Impacts of Long-Term Wheat Straw Management on Soil Hydraulic Properties under No-Tillage

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Crop residues left on the soil surface conserve soil and water, but residue impacts on near-surface soil hydraulic properties have not been widely studied. Therefore, soil hydraulic properties were determined under uncropped no-tillage (NT) plots receiving three levels of wheat (*Triticum aestivum* L.) straw mulch (0, 8, and 16 Mg ha^{-1} yr^{-1}) application for 10 consecutive yr on a Crosby silt loam (fine, mixed, active, mesic Aeric Epiaqualfs) in central Ohio. Water infiltration rates, earthworm population, saturated hydraulic conductivity (K_{sat}), soil water retention (SWR), total porosity, and pore-size distribution were determined and unsaturated hydraulic conductivity was estimated from SWR and K_{sat} data. Mulching significantly impacted hydraulic properties in the 0- to 3-cm soil depth ($P < 0.01$), but water infiltration rate was unaffected. Earthworm counts were 0 m^{-2} in the unmulched treatment, 158 ± 52 m^{-2} (mean ± SD) in treatments with 8 Mg ha^{-1} yr^{-1} of straw, and 267 ± 58 m^{-2} in those with 16 Mg ha^{-1} yr^{-1} of straw. Mulched treatments had a K_{sat} 123 times greater and retained 40 to 60% more water between 0 and −1500 kPa than the unmulched treatment. Soil porosity increased by 28% under 8 Mg ha^{-1}yr^{-1} of straw and by 44% under 16 Mg ha^{-1}yr^{-1} in the 0- to 3-cm depth compared with the unmulched treatment. Pore volume of macro- and mesopores was greater in mulched treatments and that of fine mesopores was greater in the unmulched treatment in the 0- to 3-cm depth. Straw mulching appears to be a viable practice to improve near-surface hydraulic properties in long-term NT soils, although residues may not increase water infiltration rates.

Abbreviations: K_{sat}, saturated hydraulic conductivity; $K(\theta)$, unsaturated hydraulic conductivity;NT, no-tillage; SOC, soil organic carbon; SWR, soil water retention; θ, volumetric water content; Φ_e, effective porosity; ρ_b, bulk density.

Management of crop residues in combination with NT is a proven strategy for soil and water conservation and enhancement of soil biological processes (Kladivko et al., 1997; Blanco-Canqui et al., 2006a). Crop residues left on the soil surface protect the soil against crusting, surface sealing, and detachment by intercepting and buffering the kinetic energy of rainfall and runoff (Lentz and Bjorneberg, 2003). While the benefits of using crop residues as surface mulch for reducing soil erosion are widely recognized, research data with regard to residue impacts on soil hydraulic properties such as water infiltration and hydraulic conductivity in long-term NT systems are sparse and often inconsistent. Knowledge of soil hydraulic property response to residue management is important for modeling runoff, drainage, groundwater recharge, solute transport, and soil–water–plant relationships. Water infiltration and K_{sat} not only control rainwater partitioning and the magnitude of surface runoff, but also are sensitive indicators of soil structural development.

Residue mulching may not always improve water infiltration and hydraulic conductivity in all soils because positive effects depend on the quality and quantity of residue applied, management duration, tillage system, site-specific soil properties, and climate. Barzegar et al. (2002) observed that infiltration rates and water retention at less than −100 kPa increased linearly with increases in wheat straw application rate from 0 to 15 Mg ha^{-1} combined with composted sugarcane (*Saccharum* spp.) bagasse (crushed sugarcane) and farmyard manure on a clay loam. Lentz and Bjorneberg (2003) reported that wheat straw application at rates as low as 1.5 Mg ha^{-1} increased water infiltration rates. In contrast, other studies have reported no significant impact of straw mulching on K_{sat} after 14 yr of wheat straw management on a silty clay loam (Skidmore et al.,1986) and after 20 yr of barley (*Hordeum vulgare* L.) straw management on a loam or sandy loam (Sharratt et al., 2006). In some soils, NT with residue mulch may have a lower K_{sat} than other tillage practices in spite of having more residue cover (Lampurlanes and Cantero-Martinez, 2006). These contrasting effects of straw mulching warrant additional research in long-term straw management experiments to clarify the effects of mulching on soil hydraulic properties.

A minimum and maximum threshold level of straw mulching may exist for different soils within which changes in hydraulic properties are measurable. Baumhardt and Lascano (1996) reported that additions of wheat straw above 0.7 Mg ha^{-1}

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increased rain infiltration on a clay loam, but additions above 2.4 Mg ha^{-1} had no significant effect. Soils treated with the same amount of crop residues often vary in hydraulic properties due to differences in textural characteristics. On a cracking clay soil, >8-yr NT systems under wheat stubble increased K_{sat} by about eight times, while on a sandy loam soil the NT system increased K_{sat} by only two times compared with tillage systems without stubble retention (Bissett and O'Leary, 1996). It is commonly perceived that increases in population and activity of earthworms may significantly increase infiltration and K_{sat} in NT soils with mulch due to the development of macropores (e.g., burrows) (Martens and Frankenberger, 1992; Logsdon et al., 1993). Direct relationships between earthworm numbers and water infiltration rates have not been well established, however, in soils with high earthworm activity.

