Land Use Effects on Soil Hydraulic Properties

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ABSTRACT

Tillage alters the pore structure and hydraulic properties of soils. Likewise, reestablishment of grass on cropland will, over time, produce changes in soil hydraulic properties that can influence the amount of plant available water. We conducted a study to characterize and compare soil hydraulic properties on adjacent native grassland, cropland, and Conservation Reserve Program (CRP) sites at three locations in the Texas High Plains. A tension infiltrometer was used to measure unconfined, unsaturated infiltration over a range of water tensions (0.05, 0.5, 1.0, and 1.5 kPa) at the soil surface. Intact soil cores were sampled within the Ap and Bt horizons to determine bulk density and water desorption curves, $\theta(h)$. Unsaturated hydraulic conductivity over the range of tensions $K(h)$ was estimated using Wooding's equation for steady state flow from a disk source. The van Genuchten-Mualem model was simultaneously fitted to $K(h)$ and $\theta(h)$ data to obtain parameter values for each land use treatment. Mean near-saturated hydraulic conductivities of cropland were not significantly different from grassland. However, at 1.5 kPa supply tension, cropped soils had a mean unsaturated conductivity four times greater than grassland. CRP sites had the lowest ($P < 0.05$) near-saturated hydraulic conductivities, which suggests that, after 10 years, grasses had not fully ameliorated changes in pore structure caused by tillage. Results of a 10-day simulation of evaporation from a bare soil suggest that the larger unsaturated conductivities measured for sweep-tilled cropland leads to increased evaporative losses of water as compared with other land uses.

INTRODUCTION

Hydraulic conductivity and water retention properties of soils can influence the efficient use of water and, ultimately, production potential under dryland agriculture conditions. Changes in the continuity, size, and extent of pores caused by tillage will strongly influence the surface hydraulic properties of the soil. However, studies have shown that tillage effects on infiltration rates are not consistent (Ankeny et al., 1990; Dao, 1993; Jones et al., 1994). In general, increased infiltration rates resulting from tillage operations are short lived due to settlement and crust formation (Kemper, 1993; Angulo-Jaramillo et al., 1997). Tillage under continuous cropping will also cause organic carbon levels to decline. Long-term decreases in soil organic carbon are generally believed to decrease infiltration rates (Kemper, 1993). This may be brought about by reduced mesofauna activity and associated biopores or by reduced aggregate stability leading to increased aggregate infilling, particle dispersion, and surface sealing during precipitation events.

A primary objective of the Conservation Reserve Program (CRP) was to return cropland to perennial grasses as a means to stabilize highly erodible soils. The establishment of perennial grass cover has also resulted in significant increases in soil organic carbon in the Great Plains (Gebhart et al., 1994). However, some studies have shown no apparent increases (Robles and Burke, 1998). The conversion of cropland to grasslands may also influence the flow and retention of water due to changes in soil structure (Kay, 1990). The amelioration of a consolidated soil matrix by root activity, wetting-drying cycles, and other structure forming processes will ultimately determine the degree to which CRP sites attain hydraulic properties exhibited by native grassland sites. Although infiltration rates have been measured on CRP sites in several studies (e.g., Gilley et al., 1997; Dao, 1993), a thorough characterization of the hydraulic conductivity and water retention relationships is required to assess soil water redistribution, storage, and evaporation in these systems. The objective of this study was to characterize differences in soil hydraulic properties on adjacent grassland, cropland, and CRP sites and to examine the influence of measured properties on simulated water redistribution and evaporation for these contrasting land uses.

