Available online at www.sciencedirect.com
ScienceDirect
Soil & Tillage Research 92 (2007) 144–155
Soil & Tillage Research
www.elsevier.com/locate/still

# Soil hydraulic properties influenced by corn stover removal from no-till corn in Ohio

Humberto Blanco-Canqui [a,*], R. Lal [a], W.M. Post [b], R.C. Izaurralde [c], M.J. Shipitalo [d]

[a] Carbon Management and Sequestration Center, FAES/OARDC, School of Natural Resources, The Ohio State University, 412C Kottman Hall, 2021 Coffey Road, Columbus, OH 43210-1085, USA
[b] Environmental Science Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831-6335, USA
[c] Joint Global Change Research Institute, 8400 Baltimore Ave., Suite 201, College Park, MD 20740-2496, USA
[d] USDA-ARS, North Appalachian Experimental Watershed, P.O. Box 488, Coshocton, OH 43812-0488, USA

Received 12 August 2005; received in revised form 1 February 2006; accepted 22 February 2006

## Abstract

Corn (*Zea mays* L.) stover removal for biofuel production and other uses may alter soil hydraulic properties, but site-specific information needed to determine the threshold levels of removal for the U.S. Corn Belt region is limited. This study quantified impacts of systematic removal of corn stover on soil hydraulic parameters after 1 year of stover management under no-till (NT) systems. These measurements were made on three soils in Ohio including Rayne silt loam (fine-loamy, mixed, active, mesic Typic Hapludult) at Coshocton, Hoytville clay loam (fine, illitic, mesic Mollic Epiaqualfs) at Hoytville, and Celina silt loam (fine, mixed, active, mesic Aquic Hapludalfs) at South Charleston. Interrelationships among soil properties and saturated hydraulic conductivity ($K_{sat}$) predictions were also assessed. Earthworm middens, $K_{sat}$, bulk density ($\rho_b$), soil water retention (SWR), pore-size distribution, and air permeability ($k_a$) were determined for six stover treatments. Stover treatments consisted of removing 0 (T100), 25 (T75), 50 (T50), 75 (T25), 100 (T0) and adding 100 (T200)% of corn stover corresponding to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha$^{-1}$ of stover, respectively. Stover removal reduced the number of middens, $K_{sat}$, SWR, and $k_a$, and increased $\rho_b$ at all sites ($P < 0.01$). Compared to normal stover treatment (T100), complete stover removal (T0) reduced earthworm middens 6-fold at Coshocton and about 14-fold at Hoytville and Charleston. Geometric mean $K_{sat}$ decreased from 3.1 to 0.1 mm h$^{-1}$ at Coshocton, 4.2 to 0.3 mm h$^{-1}$ at Hoytville, and 4.2 to 0.6 mm h$^{-1}$ at Charleston while soil $\rho_b$ increased about 12% in the 0–10-cm depth at Coshocton and Hoytville from T100 to T0. The SWR for T0 was about 70% of that for T100 and 58% of that for T200 at 0 to −6 kPa suctions across sites. The log $k_a$ for T200, T100, and T75 significantly exceeded that under T50, T25, and T0 at Coshocton and Charleston. Differences in the number of middens, $\rho_b$, SWR, $K_{sat}$, and $k_a$ between T100 and T200 were not generally significant although the T200 retained slightly more water for the 0 to −100 kPa at Charleston and had higher $k_a$ at Hoytville compared to T100. Measured parameters were strongly correlated, and $k_a$ was a strong $K_{sat}$ predictor. Stover harvesting induces rapid changes in soil hydraulic properties and earthworm activity, but further monitoring is needed to ascertain the threshold levels of stover removal for soil-specific conditions.


*Keywords:* No-till; Corn stover removal; Saturated hydraulic conductivity; Earthworm middens; Bulk density; Soil water retention; Air permeability

* Corresponding author. Tel.: +1 614 292 2299; fax: +1 614 292 5678.
*E-mail address:* blanco.16@osu.edu (H. Blanco-Canqui).

0167-1987/$ – see front matter 
doi:10.1016/j.still.2006.02.002

## 1. Introduction

Corn stover is a potential feedstock for biofuel production as an alternative to conventional fuels (Pacala and Socolow, 2004). Corn stover availability in the U.S. Corn Belt region (Nelson, 2002) and implications of stover use for biofuel production on a global scale (Lal, 2005) are being extensively assessed. One major implication is that stover harvesting for biofuel reduces the amount of crop residue left on the soil surface needed to maintain soil quality. The soil physical environment is highly sensitive to changes in surface residue cover (Kladivko, 1994). Corn stover mulch protects the soil surface from raindrop impact, reduces evaporation, moderates soil thermal properties, enhances biological activity, increases soil organic matter content, recycles nutrients, and improves the overall soil structure and quality (Wilhelm et al., 2004).

Intensive removal of stover as biofuel may negatively affect soil hydraulic properties. Partial stover removal (e.g., 25–30%) may be feasible, but site-specific information on the threshold removal rates for maintaining soil water retention and transmission characteristics is limited. Some estimates indicate that 20–50% of stover can be safely removed from the U.S. Corn Belt region, but these estimates are based only on the requirement to control soil erosion (Nelson, 2002; Kim and Dale, 2004). Soil erosivity is intimately linked to soil hydraulic properties as well as topographic and cover factors. Thus, the high variability of these erosion-based stover removal rates within the same region implies that threshold removal rates needed to maintain/enhance soil hydraulic properties may vary among soils. Information on the quantity of removable stover based on field experimentation for representative soils in the U.S. Corn Belt region is lacking for developing guidelines to meet energy and soil quality needs. Conducting site-specific studies on stover removal effects on soil quality remains a high research priority (Wilhelm et al., 2004).

There have been many studies on residue management for diverse tillage and cropping systems (e.g., Lal et al., 1980; Dabney et al., 2004). Most studies have two constraints relative to their usage for evaluating stover removal effects. First, they often report interrelated residue-tillage management effects and, in many cases, results are confounded with different cropping systems (Sharratt, 1996; Singh et al., 1996). A better understanding of the role of residues on soil hydraulic properties entails separating the residue effects from those of tillage-cropping systems. Experiments specifically designed to assess stover removal effects under the same tillage and cropping systems, such as NT continuous corn, are needed to quantify the effects on soil quality. Second, stover removal impacts on soil hydraulic properties are inconsistent and often contradictory. For example, Karlen et al. (1994) reported no significant difference in saturated hydraulic conductivity ($K_{sat}$) under NT corn with stover maintained, removed, and doubled in a 10-year study of silt loams. Conversely, Findeling et al. (2003), in a 4-year study, showed that $K_{sat}$ increased linearly with increasing rates of stover cover on a sandy loam. Thus, additional studies clarifying stover removal effects on a wide range of soils are warranted.

Formation and preservation of earthworm macropores in NT systems are well known (Bohlen et al., 1997; Butt et al., 1999; Shipitalo and Butt, 1999). Since stover left on the soil surface provides an abundant food source and habitat to earthworms responsible for macropore network development, its removal from NT systems may reduce earthworm populations and the number of surface-connected macropores. Earthworm burrowing and feeding activities enhance soil structure and macropore development, recycle essential nutrients, and control rates of SOC turnover and water–air flow in the soil profile (Bohlen et al., 1997). Surface sealing of open and continuous macropores due to stover removal can be a major factor in reducing near-surface parameters of water flow and gaseous diffusion and transport such as $K_{sat}$ and air permeability ($k_a$; Ela et al., 1992; Loll et al., 1999). The $k_a$ and $K_{sat}$ are functions of macropore structure and are key indicators of soil structural development (Loll et al., 1999). Changes in earthworm populations and soil macroporosity and their relations to $K_{sat}$, $k_a$ and soil water retention (SWR) resulting from systematic stover removal are poorly understood. Effects of removing wheat (*Triticum aestivum* L.) and soybean (*Glycine max* L.) residues have been investigated (Pikul and Allmaras, 1986; Skidmore et al., 1986), but few studies have assessed corn stover removal impacts on soil hydraulic properties (Karlen et al., 1994). Corn stover removal may affect soil properties differently from that of wheat and soybean residues because stover is coarser, less decomposable, and thus remains longer on the soil surface (Mankin et al., 1996).