To date, most studies have reported strong effects of residue management combined with those of tillage and cropping practices (Logsdon et al., 1993; Bissett and O'Leary, 1996; Barzegar et al., 2002), making it difficult to specifically identify the effects of residue mulch. Thus, data on the independent impacts of residue mulch on soil hydraulic properties are needed to better understand underlying processes. Furthermore, most available data on residue management impacts on soil processes are based on short-term experiments (<5 yr), which may not reflect the long-term soil response to management, especially in soils that have not yet attained a steady-state level under mulch. Long-term and well-designed experiments under different residue management scenarios but under the same tillage method (e.g., NT) provide an opportunity to clarify the effects of residue mulch on soil hydraulic properties. Therefore, the objective of this study was to quantify the impacts of wheat straw mulching on selected hydraulic properties of a Crosby silt loam after 10 yr of consistent straw management under an uncropped NT system.

MATERIALS AND METHODS

Site Description and Experimental Design

A long-term (10 yr) wheat residue management experiment established in 1996 at the Waterman Farm of the Ohio State University, Columbus, OH, was used for this study. This long-term straw management field experiment has been used to assess the impacts of surface mulching on soil organic carbon (SOC) sequestration, greenhouse gas emissions, soil structural properties, and nutrient dynamics (Jacinthe et al., 2002; Saroa and Lal, 2003, 2004; Blanco-Canqui and Lal, 2007). The soil at the site is a Crosby silt loam with a slope of about 1%. These soils are very deep, somewhat poorly drained, and developed on loamy till. The site is managed by NT management with three levels of wheat residue mulch (0, 8, and 16 Mg ha^{-1} yr^{-1}) and two levels of N fertilization (0 and 244 kg N ha^{-1}) with three replicates for a total of 18 experimental plots of 5 by 5 m arranged in a completely randomized block design. Baled, air-dry wheat straw from the previous year is applied manually to the treatment plots every spring (mid-April) preceding N fertilization. Wheat straw is uniformly manually spread on the soil surface of the corresponding treatments to simulate NT management. No crop is grown on the plots and no cultural operations are performed on the plots. Glyphosate (*N*-phosphonomethyl glycine) is applied when needed with a tractor-mounted sprayer. No wheel or animal traffic occurs on the plots except during manual straw application. Only the nine plots treated with N fertilizers were used for this study.

Field and Laboratory Measurements

A double-ring infiltrometer was used to determine the water infiltration rates in each plot using a constant-head method (Reynolds et al., 2002a). An inner ring infiltrometer of 15 cm in diameter and an outer ring of 27 cm in diameter were inserted into the soil to 15-cm depth. Infiltration was measured for 3 h with readings made at longer time intervals as the infiltration approached a constant rate. Tap water with an electrical conductivity of 0.65 dS m^{-1} and sodium adsorption ratio of 2.03 was used for the infiltration measurements. The earthworm population in each plot was estimated by counting the number of earthworms contained in 0.006 m^3 of soil (0.4-m^2 surface area by 0.15 m deep) in early September 2006. The soil cube was carefully excavated with a square spade, rapidly extracted, and immediately sifted into a tray to manually count the earthworms.

Intact soil cores were collected from the 0- to 3-, 3- to 10-, and 10- to 20-cm depth intervals with a hammer-driven core sampler in early September 2006 for the determination of K_{sat} and SWR from each of the nine plots. Metals sleeves, 7.6 cm in diameter and 3 cm tall for the 0- to-3-cm depth and 7 cm tall for the lower depths, were used to collect the intact cores. Soil cores from 3- to 10-, and 10- to 20- cm depth intervals were collected by excavating soil to 3- and 10-cm depths, respectively, and then metal sleeves were inserted with the core sampler. Soil cores were trimmed to the specified length, weighed, and saturated for 24 h from the base with de-aired tap water using a Mariotte bottle at a constant flow rate of 5 mm h^{-1} for the determination of K_{sat} using a constant-head method (Reynolds et al., 2002b).

Following K_{sat} determination, cores were resaturated with water for 24 h for the determination of SWR at 0, −0.1, −0.3, −1, −3, −6, −33, −100, −300, and −1500 kPa potentials (Dane and Hopmans, 2002). Saturated cores were weighed and placed on a tension table furnished with blotting paper and an outflow system for the determination of high-energy SWR at 0, −0.1, −0.3, −1, −3, and −6 kPa potentials. The SWR at low energy (−33, −100, −300, and −1500 kPa) was determined using a pressure plate apparatus. For the SWR determination at −33, −100, and −300 kPa, intact soil cores used for the high-energy SWR were transferred to pressure plates, drained in steps, and oven dried for volumetric water content (θ) determination. Cores were drained at each pressure level until there was no change in soil mass. Air-dried bulk samples were ground, passed through 2-mm sieves, and tightly packed in rubber rings for determination of SWR at −1500 kPa (Dane and Hopmans, 2002).

At the end of SWR measurements, soil cores were dried at 105°C for 24 h to determine bulk density (ρ_b) by the core method (Grossman and Reinsch, 2002). Total porosity of the soil, which is equivalent to the volumetric water content at saturation, was estimated from the SWR data (Dane and Hopmans, 2002). Pore-size distribution was determined from data on SWR. The equivalent pore radius was computed using the capillary rise equation (Hillel, 1998). Pore-size classes were grouped into macropores (>500 μm), coarse mesopores (25–500 μm), fine mesopores (5–25 μm), and micropores (<5 μm) (Luxmoore, 1981). Determination of infiltration rates, earthworm counts, K_{sat}, and SWR were made on three replicates corresponding to one replicate per experimental plot.