MATERIALS AND METHODS

Unconfined infiltration experiments at selected tensions using a disc infiltrometer were carried out on adjacent cropland, grassland, and CRP sites at three locations in the Texas High Plains from 23 June to 22 September, 1999 (Table 1). Mean annual precipitation for these locations ranges from 450 to 500 mm. At each location, three replicate plots for each land use treatment were selected for detailed infiltration measurements and soil sampling. Within each plot, steady-state infiltration measurements were carried out on two sites over a range of descending tensions, nominally 150, 100, 50, and 5 mm H_2O (0.05, 0.5, 1.0, and 1.5 kPa), using a 0.2 m diameter disc infiltrometer described by Evett et al. (1999). The site was prepared by removing all residues and any large clods (in tilled soils) that would interfere with achieving a level surface. A layer of fine sand approximately 10 mm thick was placed over the surface to fill depressions and facilitate contact between the soil and the nylon membrane of the infiltrometer. Once infiltration was initiated, water level in the infiltrometer tube was monitored with a pressure transducer and data logger. Water was permitted to infiltrate for at least 1.5, 1.25, 1.0, 0.75 h for supply tensions of 1.5, 1.0, 0.5, and 0.05 kPa, respectively, to ensure

Table 1. Description of study locations and land use sites.

Land use	Soil Series†		
	Pullman ‡	Pantex ‡	Ulysses
Cropland	Dryland winter wheat § and grain sorghum; sweep- tilled.	Dryland winter wheat and grain sorghum; sweep- tilled.	Dryland winter wheat and grain sorghum; sweep- tilled.
CRP	Established in 1989; Old World bluestem	Established in 1988; Old World bluestem	Established in 1988; Warm season grasses.
Grassland	Native grassland; lightly grazed.	Native grassland invaded by rescue grass; heavily grazed.	Native grassland; moderately grazed.
Cropland (no-tillage)	Dryland winter wheat-grain sorghum-fallow rotation; no-tillage since 1981.		

† Soil series are as follows: Pullman - Fine, mixed, superactive, thermic Torrertic Paleustoll, Pantex - Fine, mixed, superactive, thermic Torrertic Paleustoll, Ulysses - Fine-silty, mixed, superactive, mesic Aridic Haplustoll.

‡ The major difference between Pantex and Pullman series is the depth to carbonates in Pullman soils is less than 60 cm.

§ Botanical names are as follows: winter wheat (*Triticum aestivum* L.), grain sorghum *(Sorghum bicolor* (L.) Moench), Old World bluestem (*Bothriochoa ischaemum* (L.) Keng), and rescue grass (*Bromus unioloides* (Wild.) H.B.K.).

that near steady state conditions had been reached. Steady state volumetric flux at each supply tension was calculated using the final 0.1 h of outflow data. Additional infiltration measurements were obtained in three plots for a no-tillage field on the Pullman soil (Table 1) for both the surface and at the 0.2 m depth. In conjunction with each infiltration run, two sets of undisturbed soil samples (30-mm length × 54-mm diam.) were extracted 0.5 to 0.75 m from the disk center at the 0.01-0.04, 0.05-0.08, 0.11-0.14, and 0.15-0.18-m depth increments to obtain bulk density and initial water content measurements. An additional set of cores were extracted below the center of the disc upon the termination of each experiment. Water retention curves were obtained for the undisturbed samples using tension (0.2 - 15 kPa) and pressure (30 - 100 kPa) extraction methods for these four depth increments.

Wooding's (1968) solution for steady state flux from a circular source in conjunction with the method of Ankeny et al. (1991) was used to determine the hydraulic conductivity associated with steady-state outflow attained at each tension. Assuming the conductivity-potential relationship can be described with Gardner's (1958) exponential function, steady state outflow $Q(h)$ (m^3 s^{-1}) at supply tension h (m) can be approximated by

$$Q(h) = K(h) \cdot \left(\pi r^2 + \frac{4r}{\alpha_g} \right) \qquad \textbf{(1)}$$

where r is the radius of the infiltrometer, $K(h)$ is the unsaturated hydraulic conductivity (m s^{-1}), and α_g (m^{-1}) is the exponential term of Gardner's conductivity function. For two supply tensions, h_1 and h_2, α_g can be estimated as

$$\alpha_g = \frac{\ln\left[Q(h_2)/Q(h_1)\right]}{|h_2 - h_1|} \qquad \textbf{(2)}$$