Prediction of $K_{sat}$ for NT soils managed with differing levels of stover cover can be an important alternative to direct $K_{sat}$ measurements, which are often costly and laborious. There are a number of empirical (Rawls et al., 1993) and conceptual (Marshall, 1958; Lebron et al., 1999) equations to predict $K_{sat}$. Use of such equations for evaluating stover management effects on $K_{sat}$ for different soils is limited. Thus, there is a need to evaluate these equations with a variety of soils and levels of stover removal. Changes in soil porosity and $k_a$ resulting from stover removal may be sensitive input parameters for predicting $K_{sat}$ using available equations or for developing new equations using pedotransfer functions (PTFs). The PTFs are useful statistical tools to study site-specific interrelationships among soil properties and predict changes in $K_{sat}$ based on related soil properties (Bouma, 1989; Minasny and McBratney, 2002). Therefore, the objectives of this study were to: (1) quantify the impact of a systematic removal of corn stover on soil hydraulic parameters in different soils under NT systems in Ohio and (2) establish possible interrelationships among measured soil properties and predict changes in $K_{sat}$ using $k_a$ and effective porosity data. This study tested the hypothesis that corn stover removal causes rapid and significant changes in soil hydraulic properties even within 1 year because of significant alterations in near-surface soil properties (e.g., surface sealing, crusting, consolidation, roughness). Knowledge about the degree to which the soil hydraulic properties change over a short period (i.e., 1 year) after stover removal is vital to understanding soil processes and estimating short-term implications of stover removal.

## 2. Materials and methods

### 2.1. Site and treatment descriptions

The study was conducted using three, ongoing, long-term NT experimental sites in Ohio: the North Appalachian Experimental Watershed near Coshocton, the Western Agricultural Experiment Station near South Charleston, and the Northwestern Agricultural Experiment Station near Hoytville (Fig. 1). The project was initiated in May 2004 to characterize the effects of corn stover removal on physical quality, thermal properties, soil organic carbon (SOC) content, and crop yield under NT continuous corn. The sites were previously managed under 33-year NT continuous corn at Coshocton, 8-year continuous corn/soybean rotation under NT in conjunction with light disking in alternate years at Hoytville, and 15-year NT continuous corn/soybean rotation at South Charleston. Soil characteristics for each site are summarized in Table 1.

A randomized complete block design with six treatments replicated three times was established at each site in early May 2004. The six treatments consisted of applying 0, 25, 50, 75, 100, and 200% of corn stover on each 3 m × 3 m plot using stover from

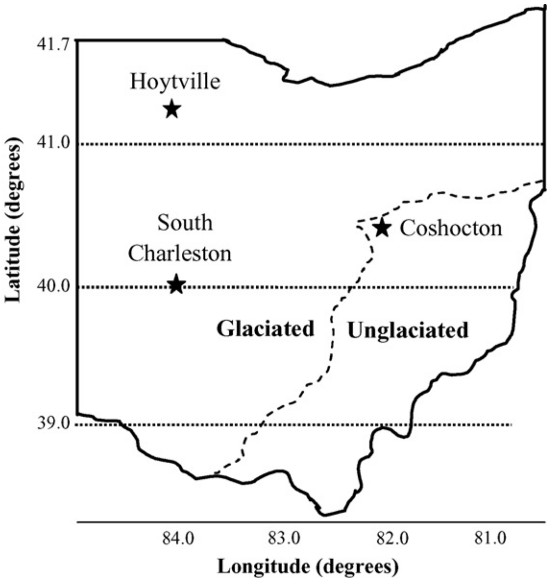


Fig. 1. Map of Ohio showing the study locations including North Appalachian Experimental Watersheds at Coshocton, Northwestern Agricultural Experiment Station at Hoytville, and Western Agricultural Experiment Station at South Charleston.

the previous year corresponding to 0, 1.25, 2.50, 3.75, 5.00, and 10.00 Mg ha$^{-1}$ of stover, respectively. The line-transect method was used to determine the percent stover cover in each plot (Sloneker and Moldenhauer, 1977). Each plot was planted to corn in mid May 2004 and then any stover shifted during planting was redistributed to the corresponding plots. Each plot comprised four rows of corn spaced 0.75 m apart. Following harvest in October 2004, the new corn stover was immediately redistributed to the corresponding treatments at the desired rate. The individual plots within blocks were borderless and were demarcated at the corners by flags to reduce interference with planting and harvesting, which were done across plots. The six stover retention rates at 0, 25, 50, 75, 100, and 200% are hereafter referred to as T0, T25, T50, T75, T100, and T200. The experimental sites are hereafter referred to Coshocton, Hoytville, and Charleston.

### 2.2. Earthworm activity and soil properties

Stover treatment effects on earthworm activity, $K_{sat}$, SWR, and $k_a$ were measured at each of the three sites. Earthworm activity was determined by counting earthworm middens on the soil surface (Whalen et al., 2004). Earthworm middens, which are small piles or structures consisting of surface residues associated with ingested and uningested soil materials covering burrows, were counted in Spring 2005 when

Table 1
Soil characteristics of the three study sites

| Agricultural sites | Geographical coordinates | Soil series and initial SOC concentrations | Classification | Soil description | Slope (%) |
|---|---|---|---|---|---|
| North Appalachian Experimental Watersheds, Coshocton, OH | 40°16′19″N and 81°51′35″W | Rayne silt loam (638 g $kg^{-1}$ silt, 153 g $kg^{-1}$ clay and 30 g $kg^{-1}$ SOC) | Fine-loamy, mixed, mesic Typic Hapludults | Deep and well drained soils formed from weathered shale and fine-grained sandstone. These soils have moderate permeability | 10 |
| Western Agricultural Experiment Station, South Charleston, OH | 39°49′31″N and 83°38′04″W | Celina silt loam (558 g $kg^{-1}$ silt, 216 g $kg^{-1}$ clay and 28 g $kg^{-1}$ SOC) | Fine, mixed, active, mesic Aquic Hapludalfs | Very deep, moderately well drained and formed in high-lime loamy till plains and moraines. Permeability is moderately slow | 2 |
| Northwestern Agricultural Experiment Station, Hoytville, OH | 41°11′24″N and 83°47′05″W | Hoytville clay loam (341 g $kg^{-1}$ silt, 437 g $kg^{-1}$ clay and 26 g $kg^{-1}$ SOC) | Fine, illitic, mesic Mollic Epiaqualfs | Very deep and very poorly drained soils formed in till that has been leveled by wave action | <1 |

midden formation should have been at a seasonal peak (Butt et al., 1999). Midden counts are an indirect measure of earthworm activity and this method was chosen to minimize soil disturbance often caused by techniques used for direct counts of earthworms (Zaller and Arnone, 1997). Middens were counted within a 1 m × 1 m area in the center of each plot. Since the number of middens was used as an indicator of earthworm population density, counts may not have represented the actual number of earthworms under a given treatment. Studies have shown, however, that earthworm populations are directly correlated with midden counts for surface-feeding, anecic earthworms (Bohlen et al., 1997). The predominant midden-building species at the three sites was expected to be *Lumbricus terrestris* L. (Butt et al., 1999).