Estimation of Unsaturated Hydraulic Conductivity

Since water-content-dependent hydraulic conductivity, $K(\theta)$, is one of the most uncertain and variable soil properties, it has been often estimated from measured K_{sat} and θ data at different soil water potentials. A number of $K(\theta)$ predictive models are available for this purpose

(Brooks and Corey, 1966; Campbell, 1974; van Genuchten, 1980). In this study, $K(\theta)$ was computed using the model of Campbell (1974):

$$K(\theta) = K_{\mathrm{sat}} \left(\frac{\theta}{\theta_s} \right)^{Ab+B} \qquad [1]$$

where θ_s is the volumetric water content at saturation, b is the soil water retention parameter or slope obtained by fitting a straight regression line to the relationship between the log-transformed soil water potential (−kPa) and the log-transformed θ, and A and B are constants dependent on soil pore-size distribution. As suggested by Campbell (1974) and Poulsen et al. (1999), in this study, A was assumed equal to 2 and B equal to 3. Since straw-management-induced changes in soil properties were mostly observed within the 0- to 3-cm soil depth, $K(\theta)$ was estimated only for this depth interval.

A one-factor ANOVA model was used to test whether water infiltration rates, K_{sat}, $K(\theta)$, SWR, total porosity, ρ_b, pore-size distribution, and earthworm counts differed among the three treatments using SAS (SAS Institute, 2006). This study assumed that differences in soil properties among the study plots at the start of the experiment were not significant. Treatment differences were compared at the 0.05 probability level unless stated otherwise.

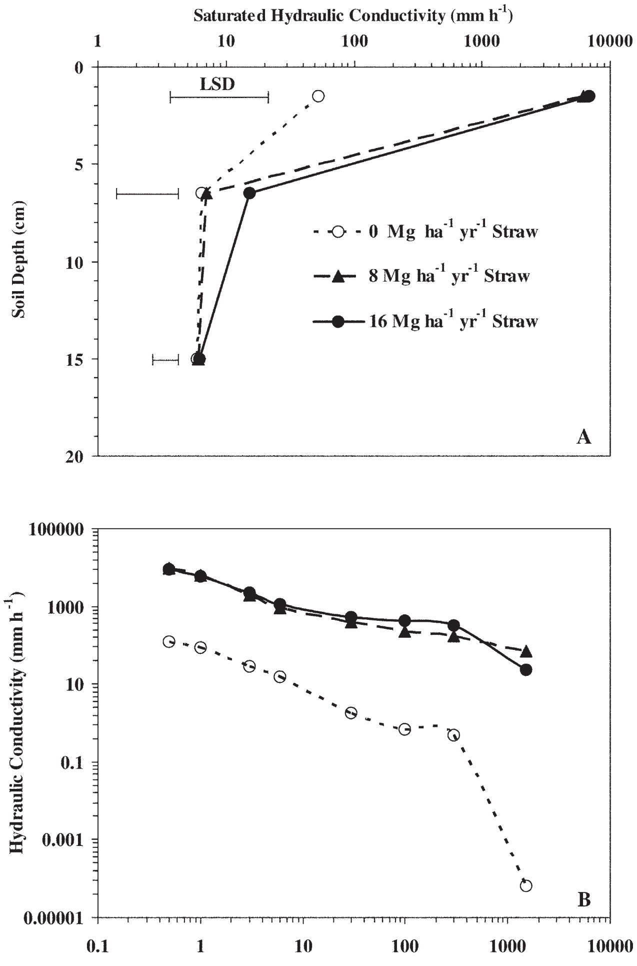

Fig. 1. Geometric means of (A) saturated hydraulic conductivity by depth and (B) unsaturated hydraulic conductivity for the 0- to 3-cm depth under an uncropped no-till system managed with three levels (0, 8, and 16 Mg ha^{-1}yr^{-1}) of wheat straw for 10 yr on a Crosby silt loam. The water-content-dependent hydraulic conductivity, *K*(θ), did not differ between 8 and 16 Mg ha^{-1}yr^{-1}, but both mulched treatments differed significantly ($P < 0.05$) from the unmulched (0 Mg ha^{-1}yr^{-1}) treatment.

RESULTS AND DISCUSSION

Mulching Effects on Hydraulic Conductivity and Earthworm Population

The annual application of wheat straw for 10 consecutive years had a large impact on K_{sat} and $K(\theta)$ in the top 3-cm depth ($P < 0.01$; Fig. 1). The geometric mean of K_{sat} was about 123 times higher in the mulched (6548 ± 2050 mm h^{-1}, mean ± SD) than in the unmulched (53 ± 50 mm h^{-1}) treatments. The mulched treatments had a greater $K(\theta)$ than the unmulched treatment at all soil water potentials (Fig. 1B). The $K(\theta)$ in mulched treatments was about 75 times higher for the 0 to −6 kPa, 300 to 600 times greater for the −33 to −300 kPa, and five orders of magnitude greater for the −1500 kPa potential than in the unmulched treatment. Changes in K_{sat} and $K(\theta)$ among treatments below the 3-cm depth were small and nonsignificant. Differences in K_{sat} (Fig. 1A) and $K(\theta)$ (Fig. 1B) between the two mulched treatments were nonsignificant, indicating that straw additions above 8 Mg ha^{-1} did not further increase soil hydraulic conductivities. The larger K_{sat} in mulched treatments than in the unmulched treatment for the 0- to 3-cm depth differed from those reported by Skidmore et al. (1986) and Sharratt et al. (2006), who observed no significant changes in K_{sat} with straw removal in the surface 0- to 10-cm soil depth after 14 and 20 yr of straw management, respectively. Differences in soil sampling depth, amount of straw mulch, and site-specific characteristics (e.g., soil texture, slope, tillage) among studies are possible explanations for these inconsistencies. In this study, the upper 3-cm soil layer under the mulched treatments was rich in freshly decomposed organic matter materials, dark in color, porous, loose, and contained visible macropores, contrasting with the characteristics under the unmulched treatment and the immediate underlying soil layer. The Munsell color for moist soil was 5.3YR 2.2/1.5 for the high-mulch treatment, 8.5YR 2.9/1.9 for the low-mulch treatment, and 9.4YR 3.3/2.5 for the unmulched treatment in the 0- to 3-cm depth. The dark soil color under the mulched treatments was due to the influence of organic matter (Blanco-Canqui and Lal, 2007).

