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SOIL HYDRAULIC CONDUCTIVITY AND RETENTION CURVES FROM TENSION INFILTROMETER AND LABORATORY DATA

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Abstract. Long term tillage effects may be characterized on the basis of changes in soil surface hydraulic properties. These properties directly influence infiltration as well as the movement of soil water to the surface during drying. We measured surface soil hydraulic properties on no-till (NT) and conventional (stubble mulch) tillage (CT) plots, each of which was farmed with either a wheat-sorghum-fallow (WSF) or a wheat-fallow (WF) rotation. The plots had been in the same treatments for 12 years. Tension infiltrometers were used to measure steady state infiltration rates at four heads, *h* (nominally -2.0, -1.5, -1.0, and -0.5 kPa, applied in that order), resulting in estimates of hydraulic conductivity, *K(h)*. Both single and multiple-reservoir infiltrometers were constructed. The multiple-reservoir infiltrometer allowed completion of infiltration to steady state at four tensions without disturbance of the flow regime or of soil contact due to re-filling of reservoirs. Hanging water column and pressure plate techniques were used to measure soil water retention values, $\theta(h)$, on undisturbed core samples. The parameter α was not well estimated by a nonlinear optimization used to find the parameters K_s and α in Wooding's equation for steady-state flow; so α was estimated as the mean of values satisfying Wooding's equation for any two tensions and flow rates. The *K(h)* and $\theta(h)$ data were fitted to Mualem's and van Genuchten's forms for the hydraulic conductivity and retention curves, respectively, using the RETC program ($r^2 \geq 0.99$). The fitted water retention curves showed marked differences between NT and CT treatments. The more dense NT soils exhibited a more gradual reduction in water content as tension increased. Fitted values of the saturated water content, θ_s, were close to the values of porosity from bulk density data, except in the case of WSFCT, which gave a fitted θ_s of 0.52, somewhat below the porosity of 0.56. The saturated water content was significantly lower (P = 0.10) for NT than for CT. For NT plots, θ_s was significantly lower for WSF than for WF. Bulk density was significantly greater for NT than for CT, and significantly greater for WSF than for WF. For WSF rotations, saturated *K* was significantly greater for CT than for NT, but not in WF rotations. The overall fitted *K(h)* curves showed that K was greater in CT than in NT for both WF and WSF rotations over most of the water content range from 0.1 to 0.5 $m^3\ m^{-3}$. These results indicate that greater runoff would be expected under no tillage.

INTRODUCTION

Water conservation is critical for sustainable agricultural systems on the High Plains. Research over a 10-year period at Bushland, TX showed that no-tillage resulted in increased soil water at planting compared with conventional tillage systems [*Jones and Popham*, 1997]. The research included rotations as varied as continuous wheat, wheat-sorghum-fallow, wheat-fallow, and continuous sorghum. Contrary to some research in the more humid eastern U.S., no-tillage in the Southern High Plains results in decreased infiltration rates and increased runoff compared with conventional till; but, soil water at planting is higher for no-tillage [*Jones et al.*, 1994]. Reduced tillage increased soil water at planting under wheat-fallow and wheat-sorghum-fallow systems at Tribune, Kansas [*Norwood et al.*, 1990]. Various hypotheses have been advanced to explain the increased soil water, including differing infiltration rates and evaporation rates. Reduced tillage resulted in higher spring soil water contents in Alberta, Canada, due to increased snow capture and possibly less evaporative loss during fallow [*Maulé and Chanasyk*, 1990]. However, much of this research has not directly addressed the underlying mechanisms leading to increased soil water.

The research area used by *Jones and Popham* [1997] was established in 1982 and consisted of a series of level bench terraces [*Eck and Jones*, 1992]. The tillage and crop rotations established on these terraces in 1984 were still in effect in 1994. We hypothesized that significant differences in soil hydraulic properties were caused by the tillage and crop rotation differences. Our objective was to find if measured soil hydraulic properties were affected by four crop rotation and tillage treatments:

WFNT - wheat-fallow, no tillage
WFCT - wheat-fallow, conventional tillage
WSFNT - wheat-sorghum-fallow, no tillage
WSFCT - wheat-sorghum-fallow, conventional tillage

In each case the conventional tillage was stubble mulch tillage.