Intact soil cores (7.6 cm deep and 7.6 cm diameter) in metal sleeves were collected from 0- to 10-cm and 10- to 20-cm depth intervals using a hammer-driven core sampler in early May 2005 before corn planting for the determination of $K_{sat}$, $\rho_b$, SWR, and $k_a$ from each of the 18 plots across the three sites. Cores were sealed in plastic bags, transported to the laboratory, trimmed, weighed, and stored at 4 °C for 2 days until $K_{sat}$ was measured using the constant head method (Reynolds et al., 2002). Fifty grams of the trimmings from each core were oven-dried at 105 °C to determine gravimetric water content (Topp and Ferré, 2002). The oven-dry weight of the trimmings was interpolated to the entire soil core, assuming that the water content of the soil in the core was the same as that of the trimmings. Bulk density ($\rho_b$) was computed based on the oven-dry weight and total volume of the soil by the core method (Grossman and Reinsch, 2002). Cores were slowly saturated for 24 h from below with de-aired tap water delivered using a Mariotte bottle at a constant flow rate of 5 mm $h^{-1}$ prior to $K_{sat}$ determination. To assess the effect of macropore flow through open-ended earthworm burrows on water movement, $K_{sat}$ was measured on cores with and without visible macropores for the T100 treatment from Hoytville, since cores from this site exhibited relatively more continuous macropores than those from Coshocton and Charleston. Macropore flow in cores was eliminated using bentonite slurry (eight parts water and one part bentonite powder) to plug the visible macropores. Use of bentonite is common for measuring soil matrix $K_{sat}$ in small cores (Klute, 1965; Blanco-Canqui et al., 2002).

Immediately after $K_{sat}$ determination, the high-energy SWR at 0, −3, −6 and −10 kPa suctions was determined on the intact cores using a tension table furnished with blotting paper and outflow system. Cores were slowly saturated, drained, and weighed at each pressure level. The SWR at low energy (−30, −100, −300, and −1500 kPa) was determined by using a pressure plate apparatus (Dane and Hopmans, 2002). For the SWR determination at −30, −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 water content determination. Air-dried bulk samples passed through 2-mm sieves and tightly packed in rubber rings were used for SWR determination at −1500 kPa.

Pore-size distribution for each treatment was determined from SWR. The equivalent pore radius was estimated using the capillary rise equation from pressure potentials at 20 °C (Hillel, 1998). Pore-size classes based on their corresponding effective diameters were grouped into macropores (>500 μm), coarse mesopores (25–500 μm), fine mesopores (5–25 μm), and micropores (<5 μm) (Luxmoore, 1981). The $k_a$ was measured on intact soil cores by the steady state method (Ball and Schjønning, 2002) using an air flow-meter (Gilmont Instrument Inc., NY). Cores were saturated and then equilibrated at −10 kPa for the measurements. The procedure consisted of placing and securing the intact cores inside the plexiglass system of the apparatus, and connecting to an air supply, and subsequently determining the pressure differential across the cores in the flow-meter to determine the air permeability according to Darcy's law. The SWR and $k_a$ were measured only for cores from the 0- to 10-cm soil depth.

### 2.3. $K_{sat}$ prediction

Physico-empirical equations based on effective porosity, total porosity, and $k_a$ of soil were tested for their ability to predict changes in $K_{sat}$ induced by stover management. Total soil porosity was estimated from $\rho_b$ while pore-size distribution and effective porosity were computed from SWR. Marshall's equation (Marshall, 1958), Kozeny-Carman model (Ahuja et al., 1984), and the modified Marshall's equation (Rawls et al., 1993) were used. A general empirical equation of $K_{sat}$ based on $k_a$ as developed by Loll et al. (1999) for a wide range of soil types, was also used Eq. (1):

$$\log K_{sat} = 1.27 \log k_a + 14.11 \quad (1)$$

### 2.4. Statistical analyses

A split-plot design with stover treatments as main plots and sampling depths as subplots was used to test whether differences in $K_{sat}$ among treatments were significant (Snedecor and Cochran, 1989). A one-factor analysis was conducted to test differences in midden numbers, $\rho_b$, SWR, and $k_a$. Analyses were performed using SAS (SAS Institute, 1999). Normality of the data was tested using the Shapiro–Wilk's *W*-test in SAS. Data on $K_{sat}$ and $k_a$ were log-transformed to normalize data, and statistical analyses were conducted using transformed data. Correlations and point-regression fits among the measured soil properties were used to identify relationships. Analyses of residuals and $r^2$ were conducted to determine the best fitting regression lines between soil properties and rates of stover cover. Stepwise multiple regression was used to develop PTFs to estimate $K_{sat}$.

## 3. Results and discussion

### 3.1. Earthworm activity

Stover management affected the number of middens at all sites ($P < 0.01$; Fig. 2). Midden numbers

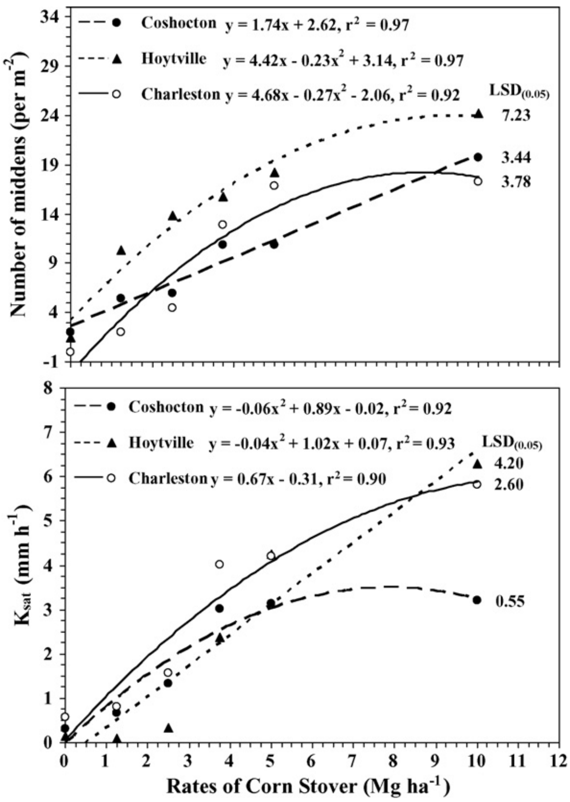


Fig. 2. Number of earthworm middens and geometric means of saturated hydraulic conductivity ($K_{sat}$) across the 0–10 and 10–20-cm depths as a function of corn stover rate at Coshocton, Hoytville, and South Charleston in Ohio. The regression functions were all significant at $P = 0.01$.

decreased linearly at Coshocton ($r^2 = 0.97$; $P < 0.01$) and quadratically at Hoytville ($r^2 = 0.97$; $P < 0.01$) and Charleston ($r^2 = 0.92$; $P < 0.01$) with stover removal rate. Complete stover removal reduced midden numbers 11-fold at Coshocton and 17-fold at Hoytville and Charleston compared to T100 and 20-fold compared to T200 across sites. Results are in accord with those reported for Rozetta and Palsgrove silt loams by Karlen et al. (1994) where normal and double stover treatments had more earthworms (78 $m^{-2}$) than unmulched treatments (53 $m^{-2}$). Other studies in the U.S. Corn Belt region have also shown enhanced earthworm activity with increasing levels of residue left on the soil surface (Bohlen et al., 1997; Willoughby et al., 1997). The higher midden-forming activity of earthworms in stover mulched plots could be attributed to the abundant food supply, protective cover, increased soil water content and favorable soil temperature under stover mulch (Shaver et al., 2002).

