DIVISION S-6—SOIL & WATER MANAGEMENT & CONSERVATION

Tillage and Crop Influences on Physical Properties for an Epiaqualf

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ABSTRACT

Tillage impacts on soil properties differ among soils. This study investigated tillage, cropping, and wheel traffic (WT) effects of 13-yr of no-tillage (NT), chisel plow (CP), and moldboard plow (MP) under continuous corn (*Zea mays* L.) and soybean (*Glycine max* L.) including a check treatment of continuous cultivated fallow (CCF) on bulk density (ρ_b), organic matter (OM), soil–water retention, and saturated hydraulic conductivity (K_{sat}) on a Mexico silt loam (fine, smectitic, mesic, Aeric Vertic Epiaqualf). Possible relationships between runoff and effective K_{sat} (K_{eff}) were also studied. Soil properties were determined on intact cores of 76-mm diam. collected from trafficked and nontrafficked positions for the 0- to 100-mm and 100- to 200-mm depths from the Midwest Research Claypan Farm erosion plots near Kingdom City, MO. Results show that the CCF had lower ρ_b, OM, K_{sat}, and higher surface runoff than other treatments ($P < 0.01$). Tillage effects on soil properties among NT, CP, and MP were small and crop dependent. Corn had lower K_{sat} (7.3 mm h^{-1}) than soybean (11.7 mm h^{-1}; $P < 0.01$). Conversely, corn had slightly higher ρ_b (1.53 Mg m^{-3}) than soybean (1.48 Mg m^{-3}; $P < 0.01$). The ρ_b increased from 1.47 to 1.52 Mg m^{-3} and OM decreased from 15.5 to 14.0 g kg^{-1} with depth ($P < 0.01$). Wheel traffic reduced K_{sat} by three times and increased ρ_b by 6% ($P < 0.01$). Bulk density was a significant predictor of log K_{sat} ($P < 0.01$) but not for soils under CCF management. The K_{eff} was not related to runoff with the exception of the CCF treatment, which had slightly more runoff and lower K_{eff} ($P < 0.05$). Overall, tillage treatments had no significant effects on soil properties; however, cropping and WT had small significant effects on ρ_b and K_{sat}.

MANY RECOGNIZE THE benefits of conservation tillage for soil and water conservation and for reduced tillage costs. There is some concern, however, that long-term use of conservation tillage may not always improve soil properties important for plant growth (Mankin et al., 1996).

Researchers have found that long-term tillage effects on soil properties such as ρ_b, soil–water retention, and K_{sat} often vary by soil (Gantzer and Blake, 1978; Culley et al., 1987; Gregorich et al., 1993). For example, moldboard plowing when compared with chisel plow and no-tillage can lower ρ_b (Hussain et al., 1998; Katsvairo et al., 2002), leave ρ_b unchanged (Karlen et al., 1994; Logsdon et al., 1999) or increase ρ_b (Lal et al., 1994). No-

tillage usually has been found to increase ρ_b compared with moldboard and chisel plow (Kitur et al., 1993; Lal, 1999). Bulk density usually is lowest immediately after tillage and increases with time as a result of rainfall-induced consolidation and surface sealing (Leij et al., 2002). The effects of tillage and management on soil–water retention are also often mixed. Allmaras et al. (1977) found no effect on soil–water retention at greater than −8 kPa, but no-till systems retained more water than CP systems at lower potentials for a Walla Walla silt loam (Typic Haploxeroll). Tollner et al. (1984) reported that MP resulted in greater soil–water retention than no-tillage at greater than −80 kPa but not at other potentials. Conversely, Lal (1999) found that tillage practices had no significant effect on soil-water retention at all potentials on a Wooster silt loam (Typic Fragiudalf). Tillage effects on K_{sat} are even more variable. The K_{sat} may be higher, equal, or lower for CP, or MP compared with NT (Gantzer and Blake, 1978; Gregorich et al., 1993; Karlen et al., 1994; Lal, 1999).

These findings suggest the need to improve the understanding of tillage and cropping effects on soil. Reports on long-term tillage effects on soil properties have been reported for a number of soils (Lindstrom et al., 1981; Blevins et al., 1983; Karlen et al., 1994; Lal, 1999; Rhoton, 2000). However, studies of tillage effects on properties for midwestern claypan soils are few. Claypan soils mainly comprise Major Land Resource Area 113 in Missouri and Illinois covering about 4 million ha (Ghidey and Alberts, 1998). They are highly erodible and their long-term productivity is easily degraded by erosion (Gantzer et al., 1990). These soils have an argillic horizon (clay contents > 400 g kg^{-1}) at 130 to 450 mm deep that has very low K_{sat} (<2 μm h^{-1}) that often causes large amounts of surface runoff during spring (Blanco-Canqui et al., 2002).

Burwell and Kramer (1983), Wendt and Burwell (1985), and Ghidey and Alberts (1998) reported on long-term tillage effects (≥10 yr) on runoff and soil loss for claypan soils. However, information on tillage-crop effects on soil properties has not been reported. Research suggests that tillage-crop effects on ρ_b, soil–water retention, and K_{sat} are often soil specific (Culley et al., 1987; Lal et al., 1994; Ankeny et al., 1995). Moreover, it is important to document any relationships between soil properties such as K_{sat} and runoff for these soils.