THEORY

Tension infiltrometers have been widely used to measure the unsaturated hydraulic properties of soil in situ [*White and Perroux*, 1987; *Smettem and Clothier*, 1989; *Somaratne and Smettem*, 1993], including changes in those properties effected by tillage practices [*Ankeny et al.*, 1990; *Sauer et al.*, 1990]. *White et al.* [1992] reviewed the use of tension infiltrometers and presented several alternative methods of measurement and analysis of the resulting data. Most methods have their theoretical basis in *Wooding*'s [1968] solution for steady state flux, Q (m s^{-1}), from a shallow circular pond of radius, r_o (m), at a supply tension, h (m):

$$Q = K_h[1 + 4\lambda_c/(\pi r_o)] \tag{1}$$

where $\lambda_c = 1/\alpha$ is the macroscopic capillary length (m), and K_h is given by *Gardner*'s [1958] exponential hydraulic conductivity function:

$$K_h = K_s \exp(\alpha h) \tag{2}$$

where K_s is the saturated hydraulic conductivity (m s^{-1}). *White and Sully* [1987] showed that the value of α may be calculated from:

$$\alpha = \frac{(\theta_h - \theta_i)(K_h - K_i)}{bS_h^2} \tag{3}$$

where S_h is the sorptivity (m s$^{-1/2}$) at the supply potential, θ_h and K_h are the water content (m^3 m^{-3}) and hydraulic conductivity (m s^{-1}) at the supply potential, θ_i and K_i are the initial water content (m^3 m^{-3}) and hydraulic conductivity (m s^{-1}), and b is a shape factor that may vary from 0.5 to $\pi/4$ but averages about 0.55. The sorptivity is readily obtained from short term infiltration data for which the cumulative infiltration, I (m), is linear with the square root of time and S_h is simply the slope of the plot of I vs. $t^{1/2}$. Since usually $K_h >> K_i$ the value of K_i is often ignored. The value of θ_i may be readily measured. Measurement of θ_h is problematic as will be discussed later.

White et al. [1992] combined Eqs. (1) and (3), with K_i assumed unimportant, to obtain:

$$K_h = Q - \frac{4bS_h^2}{(\theta_h - \theta_i)\pi r_o} \tag{4}$$

where Q is measured at steady state, and S_h is obtained from short-time data. To measure θ_h in the field, samples just under the infiltrometer must be taken at the end of the measurement immediately after the infiltrometer is removed. To ensure that the samples represent θ_h, the samples must be taken from a thin layer of soil at the surface. Sample volume tends to be small, and sampling is made more difficult if a layer of contact material (usually consisting of a fine sand) has been used, since it must be removed. Experience shows that field measured θ_h-values tend to be quite variable, enough to lead to negative values of K_h [*Logsdon and Jaynes*, 1993]. Because of the difficulty of measuring θ_h in the field, *Smettem and Clothier* [1989] estimated θ_h from retention curves measured in the laboratory on undisturbed cores.

Obtaining good data in the short time during which cumulative infiltration is still linear with $t^{1/2}$ can also be difficult in many soils, thereby limiting the usefulness of Eq. (4), as well as the usefulness of an alternative method used by *White et al*. [1992] that depends solely on measurements of S_h at several supply tensions.

Efforts to avoid problems associated with measurements of S_h and θ_h have usually relied on varying other parameters of Eq. (4) so as to allow solution of multiple versions of the equation, thus eliminating the need to measure some parameters. *Smettem and Clothier* [1989] used disks of three different radii and a regression solution to find S_h and K_h. In this method the spatial variability of soil properties may introduce unwanted noise since the different radii disks are used in different locations [*Logsdon and Jaynes*, 1993]. *Ankeny* et al. [1990] measured Q at the same location for four supply tensions. Writing equations for each successive pair of tensions, and assuming a constant value of $K(h)/\phi(h)$ (ϕ is the matrix flux potential), they solved Eq. (4) simultaneously, producing a pair of K_h estimates for each pair of Q.