Differences in the number of middens between T100 and T75 were significant at Charleston, but not at Coshocton and Hoytville. Thus, removal of 25% (1.25 Mg $ha^{-1}$) of stover at Coshocton and Hoytville did not negatively affect earthworm population, but it did at Charleston. These contrasting results among sites show the site-dependence of stover management effects on earthworm activity probably due to differences in previous management, soil properties, and microclimate. Moreover, the marked differences in type and length of tillage and cropping practices among the three soils prior to the start of the stover experiment may have influenced the differential stover removal effects on midden numbers.

There were differences in earthworm activity among stover removal rates. First, earthworms redistributed small pieces of stover on the soil surface of mulched plots, creating a dynamic fabric of stover-enriched middens. These middens were microhabitats protecting burrows and constituting unique micro-environments for stover dynamics. Second, earthworms developed a network of surface-connected burrows under the stover. Deep, vertical, burrows with diameters of 4.1 ± 0.8 mm extending beyond 20-cm soil depth were observed during soil core sampling. Third, observations during soil sampling also indicated that more earthworms than implied by the midden numbers were present in the 0–20-cm depth, indicating that midden numbers did not represent the actual number of earthworms. Fourth, while few or no earthworm middens existed on the soil surface of T0 treatments, soil sampling showed several earthworms below the soil surface, but fewer than those under mulched treatments. Earthworms below the surface probably fed on root-derived residues and soil organic matter and were probably not the surface-feeding and midden-building species, suggesting a possible shift in earthworm species composition. Reduced number of middens and surface-connected burrows in T0 could be attributed to the absence of stover mulch. Earthworm surface migration probably decreased with decrease in stover mulch cover. Moreover, burrows open to the surface under T0 and T25 were apparently blocked by soil surface sealing and crusting.

### 3.2. Saturated hydraulic conductivity and bulk density

The geometric mean of $K_{sat}$ (Fig. 2) and the mean of $\rho_b$ (Fig. 3) were affected by stover treatment at all sites. Treatment × depth interaction for $K_{sat}$ was not significant at any site ($P > 0.10$), and therefore, $K_{sat}$ by treatment was averaged across depths. The $K_{sat}$

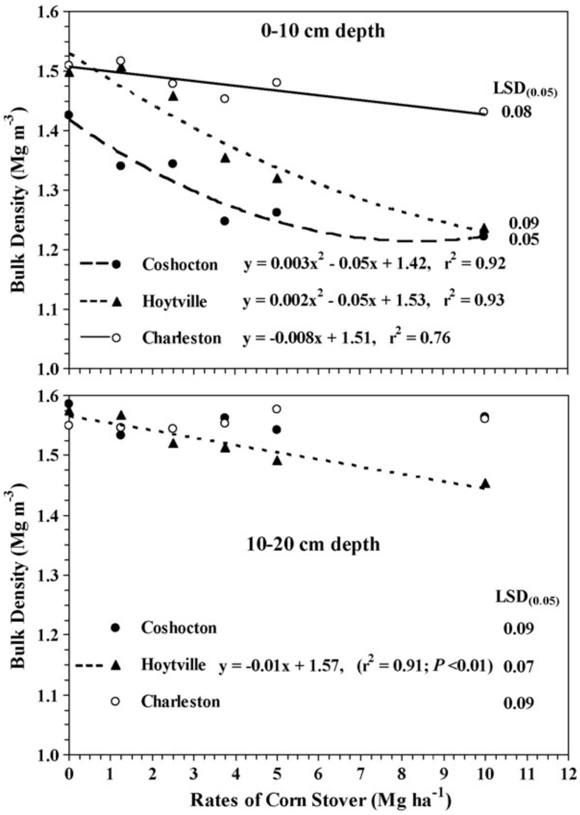


Fig. 3. Mean bulk density for two soil depths as a function of corn stover rates at Coshocton, Hoytville, and South Charleston in Ohio. Stover treatment effects on bulk density were not significant at Coshocton and Charleston sites for the 10–20-cm depth.

increased and $\rho_b$ for the 0–10-cm depth decreased with increase in stover cover. The $K_{sat}$ increased linearly at Hoytville ($r^2 = 0.93$) and quadratically at Coshocton ($r^2 = 0.92$) and Charleston ($r^2 = 0.90$) as stover cover increased from 0 to 10 Mg ha$^{-1}$ ($P < 0.01$; Fig. 2). The $K_{sat}$ decreased from 3.1 to 0.1 mm h$^{-1}$ at Coshocton, 4.2 to 0.3 mm h$^{-1}$ at Hoytville, and 4.2 to 0.6 mm h$^{-1}$ at Charleston from T100 to T0. The trend in $\rho_b$ was the opposite of $K_{sat}$ (Fig. 3). The $\rho_b$ for the 0–10-cm depth increased quadratically with increasing stover removal at Coshocton ($r^2 = 0.92$) and Hoytville ($r^2 = 0.93$), and linearly at Charleston ($r^2 = 0.76$). The decrease in $\rho_b$ from T0 to T100 was more abrupt at Coshocton (1.42 Mg ha$^{-1}$ versus 1.26 Mg ha$^{-1}$) and Hoytville (1.50 Mg ha$^{-1}$ versus 1.32 Mg ha$^{-1}$) than at Charleston (1.51 Mg ha$^{-1}$ versus 1.48 Mg ha$^{-1}$). Difference in $\rho_b$ for the 10–20-cm depth was only significant at Hoytville, in which $\rho_b$ slightly decreased in a linear trend with an increase in stover cover (Fig. 3). These variations in the magnitude of change in $K_{sat}$ and $\rho_b$ by site were most probably due to differences in soil texture and history of tillage-crop management. For example, prior to the start of this experiment, NT soils at Hoytville were disked every 2 years unlike those at the other two sites that were under continuous NT.

Our results differed from those of Karlen et al. (1994) who found no significant differences in $K_{sat}$ and $\rho_b$ at any depth when stover after harvest was maintained, removed, and doubled in NT continuous corn for 10-year in silt loams. In our study, 1 year of stover removal produced large changes in $K_{sat}$ and $\rho_b$. In the study of Karlen et al. (1994), $K_{sat}$ and $\rho_b$ were highly variable and earthworm numbers under T200 were only 1.5 times greater than under T0. Our study, earthworm middens under T200 were about 20 times higher than under T0. The $K_{sat}$ results from our study were in accord with those of Findeling et al. (2003) who observed a linear increase in $K_{sat}$ with increasing rates of stover cover in a 4-year experiment on a sandy loam.

The higher $K_{sat}$ and lower $\rho_b$ in mulched plots could be attributed to stover-induced improvements in soil structure and earthworm activity. Stover mulch probably buffered raindrop impact and reduced surface sealing and crusting. In unmulched plots the soil surface was smoother and had more massive soil structure than that in mulched plots. Stover cover enhanced midden formation, preserved structural macropores, decreased $\rho_b$, and total soil porosity. Comparison of $K_{sat}$ with and without macropore flow illustrated the dominant role of bio-channels in the by-pass flow. The $K_{sat}$ measured at Hoytville without bentonite to plug earthworm burrows (35.7 ± 5.3 mm h$^{-1}$) was 184 times higher than $K_{sat}$ with bentonite (0.19 ± 0.05 mm h$^{-1}$; $P < 0.01$). Similar studies reported that soil cores with earthworm macropores can have 2–10 times higher $K_{sat}$ than those without macropores (Schjønning et al., 2002). Although earthworm macropores may represent only a small fraction of the total soil volume, their contribution to $K_{sat}$ can be very high (Logsdon et al., 1990).

