to lower large pore spaces in more dense soils [2]. This relationship coincided with that reported by Jabro and Stevens [2] in sandy loam soils. Further, Gallage and Uchimura [28] and Chen [29] also revealed that soils with low bulk densities have lower air-entry values than soils with higher bulk density values.

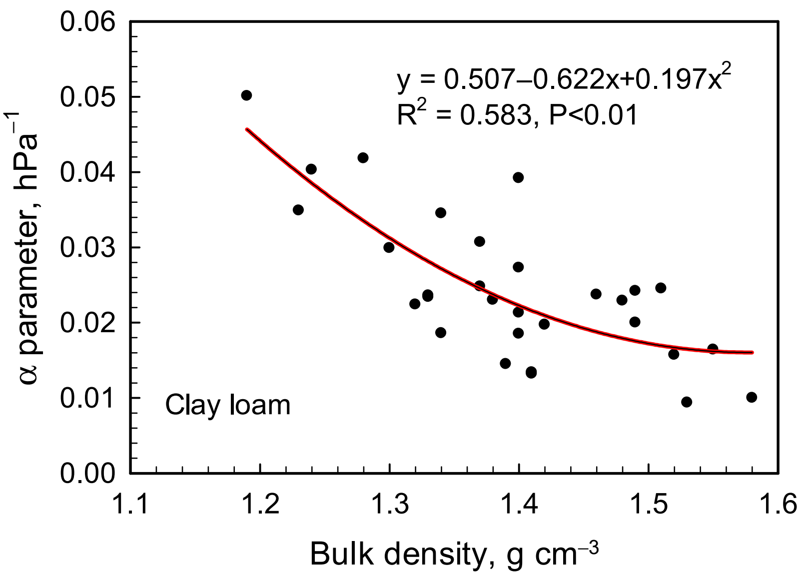

Figure 5. Effect of dry soil bulk density on the estimated α soil parameter of the vG equation of soil-water retention curve using combined datasets for three tillage treatments and two depths of a clay loam soil.

3.3. Effect of Tillage on Bulk Density and Plant Available Water Content of the Soil

Results for volumetric water contents at 33 kPa (θ_{33}), 1500 kPa (θ_{-1500}) and plant available water capacity, PAWC (θ_{33}–θ_{1500}), and soil bulk density for a clay loam are given in Tables 1 and 3.

Table 3. Volumetric water contents at 33 kPa (θ_{33}) and 1500 kPa (θ_{1500}) pressure heads, plant available water capacity, PAWC (θ_{33}–θ_{1500}) is available water content, and bulk density for a clay loam soil at 0–15, and 15–30 cm depths and their averages for conventional tillage (CT), strip tillage (ST), and no-tillage (NT) systems. Significant effects at $p \leq 0.05$.

Depth	Tillage	θ_{33}	θ_{1500}	PAWC (θ_{33}–θ_{1500})	Bulk Density
cm		$cm^3\ cm^{-3}$			$g\ cm^{-3}$
0–15	CT	0.3054	0.2484	0.0568	1.300
	ST	0.3084	0.2518	0.0566	1.332
	NT	0.2922	0.2286	0.0638	1.404
15–30	CT	0.3364	0.2586	0.0778	1.448
	ST	0.3228	0.2674	0.0548	1.436
	NT	0.3176	0.2618	0.0554	1.452
			Averaged across 2 depths		
0–30	CT	0.3209	0.2535	0.0673	1.374
	ST	0.3156	0.2596	0.0557	1.384
	NT	0.3049	0.2452	0.0596	1.428

Tillage did not significantly affect soil bulk density obtained from soil cores using the HYPROP system at 0–15 cm and 15–30 cm depths or when averaged across two depths (Table 3). These results could be linked to the reasons in previous section of this manuscript. Generally, soils under CT have smaller bulk density and associated greater total porosity within the tilled layer than under NT [29,30], who reported that the bulk density of the surface soil decreased with an increase in the degree of soil loosening by tillage. These results coincided with those obtained by Bhattacharyya et al. [7], who concluded that no significant variations in bulk density measurements among conventional tillage, minimum tillage, and zero tillage at various depths in a sandy clay loam.