Combining Eq. (1) and (2) we have:

$$Q = K_s \exp(\alpha h)\,[1 + 4/(\alpha \pi r_o)] \tag{5}$$

which describes the steady state flux in two unknowns, K_s and α. *Logsdon and Jaynes* [1993] developed a nonlinear regression method to find K_s and α from flow data measured at three supply tensions at the same location. Considerable scatter in the data were evident. *Hussen and Warrick* [1993] developed a best fit method that used the steady state Q measured at four tensions, h, to find K_s and α. They found that this multiple tension method, used with a large radius (0.1 m) disk tension infiltrometer, gave the best results among four methods including i) a single disk and tension with short term measurements for sorptivity and long term measurements for steady state flux, ii) steady state flux measurements with two disk radii, iii) single disk with steady state flux measurements at two tensions, and iv) the multiple tension method described above.

If only two tensions were used, *Hussen and Warrick* [1993] wrote Eq. (5) twice with the different tensions and solved for α:

$$\alpha = \frac{\ln\left[Q_2/Q_1\right]}{\left|h_2 - h_1\right|} \tag{6}$$

where the subscripts 1 and 2 refer to the two tensions and the corresponding steady state fluxes. If more than two tensions were used then both K_s and α were found by a best fit procedure.

Van Genuchten et al. [1991] developed the RETC computer code for fitting soil water retention, $\theta(h)$, and hydraulic conductivity vs. tension, $K(h)$, data to models of the $\theta(h)$ and $K(h)$ functions. We used RETC to fit our data to *van Genuchten*'s [1980] water retention model:

$$\theta(h) = \theta_r + \frac{\left(\theta_s - \theta_r\right)}{\left[1 + (\alpha h)^n\right]^m} \tag{7}$$

where $\theta(h)$ is the water content (m^3 m^{-3}) at tension h (m); θ_r and θ_s are the residual and saturated water contents, respectively; and α, m and n are fitting constants. Also in RETC we used *Mualem*'s [1976] hydraulic conductivity model:

$$K(h) = K_s S_e^L[\mathrm{f}(S_e)/\mathrm{f}(1)]^2 \tag{8}$$

where $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$, L is a fitting parameter often taken as 0.5 and

$$\mathrm{f}(S_e) = \int_0^{Se} h^{-1}(x)dx \tag{9}$$

and

$$\mathrm{f}(1) = \int_0^{1} h^{-1}(x)dx \tag{10}$$

METHODS

Between July 25 and Nov. 10, 1994, we measured surface soil hydraulic properties on three replicate plots each of four rotation-by-tillage treatments established in 1982. Each replicate was on a level terrace, 9.1-m wide by 158.5-m long across the slope, on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) at the USDA-ARS Conservation and Production Research Laboratory at Bushland, TX. Treatments were arranged in a randomized block design with three replications, each consisting of a single terrace. Rotations were wheat-sorghum-fallow (WSF), and wheat-fallow (WF). Tillage treatments were either no-tillage (NT) or conventional (stubble mulch) tillage (CT) on each rotation. At 3 or more sites in each plot, a 0.20-m diameter disk infiltrometer was run to steady state at each of 4 tensions, nominally 2.0, 1.5, 1.0, and 0.5 kPa, applied in that order. Steady state was determined by following the drop in water column height per unit time. Tensions were re-measured at steady state. Our single reservoir tension infiltrometers were modeled after those described by *Perroux and White* [1988] with the addition of a conical roof in the base to allow any small air leakage through the membrane to bubble up through the reservior tube to the air space at the tube's top (Fig. 1). The single reservoir infiltrometer sometimes ran out of water before steady state at four tensions could be measured, so we designed a multiple reservoir infiltrometer and used it for some measurements (Fig. 2).

Initial water content, bulk density and water desorption were measured on 0.05-m diameter (67.8 cm^3) undisturbed cores, taken from the A horizon and weighed, using hanging water column and pressure plate methods to 1.5 MPa tension, followed by oven drying at 105°C for 48 hours and re-weighing. Forty cores were collected from each plot for a total of 480 cores. Tensions of 0.5, 1.0, 1.5, 2.0, 2.5, 5.0, 10.0, and 15.0 kPa were used for the hanging water column experiments. Pressures of 33, 55, 100, 500, and 1500 kPa were used for pressure plate measurements.

