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Short communication

Long-term tillage impact on soil hydraulic properties

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ABSTRACT

An improved understanding of the impact of tillage systems on soil hydraulic properties is necessary to conserve and manage soil water under a changing climate. The objective of this study was to specifically measure soil hydraulic properties (total porosity, water infiltration, saturated hydraulic conductivity, and water retention characteristics) in no-till, chisel plow, disk, and moldboard plow systems under rainfed continuous corn (*Zea mays* L.) after 35 yr on silty clay loam soils in eastern Nebraska. We measured ponded water infiltration (positive soil water pressure) and tension (−1 kPa matric potential) infiltration to exclude macropore (>125 μm diameter) flow. Tillage treatments affected ponded infiltration only. Moldboard plow significantly increased ponded infiltration rate by 21.6 cm h^{-1} at 5 min and by 8.8 cm h^{-1} at 60 min compared with no-till. However, when compared with disk and chisel, moldboard plow increased ponded infiltration rates at all measurements times, which lasted 3 h. Regarding cumulative infiltration, moldboard plow increased cumulative infiltration by 26.9 cm to 39.0 cm after 3 h compared with other tillage systems. Similarities in tension infiltration suggest that the higher ponded infiltration for moldboard plow was most likely due to the presence of voids or fractures (>125 μm) created by full inversion tillage. Total porosity, saturated hydraulic conductivity, and water retention among the treatments did not differ. Overall, soil hydraulic properties did not differ among tillage systems except water infiltration in these silty clay loam soils after 35 yr of management.

1. Introduction

An improved understanding of the impacts of tillage systems on soil hydraulic properties is necessary to conserve and manage soil water under different soil types, management scenarios, and climates. This knowledge is particularly important in water-limited or rainfed regions such as the western Corn Belt. Soil hydraulic properties such as water infiltration, hydraulic conductivity, and water retention determine the ability of the soil to capture and store precipitation or irrigation water. Soils that drain rapidly when wet and retain water under drought conditions are important for agricultural production under increasing climate fluctuations that is expected to include more intense and frequent rainstorms or droughts in the future (Pryor et al., 2014).

Different tillage practices could affect the ability of the soil to adsorb and retain water, depending on the level of soil disturbance. Previously published studies comparing soil hydraulic properties among tillage systems have reported some inconsistent results. For example, no-till management, which is a leading conservation tillage system for reducing both soil erosion and production costs may increase (Stone and Schlegel, 2010), reduce (Unger, 1992; Baumhardt et al., 1993) or not affect (Unger, 1992; Pikul and Aase, 1995) water infiltration compared with other tillage systems. Similarly, no-till management may also increase (Lyon et al., 1998) or have no effect (McVay et al., 2006) on soil water retention. Effects on saturated hydraulic conductivity can be even more inconsistent (Blanco-Canqui et al., 2004). On one hand, tillage could increase water infiltration by disrupting compacted layers and loosening the soil relative to no-till management. On the other hand, tillage can reduce infiltration by reducing soil aggregate stability and macroporosity, increasing surface crusting, and causing soil consolidation after tillage in the absence of crop residues on the soil surface (Unger, 1992). The contrasting tillage effects and mixed findings warrant the need for additional research to better understand how tillage systems affect water flow and retention characteristics in the soil.

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Duration of tillage management can be a major factor in revealing tillage impact on soil hydraulic properties because these properties are often measurable in the long term (>10 yr). Thus, existing long-term tillage experiments could be ideal laboratories. The scant data on soil hydraulic properties from long-term experiments limit our understanding of the implications of different tillage management scenarios on soil water management. Thus, the objective of this study was to evaluate soil hydraulic properties such as total porosity, water infiltration, saturated hydraulic conductivity, and water retention characteristics under no-till, chisel plow, disk, and moldboard plow systems in rainfed continuous corn in eastern Nebraska.

2. Materials and methods

2.1. Site description

A long-term tillage experiment established in 1980 at the University of Nebraska's Rogers Memorial Farm (latitude 40.843, longitude 96.465; 368 m above sea level) about 19 km east of Lincoln, NE, under natural rainfall conditions was used for this study. The mean annual precipitation from 2004 to 2013 for the study site was 693 mm. The soil is classified as Aksarben silty clay loam (fine, smectitic, mesic Typic Argiudolls) and Wymore silty clay loam (fine, smectitic, mesic Aquertic Argiudolls). These upland soils are deep, moderately well-drained, and formed in loess parent material.