The K_{sat} in the 0- to 3-cm depth was 600 to 700 times greater than that below 3 cm in the mulched treatments ($P < 0.001$; Fig. 1A). Had soil cores for K_{sat} been collected from the surface to a depth >3 cm, K_{sat} values for the surface may have been different due to low K_{sat} of the underlying soil layer (9.6 mm h^{-1}) since the effective K_{sat} is controlled by the most water-restrictive layer. In the studies by Skidmore et al. (1986) and Sharratt et al. (2006), soil cores were collected from the 0- to 5-cm depth, rather than from 0- to 3-cm depth as in this study. We hypothesize that the deeper cores resulted in a lower effective K_{sat} that reduced or masked differences in K_{sat} among straw treatments. These considerations suggest that sampling depth is critical to evaluating differences in K_{sat} among different mulch treatments.

The reason for the large increase in K_{sat} in the 0- to 3-cm depth is attributed to the effect of straw mulching on the earthworm population. The unmulched treatment had no earthworms (0 m^{-2}), whereas the mulched treatments with 8 Mg ha^{-1} of straw had 158 ± 52 earthworms m^{-2} and the mulched treatment with 16 Mg ha^{-1} had 267 ± 58 earthworms m^{-2}. These results show that the earthworm population increased with increasing rate of straw application. The number of earthworms in the treatment with 8 Mg ha^{-1} of straw was significantly (P = 0.07) lower than that in the treatment with 16 Mg ha^{-1} of straw at the 0.10 probability level. Most of the earthworms (>90%) were, however, concentrated near the soil surface within the 0- to 3-cm depth, which explains why K_{sat} was higher only within this depth interval. The localized confinement or stratification of earthworms was probably due to the near-surface concentration of organic matter and habitat (i.e., straw). Residue mulch strongly modifies the soil microclimate by reducing evaporation, increasing available water content, and reducing abrupt changes in soil temperature (Blanco-Canqui et al., 2006b). Straw was left on the soil surface year after year and not incorporated into the soil. The surface mulch was the only source of organic matter for faunal activity, as production of belowground plant biomass (e.g., roots) was practically negligible. Results show that surface straw mulching greatly enhanced the earthworm population, but in the absence of plant roots and other organic matter sources in the subsoil, the earthworms were confined to the soil surface that remained covered with dense straw throughout the 10-yr study period. The predominant earthworm species in this soil is *Lumbricus terrestris* L. (Shipitalo and Butt, 1999). The density of earthworms in this soil was greater than that reported for NT fields in midwestern USA soils. Jordan et al. (1997) observed that NT soils under continuous corn (*Zea mays* L.), continuous soybean [*Glycine max* (L.) Merr.], and in a corn–soybean rotation had between 123 and 144 earthworms m^{-2} in a silt loam in Missouri. In this study, treatments with 16 Mg ha^{-1} of straw had about twice as many earthworms as that reported by Jordan et al. (1997). The high rate of mulch application may explain the large increase in the number of earthworms. Large variations in earthworm numbers among soils are not, however, uncommon. Kladivko et al. (1997) observed that earthworm numbers varied between 2 and 343 m^{-2} in >5-yr-old NT systems on a wide range of soils including sandy loam, silt loam, loam, and silty clay loam in Indiana and Illinois. In this study, since absence of straw mulch resulted in a complete elimination of earthworms, we hypothesized that the earthworm population may be a sensitive attribute that characterizes straw management implications in some soils.

Mulching Effects on Water Infiltration

Straw management had no significant effect on water infiltration rates (P > 0.10; Fig. 2A). The lack of significant differences in infiltration was rather surprising because the greater earthworm population observed at or near the soil surface of the mulched treatments was expected to significantly increase water infiltration. While various reports indicate that the presence or absence of earthworms determines the decrease or increase in water infiltration in mulched NT soils (Kladivko et al., 1997), our results show that increases in earthworm population by mulching do not always increase the water infiltration rate in all soils, especially if mulching promotes stratification of earthworm activity. These results suggest that mulching enhanced the proliferation of shallow-dwelling endogenic earthworms; thus these earthworms may not have developed vertical and interconnected burrows that were significant enough in size and number to increase the water infiltration rate. Additional research on macropore dimensions, continuity, orientation, and abundance for the whole soil profile is warranted in these long-term straw treatments to fully understand their role in decreased water infiltration rates. We also hypothesize that despite the increased biological activity in the soil studied, water infiltration rates may not always be enhanced if the earthworm burrows are discontinuous and less abundant below the 3-cm depth and are discontinuous in the subsoil.