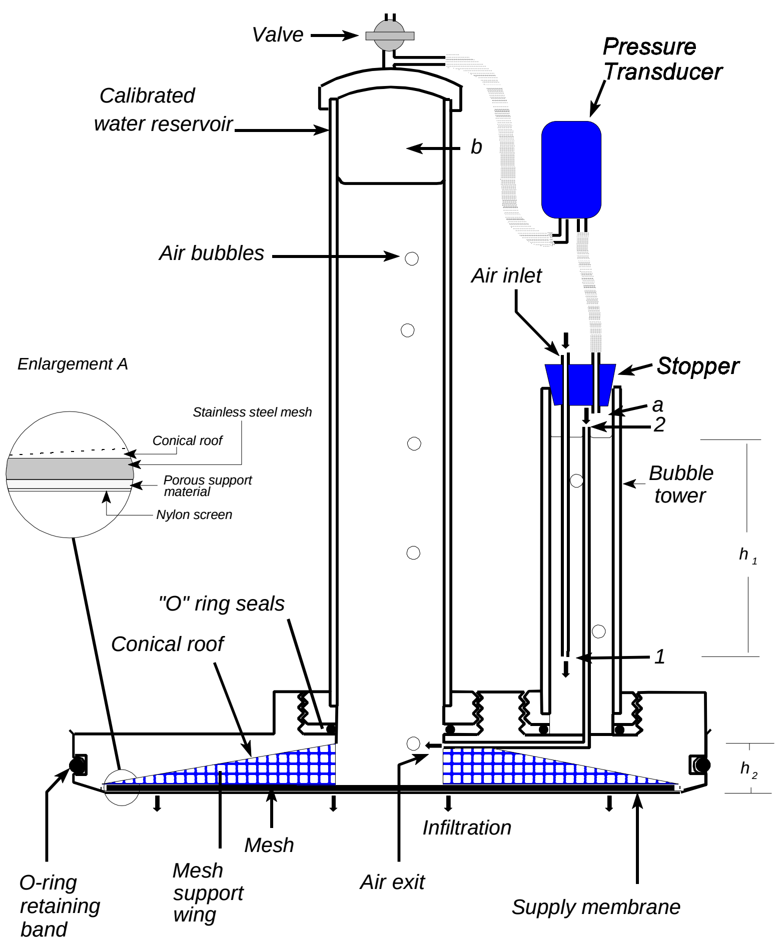

Figure 1. Single reservoir tension infiltrometer
with conical roof in base.

Core samples were oven dried for determination of bulk density and porosity after the retention experiments. Retention data for a sample were excluded from the final data sets if the sample bulk density varied widely from the mean bulk density or if the saturated water content (for hanging water column data) was widely different from the average porosity. Equation (6) was used to find values of α corresponding to each combination of two of the tensions used in a particular infiltrometer run. For each α-value an estimate of K_s was generated from Eq. (5). The mean values of α and K_s were then used to initialize a nonlinear optimization using Eq. (5), following *Hussen and Warrick* [1993], to obtain K_s and α for each infiltrometer run. Version 4 of Quattro Pro was used for the optimization. An objective function, Φ, for the optimization can be written as:
where the Q_i are the steady state infiltration rates measured at the four tensions, and the

$$\Phi = \sum_{i=1}^{4} \left[Q_i - Q_i(K_s, \alpha) \right]^2 \qquad (11)$$

$Q_i(K_s,\alpha)$ are the Eq. (5) predictions of steady state flow for the optimized parameters K_s and α. Finally, for each run, hydraulic conductivities $K(h)$ were calculated corresponding to the tensions used when running the infiltrometers.

The RETC code was used to fit our water retention and K_h data to Eq. (6) and (7). We at first experienced difficulty because RETC did not converge on a solution. Examination of the computer code revealed an error in dimensioning an array variable that caused problems with data sets of over 100 data pairs. Changing the dimension of the array from 100 to 200 allowed us to run the program with our four data sets, each of which included over 100 data pairs. We eventually re-wrote the program in BASIC to allow run time re-dimensioning of variable arrays so that data sets of arbitrary size could be accommodated. In the BASIC version we also added code to allow the user to set the confidence level for parameter estimates.