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Abbreviations: CCF, continuous cultivated fallow; CP, chisel plow; K_{eff}, effective saturated hydraulic conductivity; K_{sat}, saturated hydraulic conductivity; MP, moldboard plow; NT, no-tillage; OM, organic matter; USLE, Universal Soil Loss Equation; ρ_b, bulk density.

Work relating measured K_{sat} to runoff for different till-age treatments is limited (Risse et al., 1995; Blanco-Canqui et al., 2002). Furthermore, the interrelationships among ρ_b, OM, soil–water retention, and K_{sat} induced by long-term tillage-crop management systems are important and can help development of hydrologic models (Edwards, 1982). Tillage changes in one soil property may cause associated changes in other soil properties (Culley et al., 1987).

Studies on WT effects on soil properties in long-term tillage systems for claypan soils are also limited (Lindstrom et al., 1981; Lal, 1999). Traffic compacts soil, and often reduces K_{sat} and increases ρ_b (Culley et al., 1987). In some cases, traffic may have little effect (Lindstrom et al., 1981). The size of traffic-induced changes in soil properties is often site specific depending on texture, duration of tillage and crop management, equipment, and climate (Lindstrom et al., 1981). A better under-standing of long-term tillage-crop systems on soil properties on claypan soils is needed to ensure the best management for these soils.

The objectives of our study are to (i) determine the impact of long-term tillage treatments of NT, CP, and MP under corn and soybean management including a control treatment of CCF on ρ_b, OM, soil-water retention, and K_{sat} after 13 yr, (ii) evaluate the effects of WT, and (iii) determine the possible utility of using K_{sat} determined on intact cores for estimating differences in runoff among the treatments.

MATERIALS AND METHODS

This study was conducted on natural runoff-erosion plots located at the Midwest Research Claypan Farm (McCredie), Kingdom City, MO. The soil is a Mexico silt loam on a slope of 3%. Runoff plots (3.2 by 27.6 m) were established in 1941, and operated continuously until 1995 to evaluate management effects on surface runoff and soil loss for development of the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978; Ghidey and Alberts, 1998).

In 1981, plots studied in this paper were evaluated for uniformity of soil depth, texture, OM, erosion and runoff. No significant differences in these properties were found (Wendt et al., 1986). In 1982, a replicated study was initiated to examine the effects of NT, CP, and MP planted to corn and soybean, and a CCF (a check treatment) on runoff and erosion. The study initially had four replicates in a completely randomized block design with treatments remaining in the same locations over time. The results of the study are reported by Ghidey and Alberts (1998). In 1992, two blocks of the 1982 experiment were removed for other uses, resulting in a continuing experiment with seven treatments and two replicates for a total of 14 plots. The CP plots were chiseled twice before planting using a tractor weighing 3.6 Mg. Primary and secondary tillage depths were approximately 150 and 80 mm, respectively. The MP plots were plowed with a 2-bottom plow pulled with a tractor weighing 2.6 Mg a day before planting. Anhydrous ammonia was knifed in to all corn plots before planting. Each plot was planted with a four-row planter. Row spacing was 0.76 m, with rows remaining in the same location over time. A rear-mounted cultivator on the 2.6-Mg tractor was used for weed control in CP and MP plots. Wheel traffic for tractor and implements occurred between the first and second rows and between the third and fourth rows. After grain harvest,

cornstalks were chopped and residues left on the soil surface. The CCF treatment was spring moldboard plowed, disked, and cultivated after major rainfall events to break soil crusts and to kill weeds. Collection of runoff and eroded sediment was terminated in April 1995, and the soil was left undisturbed for 60 d before sampling.

Intact 76 by 76 mm diam. soil cores were taken from all plots in June 1995. Three replicate cores were collected vertically from 0 to 100 and 100 to 200 mm from trafficked and nontrafficked interrow positions for a total of 168 cores. Cores were taken in an upslope plot position. A double-cylinder, hammer-driven core sampler was used to collect cores manually to ensure sampling with minimal disturbance (Blake and Hartge, 1986). Cores were sealed in 2-mil plastic bags, transported to the laboratory, and stored at 4°C for ≤3 d before taking measurements. Samples were slowly wet from the bottom with de-aired tap water using a Mariotte bottle having a supply of approximately 3 mm h^{-1} increase in head. The EC of the water was 0.68 dS m^{-1}, and the sodium adsorption ratio (SAR) of the water was 2.34. The K_{sat} was determined by either the constant- or falling-head methods where appropriate (Klute and Dirksen, 1986). An 8:1 water/bentonite slurry was used to seal macropores (≥1 mm diam.) and the interfacial voids between the soil sample and the core cylinder wall to minimize bypass flow. The reason for this was to eliminate the free flow of water through these voids. Elimination of bypass flow in small cores during K_{sat} determinations is a recommended methodology (Klute, 1965; Blanco-Canqui et al., 2002).

The high-energy soil water retention (0 to −16 kPa) was determined on intact cores using Büchner funnels by applying the desired pressure, measuring outflow, drying the cores at 35°C for 4 d, and recording the oven-dry weight (Gardener, 1986). Because drying soil at 105°C irreversibly alters soil, samples used for high-energy measurements were dried only at 35°C. A 10 g sample of 35°C-dry sample was dried at 105°C to compute its true oven-dry weight for calculation of bulk density of the entire core (Blake and Hartge, 1986). The low-energy soil water retention (−30 to −1500 kPa) was determined using a pressure plate apparatus (Gardner, 1986). Intact soil slices, 10 mm thick, were saturated in 20 by 78 mm rings placed on a ceramic plate for water retention determinations at −30,−100, and −200 kPa. For water retention determinations less than −500 kPa, soil samples were sieved through a 2-mm sieve and packed to a 10-mm depth in rings (Gardner, 1986). Organic matter was determined by dry combustion using a Leco CR-12 C analyzer (Nelson and Sommers, 1982). Samples for OM were sieved through a 2-mm sieve. Low OM samples were determined on 500-mg samples while high OM samples were determined on 250-mg for samples, and then combusted at 900°C. Organic matter was calculated by dividing the organic C using a conversion constant of 0.58.