The experiment was originally designed as a randomized complete block (six replications) with six tillage treatments in continuous corn as main plots. The tillage treatments were chisel plow, tandem disk, moldboard plow, no-till, ridge-till, and subsoil tillage. Whole tillage plots were modified in the fall of 2014 by converting all tilled treatments to no-till to answer other research questions. Tillage operations were done in the fall after corn harvest each year from 1980 to 2014. After grain harvest each year, corn was chopped and tillage treatments were applied. Tillage depth was 25 cm for the chisel and moldboard plow treatments. Chisel shanks with straight points at 25 cm spacing were used. The depth of tillage for the disk treatment was approximately 10 cm. Residue was chopped in spring for the disk and no-till treatments. All tilled treatments except ridge-till were disked to <10 cm depth in spring before planting. No primary or secondary pre-plant tillage operations were done on no-till treatment.

The original design was then modified in 1986 to a randomized complete block design with a split-plot arrangement of cropping systems. Subplot treatments were continuous corn, continuous soybean (*Glycine max* L.), and a 2-yr soybean-corn rotation, with both phases present each year. Whole tillage plots were 18.3 m (24 rows, 0.76-m between rows) by 22.9 m. Subplots were 4.6 (six rows, 0.76-m between rows) by 22.9 m. The present study considers four tillage systems (no-till, tandem disk, chisel plow, and moldboard plow) under continuous corn.

Corn was planted usually in the first two weeks of May at 76-cm row spacing. Corn hybrids planted each year were chosen from commercially available selections adapted to the area. However, glyphosate-resistant corn hybrids have been planted since 1999. Other cultural practices were similar to those used by local producers. Nitrogen fertilizer was applied at the V3 growth stage on the corn at 113 kg N ha^{-1} as ammonium nitrate from 1986 to 2003 and at 168 kg N ha^{-1} from 2004 to 2014 as urea (Sindelar et al., 2015). Other plant nutrients were within acceptable levels for corn and soybean production (Sindelar et al., 2015). Further details on the experiment establishment and management are described by Varvel and Wilhelm (2011) and Sindelar et al. (2015).

2.2. In situ field measurements and soil sampling

Field measurements and soil sampling were conducted in June 2015, which was about one year after the last tillage operations. We measured water infiltration, bulk density to compute porosity, saturated hydraulic conductivity, and water retention characteristics. These properties were selected because data on the above hydraulic properties from long-term (>35 yr) experiments are limited and the few published data reported some mixed findings, which warrant further investigation.

Water infiltration was measured under: i) −1 kPa matric potential using tension infiltrometer (Perroux and White, 1988) and ii) ponded conditions using double ring infiltrometers (Reynolds et al., 2002a). Water infiltration under the negative pressure (−1 kPa matric potential) was determined using a tension infiltrometer with a wetting area of 0.03 m^2 (Perroux and White, 1988). The negative pressure was used to exclude macropore (>125 μm diameter) contribution to the total water flow in the soil, allowing the measurement of water infiltration through the soil matrix. Surface residues were removed and 4 mm layer of fine silica sand was placed on the soil surface to provide good contact between the soil and the tension infiltrometer (Perroux and White, 1988). The water infiltration under tension was measured for 30 min, with reservoir level readings taken every minute.

For the ponded water infiltration measurement, an inner ring with 20 cm diameter was nested within an outer ring with 40 cm diameter. The rings were carefully inserted to 10–15 cm depth of the soil with surface free of cracks and plant residues. Tap water was added to both rings and the water levels in both the outer and inner rings were at the same height during the measurement. The tap water had an electrical conductivity of 0.75 dS m^{-1} and a pH of 7.1. The infiltration rate was measured for 3 h by recording the change in water level height in the inner ring at specific time intervals. Water level in the rings was maintained between 5 cm and 10 cm height. Water infiltration rate (cm h^{-1}) and cumulative water infiltration (cm) were computed after 3 h.

Intact soil cores were collected from non-trafficked rows for the measurement of soil bulk density, saturated hydraulic conductivity, and water retention characteristics. Two intact soil cores (7.5 cm diam. and 7.5 cm long) per plot were collected using a hammer-driven core sampler for depths of: 0–7.5, 7.5–15, 15–22.5, and 22.5–30 cm. Soil cores were sealed in plastic bags, transported to the laboratory, trimmed, and stored at 4 °C prior to laboratory measurements.