However, soil bulk density was significantly affected by soil depth (Tables 1 and 3). These results concurred with those obtained by Pena-Sancho et al. [1].

The PAWC of soil is the maximum amount of water that can be used by plants [2]. It is usually calculated as the difference between amounts of water content held by the soil at field capacity and permanent wilting point, typically defined at volumetric water content (θ_{-1500}) at 1500 kPa [18]. While soil water contents at field capacity vary with different soil textures and conditions, we use water contents at a pressure head of 33 kPa (θ_{33}) to define volumetric water content at field capacity for the clay loam soil at the study site [2].

Volumetric water content at 33 and 1500 kPa and PAWC of the soil obtained from the fitted SWRC, did not differ significantly among the three tillage systems at either depth or in the combined depth due to the reasons discussed in previous sections (Table 3).

Results in Table 3 showed that the vG model slightly underestimated water content at 33 kPa (θ_{33}) pressure head and greatly overestimated water content (θ_{1500}) at 1500 kPa pressure head, resulting in smaller values of PAWC (θ_{33}–θ_{1500}) under three tillage systems at both depths. Regardless of tillage type, actual soil water contents at field capacity and permanent wilting point were about 35% and 17%, respectively, for the clay loam soil used in this study. These two water content levels were determined from in-situ SWRC and Watermark soil moisture sensors measurements [31].

3.4. Effect of Tillage on Soil Pore-Size Distribution (PSD)

Soil pore diameter (D) was calculated for any given matric suction (h) using Equation (3) [3]. Soil specific water capacity (C(h), cm^{-1}) or PSD (slope of the curve) was calculated using Equation (2) and estimated vG parameters in Table 2 for CT, ST, and NT at 0–15 cm, 15–30 cm depths and within both depths (0–30 cm). The C(h) results were plotted versus soil pore diameter (D) for CT, ST, and NT at 0–15 cm, 15–30, and 0–30 cm depths and illustrated in Figures 6–8, respectively. These functions indicated that the C(h) for three tillage systems at both depths were well described by the unimodality of the vG function.

Similar results were found by Jabro and Stevens [3], Hill et al. [6], and Pecan, et al. [13] under various tillage systems and soil textures.

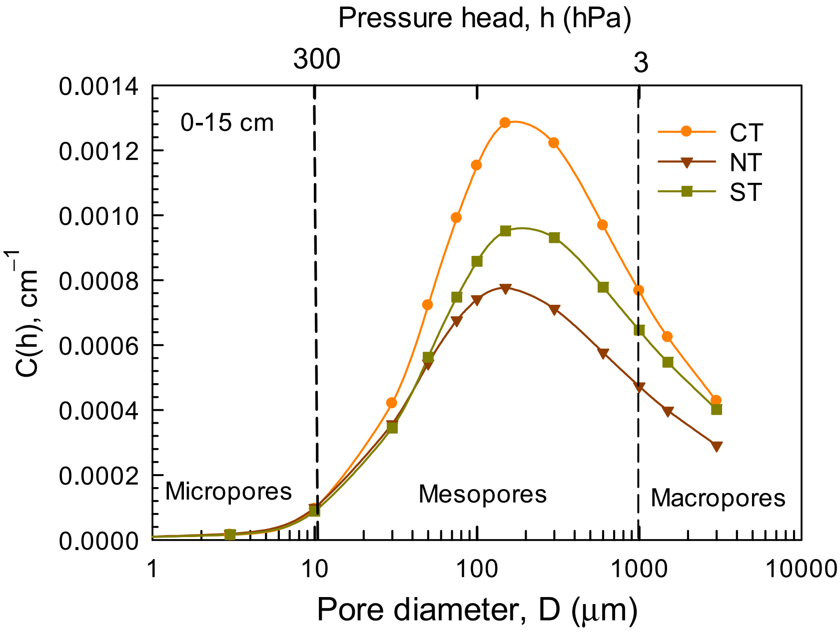

Figure 6. Specific water capacity (C(h)) as a function of pore diameter (D) for conventional tillage (CT), strip tillage (ST), and no-tillage (NT) at 0–15 cm soil depth of a clay loam soil.