The runoff–K_{sat} relationship was studied using a K_{eff} of the cores. The K_{eff} was calculated as

$$K_{eff} = L_T/(L_1/K_{sat1} + L_2/K_{sat2}) \qquad [1]$$

where L_T is the total thickness of the 0- to 200-mm depth; L_1, and L_2 are layer thickness values, and K_{sat1} and K_{sat2} are the K_{sat} values for the two depth intervals (0–100 and 100–200 mm; Jury et al., 1991). Because trafficked and nontrafficked zones within the plot differed in width, weighted K_{eff} values over traffic positions were computed where the mean K_{eff} from the trafficked or nontrafficked positions was multiplied by the corresponding width of the trafficked (0.76 m) and nontrafficked (2.44 m) width and divided by the total width (3.2 m) of the runoff plot.

Rainfall and runoff data from 1991 to 1995 collected on a

storm-basis were used to investigate any relationship between runoff and K_{eff}. Runoff from the 3.2 by 27.6 m plots was collected in a series of two tanks. When the first tank was filled, runoff then flowed through a nine-slot divisor and 1/9th of runoff was then collected in the second tank (Ghidey and Alberts, 1998). The combined tank-series can collect a maximum of 180 mm of runoff. After a runoff event, the sediment-runoff mixture volume was measured and then stirred thoroughly into suspension to obtain three triplicate 1-L samples for sediment concentration determination gravimetrically (Brakensiek et al., 1979). Only runoff data collected from harvest until spring tillage was used in the analysis to ensure that the soil conditions were similar to those of the soil cores collected for K_{eff} determination. This corresponds with the USLE crop stage Period P4 "Residue or Stubble," (Wischmeier and Smith, 1978). In 1995, runoff measurements ceased in April. Snowmelt runoff and rainfall runoff that occurred on frozen soil were excluded from the study. Snowmelt runoff was excluded according to the USLE guidelines to evaluate the runoff-K_{sat} relationship by rainfall-event size. Cumulative runoff for all storms during Period P4 was calculated and used to study any relationship with K_{eff}. In addition, a select group of medium rainstorms (those between 13 and 54 mm) during Period P4 was created from the data that would be expected to reflect the greatest treatment effect related to soil K_{eff}. Small rainstorms (<15 mm) produce little or no runoff. For large rainfall events (>50 mm), rainfall greatly exceeds infiltration capacity diminishing any differences among treatments to a small fraction of observed runoff, making differences small. Runoff associated with these medium rainstorms was summed over the four seasonal periods (1991-1995) and used in analyzing any relationship between cumulative runoff and K_{eff}.

A split-split plot design was used for analysis, with tillage as the main effect, WT as the first split, and depth as the second split. Six, single-degree of freedom contrasts, were used to test differences among tillage and crop treatments. The contrasts were: (i) NT vs. the average of MP and CP [NT vs. (MP + CP)], (ii) MP vs. CP, (iii) Corn vs. Soybean, (iv) an interaction of tillage with crop [NT vs. (MP + CP) × Crop], (v) an interaction of MP vs. CP with crop [(MP vs. CP) × Crop], and (vi) CCF vs. (NT + MP + CP). Computations were done using SAS statistical software (SAS Institute, 1999). Stepwise regression was conducted to evaluate relationships of log K_{sat} with ρ_b, OM, and macroporosity (pores that drain at greater than −2 kPa of soil–water potential). Mean data were depicted using box-whisker plots.

RESULTS AND DISCUSSION

Bulk Density

Mean ρ_b values for all treatments, traffic positions, and depths and the summary of the analysis of variance (ANOVA) are presented in Table 1. The ρ_b values averaged across depths for trafficked and nontrafficked zones are given in Fig. 1. Tillage effects on ρ_b among NT, CP, and MP were not significant. The small effects depended on the crop as shown by the interaction [NT vs. (MP + CP)] × Crop ($P < 0.01$; Table 1). The interaction shows that NT in soybean had a slightly lower ρ_b (1.47 Mg m^{-3}) than the average of MP and CP tillage (1.49 Mg m^{-3}), whereas NT in corn had greater ρ_b (1.55 Mg m^{-3}) than the average of MP and CP (1.52 Mg m^{-3}; Table 2). The relative higher ρ_b found in NT corn in this study agrees with an 8-yr tillage study that showed higher ρ_b in NT (1.39 Mg m^{-3}) than in MP (1.31 Mg m^{-3}) on a Grantsburg

Table 1. Means of bulk density (n = 6) of no-tillage (NT), chisel plow (CP), and moldboard plow (MP) treatments under corn (*Zea mays* L.) and soybean (*Glycine max* L.) including a check plot of continuous cultivated fallow (CCF), and analysis of variance of the data.