Differences in $K_{sat}$ among T200, T100, and T75 were not significant, nor were those between T0 and T25. The rapid increase in $K_{sat}$ with increase in stover retention from T0 to T75 followed by small changes between T75 and T100, as portrayed by the quadratic function in Fig. 2 for Coshocton and Charleston, suggests that a threshold level of stover removal may be about 25% whereas stover removal at rates >25% (>1.25 Mg ha$^{-1}$) could negatively impact $K_{sat}$. Conversely, the linear increase in $K_{sat}$ with increase in stover retention at Hoytville indicates that any removal of stover would have a negative effect on $K_{sat}$ in these soils. Thus, high stover removal rates could adversely affect $K_{sat}$ and $\rho_b$, but more research is warranted to elucidate the long-term implications of stover harvesting on soil physical quality.

### 3.3. Soil water retention and pore-size distribution

Stover management induced large and significant differences in SWR in the 0–10-cm soil depth particularly between 0 and −100 kPa soil water potential (Fig. 4). The SWR decreased with increasing stover removal rates ($P < 0.01$). The large differences in SWR were rather surprising, indicating that even 1 year of stover removal profoundly impacted the soil's capacity to retain water. The high SWR at 0 kPa with increasing stover cover showed that mulching increased total soil porosity, which explains the higher $K_{sat}$ in mulched plots. Overall, T200, T100, and T75 retained significantly greater water than T0 at all potentials ($P < 0.01$). The magnitude of SWR differences, however, varied among sites (Fig. 4). The T100 retained 1.2 times greater water at Coshocton and Charleston, and 1.5 times greater water at Hoytville than T0 in the 0 to −6 kPa. Morachan et al. (1972) also observed that SWR between −0.1 and −1500 kPa increased with an increase in stover retention rate on a Marshall silty clay loam.

The SWR for T100 did not differ from that of T75 at Coshocton, indicating that removal of 25% (1.25 Mg ha$^{-1}$) of stover did not significantly reduce SWR capacity. In contrast, T100 retained significantly greater water than T75 between 0 and −100 kPa at Hoytville and between −10 and −300 kPa at Charleston.

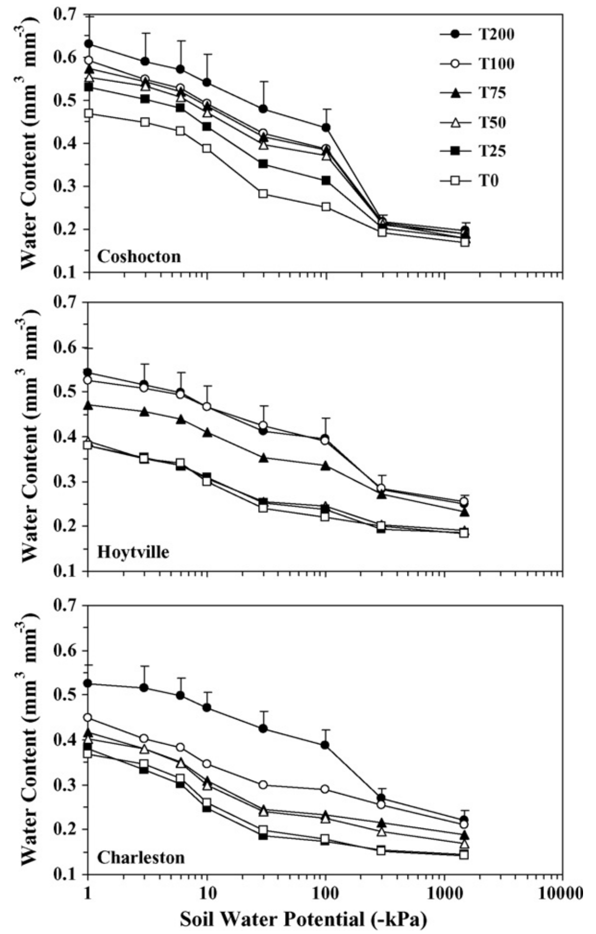


Fig. 4. Soil water retention curves as affected by stover retention rate of 10 (T200), 5 (T100), 3.75 (T75), 2.5 (T50), 1.25 (T25), and 0 (T0) Mg ha$^{-1}$ of stover at Coshocton, Hoytville, and South Charleston in Ohio. Error bars signify $LSD_{0.05}$ values at each soil water pressure potential.

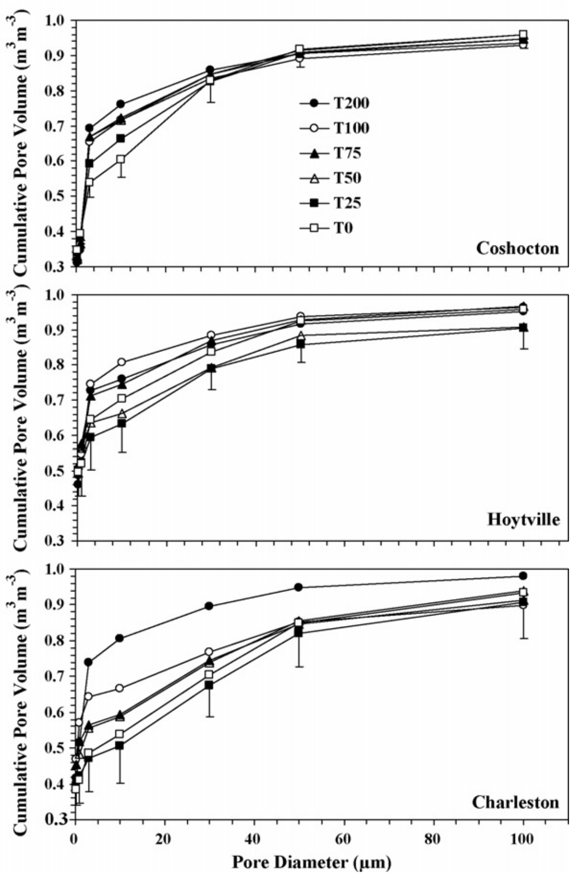


Fig. 5. Soil pore-size distribution as affected by stover retention rate of 10 (T200), 5 (T100), 3.75 (T75), 2.5 (T50), 1.25 (T25), and 0 Mg ha$^{-1}$ of stover (T0) at Coshocton, Hoytville, and South Charleston in Ohio. Pore diameters from 25 to 100 μm are classified as coarse mesopores, 5 to 25 μm as fine mesopores, and <5 μm as micropores. Error bars signify $LSD_{0.05}$ values for each pore diameter.

Difference in SWR above and below >3.75 Mg ha$^{-1}$ stover retention (T75) was the most striking at Hoytville. The large differences in SWR for the higher suctions at Hoytville (44% clay) and Charleston (22%) than at Coshocton (15% clay) suggested that the effect of stover removal was exacerbated with an increase in clay content. Greater SWR with an increase in stover retention was most likely due to improved soil structure and continued addition of partially decomposed organic materials from stover mulch. Organic materials from slowly decomposing stover interact with the soil matrix and increase the total specific surface area of the soil essential to adsorption of water molecules (Kladivko, 1994).