provided that α_g is constant over the range h_1 to

h_2. Equation (2) was used to calculate α_g using the three pairs of supply tensions, namely, the 0.05- and 0.5-, 0.5- and 1.0-, and 1.0- and 1.5-kPa tensions. Hydraulic conductivity was determined for each supply tension using Eq. (1) in the manner of Ankeny et al. (1991) by taking the arithmetic average of $K(h)$ determined using left and right side estimates of α_g when available. Saturated hydraulic conductivity, $K(0)$, was estimated by extrapolating Gardner's conductivity function to $h = 0$ using $K(h)$ and α_g obtained from the lowest supply tension.

The van Genuchten-Mualem model

$$\theta(h) = \theta_r + \frac{\theta_s - \theta_r}{\left(1 + |\alpha h|^n\right)^m} \qquad \textbf{(3)}$$

$$K(\theta) = K_s\, S^{\frac{1}{2}} \left[1 - \left(1 - S^{\frac{1}{m}}\right)^m\right]^2 \qquad \textbf{(4)}$$

(Mualem, 1976; van Genuchten, 1980) was used to describe the constitutive soil hydraulic properties where θ ($m^3\ m^{-3}$) is the volumetric water content, h is the pressure head (m), θ_r and θ_s are the residual and saturated water contents ($m^3\ m^{-3}$), respectively, K_s is the saturated hydraulic conductivity ($m\ s^{-1}$), S is the fluid saturation ratio $(\theta-\theta_r)/(\theta_s-\theta_r)$, m=1-(1/n), and n and α (m^{-1}) are empirically fitted parameters. The $\theta(h)$ and $K(h)$ relationships in Eqs. (3) and (4) were simultaneously fitted to the $\theta(h)$ and $K(h)$ data obtained for each plot (i.e., two infiltration runs and typically five sets of water retention curves for the 0.01-0.04 and 0.05-0.08-m depth increments) using the RETC code of van Genuchten et al.(1991). For these nonlinear regressions, K_s, θ_s, n and α were fitted while θ_r was held constant at 0.005 $m^3\ m^{-3}$. Analysis of variance for conductivity and bulk density data was performed using General Linear Models of SAS (1989). A randomized block design was used with land use as the main effect and location as a blocking effect. Means separation was carried out using Tukey's significant difference test. For all statistical analysis, effects were declared significant at the 0.05 probability level.

The methodology used to obtain $K(h)$ and $\theta(h)$ relationships was examined by comparing simulated with measured infiltration rates for a dry soil ($\theta \approx 0.1\ m^3\ m^{-3}$) under a 1.5-kPa supply tension. Infiltration into a radially symmetric 2-dimensional flow region was simulated by solving Richards' equation using the hydraulic properties calculated in Eqs. (3) and (4) and the measured initial water content profile. A mechanistic water balance model, ENWATBAL (Evett and Lascano, 1993) was used to compare land use effects on soil water distribution and evaporation from a bare soil. Infiltration of a 50-mm rainfall event over a three-hour period, and subsequent redistribution and evaporation were simulated with ENWATBAL using meteorological data and fitted hydraulic functions obtained for each land use treatment. To insure that simulated results for all land uses reflected only measured properties, the $K(h)$ and $\theta(h)$ relationships beyond 2.0 and 100 kPa, respectively, were set equivalent to those obtained for the no-tillage treatment.