2.3. Laboratory measurements and data analysis

Saturated hydraulic conductivity was measured using the constant head method (Reynolds et al., 2002b). Soil cores were slowly saturated for 24 h from the bottom with de-aired tap water delivered using a Mariotte bottle at a constant flow rate of 5 mm h^{-1}. The tap water had an electrical conductivity of 0.60 dS m^{-1} and a pH of 7.4. Saturated soil cores were transferred to the permeameter to measure saturated hydraulic conductivity under constant head for 30 min. Immediately after saturated hydraulic conductivity determination, water retention at 0, −1, and −3 kPa matric potentials was determined on the intact soil cores using a tension table Soil cores were slowly resaturated, weighed, and placed on the tension table. The cores were drained on the tension table and weighed at each pressure level. Next, water retention at −10, −33, −100, −400 and −1500 kPa was determined by using pressure plate apparatus (Dane and Hopmans, 2002). For water retention determination at matric potentials between −10, and −400 kPa, the intact soil cores were transferred from the tension table to the pressure extractors, drained at each pressure head, and weighed after drainage stopped. At the end of the determination at

−400 kPa matric potential, all soil cores were weighed and a subsample was oven-dried at 105 °C to determine gravimetric water content and bulk density by the core method (Grossman and Reinsch, 2002). Another subsample was air-dried, crushed, passed through 2-mm sieves, and tightly packed in rubber rings to determine water retention at −1500 kPa potential using pressure extractors. Plant available water was computed as the difference in water content between −33 and −1500 kPa matric potentials (Dane and Hopmans, 2002). Porosity was computed from the bulk density data assuming that particle density is equal to 2.65 Mg m^{-3} (Grossman and Reinsch, 2002).

2.4. Statistical analysis

The normality test using PROC UNIVARIATE in SAS showed that data on saturated hydraulic conductivity were not normally distributed. Log-transformation was used to normalize data prior to the analysis of treatments effects. Statistical differences in the measured soil properties among tillage treatments were analyzed using PROC MIXED in SAS (SAS Institute, 2016). Tillage treatments were the fixed factor and the replication was the random factor. Analysis of differences in ponded and tension water infiltration data was conducted by time. Differences among treatments means are reported at the 0.05 probability level.

3. Results and discussion

3.1. Water infiltration

Tillage treatments had a significant effect on water infiltration rates (Fig. 1A) and cumulative infiltration (Fig. 1B) when measured under ponded conditions. Differences were, however, only significant between moldboard plow and the rest of the tillage systems (no-till, disk, and chisel plow). The trend followed this order: Moldboard plow > No-till = Disk = Chisel plow (Fig. 1A and B). Moldboard plow increased water infiltration rates between 74% and 90% compared with no-till in the first 60 min of infiltration (Fig. 1A). For example, infiltration rate under moldboard plow was greater than under no-till management by 21.6 cm h^{-1} at 5 min and by 8.8 cm h^{-1} at 60 min. Between 60 min and 180 min of measurement, infiltration rates between moldboard plow and no-till did not differ. In contrast, when compared with disk and chisel plow systems, the moldboard plow system consistently increased water infiltration rate during the 3 h of measurement (Fig. 1A). Furthermore, differences in water infiltration between moldboard and chisel plow were larger than between moldboard plow and disk (Fig. 1A), indicating that chisel plow had the lowest infiltration rate. Moldboard plow also had significant effects on cumulative water infiltration (Fig. 1B). Cumulative infiltration under moldboard plowed plots was larger than under no-till and disked plots by 26.9 cm and larger than chisel plowed plots by 39.0 cm at the end of the 3 h of measurement (Fig. 1B). Similar to the infiltration rates, the moldboard plow system had the highest cumulative infiltration and chisel plow the lowest (Fig. 1B).

Our study also showed that tillage treatment effects on infiltration rate and cumulative infiltration measured at −1 kPa pressure head with the tension infiltrometer to reduce macropore flow were not significant (Fig. 2A and B). Cumulative infiltration measured by the tension infiltrometer was about half the cumulative infiltration measured with the double ring infiltrometers under ponded conditions (Fig. 2B). The lower cumulative infiltration under the tension infiltrometer compared with that under ponded conditions was expected as contribution of macropores (>150 mm in diameter) to the total water flow is reduced or eliminated under the negative pressure by the tension infiltrometer.