	Treatment means								
	Crop								
	Corn				Soybean				
Depth mm	MP	CP	NT	Mean	MP	CP	NT	Mean	CCF
	Mg m^{-3}								
	Trafficked								
0–100	1.52	1.50	1.60	*1.54*	1.50	1.52	1.52	*1.51*	1.45
100–200	1.59	1.55	1.60	*1.58*	1.59	1.62	1.54	*1.58*	1.46
Mean	*1.56*	*1.53*	*1.60*		*1.54*	*1.57*	*1.53*		*1.46*
	Nontrafficked								
0–100	1.49	1.45	1.48	*1.47*	1.41	1.36	1.38	*1.38*	1.38
100–200	1.52	1.51	1.53	*1.52*	1.42	1.47	1.43	*1.44*	1.45
Mean	*1.50*	*1.48*	*1.50*		*1.42*	*1.42*	*1.40*		*1.42*
CV = 4.7%									

Analysis of variance		
Source of variation	df	$P > F$
Block	1	
Treatments, TRT	(6)	<0.01**
NT vs. (MP + CP)	1	
MP vs. CP	1	
Crop	1	<0.01**
[NT vs. (MP + CP)] × Crop	1	<0.01**
(MP vs. CP) × Crop	1	<0.01**
CCF vs. (NT + CP + MP)	1	<0.01**
Error I	6	
Wheel traffic, WT	1	<0.01**
TRT × WT	6	
Error II	7	
Depth	1	<0.01**
Depth × WT	1	
TRT × Depth	6	
TRT × WT × Depth	6	
Error III	14	
Total	55	

** Significant at the 0.01 level.

silt loam (Typic Fragiudalf; Hussain et al., 1998). The tillage by crop interaction for ρ_b [(MP vs. CP) × Crop] was significant (Table 1). The interaction reflects the fact that ρ_b of MP in corn (1.53 Mg m^{-3}) was slightly higher than the ρ_b of CP (1.50 Mg m^{-3}), whereas MP in soybean (1.48 Mg m^{-3}) was slightly lower than CP (1.49 Mg m^{-3}). The MP in corn was slightly more compact than CP, but this was not the case for soils under soybean.

Crop grown had a significant effect on ρ_b ($P < 0.01$; Table 1). Corn resulted in slightly higher ρ_b (1.53 Mg m^{-3}) than soybean (1.48 Mg m^{-3}). We speculate that this may be a result of the differential soil water content at the time of planting that influences soil compaction. Less surface residue occurred with soybeans compared with corn (Gantzer et al., 1987) allowing soil to dry more thoroughly before planting, thus reducing the potential for compaction. The largest tillage effect occurred from the CCF treatment. The CCF averaged across traffic and depth had the lowest ρ_b (1.44 Mg m^{-3}), which was highly significant ($P < 0.01$) as shown in Table 1. This is attributed to the continuous loosening by tillage.

Wheel traffic had a significant effect on ρ_b ($P < 0.01$; Table 1). Figure 1 shows that soils under the wheel
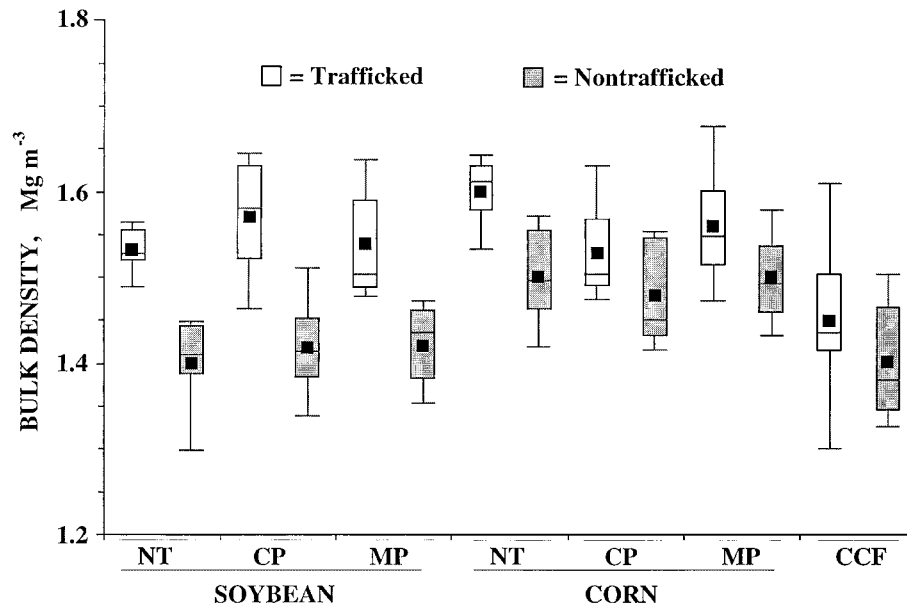
Fig. 1. Bulk density of the tillage-crop treatments for trafficked and nontrafficked interrows averaged across both depths of the runoff-erosion plots at the Midwest Claypan Farm near Kingdom City, MO. NT = No-tillage; CP = Chisel plow; MP = Moldboard plow; CCF = Continuous cultivated fallow.

trafficked interrow had higher ρ_b (1.54 Mg m^{-3}) than nontrafficked interrows (1.45 Mg m^{-3}). This agrees with results from Vervoort et al. (2001) who found higher ρ_b (1.49 Mg m^{-3}) in trafficked vs. nontrafficked zones (1.43 Mg m^{-3}) on a Grenada silt loam (Oxyaquic Fraglossudalfs). Another study on a Capac loam (Aeric Ochraqualfs) reported that WT increased ρ_b by 29% in tilled soils (Pierce et al., 1994). The higher ρ_b in trafficked positions implies soil consolidation and reduction of macropores resulting in decreased soil porosity; however, it is not likely to reduce plant root growth as it is below the growth limiting value of ρ_b (1.55 Mg m^{-3}; Radcliffe et al., 1988).