RESULTS AND DISCUSSION

Conductivity and retention relationships

Measured infiltration rates at tensions of 0.05- 0.5- 1.0- and 1.5-kPa for grassland on the Pullman soil are shown in Fig. 1. The slope of the curve for the transformed data, α_g, was not constant over the range in tensions. In fact, across all locations and land treatments, α_g consistently increased with decreasing tensions. Similar trends of the slope of Gardner's exponential conductivity function have also been reported by Ankeny et al. (1991) and Clothier and Smettem (1990) for structured soils. Thus, as suggested by Logsdon (1999), a single value

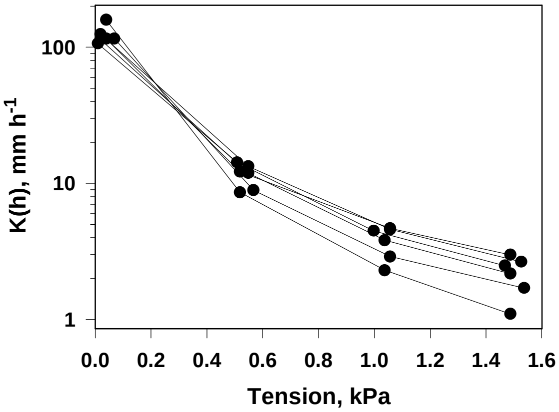

Fig. 1. The $K(h)$ relationships for grassland on the Pullman soil demonstrating an increasing slope with decreasing tensions.

of the slope for a range of tensions near saturation will often be inadequate for representing conductivity.

The fit of the van Genuchten Eq. (3) to water retention data resulted in convergence problems and large asymptotic standard errors (i.e., 10^6) for α and n. The three-parameter $\theta(h)$ relationship described by Eq. (3) is probably overspecified since a fit of the two-parameter power function of Campbell (1985) yielded much lower standard errors and essentially identical sum of squared residuals. Notwithstanding, the simultaneous fit of the van Genuchten-Mualem equations to water retention *and* conductivity data resulted in low standard errors and acceptable fits to observed conductivity relationships (Fig. 2a). These fits also generated satisfactory estimates of the water retention curve, except at water contents near saturation and, in some cases, near the dry end (Fig. 2b). The resultant parameter values averaged over three plots (Table 2) were uniform among similar land uses across locations and exhibited consistent trends across land use treatments.

Outflow volumes from the disc infiltrometer into a dry soil at the 1.5 kPa supply tension were

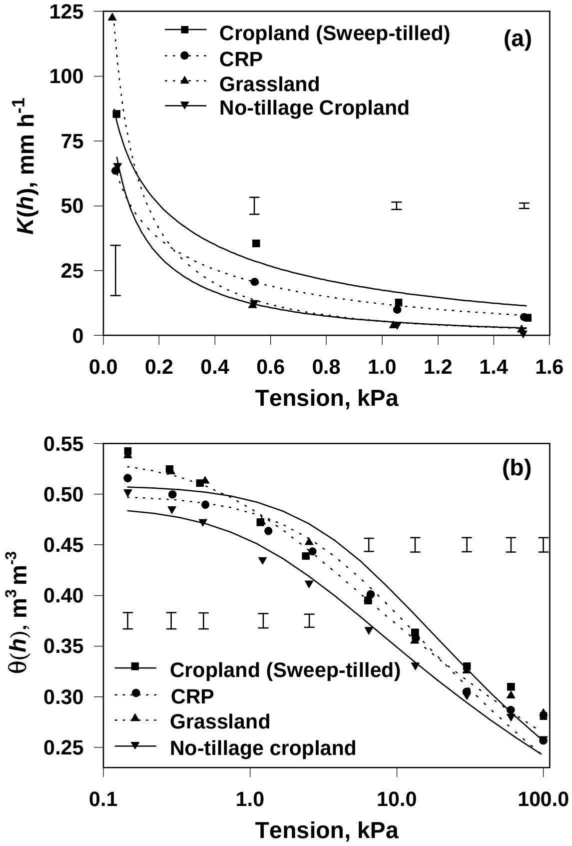

Fig. 2. The observed (symbol) and predicted (line) K(h) (**a**) and $\theta(h)$ (**b**) relationships for the Pullman soil. Error bars are least significant differences across all plots at this location for a particular supply tension.

compared with infiltration solved using the van Genuchten-Mualem estimates of the constitutive relationships and Richards' equation for radially symmetric 2-dimensional flow. For these comparisons, the pore volume of the dry sand was subtracted from measured outflow volumes to correct for the initial saturation of sand with differing hydraulic properties. In general, satisfactory estimates of infiltration into a dry soil were obtained using the Ankeny et al. (1991) method to calculate the conductivity relationship in conjunction with the simultaneous fit of conductivity and retention data with Eqs. (3) and (4). The measured and

Table 2. Fitted parameter values and standard deviations obtained from the simultaneous fit of the $K(h)$ and $\theta(h)$ data to Eqs. (3) and (4).