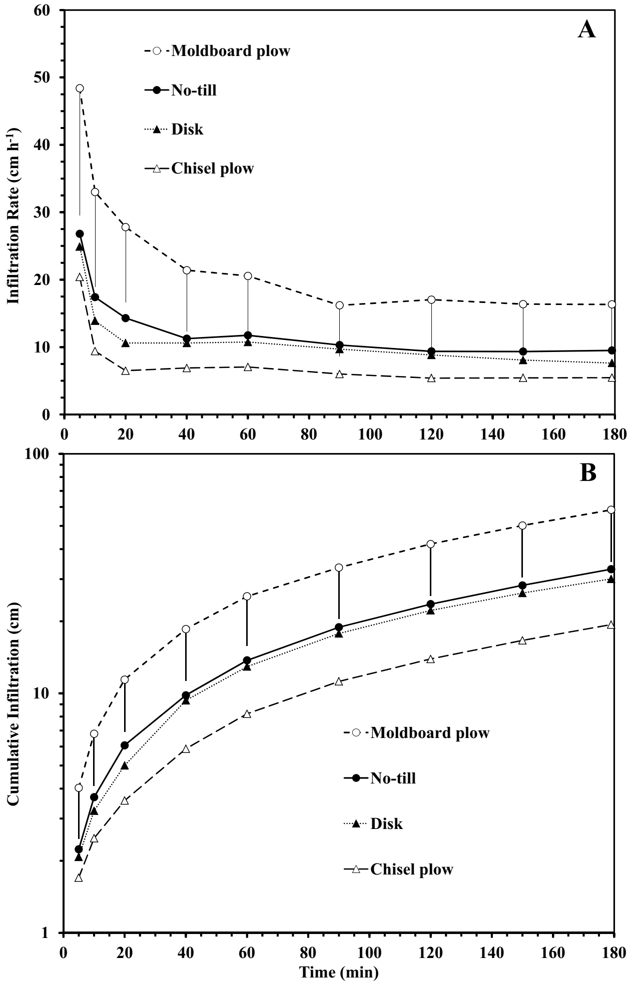

Fig. 1. Infiltration rate (A) and cumulative infiltration (B) measured under ponded conditions for long-term (35 yr) tillage systems under continuous corn for a rainfed experiment in eastern Nebraska. The error bars represent the LSD values to compare means.

Results indicate that moldboard plow increased ponded water infiltration compared with no-till, disk, and chisel plow systems in this soil. The higher infiltration in moldboard plowed soils can be attributed to fractures or voids created by the intensive and deep tillage. While soil porosity between moldboard plow and no-till did not statistically differ (data not shown), based on visual observations during the infiltration measurements, soil surface in moldboard plowed plots appeared to be less consolidated than in other tillage systems almost a year after tillage. The lower infiltration in no-till compared with moldboard plowed plots and no differences from disk and chisel plow indicate that long-term no-till may not increase water infiltration relative to other tillage systems. Previous studies have found that no-till management may increase (Stone and Schlegel, 2010) or reduce (Baumhardt et al., 1993 Wienhold and Tanaka, 2000) water infiltration compared with plow till systems. It is important to note that the use of moldboard plow system is no longer common in the study region. Thus, the lack of significant differences in water infiltration among no-till, disk, and chisel plow may have broader and more practical implications for water management in this region. Results of water infiltration suggest that these three tillage systems were similar in their ability to capture precipitation or irrigation water. Based on the results from both infiltration