Stover removal had less of an effect on pore-size distribution than on other measured properties (Fig. 5). Due to high variability, differences in macro- and

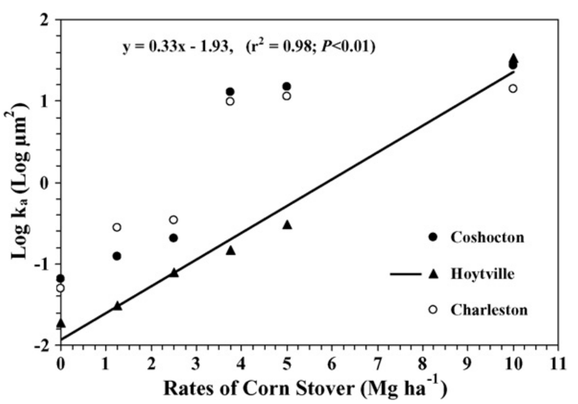


Fig. 6. Log-transformed air permeability (log $k_a$) as a function of corn stover retention rate at Coshocton, Hoytville, and South Charleston in Ohio. Regression between bulk density and stover treatment was not significant for Coshocton and Charleston.

microporosity were unaffected by stover removal ($P > 0.10$). No differences in coarse mesoporosity were observed except at Charleston where cumulative volume of coarse mesopores for T200 was significantly higher than that for other treatments. The largest effect of stover removal was observed for fine mesopores. The T200, T100, and T75 had greater cumulative volume of fine mesopores than T50, T25, and T0 across soils. These results suggest that soils with stover retention rates >3.75 Mg $ha^{-1}$ would drain faster than those with retention rates <3.75 Mg $ha^{-1}$. More importantly, the volume of 5–25-μm water retention pores increased with an increase in stover retention rate.

### 3.4. Air permeability

The log $k_a$ was affected by stover levels at all sites ($P < 0.01$; Fig. 6). The log $k_a$ increased linearly ($r^2 = 0.98$; $P < 0.01$) with an increase in stover retention rates at Hoytville. At Coshocton and Charleston, the response of log $k_a$ to stover retention rate was grouped into two categories: (i) T200, T100, and T75 with high log $k_a$ and (ii) T50, T25, and T0 treatments with low log $k_a$ ($P < 0.01$). On average, the log $k_a$ for T200, T100, and T75 was 1.3 times higher than for T50, T25, and T0 at Coshocton and Charleston. This clear separation of treatment effects into two

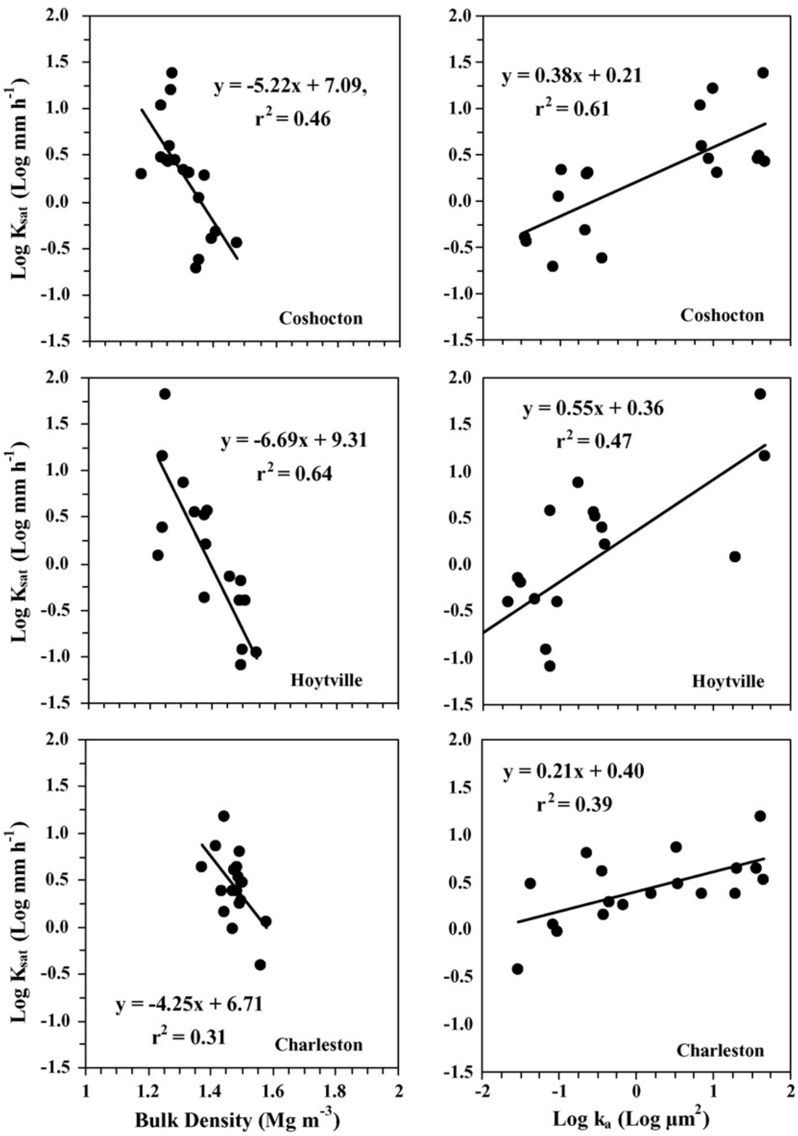


Fig. 7. Functional relationships of log-transformed saturated hydraulic conductivity (log $K_{sat}$), bulk density, and log-transformed air permeability (log $k_a$) for Coshocton, Hoytville, and South Charleston in Ohio. Regression functions were all significant at the $P \leq 0.01$.

groups suggested that stover removal rates <1.25 Mg $ha^{-1}$ would not significantly affect $k_a$. At Hoytville, T25 and T0 had lower log $k_a$ than the other stover levels. Compared to other sites, $k_a$ at Hoytville for T100 and T75 was significantly lower. Trends in $k_a$ were similar to those of $K_{sat}$, increasing with an increase in stover retention rates. Air flow through soil would be comparable to water flow at low suctions, occurring preferentially through large and continuous macropores (Iversen et al., 2003). The increase in $k_a$ with an increase in stover retention paralleled the increase in $\rho_b$ (Fig. 3), suggesting that air flow occurred predominantly through structural macropores in accordance with Pouseuille's law. Overall, stover removal at rates >25% (1.25 Mg $ha^{-1}$) would significantly alter the dynamics of air flow and gaseous exchange in these soils.

Unlike some of the previous studies which did not observe significant stover treatment effects on soil properties because of the high variability of the data, in this study, effects of stover treatments on water and air flow through the soil were not only rapid but also significant although the magnitude of changes varied with soil. These significant differences may be attributed to the uniformity of the experimental units in terms of soil and slope.