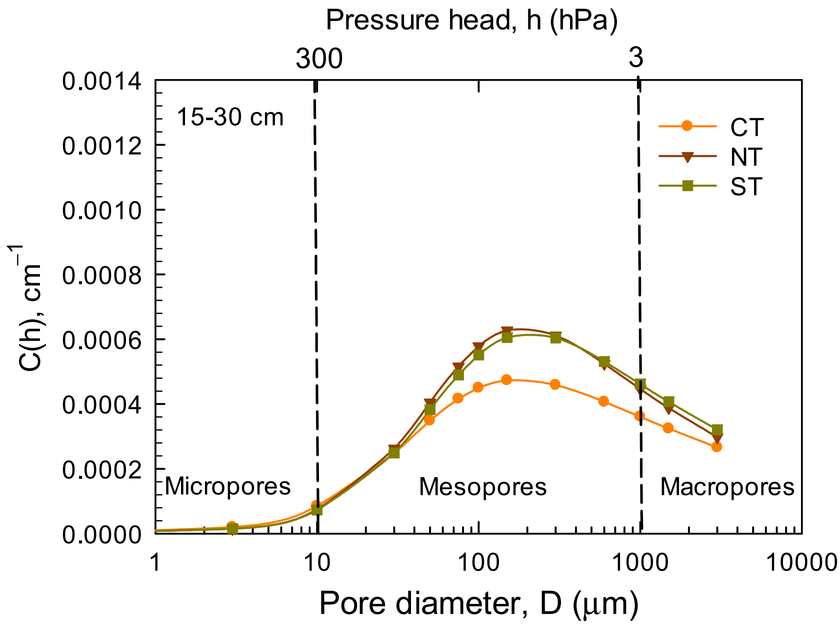

Figure 7. Specific water capacity (C(h)) as a function of pore diameter (D) for conventional tillage (CT), strip tillage (ST), and no-tillage (NT) at 15–30 cm soil depth of a clay loam soil.

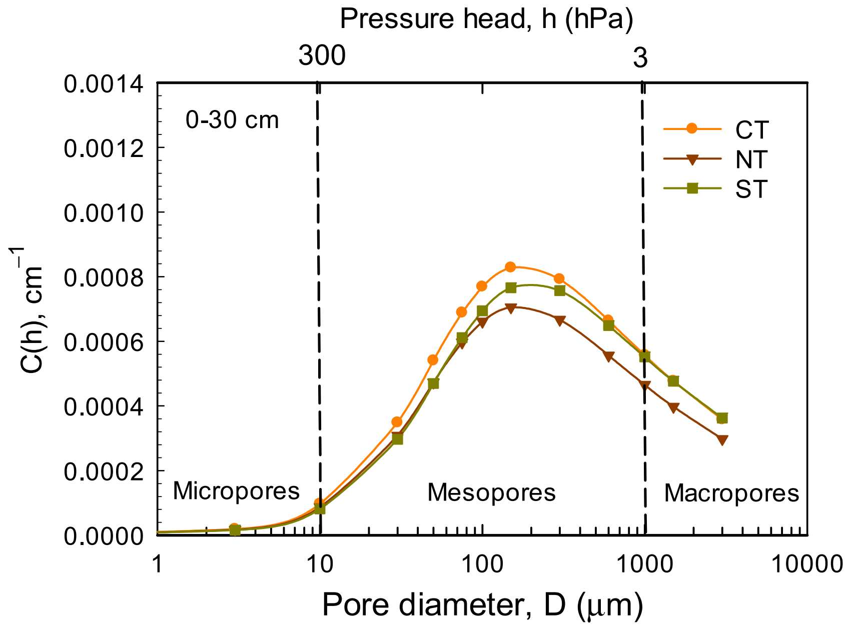

Figure 8. Specific water capacity (C(h)) as a function of pore diameter (D) for conventional tillage (CT), strip tillage (ST), and no-tillage (NT) at 0–30 cm soil depth of a clay loam soil.