Land use	Parameter Estimates†							
	θ_s		α		n		K_s	
	$m^3\ m^{-3}$		m^{-1}		-		mm h^{-1}	
			Pullman					
Cropland	0.509	(0.008)	2.36	(0.21)	1.217	(0.008)	215	(69)
CRP	0.499	(0.008)	2.70	(0.40)	1.221	(0.022)	165	(52)
Grassland	0.535	(0.042)	10.25	(6.90)	1.154	(0.019)	791	(477)
No-Tillage Cropland	0.488	(0.013)	6.88	(1.62)	1.167	(0.037)	368	(208)
			Pantex					
Cropland	0.484	(0.039)	2.77	(1.00)	1.213	(0.045)	178	(123)
CRP	0.458	(0.006)	3.03	(1.40)	1.174	(0.049)	121	(61)
Grassland	0.510	(0.004)	4.64	(2.68)	1.171	(0.035)	166	(92)
			Ulysses					
Cropland	0.487	(0.022)	2.28	(0.88)	1.249	(0.044)	202	(68)
CRP	0.481	(0.025)	5.77	(0.65)	1.161	(0.022)	196	(11)
Grassland	0.479	(0.020)	7.55	(2.38)	1.142	(0.020)	422	(164)

† Mean and (standard deviation) of three replicates.

predicted cumulative infiltration depths and corresponding fluxes for a CRP site are compared in Fig. 3. The final measured flux of 37.0 mm h^{-1} compares well with the simulated flux of 38.0 mm h^{-1} at t = 1.9 h. However, conductivities calculated using Wooding's Eq. (1) usually exceeded the predicted $K(h)$ at the measured supply tension when final steady state fluxes were similar. For example, in Fig. 3 the conductivity calculated using Wooding's equation with the measured data yields 9.6 mm h^{-1} whereas $K(h)$ calculated with Eq. (4) yields a lower value of 7.9 mm h^{-1}.

Influence of land use

Land use was the major factor responsible for explained variability in $K(h)$, bulk density, α and n. (Here $K(0)$, $K(5)$, $K(50)$, $K(100)$ and $K(150)$ are the conductivities calculated using Wooding's Equation at 0, 5, 50, 100, and 150 mm supply tensions, respectively.) The mean saturated conductivity $K(0)$ on grassland and sweep-tilled cropland was greater ($P < 0.05$) than on CRP land (Table 3). Hydraulic conductivities for sweep-tilled cropland on the Pullman soil were also greater than on no-tillage plots throughout the entire measured range (Fig. 2a). Evett et al. (1999) also obtained similar results for these tillage systems on a Pullman soil. Although sweep-tilled cropland has an initially higher saturated conductivity, Jones et al. (1994) found that final steady state infiltration rates were similar on a Pullman soil after reconsolidation and crusting of the tilled surface. The bulk density of the surface 0.05 m on CRP land was only slightly greater than cropland and grassland bulk densities (Table 3). At the 0.05 to 0.08 m increment, cropland bulk

Table 3. Mean values of soil physical properties by land use.