The depth effect on ρ_b was significant ($P < 0.01$; Table 2). The ρ_b at the 0- to 100-mm depth was lower (1.47 Mg m^{-3}) than at the 100- to 200-mm depth (1.52 Mg m^{-3}) for all treatments. Lower ρ_b at the upper depth is commonly due to the greater amounts of organic material near the surface, lower overburden pressure, and greater disturbance. The increase of ρ_b with depth is consistent with a study on a Maury silt loam soil (Typic Paleudalfs) by Ismail et al. (1994) who showed that ρ_b under NT and MP in corn decreased with depth after 20-yr of tillage.

Our results show that tillage effects on ρ_b were small; however, crop had a significant effect where corn increased ρ_b compared with soybean. Differences in ρ_b among NT, CP, and MP were not significant and would not limit crop production.

Organic Matter

Geometric means of OM values and the ANOVA summary are shown in Table 2. Values for all treatment-depths averaged across traffic are presented in Fig. 2. Normality tests showed that OM data were nonnormally distributed ($P < 0.01$). Since a logarithmic transforma-

tion improved the normality, statistics were conducted on log-transformed OM data. The tillage by crop contrast of NT vs. the average of CP and MP and the interaction [NT vs. (MP + CP)] × Crop was significant ($P < 0.04$; Table 2). The interaction of tillage treatments with crop is illustrated by the fact that NT in corn (19.3 g kg^{-1}) had higher OM than the average of the MP and CP treatments (14.8 g kg^{-1}), but not in soils under soybean. The greater amount of corn residues in NT increased OM content in contrast with soils in soybean. The higher OM in NT corn agrees with studies conducted for other silt loam soils. Blevins et al. (1983) reported that after 10-yr of continuous tillage, NT in corn had higher OM content (47 g kg^{-1}) than MP (24 g kg^{-1}) on a Maury silt loam (Typic Paleudalfs). After 4-yr tillage, Rhoton (2000) also showed that NT soils in corn had higher OM (32 g kg^{-1}) than MP soils (19.1 g kg^{-1}) at the 0- to 25-mm depth on a Grenada silt loam (Glossic Fragiudalfs). The higher OM content in NT corn (19.3 g kg^{-1}) is a result of corn residue near the soil surface. In contrast, inverted crop residues in MP treatments are mixed throughout the depth of tillage.

Crop had no significant effect on OM ($P = 0.07$; Table 2). Organic matter in corn averaged across tillage, traffic, and depth (16.3 g kg^{-1}) was slightly higher than in soybean (14.5 g kg^{-1}). Corn is a high biomass-crop resulting in increased OM content compared with soybean. Greater OM in corn may also be attributed to a lower rate of corn residue decomposition than for soybean residues (Broder and Wagner, 1988). The major effect of long-term tillage occurred for the CCF treatment. The CCF had the lowest OM (9.8 g kg^{-1}) of all treatments (15.3 g kg^{-1}) averaged across traffic and depth, which was highly significant ($P < 0.01$). Results indicate that excessive cultivation leads to significant decline of OM in accord with Cambardella and Elliot

Table 2. Geometric means of organic matter (n = 6) of no-tillage (NT), chisel plow (CP), and moldboard plow (MP) treatments under corn (_Zea mays_ L.) and soybean (_Glycine max_ L.) including a check plot of continuous cultivated fallow (CCF), and analysis of variance of the data.

Depth mm	Corn MP	Corn CP	Corn NT	Mean	Soybean MP	Soybean CP	Soybean NT	Mean	CCF
				g kg⁻¹					
				Trafficked					
0–100	15.8	14.4	24.2	_18.1_	14.5	16.2	17.4	_16.0_	10.0
100–200	12.1	15.9	18.9	_15.6_	15.2	11.8	11.1	_12.7_	9.5
Mean	_14.0_	_15.2_	_21.5_				14.9	14.0 14.3	9.8
				Nontrafficked					
0–100	15.5	14.9	20.3	_16.9_	14.4	14.6	15.7	_14.9_	9.4
100–200	14.7	14.8	13.6	_14.3_	15.6	13.7	13.1	_14.1_	15.6
Mean	_15.1_	_14.9_	_16.9_		15.0	14.2	14.4		12.5
CV = 3.8%									

Source of variation	df	P > F
	Analysis of variance	
Block	1	
Treatments, TRT	(6)	<0.01**
NT vs. (MP + CP)	1	<0.04*
MP vs. CP	1	
Crop	1	0.07
[NT vs. (MP + CP)] × Crop	1	<0.04*
(MP vs. CP) × Crop	1	
CCF vs. (NT + CP + MP)	1	<0.01**
Error I	6	
Wheel traffic, WT	1	
TRT × WT	6	
Error II	7	
Depth	1	<0.01**
Depth × WT	1	
TRT × Depth	6	
TRT × WT × Depth	6	
Error III	14	
Total	55	

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

(1992) who reported that OM in NT was 1.4 times higher than in bare-fallow soil after 20-yr tillage on a Duroc loam (Pachic Haplustolls).