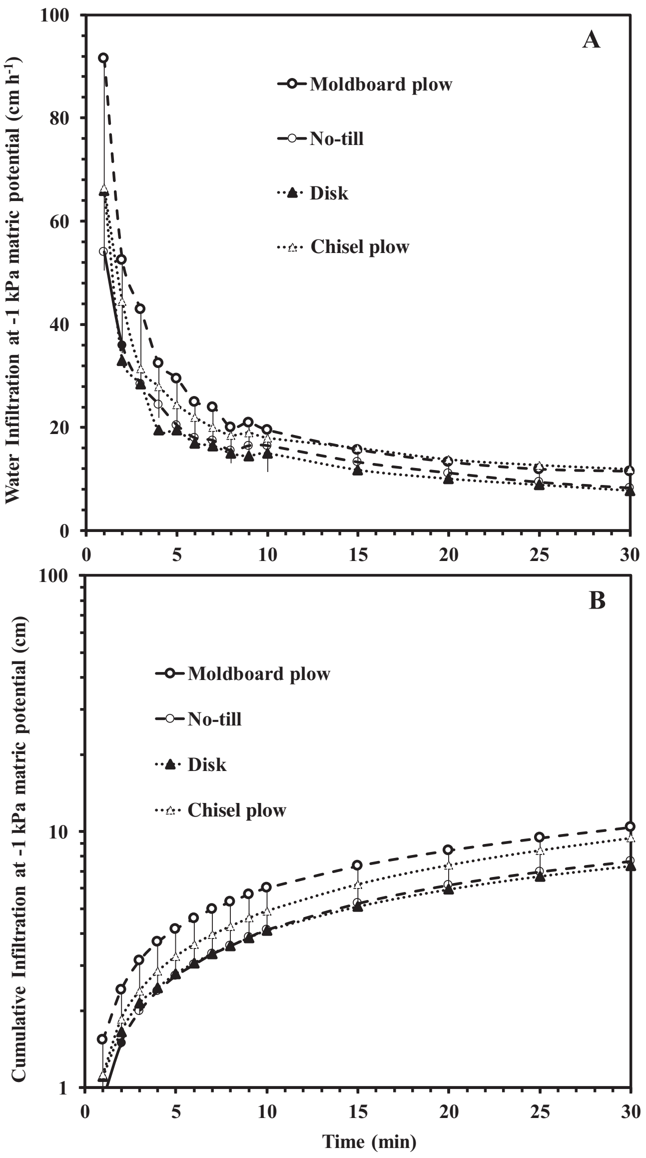

Fig. 2. Infiltration rate (A) and cumulative infiltration (B) measured under −1 kPa matric potential with a tension infiltrometer for tillage systems under continuous corn for a rainfed experiment in eastern Nebraska. The error bars represent the LSD values to compare means.

techniques, the greater water infiltration rates and cumulative infiltration found under ponded conditions (Fig. 1A and B) than under tension (Fig. 2A and B) for moldboard plow were most likely due to the presence of voids or fractures created by the full inversion tillage. These results imply that water infiltration under tension through the soil matrix did not benefit from macropore channels or differ among the four tillage systems.

3.2. Soil porosity, hydraulic conductivity, and water retention

Differences in bulk density, soil porosity, saturated hydraulic conductivity, water retention, and plant available water among the four tillage treatments were not significant at any soil depth. Only data for the 0–7.5-cm depth are reported in Table 1. Data on saturated hydraulic conductivity were variable. The coefficient of variation for the saturated hydraulic conductivity was 115%, which is within the range of coefficient of variation (100–400%) reported in similar studies (Reynolds et al., 2000; Gwenzi et al., 2011). Note that the data on ponded steady-state infiltration rates (equilibrium infiltration; Fig. 1A), which are similar to field saturated hydraulic conductivity, were significant among the four treatments. This finding corroborates that water infiltration measurement in the field could be a more representative approach to estimate saturated hydraulic conductivity and evaluate its differences among treatments relative to the use of small soil cores for its determination (7.5 cm by 7.5 cm; Reynolds et al., 2002b). Small cores can be susceptible to compaction or disturbance during sampling, which could rapidly alter hydraulic conductivity measurements.

Results indicate that long-term tillage systems did not differently impact soil porosity, saturated hydraulic conductivity, water retention, and plant available water. For the same experiment, Varvel and Wilhelm (2011) reported that the no-till management had larger soil organic C stocks than the other tillage systems. We thus expected that such an increase in soil organic C could have resulted in improved soil porosity, saturated hydraulic conductivity, and water retention capacity (Rawls et al., 2003), but that was not the case in this study. The lack of significant tillage differences in water retention is consistent with other studies reporting mixed effects of no-till on water retention even in the long term. No-till management may (Lyon et al., 1998; Tanaka and Anderson, 1997; Stone and Schlegel, 2010) or may not (Blanco-Canqui et al., 2004; McVay et al., 2006) increase soil water retention. Additionally, Rawls et al. (2003) indicated that changes in soil C concentration may or may not increase soil water retention, depending on clay content, initial organic matter content, and their site-specific interactions.