### 3.5. Interrelationships among measured soil properties

High and significant correlations existed among several soil properties. The log $K_{sat}$ was positively correlated with number of earthworm middens ($P < 0.01$). Earthworm midden numbers explained 45% of the variability in $K_{sat}$. Open-ended burrows observed in some soil cores were conduits for rapid saturated flow and high $K_{sat}$. A decrease in $\rho_b$ increased $K_{sat}$ ($P < 0.01$; Fig. 7). The increase in $\rho_b$ with an increase in stover removal decreased total porosity and $K_{sat}$. Variation in $\rho_b$ explained 46% of the variability in log $K_{sat}$ at Coshocton, 64% at Hoytville, and 31% at Charleston (Fig. 7). Favorable soil structure with mulching may have been responsible for the higher $K_{sat}$ across all soils. Singh et al. (1996) also reported that straw mulching increased $K_{sat}$ compared with unmulched soils. Log $K_{sat}$ was linearly correlated to log $k_a$ at all three sites ($P < 0.01$; Fig. 7). Changes in log $k_a$ explained 61% of the variability in $K_{sat}$ at Coshocton, 47% at Hoytville, and 39% at Charleston. These results indicating significant $K_{sat}$–$k_a$ relationships were in accord with several studies and indicated that $k_a$ could be a strong predictor of $K_{sat}$ (Loll et al., 1999; Iversen et al., 2003). Differences among sites in the slopes and intercepts of regressions in Fig. 7 indicated site-specificity. Similar to $K_{sat}$, $k_a$ was also positively correlated with the number of earthworm middens, and negatively with $\rho_b$ (Fig. 6). Variation in the number of middens accounted for 45% of the variability in $k_a$. Other studies have reported that $k_a$ can be directly correlated with earthworm population density (Springett et al., 1992). Earthworms, through their burrowing activities, provide pathways for rapid $O_2$ and $CO_2$ flow in the soil profile (Savin et al., 2004).

### 3.6. $K_{sat}$ predictions and development of pedotransfer functions

Predicted $K_{sat}$ using physically-based models (Marshall, 1958; Ahuja et al., 1984; Rawls et al., 1993) was not strongly associated with measured $K_{sat}$ ($P > 0.10$), indicating that these models were not sufficiently sensitive to changes in $K_{sat}$ due to measured changes in effective porosity and pore-size distribution. Conversely, the PTF in Eq. (1) performed better than the physical models, explaining 43% of the variance in measured log $K_{sat}$ across sites (Fig. 8). The PTF, however, overestimated measured values by 11-fold. Site-specificity of PTFs may explain the overestimation. Alternatively, based on the strong correlations in this study, $K_{sat}$ predictive PTFs were developed using the measured properties as input for each site and across three sites (Table 2). The $k_a$ was a significant determinant of $K_{sat}$ at Coshocton and Charleston, while $\rho_b$ was a potential input to predict $K_{sat}$ at Hoytville.

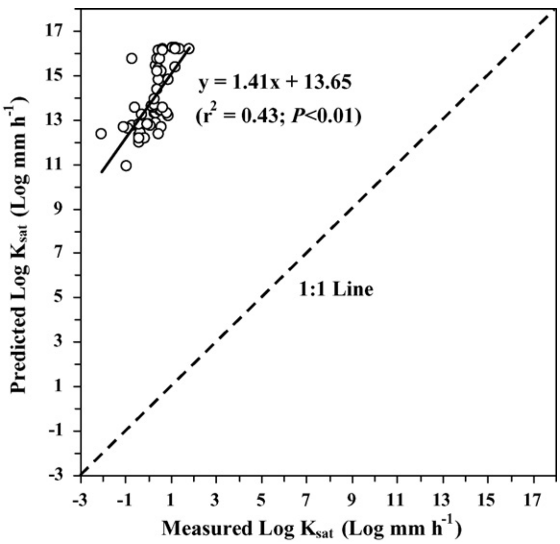


Fig. 8. Comparison of measured and predicted log-transformed saturated hydraulic conductivity (log $K_{sat}$) using the pedotransfer function of Loll et al. (1999).

Table 2
Regression coefficients for the pedotransfer functions of saturated hydraulic conductivity using bulk density ($\rho_b$) and log-transformed air permeability ($\log k_a$) as predictors for the soils at the Coshocton, Hoytville, and South Charleston sites in Ohio

| Variable | Coshocton | | Hoytville | | Charleston | | Across sites | |
|---|---|---|---|---|---|---|---|---|
| | Parameter estimate | $P < F$ | Parameter estimate | $P < F$ | Parameter estimate | $P < F$ | Parameter estimate | $P < F$ |
| Intercept | 0.21 | 0.04 | 9.31 | <0.01 | 0.40 | <0.01 | 0.26 | <0.01 |
| Log $k_a$ | 0.38 | <0.01 | | | 0.21 | <0.01 | 0.38 | <0.01 |
| $\rho_b$ | | | −6.69 | <0.01 | | | | |
| $r^2$ | 0.61 | | 0.64 | | 0.39 | | 0.43 | |

Across sites, $k_a$ was the single best predictor of $K_{sat}$. Loll et al. (1999) also observed that $\log k_a$ was the most sensitive parameter to estimate $K_{sat}$. The $k_a$ is easier to measure than $K_{sat}$ (Loll et al., 1999).

## 4. Conclusions

Corn stover removal can rapidly alter earthworm activity, water retention and transmission, and air flow, as shown for this study for 1 year, across three soils in Ohio. Improvements in earthworm population and hydraulic properties attributed to long-term NT management can be quickly negated if stover is harvested for biofuel production or other uses. The magnitude of stover removal effects, however, may vary among soils due to differences in soil properties and type and length of previous tillage and crop management. Maintaining crop residue on the soil surface is essential to enhancing earthworm activity and improving near-surface soil water and air flow parameters. Removal of stover for biofuel production from NT management systems at rates <1.25 Mg ha$^{-1}$ may not be detrimental to soil properties. Continuous monitoring of long-term studies will be needed to fully discern the effects of stover removal on soil physical properties to develop sustainable thresholds for stover removal. Pedotransfer functions based on air permeability may be useful approaches to predict saturated hydraulic conductivity under variable rates of stover retention.

## Acknowledgements

The authors express their thanks to Clarence Renk, Farm Manager at the Western Agricultural Experiment Station, South Charleston, OH and Matthew H. Davis, Farm Manager at the Northwestern Agricultural Experiment Station, Hoytville, OH for their help with the establishment and management of the experimental plots. Research conducted within the CSiTE (Consortium for Research on Enhanced Carbon Sequestration in Terrestrial Ecosystems) program. CSiTE is supported by the U.S. Department of Energy, Office of Science as part of the Terrestrial Carbon Sequestration program in the Office of Biological and Environmental Research.

## References

Ahuja, L.R., Naney, J.W., Green, R.E., Nielsen, D.R., 1984. Macroporosity to characterize spatial variability of hydraulic conductivity and effects of land management. Soil Sci. Soc. Am. J. 48, 699–702.

Ball, B.C., Schjønning, P., 2002. Air permeability. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 1141–1182.

Blanco-Canqui, H., Gantzer, C.J., Anderson, S.H., Alberts, E.E., Ghidey, F., 2002. Saturated hydraulic conductivity and its impact on simulated runoff for claypan soils. Soil Sci. Soc. Am. J. 66, 1596–1602.

Bohlen, P.J., Parmelee, R.W., McCartney, D.A., Edwards, C.A., 1997. Earthworm effects on carbon and nitrogen dynamics of surface litter in corn agroecosystems. Ecol. Applic. 7, 1341–1349.

Bouma, J., 1989. Using soil survey data for quantitative land evaluation. Adv. Soil Sci. 9, 177–213.

Butt, K.R., Shipitalo, M.J., Bohlen, P.J., Edwards, W.M., Parmelee, R.W., 1999. Long-term trends in earthworm populations of cropped experimental watersheds in Ohio, USA. Pedobiologia 43, 713–719.

Dabney, S.M., Wilson, G.V., McGregor, K.C., Foster, G.R., 2004. History, residue, and tillage effects on erosion of loessial soil. Trans. ASAE 47, 767–775.

Dane, J.H., Hopmans, J.H., 2002. Water retention and storage. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 671–717.