Wheel traffic had no effect on OM (Table 2). As expected, WT would not significantly affect OM (Pierce et al., 1994; Lal, 1999). The OM distribution was significantly influenced by depth ($P < 0.01$; Table 2). The OM averaged across tillage-crop and traffic at the 0- to 100-mm depth (15.5 g kg⁻¹) was significantly higher than at the 100- to 200-mm depth (14.0 g kg⁻¹). This is caused by the greater concentration of OM near the soil surface (Pierce et al., 1994; Rhoton, 2000).

Soil–Water Retention

Soil–water retention data averaged across crop, WT, and depth for all treatments are given in Fig. 3A, and soil–water retention data for trafficked and nontrafficked zones in CCF are presented in Fig. 3B. Analysis of variance results for −4 kPa are given in Table 3. Because differences were greater at high-energy potentials, only data greater than −100 kPa are plotted in Fig. 3. Tillage and cropping effects on soil–water retention among NT, CP, and MP were not significant. In contrast, tillage effects on CCF were significant ($P <$

0.05). Comparison of regression lines in Fig. 3A between CCF and the average of NT, CP, and MP treatments using analysis of covariance showed that the slopes of the lines were not significantly different ($P > 0.07$) and the elevations of the regression lines differed ($P < 0.05$; Snedecor and Cochran, 1989). Results indicated that CCF retained more water than the average of NT, CP, and MP at high-energy soil–water potentials ($P < 0.01$). The water content for CCF was approximately 4% higher at −1 kPa and approximately 2% higher at −100 kPa as compared with the average for NT, CP, and MP (Fig. 3A). Continuous cultivation increases fine pores, lowers OM content, and destroys macropores (Jordan et al., 1997; Hussain et al., 1998).

Wheel traffic had no effect on soil–water retention among NT, CP, and MP, but there was a significant effect on CCF treatment at most potentials ($P < 0.05$). Analysis of covariance of the regression lines for trafficked and nontrafficked positions for CCF in Fig. 3B showed that the slopes of the lines were not significantly different ($P > 0.10$) but differed in elevations of the regression lines ($P < 0.01$). These results thus show that water retention in CCF in trafficked interrows was higher than in nontrafficked interrows at high-energy soil–water potentials. The combined effect of tillage and decrease in large water conducting macropores increased the water retention in trafficked CCF, which is in agreement with Culley et al. (1987) who also found greater soil–water retention in trafficked zones than nontrafficked zones from −0.5 to −6 kPa on a Webster silty clay loam (Typic Haplaquoll).

Depth had a significant effect on soil–water retention only at −4 ($P < 0.01$) and −1.5 MPa ($P < 0.05$) of soil–water potential. Mean water content averaged across tillage-crop and traffic was 0.36 mm mm⁻³ at the 0- to 100-mm depth and 0.39 mm mm⁻³ at the 100- to 200-mm depth for the −4 kPa, while the averaged values for the −1.5 MPa were 0.12 mm mm⁻³ at the 0- to 100-mm depth and 0.14 mm mm⁻³ at the 100- to 200-mm depth. The greater soil–water retention at the lower depth may be due to higher proportion of micropores and more compaction compared with the upper depths (Radcliffe et al., 1988). Overall, the effects of tillage-crop, WT, and depth on soil–water retention were small, and differences were not significant in most cases except for CCF that retained the highest amount of water of all treatments for high energy soil–water potential.

Saturated Hydraulic Conductivity

Geometric means of K_{sat} and the related ANOVA summary are presented in Table 3. The geometric mean K_{sat} values averaged across depth for trafficked and nontrafficked positions are presented as a box-whisker plot in Fig. 4. Data were found to be significantly nonnormal ($P < 0.01$). Therefore, statistical analysis was performed on log-transformed values. No differences were found for the single-df contrast of NT vs. (CP and MP) averaged across traffic, depth, and crop ($P = 0.57$).

Our results indicate that the tillage effects on K_{sat} are small. The naturally compacted soil in NT did not reduce
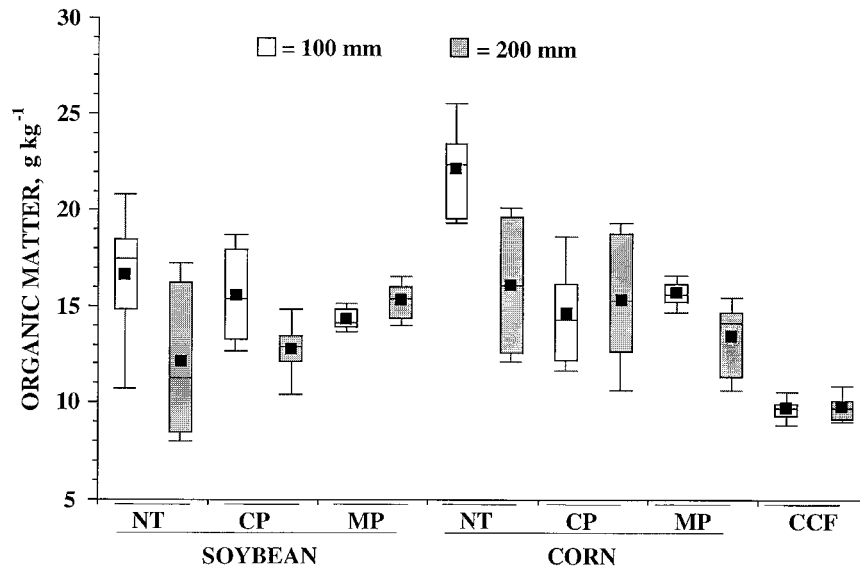
Fig. 2. Geometric means of organic matter of the tillage-crop treatments for the 0- to 100- and 100- to 200-mm depths averaged across traffic for the runoff-erosion plots at the Midwest Claypan Farm near Kingdom City, MO. NT = No-tillage; CP = Chisel plow; MP = Moldboard plow; CCF = Continuous cultivated fallow.