Data also suggest that no-till farming even in the long term (35 yr) may have limited or no positive effect on increasing water infiltration and retention compared with moldboard plow and conventional tillage systems such as disk and chisel plow. Based on the results, we suggest that additional practices such as addition of cover crops may be needed to enhance the potential of no-till farming to improve soil hydraulic properties relative to

Table 1
Soil hydraulic properties for the 0–7.5 cm soil depth as affected by long-term (35 yr) tillage systems under continuous corn for a rainfed experiment in eastern Nebraska. Similar to the 0–7.5 cm soil depth, differences in soil hydraulic properties at deeper depths were not significant and were not included in this table.

Treatment	Bulk Density	Saturated Hydraulic Conductivity	Matric Potential (−kPa)								Plant Available Water
			0	−1	−3	−10	−33	−100	−400	−1500	
	Mg m^{-3}	cm h^{-1}	Volumetric Water Content (m^3 m^{-3})								cm
Moldboard plow	1.19	12.71	0.52	0.48	0.44	0.40	0.38	0.37	0.34	0.21	1.27
No-till	1.19	20.77	0.52	0.47	0.44	0.39	0.38	0.37	0.34	0.20	1.35
Disk	1.22	3.80	0.50	0.47	0.45	0.40	0.38	0.36	0.33	0.19	1.42
Chisel plow	1.22	23.66	0.50	0.45	0.43	0.38	0.36	0.35	0.32	0.20	1.20
p-value	*0.93*	*0.17*	*0.27*	*0.19*	*0.53*	*0.79*	*0.57*	*0.75*	*0.62*	*0.11*	*0.38*

conventional tillage systems in this region (Blanco-Canqui et al., 2011). Our results also corroborate that no-till impacts on most soil hydraulic properties can be highly site specific (Baumhardt et al., 1993; Stone and Schlegel, 2010). Results also suggest that management duration may not be the only factor that affects changes in soil hydraulic properties.

It is important to restate that soil hydraulic properties in this study were measured about one year after the last tillage operations. Differences in soil hydraulic attributes among tillage systems can vary with time after tillage (Strudley et al., 2008). Thus, monitoring changes in soil hydraulic properties on a temporal basis across seasons is needed to better characterize tillage effects. For example, differences in water infiltration and soil porosity between no-till and plow till soils can be the highest immediately after tillage and decrease with time as the loose tilled soil collapses and consolidates due to overburden pressure and raindrop impacts (Strudley et al., 2008). Based on this consideration, water infiltration in moldboard plowed plots would have been larger than in no-till plots should we had measured these properties soon after tillage. Hydraulic properties such as water infiltration, porosity, and saturated hydraulic conductivity are more readily altered by tillage operations due to changes in soil structure compared with water retention capacity at high suctions (i.e., −1500 kPa or permanent wilting point), which is less affected by changes in soil structural characteristics. In this study, for the given soil types, water retention between no-till and other tillage systems did not differ (Table 1), suggesting that long-term no-till may not improve water retention capacity regardless of measurement time following tillage.

4. Conclusions

Results from this long-term study indicate that soil physical characteristics among no-till, disk, chisel, and moldboard plow were similar except for water infiltration under ponded conditions. Moldboard plowed soils had greater ponded infiltration rates and cumulative infiltration compared with no-till, disk, and chisel plow systems. Infiltration rate and cumulative infiltration determined at −1 kPa pressure head with the tension infiltrometer to reduce macropore flow did not, however, differ among the tillage treatments. Thus, the increased water infiltration under ponded conditions for the moldboard plow system and similarities in infiltration among tillage systems when macropore flow was eliminated suggest that inversion tillage with moldboard plow probably created some fractures in the soil structure, which increased infiltration, relative to other tillage systems. Differences in soil porosity, saturated hydraulic conductivity, and water retention characteristics among the four tillage systems were not significant. These results suggest that no-till management may not retain more water than other tillage systems in this soil even in the long term. While differences in ponded infiltration could be the result of macropore flow, the other soil hydraulic parameters appeared to be independent of that macropore contribution. Overall, no-till management potential for improving soil hydraulic properties appears to be limited under the conditions of this study.

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