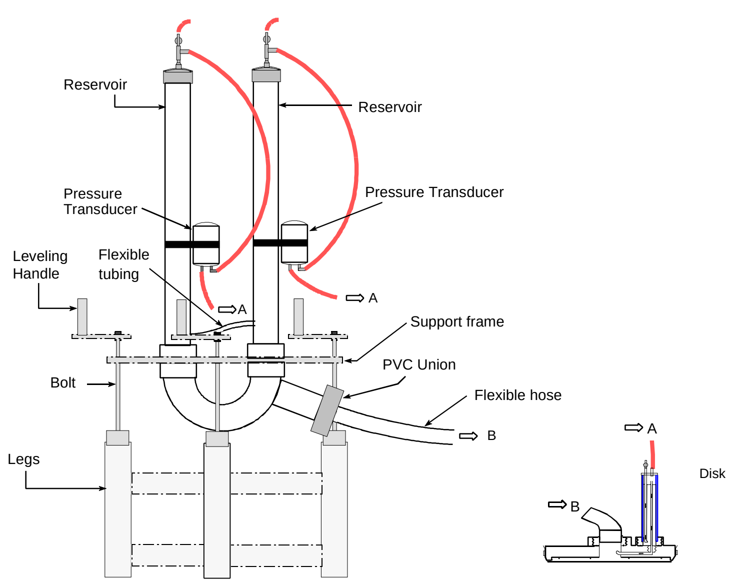

Figure 2. Multiple reservoir tension infiltrometer.

RESULTS

Duncan multiple range tests showed that bulk density was significantly greater in NT than CT (Table 1). Within NT, the bulk density was significantly greater for WSF than for WF (P = 0.05), which is understandable given the increased traffic from harvest on WSF and the fact that sorghum stubble typically gives less protection to the soil surface than wheat stubble. There was no significant difference in bulk density between WSF and WF for CT treatments.

We initially attempted to find K_s and α by nonlinear optimization of Eq. (5) alone, but found that α remained essentially at its initial value, and that only K_s was optimized. That is why we used Eq. (6) to calculate estimates of α for each pair of tensions and used the mean α value to initialize the nonlinear optimization. The lack of change in α during optimization may be due to a weakness in the Quattro Pro nonlinear optimization routines. However, plotting the objective function for a region around the optimum values of K_s and α showed that Eq. (5) was only weakly dependent on the value of α (Fig. 3). *Šimůnek and van Genuchten* [1997], using numerically generated cumulative infiltration curves for three tensions, found that the cumulative infiltration curves alone were not sufficient to uniquely determine K_s, α, n, and θ_s. But, the response surfaces they plotted did appear to show that K_s and α could be uniquely determined if n and θ_s were fixed. Our results are somewhat different in that we found that α was difficult to estimate uniquely. However, our optimization assumes the exponential form of the hydraulic conductivity equation rather than *Mualem*'s [1976] form. Also, we used only steady state flow rates while *Šimůnek and van Genuchten* [1997] used all points along the cumulative infiltration curve in their optimizations.

Water desorption and hydraulic conductivity data were simultaneously fit, using RETC, to *van Genuchten*'s (VG) and *Mualem*'s (MU) equations for water retention and hydraulic conductivity, with r^2 of 0.99 for all 4 treatments (Table 2). The restriction $m = 1 - 1/n$ was applied. Fitting θ_r in some cases resulted in abnormally large residual water contents exceeding 0.15 so θ_r was fixed at 0.01. Also, fitting L sometimes resulted in abnormally large negative values of L (< -15). This caused the $K(h)$ function to yield increasing K as tension increased, an unrealistic result. Therefore L was fixed at 0.5. Fitted parameters hence were θ_s, α, n and K_s (Table 2). Good fits were dependent on removing outliers from the data sets. In this regard, the fits became much better when we went through the data and removed all desorption data for samples with bulk densities that varied far from the mean bulk density for a treatment. We observed in the field that it was especially difficult to obtain undisturbed soil cores from the CT treatments, which had less consolidated surfaces than did NT treatments.