K_{sat} (Table 3). The effects of long-term tillage are similar to results by Blevins et al. (1983) who found no differences in K_{sat} between NT and MP on a Maury silt loam after 10-yr of tillage, and with Gregorich et al. (1993) who reported that K_{sat} did not differ between no-till and tilled soils on a poorly drained clay loam soil (Aquoll) after 20-yr of tillage. These findings, also agree with results reported on a Le Sueur clay loam (Aquic Argiudoll) soil having 28% clay-size particles by Gantzer and Blake (1978).

The type of crop grown had a significant effect on K_{sat} ($P < 0.01$; Table 3). The K_{sat} under soybean management (11.7 mm h^{-1}) was 1.6 times higher than under corn management (7.3 mm h^{-1}). The K_{sat} differences may be partially explained by the lower ρ_b in soybean and higher ρ_b in corn. The K_{sat} was negatively correlated with ρ_b ($r = -0.54, P < 0.05$). Mankin et al. (1996), while investigating the cropping effects on soil properties in the major corn and soybean production regions in the USA, found higher K_{sat} in soybean than in corn particularly in clay soils. While crop residue from soybean is only about 50% of that from corn, soybean residues have a greater proportion of soluble compounds, lower cellulose, and are more easily decomposed into humidified organic compounds interacting with soil particles and probably improving soil aggregation and water infiltration (Broder and Wagner, 1988).

The K_{sat} for CCF was five times lower (1.9 mm h^{-1}; $P < 0.01$) than the average of the other treatments (9.5 mm h^{-1}). This lower K_{sat} reflects the impact of frequent cultivation on reducing the OM, and thus deteriorating soil aggregation and destroying macropores (Radcliffe et al., 1988; Jordan et al., 1997). Because of the lower K_{sat}, less infiltration and higher runoff are expected from CCF management compared with NT, CP, and MP tillage.

Wheel traffic reduced K_{sat} in all tillage treatments ($P < 0.01$). Figure 4 shows that K_{sat} in nontrafficked

zones averaged across tillage, crop, and depth was 3.1 times higher (14.3 mm h^{-1}) than K_{sat} in trafficked zones (4.4 mm h^{-1}). The higher K_{sat} values in nontrafficked positions are in accord with Culley et al. (1987) who found that nontrafficked K_{sat} was nine times higher than trafficked K_{sat} on a Webster silty clay loam. The reduction of K_{sat} from equipment traffic is caused primarily by soil surface consolidation associated with increased bulk density and reduced soil porosity. Lindstrom et al. (1981) on a Nicollet clay loam (Aquic Hapludolls) found that WT reduces the random roughness of the soil surface and compacts the plow layer resulting in decreased water infiltration rates.

In general, the K_{sat} did not vary significantly with depth (Table 3). The K_{sat} averaged across tillage, crop, and traffic was 9.4 mm h^{-1} in the 0- to 100-mm depth, and 9.2 mm h^{-1} in the 100- to 200-mm depth. Our results agree with Lal (1999) who found no K_{sat} differences with depth under NT, CP, and MP management after 5-yr tillage in Ohio. Unlike ρ_b, the K_{sat} distribution with depth did not change significantly.

Effects of 13-yr continuous tillage management on K_{sat} were for the most part small, but cropping system had a significant effect on K_{sat}. The nonsignificant changes in K_{sat} found in this study suggest that long-term NT, CP, and MP management in claypan soils would not be expected to affect crop production. The main finding was that the CCF treatment reduced K_{sat} by five times ($P < 0.01$).