The lack of mulching effect on infiltration in this study is in contrast with various other studies that have reported that an increase in mulch application rate results in corresponding increases in water infiltration rates. Sharratt et al. (2006) reported that retaining barley straw and stubble on the soil surface following harvest each year for 20 yr increased steady-state infiltration rates (73 mm h^{-1}) by 35% compared with removal of straw and stubble (54 mm h^{-1}) on a silt loam in subarctic Alaska. Govaerts et al. (2007) also observed that NT soils mulched with wheat straw had infiltration rates 50% greater than those without straw in a subtropical soil in Mexico after 12 yr

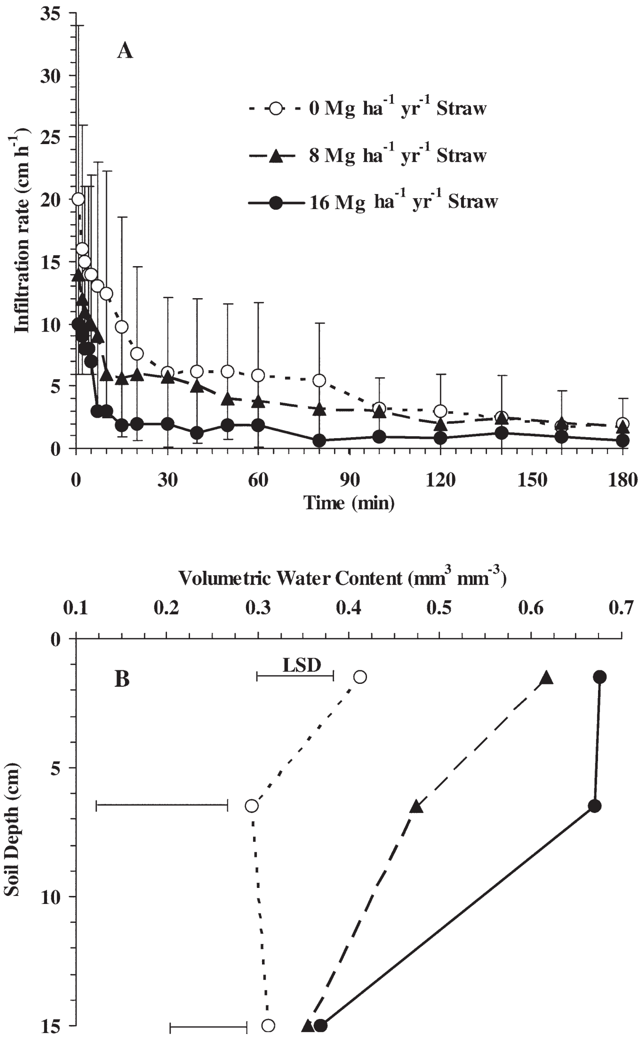

Fig. 2. Mean (A) water infiltration rates and (B) antecedent volumetric water content for 10 yr on a Crosby silt loam under an uncropped no-till system managed with three levels (0, 8, and 6 Mg $ha^{-1}yr^{-1}$) of wheat straw. Error bars represent the standard deviation of the mean of infiltration rates for each time of measurement.

of straw management. Similarly, Singh and Malhi (2006) reported greater infiltration rates (approximately 88 mm h^{-1}) in mulched than in unmulched NT systems for a silt loam (Black Chernozem) with 38 g SOC kg^{-1}. The results of this study are, however, similar to those reported by Singh and Malhi (2006), who observed no effect of straw mulching on infiltration rate on a silt loam (Gray Luvisol) in Canada. This inconsistent response of water infiltration to mulching corroborates the large spatial variability generally associated with soil. In this study, the presence of massive and somewhat poorly drained subsoil horizons probably counteracted any improvements in infiltration by mulching. The higher K_{sat} observed in the 0- to 3-cm depth did not result in corresponding increases in water infiltration, as vertical infiltration was probably limited by the slowly permeable layers underlying the straw-management-induced permeable, but shallow, soil surface layer (approximately 3 cm). There was a visual concentration of straw-derived organic materials near the soil surface, supporting significant stratification of mulch effects. Straw mulching developed a 3 ± 1 cm, somewhat dark-colored layer near the soil surface with contrasting properties from the underlying horizons. This organic-matter-enriched layer, consisting of soil intermixed with decomposed and partly decomposed organic materials, builds up with time and may tend to retard or even restrict water infiltration in cool and temperate soils, particularly in long-term residue management systems (Sharratt et al., 2006).