The majority of the pore spaces and distribution was within the meso-pore class (10–1000 μm), which lose soil water at matric suctions between 300 and 3 hPa for the three tillage systems at both depths. Soil macro-pores and micro-pores made up smaller fractions of total pore space than meso-pores within each tillage system and depth (Figures 6–8).

The peaks of the PSD curves denote the matric suctions at which the greatest number of soil pores drain [3,32,33] that is equal to the largest slopes, named as inflection points of SWRCs [3].

The maximum slopes for the CT, ST, and NT curves at the 0–15 cm depth were 0.00128, 0.000952 and 0.00215 cm^{-1}, respectively; while the maximum slopes for the CT, ST and NT curves at the 15–30 cm depth were 0.000473, 0.000605 and 0.000628 cm^{-1}, respectively. These slopes at both depths correspond to pore diameter of 150 μm, which is equivalent to matric suction of 20 hPa (Figures 6 and 7).

Statistical results from one-way ANOVA showed that tillage had no significant impact on PSD for all three pore-size classes at both soil depths due to a considerable soil disturbance and loosening caused by the sugarbeet root harvest process in the fall of 2018. However, mean values of PSD for pore sizes between 100 to1000 μm within the meso-pores class under CT (0.00108) were significantly greater than those for ST (0.00083) and NT (0.00066) at the 0–15 cm depth due to additional soil disturbance, forming more pore spaces in the CT plots than ST and NT plots at this depth (Figure 6). Meanwhile, at this pore size range, contrasting results were observed at the 15–30 cm depth, where average values of PSD were significantly smaller in CT (0.00043) compared to ST (0.00054) and NT (0.00056) practices (Figure 7). However, there were no significant differences between the means of PSD among three tillage systems across the two soil depths at pore sizes ranging from 100 to 1000 μm (Figure 8). The effect of tillage on PSD can vary, depending on the type of tillage and soil [3,6]. Soils under CT have a greater proportion of large pores compared to soils under ST and NT systems. The PSD of soil is an important indicator of soil quality, that affects plant growth, water movement, water retention, crop production and many other processes in soils.

4. Conclusions

The results from this study did not support our hypothesis that SWRCs, estimated parameters, and pore-size distribution would vary significantly among CT, ST, and NT systems at 0–15 cm and 15–30 cm depths in a clay loam soil.

Our results indicated that all soil parameters of the vG equation and plant-available soil water content were not significantly affected by the type of tillage, largely due to soil disturbance under the three tillage systems considered in this study. Soil under both ST and NT systems was substantially disturbed during the sugarbeet root harvest in the fall of 2018. Therefore, the effect of tillage on the SWRC shape and its parameters becomes less relevant under highly disturbed conditions. Since all plots under the three tillage systems were subjected to similar disturbances during the sugarbeet harvest, soil water retention was influenced more by clay content than by tillage type.

Regardless of the tillage system, SWRCs continue to be important in assessing irrigation scheduling and management, as well as predicting water flow in soils.

Additional research is needed to explore the effect of various tillage practices and surface residue management on soil physical and hydraulic properties, considering different soil types, cropping systems, and environmental conditions. Such studies could provide critical information to improve our understanding of how tillage and cover cropping practices impact soil health and environmental quality.