TABLE 1. Bulk Density Analysis by Duncan Multiple Range Test

Duncan Group	Bulk density (Mg m^{-3})	Porosity (m^3 m^{-3})	N	Treatment
A	1.563	0.410	36	WSFNT
B	1.452	0.452	29	WFNT
C	1.157	0.563	40	WSFCT
C	1.103	0.584	50	WFCT

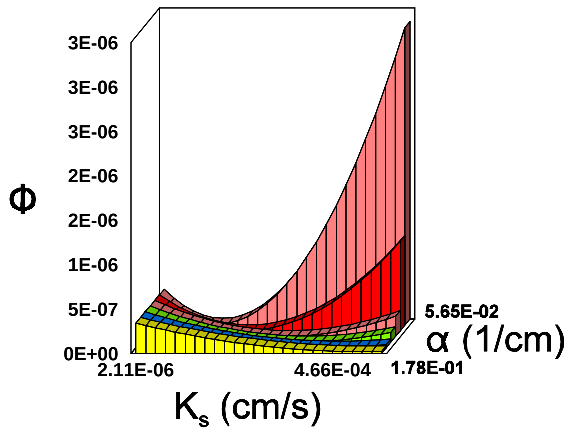

Figure 3. Objective function, Φ, around optimum values of K_s and $\alpha = 1/\lambda_c$ for a typical four-tension infiltrometer run.

TABLE 2. Results from Parameter Fitting with RETC

		95% Confidence Intervals			
Treatment	Parameter	Lower	Upper	SE	t
		θ_s (m^3 m^{-3})			
WFNT	0.435	0.424	0.446	5.48E-03	79.5
WFCT	0.553	0.537	0.569	8.02E-03	69.0
WSFNT	0.412	0.403	0.421	4.65E-03	88.7
WSFCT	0.525	0.507	0.543	9.08E-03	57.8
		α (m^{-1})			
WFNT	1.44	0.88	1.99	0.28	5.2
WFCT	8.17	5.95	10.39	1.12	7.3
WSFNT	0.57	0.31	0.83	0.13	4.3
WSFCT	12.69	8.27	17.12	2.24	5.7
		n			
WFNT	1.171	1.150	1.192	1.07E-02	109.0
WFCT	1.248	1.231	1.265	8.72E-03	143.1
WSFNT	1.190	1.156	1.223	1.69E-02	70.3
WSFCT	1.189	1.174	1.204	7.69E-03	154.6
		K_s (m s^{-1})			
WFNT	1.17E-05	5.44E-06	1.79E-05	3.13E-06	3.7
WFCT	4.48E-05	1.75E-05	7.22E-05	1.38E-05	3.2
WSFNT	1.73E-06	7.06E-07	2.75E-06	5.16E-07	3.4
WSFCT	9.94E-05	2.32E-05	1.76E-04	3.85E-05	2.6

Consistent with the bulk density data, the saturated water content was significantly lower in NT than CT; and, for NT plots, the saturated water content was significantly lower for WSF than for WF (P = 0.05, Table 2 comparisons are unprotected from type II error). Values for K_s were significantly higher for CT than for NT in WSF rotations but not in WF rotations. Other parameters of the VG and MU equations were sometimes significantly different across NT vs. CT or WSF vs. WF treatments. The value of α was quite variable, but not outside the range of values found for clay and silty clay soils by *Yates et al.* [1992] in their study of 36 soils. Values of n did not vary much by treatment and were within the range reported by *Yates et al.* [1992].

The fitted water retention curves show marked differences between NT and CT treatments (Fig. 4). The more dense NT soils had a less steep drop off of water content as tension increased. The fitted values of θ_s tended to be close to, but lower than, the values of porosity calculated from bulk density data; except for WSFNT for which the two values were practically the same. Since the fitted θ_s values were derived from data gathered under tension we did not expect them to be as high as porosity, because there were likely macropores that were never filled under tension, especially for the CT treatments.

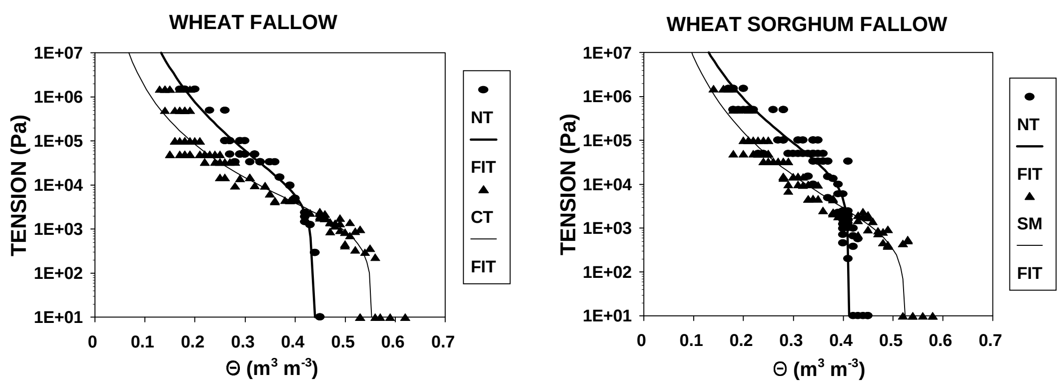

Figure 4. Soil water retention curves for wheat-fallow (left) and wheat-sorghum-fallow (right) rotations, for both no tillage (NT) and conventional tillage (CT). (FIT = Fitted curves)