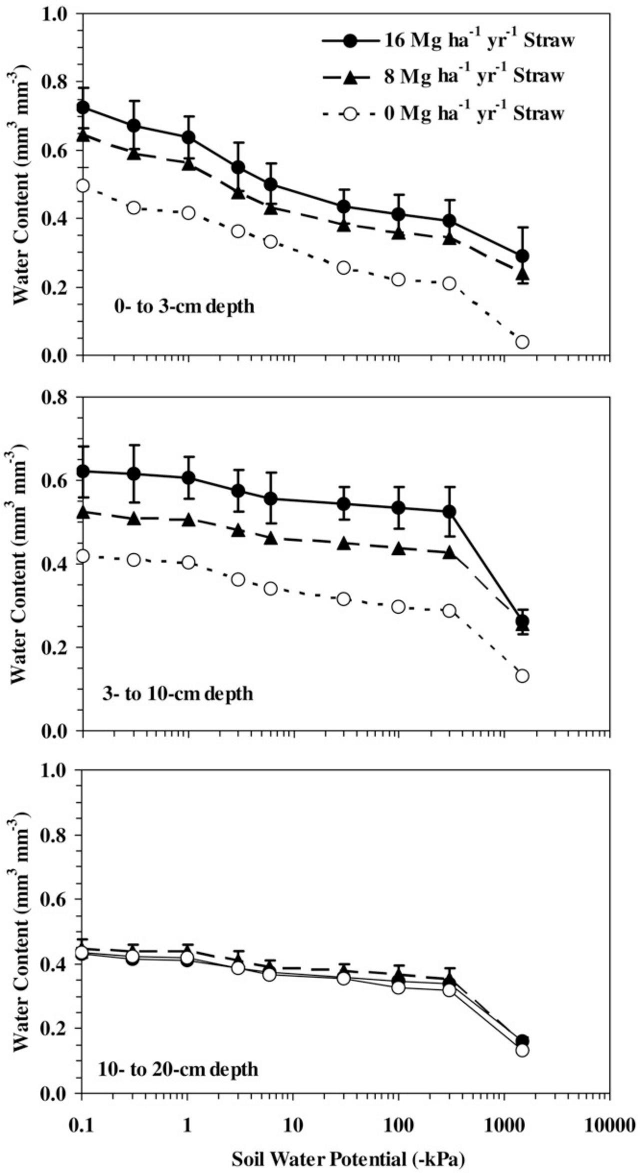

Fig. 3. Soil water characteristic curves for three depth intervals under an uncropped no-till system managed with three levels (0, 8, and 6 Mg $ha^{-1}yr^{-1}$) of wheat straw for 10 yr on a Crosby silt loam. Error bars represent the LSD values to compare differences in treatment effects at each pressure head.

While cultivated soils are generally assumed to be hydrophilic (Wallis and Horne, 1992), heavily mulched plots may exhibit some water repellency, depending on the tillage system and the quantify and quality of soil organic matter (SOM) (Hallett et al., 2001). For the soil of this study, Blanco-Canqui and Lal (2007) observed that soil aggregates under the mulched treatments were slightly more hydrophobic than those under the unmulched treatment. Likewise, Hallett et al. (2001) reported that NT soils with residue mulch were significantly more water repellent than plowed soils. The SOM-derived exudates and humic substances form hydrophobic surface films on primary and secondary soil particles (Chenu et al., 2000). While slow wetting has beneficial effects on soil structural stability by reducing slaking and increasing stability of aggregates, increased water repellency can reduce water infiltration and increase runoff rates in some agricultural soils (Buczko et al., 2006). Thus, the slightly higher water repellency in mulched treatments in this study possibly contributed to the reduced water infiltration in mulched treatments.

The unmulched treatment tended to have greater infiltration rates than the mulched treatments, but differences were not statistically significant due to high variability (Fig. 2A). The tendency for greater infiltration in the unmulched treatment may be due to differences in antecedent soil water content, rates of soil water evaporation, and potential hydrophobic properties. The soil under the mulched treatments was wetter than under the unmulched treatment right before the infiltration tests ($P < 0.01$). In the 0- to 3-cm depth, the soil water content under the high-mulch treatment (16 Mg ha^{-1} yr^{-1}) was 66% greater and that under the low-mulch treatment (8 Mg ha^{-1} yr^{-1}) was 51% greater than under the unmulched treatment (Fig. 2B). In the 3- to 10-cm depth, the soil water content under the high-mulch treatment was 2.3 times greater and that under the low-mulch treatment was 1.6 times greater than under the unmulched treatment. The greater water content and possibly lower evaporation rates in mulched treatments probably reduced the initial infiltrability and led to a rapid attainment of the steady-state infiltration rates (Wangemann et al., 2000). Additional research on the implications of different residue management scenarios on water repellency of soils is warranted.

Mulching Effects on Soil Water Retention

Straw mulching increased the soil's capacity to retain water at all soil water potentials (0 to −1500 kPa) in the top 10 cm ($P < 0.01$; Fig. 3). Soil mulched with 16 Mg $ha^{-1}yr^{-1}$ of straw retained about 40% more water between 0 and −6 kPa and 45 to 60% more water between −6 and −1500 kPa than the unmulched treatment in the 0- to 3-cm depth. The unmulched treatment drained more rapidly than the mulched treatments between −300 and −1500 kPa (Fig. 3). Differences in SWR between 8 and 16 Mg $ha^{-1}yr^{-1}$ of straw mulch were small and generally nonsignificant in the 0- to 3-cm depth, although the soil mulched with 16 Mg ha^{-1}yr^{-1} consistently maintained a greater water content that the other treatments.

In the 3- to 10-cm depth, the unmulched treatment retained 25 to 50% less water than the low-mulch treatment and 45 to 70% less water than the high-mulch treatment, indicating greater SWR in treatments with increasing mulch rates. In the 10- to 20-cm depth, SWR was unaffected by mulching, indicating that the beneficial effects of long-term surface mulching were mostly confined to surface soil layers. The greater water retention capacity of mulched treatments is probably explained by the high water adsorption capacity of straw-derived organic materials. Decomposed organic materials possess greater specific surface area and thus adsorb more water than inorganic soil particles (Kladivko, 1994).