Author Contributions: Conceptualization, J.J.; methodology, J.J.; formal analysis, J.J.; investigation, J.J.; resources, J.J. and W.S.; data curation, J.J.; writing—original draft preparation, J.J.; writing—review and editing, J.J., W.S., W.I., U.S., B.A., S.D. and C.C.; visualization, J.J. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

Acknowledgments: The authors would like to extend their sincere thanks to Dale Spracklin for his assistant with soil sampling, measurements and summarizing the data. We also acknowledge the substantial contributions from Montana State University, Eastern Agricultural Research Center personnel and express appreciation to them for providing land, equipment and expertise that were critical for the completion of this collaborative research.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Pena-Sancho, C.; Lopez, M.V.; Gracia, R.; Moret-Fernandez, D. Effect of tillage on the soil water retention curve during a fallow period of a semiarid dryland. *Soil Res.* **2017**, *55*, 114–123. [CrossRef]
2. Jabro, J.D.; Stevens, W.B. Soil-water characteristic curves and their estimated hydraulic parameters in no-tilled and conventionally tilled soils. *Soil Tillage Res.* **2022**, *219*, 105342. [CrossRef]
3. Jabro, J.D.; Stevens, W.B. Pore size distribution derived from soil-water retention characteristic curve as affected by tillage intensity. *Water* **2022**, *14*, 3517. [CrossRef]
4. Assouline, S. Modeling the relationship between soil bulk density and the water retention curve. *Vadose Zone J.* **2006**, *5*, 554–563. [CrossRef]
5. Cassaro, F.; Borkowski, A.K.; Pires, L.F.; Rosa, J.A.; Saab, S.C. Characterization of a Brazilian clayey soil submitted to conventional and no-tillage management practices using pore size distribution analysis. *Soil Tillage Res.* **2011**, *111*, 175–179. [CrossRef]
6. Hill, R.L.; Horton, R.; Cruse, R.M. Tillage effects on soil water retention and pore size distribution of two Mollisols. *Soil Sci. Soc. Am. J.* **1985**, *49*, 1264–1270. [CrossRef]
7. Bhattacharyya, R.; VedPrakash, S.K.; Gupta, H.S. Effect of tillage and crop rotations on pore size distribution and soil hydraulic conductivity in sandy clay loam soil of the Indian Himalayas. *Soil Tillage Res.* **2006**, *86*, 129–140. [CrossRef]
8. Daraghmeh, O.A.; Jensen, J.R.; Petersen, C.T. Near-saturated hydraulic properties in the surface layer of a sandy loam soil under conventional and reduced Tillage. *Soil Sci. Soc. Am. J.* **2008**, *72*, 1728–1737. [CrossRef]
9. Castellini, M.; Fornaro, F.; Garofalo, P.; Giglio, L.; Rinaldi, M.; Ventrella, D.; Carolina, V.; Vonella, A.V. Effects of no-tillage and conventional tillage on physical and hydraulic properties of fine textured soils under winter wheat. *Water* **2019**, *11*, 484. [CrossRef]
10. Bahmani, O. Evaluation of the short-term effect of tillage practices of soil hydro-physical properties. *Polish. J. Soil Sci.* **2019**, *52*, 43–57. [CrossRef]