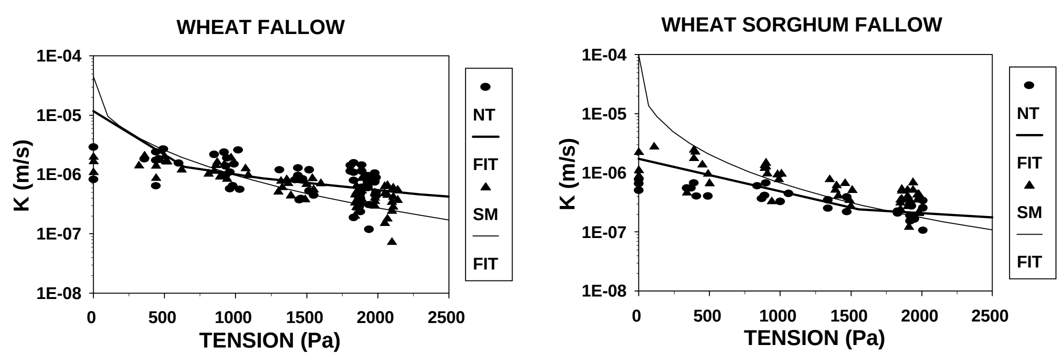

Figure 5. Curves of hydraulic conductivity, K, vs. tension for wheat-fallow (left) and wheat-sorghum-fallow (right) rotations, for both no tillage (NT) and conventional tillage (CT). (FIT = Fitted curves)

The overall fitted *K(h)* curves showed that *K* was greater in CT than in NT for both WF and WSF rotations over most of the water content range from 0.1 to 0.5 $m^3 m^{-3}$ (Fig. 5). These results indicate that greater runoff would be expected for NT compared with CT treatments. For CT treatments, the *K* curves tended to abrubtly increase (higher *K* values) as tension dropped to zero, compared with the *K* curves for NT, which showed much lower *K*-values at saturation. This was realistic in that the CT treatments had more macropores that would become involved in flow as the soil reached saturation.

SUMMARY

Water retention was measured over a range of 0 to 1500 kPa for four tillage by crop sequence treatments. The tillage types were no tillage (NT) and conventional (stubble mulch) tillage (CT). Each tillage was applied to two different crop sequences, wheat fallow (WF) and wheat sorghum fallow (WSF) for a total of four treatments: WFNT, WFCT, WSFNT, and WSFCT. Steady-state soil water flux from a circular area at constant tension at the soil surface was measured at four tensions (0.5, 1.0, 1.5 and 2.0 kPa) using disk infiltrometers. We attempted to fit the parameters K_s and α in Wooding's steady state equation by nonlinear optimization; but it was not possible to simultaneously fit K_s and α since α never varied from its initial value during the optimizations. Therefore, we used an estimation procedure to fix α before each fit. From these data the soil hydraulic conductivities, *K(h)*, at the corresponding tensions were calculated. The retention and *K(h)* data were simultaneously fit with *van Genuchten*'s [1980] and *Mualem*'s [1976] functions, respectively, using the RETC program.

Excellent fits were obtained and resulting curves of $\theta(h)$ and *K(h)* showed marked and significant differences between NT and CT and between WF and WSF cropping sequences. No tillage resulted in more dense soil with lower hydraulic conductivity near saturation, but higher predicted hydraulic conductivity at higher tensions compared with CT. No tillage resulted in retention curves with a less steep decrease in soil water content as tension increased compared with CT, and with higher water contents at tensions greater than about 8 kPa. We conclude that NT results in lower infiltration and higher runoff under our conditions. Even though the retention data were from a drying process, while the infiltrometer data were from a wetting process, we feel that the combined data are useful for efficiently characterizing field soil hydraulic properties.

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