Land Use	$K(0)$	$K(5)$	$K(50)$	$K(100)$	$K(150)$	Bulk Density			
						.01-.04 m	.05-.08 m	.11-.14 m	.15-.18 m
	mm h^{-1}	mm h^{-1}	mm h^{-1}	mm h^{-1}	mm h^{-1}	Mg m^{-3}	Mg m^{-3}	Mg m^{-3}	Mg m^{-3}
Cropland	86.6 a †	79.0 a	32.0 a	12.9 a	8.5 a	1.18 a	1.29 a	1.38 a	1.46 a
CRP	48.8 b	44.1 b	13.5 b	5.7 b	3.7 b	1.25 b	1.39 b	1.34 a	1.41 a
Grassland	94.0 a	80.1 a	11.4 b	3.8 b	2.0 b	1.17 a	1.36 b	1.37 a	1.40 a

† Mean values in the same column with different letters are significantly ($P < 0.05$) different using Tukey's HSD test.

densities were lower. At greater depths, no significant differences in bulk density were detected among all land use treatments.

The hydraulic conductivity of sweep-tillage cropland exceeded ($P < 0.05$) conductivities of grassland and CRP sites at supply tensions greater than 0.5 kPa. At the largest tension $K(150)$ was four times greater with sweep-tillage cropland than for grassland (Table 3). The no-tillage cropland also had considerably lower unsaturated conductivity than sweep-tilled cropland for the Pullman soil. The fact that hydraulic conductivity at the lowest tension was

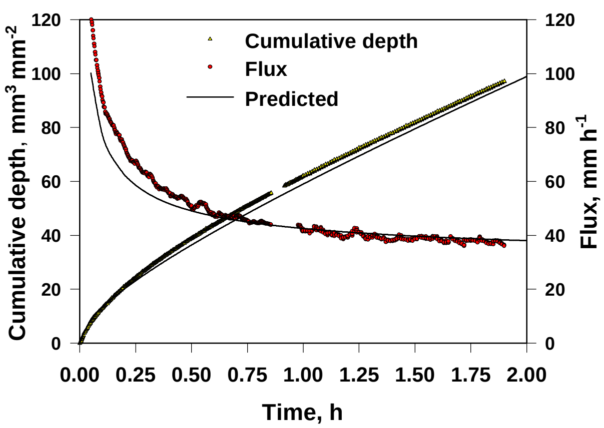

Fig. 3. Measured and predicted cumulative depth and corresponding area-averaged flux for a Pullman CRP subplot at a supply tension of 1.5 kPa. Measured cumulative depth has been adjusted to account for the initial rapid flux of water into dry contact sand.

higher in tilled soils was evidenced by a consistently larger wetted diameter surrounding the infiltrometer during infiltration runs. These observations parallel the fitted value of n for the van Genuchten-Mualem conductivity-retention functions (Table 2). A larger value of n generates a more gradual slope in the $K(h)$ relationship and consequently greater lateral (and vertical) spreading of the wetting front. It has generally been concluded that, under bare soil conditions, soil water is conserved when a soil mulch is present at the surface to disrupt capillary continuity (Hammel et al., 1981; Papendick et al., 1973). However, studies that have measured infiltration at large tensions ($h >$ 1.0 kPa) using infiltrometers have typically indicated a lack of significant difference in unsaturated conductivity due to tillage effects (Ankeny et al. 1990; Logsdon et al. 1993). Our results suggest a larger unsaturated conductivity and a more gradual decrease in conductivity for tilled surfaces that implies larger evaporation rates near the surface. Although a soil mulch may be created initially by sweep-tillage, reconsolidation over time may negate this effect. For the tilled cropland used in this study, sweep-tillage was performed one to two months prior to infiltration measurements. Additionally, our results are more applicable to the wet end of the $K(h)$ (h < 2 kPa) whereas other studies (e.g., Hammel et al., 1981) focused on the dry end (h

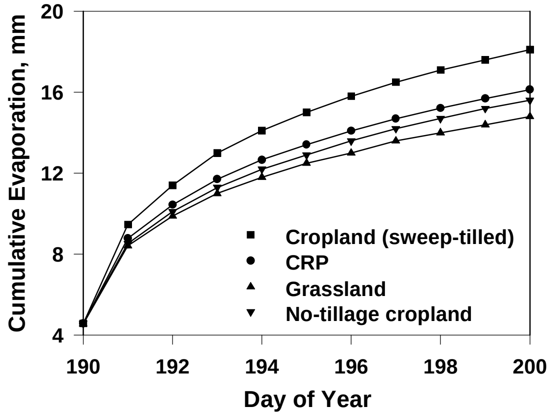

Fig. 4. Simulated cumulative evaporation from a bare soil for four land uses for the Pullman soil.