Mulching Effects on Bulk Density, Total Porosity, and Pore-Size Distribution

Straw management had a very large impact on ρ_b in the 0- to 10-cm depth (P = 0.001; Fig. 4). The ρ_b under the high-mulch treatment was 58% lower and that under the low-mulch treatment was 19% lower than the ρ_b under the unmulched treatment for the 0- to 3-cm depth. Differences in ρ_b between mulched and unmulched treatments were smaller in the 3- to 10-cm depth than in the 0- to 3- cm depth. In the 3- to 10-cm depth, ρ_b under the high-mulch treatment was only 36% lower and that under the low-mulch treatment was 9% lower than ρ_b under the control. Differences in ρ_b among the treatments were nonsignificant in the 10- to 20-cm depth.

The decrease in ρ_b values from 1.32 Mg m^{-3} (control) to 1.11 Mg m^{-3} for the low-mulch treatment (8 Mg ha^{-1}) and to 0.84 Mg m^{-3} for the high-mulch treatment (16 Mg ha^{-1}) was surprisingly large in the 0- to 3-cm depth. These results are, however, similar to those reported by Lal (2000), who observed that annual application of 16 Mg ha^{-1} of rice (*Oryza sativa* L.) straw for 3 yr decreased ρ_b from 1.20 to 0.98 Mg m^{-3} on a sandy loam. Similarly, Blanco-Canqui et al. (2006a) reported that corn stover mulching at 5 and 10 Mg ha^{-1} for a period of 1 yr reduced ρ_b from 1.42 Mg m^{-3} (control) to 1.26 and 1.22 Mg m^{-3}, respectively, in NT systems in a silt loam. The low values (<1 Mg m^{-3}) of ρ_b for NT and residue management systems are not very uncommon in silt loams (Sharratt, 1996; Sharratt et al., 2006). The large decrease in ρ_b with mulching in our study is attributed to the high concentration of SOC and earthworms in the 0- to 3-cm depth. Indeed, Blanco-Canqui and Lal (2007) observed that the SOC concentration in the surface 2-cm depth for the same experiment was 11.7 g kg^{-1} for the control, 49.4 g kg^{-1} for the low-mulch treatment, and 72.3 g kg^{-1} for the high-mulch treatment. Similar studies on a silt loam in Alaska showed that straw and stubble management for 20 consecutive yr had formed thick organic layers near the soil surface, which did not exist after 7 yr of straw management (Sharratt, 1996; Sharratt et al., 2006).

Straw mulching also had a significant effect on total soil porosity and pore-size distribution in the 0- to 3-cm depth (Fig. 3 and 5). The low ρ_b values for the mulched treatments compared with control (Fig. 4) further support the high values of total porosity. The total porosity was 0.50 ± 0.01 m^3 m^{-3} for the unmulched control, 0.64 ± 0.09 m^3 m^{-3} for the low-mulch treatment, and 0.72 ± 0.02 m^3 m^{-3} for the high-mulch treatment in the 0- to 3-cm soil depth. These results show that mulching with 8 and 16 Mg ha^{-1}yr^{-1} of straw increased total porosity by 28 and 44%, respectively, over the unmulched control. The ρ_b and total porosity for the mulched treatments abruptly decreased with depth compared with those in the control (P = 0.02; Fig. 3 and 4).

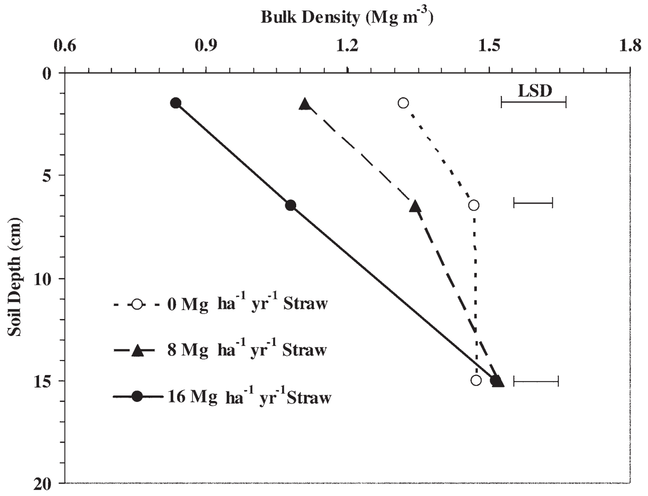

Fig. 4. Soil bulk density with depth under an uncropped no-till system managed with three levels (0, 8, and 16 Mg ha^{-1}yr^{-1}) of wheat straw for 10 yr on a Crosby silt loam.