11. Talukder, R.; Plaza-Bonilla, D.; Cantero-Martinez, C.; Ole, W. Soil hydraulic properties and pore dynamics under different tillage and irrigated crop sequences. *Geoderma* **2023**, *430*, 116293. [CrossRef]
12. van Genuchten, M.T. A closed form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.* **1980**, *44*, 892–898. [CrossRef]
13. Pecan, U.; Pintar, M.; Mihelic, R.; Kastelec, D. Variability of in situ soil water retention curves under different tillage systems and growing seasons. *Soil Tillage Res.* **2023**, *233*, 105779. [CrossRef]
14. Schindler, U.; Durner, W.; von Unold, G.; Muller, L. Evaporation method for measuring unsaturated hydraulic properties of soils: Extending the measurement range. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1071–1083. [CrossRef]
15. Haghverdia, A.; Öztürkb, H.S.; Durner, W. Measurement and estimation of the soil water retention curve using the evaporation method and the pseudo continuous pedotransfer function. *J. Hydrol.* **2018**, *563*, 251–259. [CrossRef]
16. Shokrana, M.S.; Ghane, E. Measurement of soil water characteristic curve using HYPROP2. *Methods X*, **2020**, *7*, 100840. [CrossRef]
17. Singh, A.; Verdi, A. Estimating the soil water retention curve by the HYPROP-WP4C system, HYPROP-based PCNN-PTF and inverse modeling using HYDRUS-1D. *J. Hydrol.* **2024**, *639*, 131657. [CrossRef]
18. Hillel, D. *Soil and Water, Physical Principle and Processes*; Academic Press, Inc.: New York, NY, USA, 1971.
19. Startsev, A.D.; McNabb, D.H. Skidder traffic effects on water retention, pore size distribution, and van Genuchten parameters of Boreal forest soils. *Soil Sci. Soc. Am. J.* **2001**, *65*, 224–231. [CrossRef]
20. Antinoro, C.; Arnone, E.; Noto, L.V. The use of soil retention curve models in analyzing slope stability in differently structured soils. *Catena* **2017**, *150*, 133–145. [CrossRef]
21. Hawal, H.M.; Lawal, A.B. Pore size distribution and soil hydro physical properties under different tillage practices and cover crops in a typic haplusult in northern Nigeria. *Trop. Subtrop. Agroecosyst.* **2017**, *20*, 111–129.
22. Jensen, J.L.; Schjønning, P.; Watts, C.W.; Christensen, B.T.; Munkholm, L.J. Soil water retention: Uni-modal models of pore-size distribution neglect impacts of soil management. *Soil Sci. Soc. Am. J.* **2019**, *83*, 18–26. [CrossRef]
23. Dlapa, P.; Hriník, D.; Hrabovský, A.; Ivan Šimkovic, I.; Hubert Žarnovičan, H.; Sekucia, F.; Kollár, J. The impact of land-use on the hierarchical pore size distribution and water retention properties in loamy soils. *Water* **2020**, *12*, 339. [CrossRef]
24. Luxmoore, R.J. Micro-, meso-, macroporosity of soil. Letter to the editor. *Soil Sci. Soc. Am. J.* **1981**, *45*, 671–672. [CrossRef]
25. SAS Institute. *The SAS System for Windows*; Version 9.2; SAS Institute: Cary, NC, USA, 2011.
26. Available online: https://www.farmprogress.com/management/tillage-radish-cover-crop-tips-to-maximize-its-benefits (accessed on 6 November 2024).
27. Jabro, J.D.; Iversen, W.M.; Evans, R.G.; Allen, B.L.; Stevens, W.B. Repeated freeze-thaw cycle effects on soil compaction in a clay loam in northeastern Montana. *Soil Sci. Soc. Am. J.* **2014**, *78*, 737–744. [CrossRef]
28. Gallage, C.P.K.; Uchimura, T. Effects of dry density and grain size distribution on soil-water characteristics curves of sandy soils. *Soils Found.* **2010**, *50*, 161–172. [CrossRef]
29. Chen, Y. Soil-water retention curves derived as a function of soil dry density. *GeoHazards* **2018**, *1*, 3–19. [CrossRef]
30. Osunbitan, J.A.; Oyedele, D.J.; Adekalu, K.O. Tillage effects on bulk density, hydraulic conductivity, and strength of a loamy sand soil in southwestern Nigeria. *Soil Tillage Res.* **2005**, *82*, 57–64. [CrossRef]
31. Jabro, J.D.; Stevens, W.B.; Iversen, W.M.; Allen, B.L.; Sainju, U.M. Irrigation scheduling based on wireless sensors output and soil-water characteristic curve in two soils. *Sensors* **2020**, *20*, 1336. [CrossRef]
32. Taylor, S.A.; Ashcroft, G.L. *Physical Edaphology—The Physics of Irrigated and Nonirrigated Soils*; W.H. Freeman and Company: San Francisco, CA, USA, 1972.
33. Wang, H.; Ni, W.; Li, X.; Li, L.; Yuan, K.; Nie, Y. Predicting the pore-size distribution curve based on the evolution machanism of soi-water charactersitic curve. *Environ. Earth Sci.* **2022**, *81*, 23. [CrossRef]