Ela, S.D., Gupta, S.C., Rawls, W.J., 1992. Macropore and surface seal interactions affecting water infiltration into soil. Soil Sci. Soc. Am. J. 56, 714–721.

Findeling, A., Ruy, S., Scopel, E., 2003. Modeling the effects of a partial residue mulch on runoff using a physically based approach. J. Hydrol. 275, 49–66.

Grossman, R.B., Reinsch, T.G., 2002. Bulk density and linear extensibility. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 201–225.

Hillel, D., 1998. Environmental Soil Physics. Academic Press Inc., San Diego, California.

Iversen, B.V., Moldrup, P., Schjønning, P., Jacobsen, O.H., 2003. Field application of a portable air permeameter to characterize spatial variability in air and water permeability. Vadose Zone J. 2, 618–626.

Karlen, D.L., Wollenhaupt, N.C., Erbach, D.C., Berry, E.C., Swan, J.B., Eash, N.S., Jordahl, J.L., 1994. Crop residue effects on soil quality following 10 years of no-till corn. Soil Till. Res. 31, 149–167.

Kim, S., Dale, B.E., 2004. Global potential bioethanol production from wasted crops and crop residues. Biomass Bioenerg. 26, 361–375.

Kladivko, E.J., 1994. Residue effects on soil physical properties. In: Unger, P.W. (Ed.), Managing Agricultural Residues. Lewis Publishers, Boca Raton, FL, pp. 123–162.

Klute, A., 1965. Laboratory measurement of hydraulic conductivity of saturated soil. In: Black, C.A. (Ed.), Methods of Soil Analysis. Part 1. Agron. Monogr. 9. ASA and SSSA, Madison, WI, pp. 210–221.

Lal, R., De Vleeschauwer, D., Nganje, R.M., 1980. Changes in properties of a newly cleared tropical Alfisol as affected by mulching. Soil Sci. Soc. Am. J. 44, 827–833.

Lal, R., 2005. World crop residues production and implications of its use as a biofuel. Environ. Int. 31, 575–584.

Lebron, I., Schaap, M.G., Suarez, D.L., 1999. Saturated hydraulic conductivity prediction from microscopic pore geometry measurements and neural network analysis. Water Resour. Res. 35, 3149–3158.

Logsdon, S.D., Allmaras, R.R., Wu, L., Swan, J.B., Randall, G.W., 1990. Macroporosity and its relation to saturated hydraulic conductivity under different tillage practices. Soil Sci. Soc. Am. J. 54, 1096–1101.

Loll, P., Moldrup, P., Schjønning, P., Riley, H., 1999. Predicting saturated hydraulic conductivity from air permeability: application in stochastic water infiltration modeling. Water Resour. Res. 35, 2387–2400.

Luxmoore, R.J., 1981. Microporosity, mesoporosity, and macroporosity of soil. Soil Sci. Soc. Am. J. 45, 671–672.

Mankin, K.R., Ward, A.D., Boone, K.M., 1996. Quantifying changes in soil physical properties from soil and crop management: a survey of experts. Trans. ASAE 39, 2065–2074.

Marshall, T.J., 1958. A relationship between permeability and size distribution of pores. J. Soil Sci. 9, 1–8.

Minasny, B., McBratney, A.B., 2002. Uncertainty analysis of pedotransfer functions. Eur. J. Soil Sci. 53, 417–429.

Morachan, Y.B., Moldenhauer, W.C., Larson, W.E., 1972. Effects of increasing amounts of organic residues on continuous corn: I. Yields and soil physical properties. Agron. J. 64, 199–203.

Nelson, R.G., 2002. Resource assessment and removal analysis for corn stover and wheat straw in the Eastern and Midwestern United States—rainfall and wind-induced soil erosion methodology. Biomass Bioenerg. 22, 349–363.

Pacala, S., Socolow, R., 2004. Stabilization wedges: solving the climate problem for the next 50 years with current technologies. Science 305, 968–972.

Pikul Jr., J.L., Allmaras, R.R., 1986. Physical and chemical-properties of a Haploxeroll after 50 years of residue management. Soil Sci. Soc. Am. J. 50, 214–219.

Rawls, W.J., Brakensiek, D.L., Logsdon, S.D., 1993. Predicting saturated hydraulic conductivity utilizing fractal principles. Soil Sci. Soc. Am. J. 57, 1193–1197.

Reynolds, W.D., Elrick, D.E., Youngs, E.G., 2002. Field methods (vadose and saturated zone techniques). In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 817–877.

SAS Institute, 1999. SAS/STAT User's Guide. Version Windows 8. SAS Institute Inc., Cary, NC.

Savin, M.C., Gorres, J.H., Amador, J.A., 2004. Microbial and microfaunal community dynamics in artificial and *Lumbricus terrestris* (L.) burrows. Soil Sci. Soc. Am. J. 68, 116–124.

Schjønning, P., Munkholm, L.J., Moldrup, P., Jacobsen, O.H., 2002. Modelling soil pore characteristics from measurements of air exchange: the long-term effects of fertilization and crop rotation. Eur. J. Soil Sci. 53, 331–339.

Sharratt, B.S., 1996. Tillage and straw management for modifying physical properties of a subarctic soil. Soil Till. Res. 38, 239–250.

Shaver, T.M., Peterson, G.A., Ahuja, L.R., Westfall, D.G., Sherrod, L.A., Dunn, G., 2002. Surface soil physical properties after twelve years of dryland no-till management. Soil Sci. Soc. Am. J. 66, 1296–1303.

Shipitalo, M.J., Butt, K.R., 1999. Occupancy and geometrical properties of *Lumbricus terrestris* L-burrows affecting infiltration. Pedobiologia 43, 782–794.

Singh, B., Chanasyk, D.S., McGill, W.B., 1996. Soil hydraulic properties of an Orthic Black Chernozem under long-term tillage and residue management. Can. J. Soil Sci. 76, 63–71.

Skidmore, E.L., Layton, J.B., Armbrust, D.V., Hooker, M.L., 1986. Soil physical-properties as influenced by cropping and residue management. Soil Sci. Soc. Am. J. 50, 415–419.

Sloneker, L.L., Moldenhauer, W.C., 1977. Measuring the amounts of crop residue remaining after tillage. J. Soil Water Conserv. 32, 231–236.

Snedecor, G.W., Cochran, W.G., 1989. Statistical Methods, 8th ed. Iowa State University Press, Ames, IA.

Springett, J.A., Gray, R.A.J., Reid, J.B., 1992. Effect of introducing earthworms into horticultural land previously denuded of earthworms. Soil Biol. Biochem. 24, 1615–1622.

Topp, G.C., Ferré, P.A., 2002. Water content. In: Dane, J.H., Topp, G.C. (Eds.), Methods of Soil Analysis. Part 4. Agron. Monogr. 5. SSSA, Madison, WI, pp. 417–422.

Whalen, J.K., Sampedro, L., Waheed, T., 2004. Quantifying surface and subsurface cast production by earthworms under controlled laboratory conditions. Biol. Fert. Soils 39, 287–291.

Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B., Linden, D.R., 2004. Crop and soil productivity response to corn residue removal: a literature review. Agron. J. 96, 1–17.

Willoughby, G.L., Kladivko, E.J., Savabi, M.R., 1997. Seasonal variations in infiltration rate under no-till and conventional (disk) tillage systems as affected by *Lumbricus terrestris* activity. Soil Biol. Biochem. 29, 481–484.

Zaller, J.G., Arnone III, J.A., 1997. Activity of surface-casting earthworms in a calcareous grassland under elevated atmospheric $CO_2$. Oecologia 111, 249–254.