> 200 kPa). Nonetheless, results of simulation studies by Workman and Skaggs (1994) suggest that evapotranspiration is most sensitive to differences in the $K(h)$ relationship between 0 and 15 kPa tension.

To illustrate the influence of the soil hydraulic relationships on water balance, the constitutive relationships for the Pullman soil in Table 2 were used for water redistribution and evaporation calculations with ENWATBAL. Simulated cumulative bare soil evaporation for the Pullman soil after a 50 mm rainfall that occurred on DOY 189 are shown in Fig. 4. Runoff was not produced by any of the simulations. Evaporation rate on DOY 190 was energy limited and controlled by meteorological variables but, thereafter, evaporation rates of sweep-tilled cropland were greater than all other land uses until DOY 200 when cumulative evaporation exceeded grassland by 20%. After DOY 200, evaporation rates were essentially equivalent for all treatments since water content near the surface had reached a level where the hydraulic properties were forced to match. Setting $\theta(h)$ for the cropland simulation equivalent to the no-tillage retention curve throughout the entire pressure range resulted in essentially the same evaporation rates under cropland. Thus the $K(h)$ relationship near the surface was the principal factor that controlled soil evaporation under the conditions of this simulation.

Cumulative evaporation in Fig. 4 decreased with increasing time since tillage operations had been performed (the no-tillage fields were established 8 years prior to CRP establishment on the Pullman soil). Similarly, Zhai et al. (1990) noted that declines in soil water content immediately after a rain were significantly larger for a recently established no-tillage field as compared to a no-tillage field that was established 15 years prior to the study. Near-surface development of soil structure may give rise to this apparent dependency of evaporation with time since tillage. Shrink-swell cycles and/or biological activity over time gives rise to development of *stable* macropores that may form barriers to unsaturated flow. Although unsaturated conductivity at 2.0 KPa has been shown to be inversely related to macropore volume (Schwartz, 1998) more information on conductivity relationships at greater potentials need to be examined before any general conclusions can be drawn. During intense rainfall events, large cracks and biopores may also conduct water to deeper soil layers where it has a lower probability of being evaporated (Ehlers, 1975).

CONCLUSIONS

Results of this study indicated that land use practices had a greater effect on water movement in soils than soil type. As such, the parameterization of soil hydraulic properties solely based on soil type may lead to poor assessments of precipitation use efficiency. Conservation Reserve Program sites had significantly lower near-saturated conductivities than native grassland counterparts. Apparently, the degree of macropore development on CRP sites required to obtain the high saturated conductivities characteristic of native grasslands would take considerably longer than ten years. Increased saturated conductivity appears to be more a function of the size, arrangement, and distribution of pore space rather than total pore space because large variations in bulk densities between land use treatments were not evident.

Results of this study also suggests that unsaturated conductivity of the surface horizon may be more important than saturated conductivities in elucidating the precipitation use efficiencies of contrasting land uses in a dryland cropping scenario. Even though sweep tilled soil had high saturated conductivities, it also had an unsaturated conductivity four times greater than grassland soils at the 1.5 kPa supply tension. The higher surface conductivity tends to increase evaporation. Increased evaporative losses may only occur when the tilled surface has settled. Nonetheless, surface tillage required to create a soil mulch more resistant to evaporation may expose the wetter soil below and thereby further increase evaporative water losses. Native grasslands appear to be relatively efficient systems with regard to precipitation use since they exhibited large saturated conductivities in conjunction with low unsaturated conductivities.

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