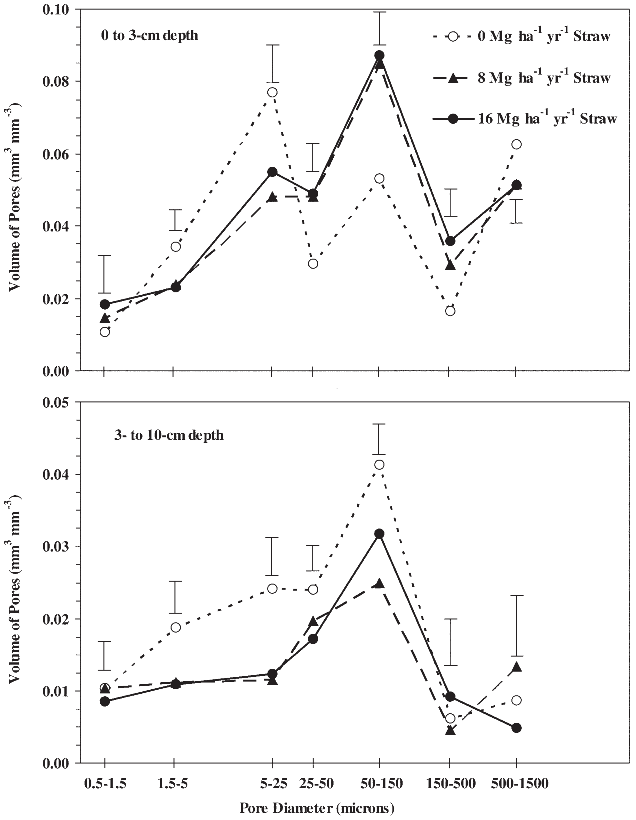

Fig. 5. Pore-size distribution expressed as fraction of pore volume per pore diameter within two soil depth intervals under an uncropped no-till system managed with three levels (0, 8, and 6 Mg ha^{-1}yr^{-1}) of wheat straw for 10 yr on a Crosby silt loam. Error bars represent the LSD values to compare differences in treatment effects within each pore-size interval.

Volumes of macropores (>500 μm) and coarse mesopores (25–500 μm) were greater under mulched treatments, indicating that straw mulching promoted the formation of macropores in the 0- to 3-cm depth (Fig. 5). For the same depth, pore volumes of fine mesopores (5–25 μm) and micropores (1.5–5 μm) were greater in the unmulched than the mulched treatments. No differences in pore volume between the two mulched treatments were observed at any depth. The activity of earthworms and related fauna probably contributed to the formation of >50-μm pores in the mulched treatments near the surface. The >50-μm pores in the mulched treatments were about twice the volume of those in the unmulched control. The presence of straw mulch probably increased the soil organic matter content and protected the surface-connected earthworm channels or macropores by intercepting raindrops and improving surface soil structural stability (Kladivko, 1994).

The significant increase in pore volume of macro- and mesopores by straw mulching was similar to the increase in K_{sat}. To investigate the relationship between soil pore volume and K_{sat}, effective porosity (Φ_e), which represents the fraction of the total soil pore volume controlling saturated water flow through the soil, was computed as the difference between the total porosity and θ at −33 kPa (Ahuja et al., 1984). The estimated Φ_e was a significant predictor of K_{sat}, explaining 43% of the variability in log K_{sat} (Fig. 6). The importance of Φ_e for predicting K_{sat} is in accord with Ahuja et al. (1984), who developed a model that indicated Φ_e may be the single most important soil parameter to predict K_{sat}. These results show that improvements in soil porosity with straw application significantly contributed to the increase in K_{sat}.

CONCLUSIONS

This study shows that straw management under NT for 10 consecutive yr on a Crosby silt loam induced significant changes in selected soil hydraulic properties. The significant impacts are, however, mostly confined to the upper 3-cm layer. No-tillage management, in conjunction with application of large quantities of straw mulch on the soil surface, increased saturated and unsaturated hydraulic conductivities, earthworm population, soil water retention, bulk density, total soil porosity, and macroporosity. The greater saturated hydraulic conductivity in mulched treatments is partly due to an increase in effective soil porosity. Straw-management-induced changes in these soil properties were large and generally highly significant within the 0- to 3-cm soil depth. Despite having a higher number of earthworms, high rates of straw application did not, however, increase water infiltration rates. Based on the results of this study and other similar studies, it appears that the mulching effects on infiltration are inconsistent. In the soil of this study, straw mulching had more positive effects on near-surface water retention and macroporosity than on water infiltration. Overall, this study revealed that surface mulching with wheat straw in a long-term NT system on a Crosby silt loam improved soil hydraulic properties only near the surface, indicating a significant stratification of the effects of mulching. Caution must be exercised, however, when extrapolating the results from this study to large-scale field conditions. While this study provided useful insights into the independent effects on soil hydraulic properties of long-term mulching with large amounts of straw, results may have been different had crops been grown on the study plots due to crop residue–tillage–cropping system interactions and belowground (e.g., roots) biomass input.

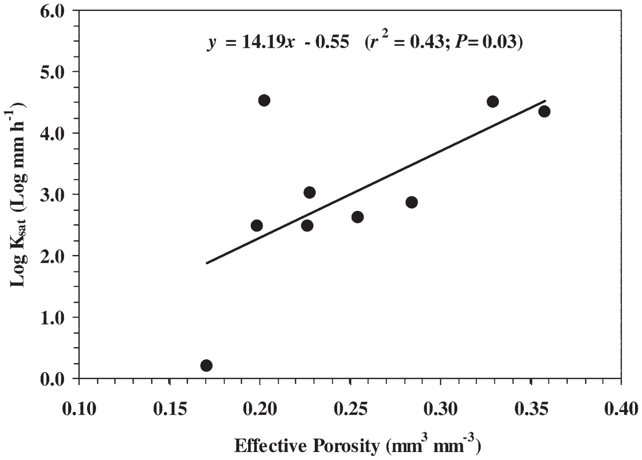

Fig. 6. Log-transformed saturated hydraulic conductivity (K_{sat}) as a function of effective porosity as affected by 10 yr of straw management on a Crosby silt loam.

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