Interrelationships of Soil Properties

Investigation of relationships of log K_{sat} with ρ_b, OM, and macroporosity among NT, CP, and MP treatments using regression showed that ρ_b was the only significant variable related with log K_{sat}. The relationship found was:
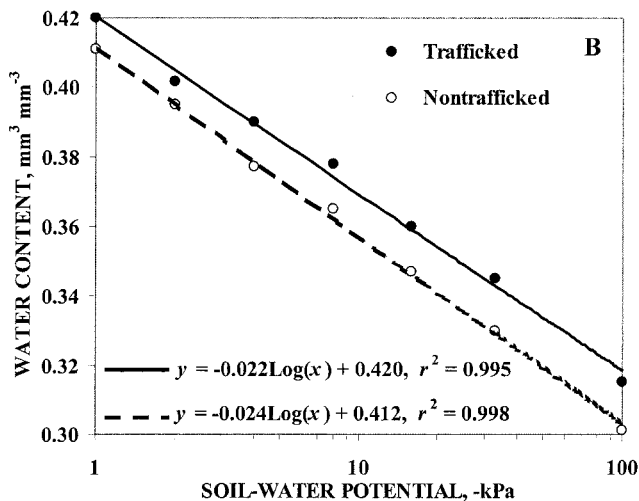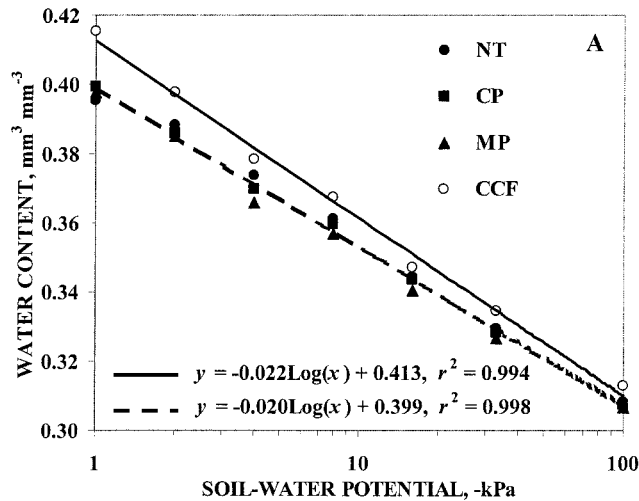
Table 3. Geometric means of saturated hydraulic conductivity (K_{sat}) ($n = 6$) for no-tillage (NT), chisel plow (CP), moldboard plow (MP) treatments under corn and soybean including a check plot of continuous cultivated fallow (CCF), and analysis of variance of K_{sat} and soil-water retention (SWR) data.

	Treatment means								
	Crop								
	Corn				Soybean				
Depth mm	MP	CP	NT	Mean	MP	CP	NT	Mean	CCF
				— mm h^{-1} —					
				Trafficked					
0–100	3.6	6.1	6.0	*5.23*	3.3	5.1	4.8	*4.40*	1.8
100–200	2.9	3.8	3.9	*3.53*	2.6	7.8	4.4	*4.92*	0.8
Mean	*3.3*	*4.9*	*5.0*		*3.0*	*6.5*	*4.6*		*1.3*
				Nontrafficked					
0–100	6.7	11.1	14.5	*10.8*	22.1	21.2	13.9	*19.1*	4.5
100–200	7.8	13.0	7.6	*9.47*	17.6	29.1	9.0	*18.6*	0.4
Mean	*7.3*	*12.0*	*11.1*		*19.9*	*25.1*	*11.4*		*2.4*
CV = 18.9%									

Analysis of variance

Source of variation	df	K_{sat} $P > F$	SWR −4 kPa $P > F$
Block	1		
Treatments, TRT	(6)	<0.02**	<0.03**
NT vs. (MP + CP)	1		
MP vs. CP	1		
Crop	1	<0.01**	
[NT vs. (MP + CP)] × Crop	1		
(MP vs. CP) × Crop	1		
CCF vs. (NT + CP + MP)	1	<0.01**	<0.04*
Error I	6		
Wheel traffic, WT	1	<0.01**	<0.03*
TRT × WT	6		
Error II	7		
Depth	1		<0.01**
Depth × WT	1		
TRT × Depth	6		
TRT × WT × Depth	6		
Error III	14		
Total	55		

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

Fig. 3. Soil–water retention of (A) the tillage-crop treatments averaged across crop, traffic, and depth, and (B) trafficked and nontrafficked positions averaged across depth in CCF for the runoff-erosion plots at the Midwest Claypan Farm near Kingdom City, MO. NT = No-tillage; CP = Chisel plow; MP = Moldboard plow; CCF = Continuous cultivated fallow.

$$\text{Log } K_{sat} = 12.74 - 7.13 \times \rho_b \qquad r^2 = 0.53$$

The intercept and the slope for the NT, CP, and MP treatments were significant at $P < 0.01$. The negative slope implies that the conductivity would decrease with increasing ρ_b. The ability for ρ_b to predict log K_{sat} in NT, CP, and MP treatments is corroborated by work of Edwards (1982). However, it was found that the regression of ρ_b on log K_{sat} for the CCF treatment was not significant ($P > 0.10$). Despite the fact that this treatment had lower bulk densities, the conductivities were often the lowest. The fact that ρ_b was not significantly related to conductivity for the CCF is at odds with knowledge that low ρ_b is often related to increased K_{sat}. We attribute this behavior to structural instability of soil aggregates in the CCF treatment due to intensive cultivation, which decreased OM, and weakened soil aggregates. On wetting, aggregates slump, causing de-

creased pore continuity, thus lowering K_{sat}. Overall, macroporosity was highly correlated with ρ_b ($r = -0.83$) and moderately correlated with conductivity for all treatments ($r = 0.44$). An interesting finding is that ρ_b and K_{sat} in the CCF treatment were the lowest of all tillage-crop treatments. In contrast, NT, CP, and MP management had no significant differences in ρ_b and K_{sat}.

Runoff–K_{eff} Relationship

The graphs of cumulative runoff versus log K_{eff} for the tillage-crop treatments in January through April 1995 and during the Period P4 in 1991 through 1995 are depicted in Fig. 5. The runoff–K_{eff} linear regression using cumulative runoff data from January to April of 1995 where soil conditions would be nearly the same as those during our soil sampling date (14 June 1995) showed no relationship between runoff and K_{eff} ($r^2 = 0.01$). In addition to the above analysis, an investigation of a longer-term runoff–K_{eff} regression was conducted using cumulative runoff data from 1991 through 1995. The linear regression indicated that K_{eff} was not related to runoff from NT, CP, and MP under corn and soybean for all runoff events and rainfall storm sizes between
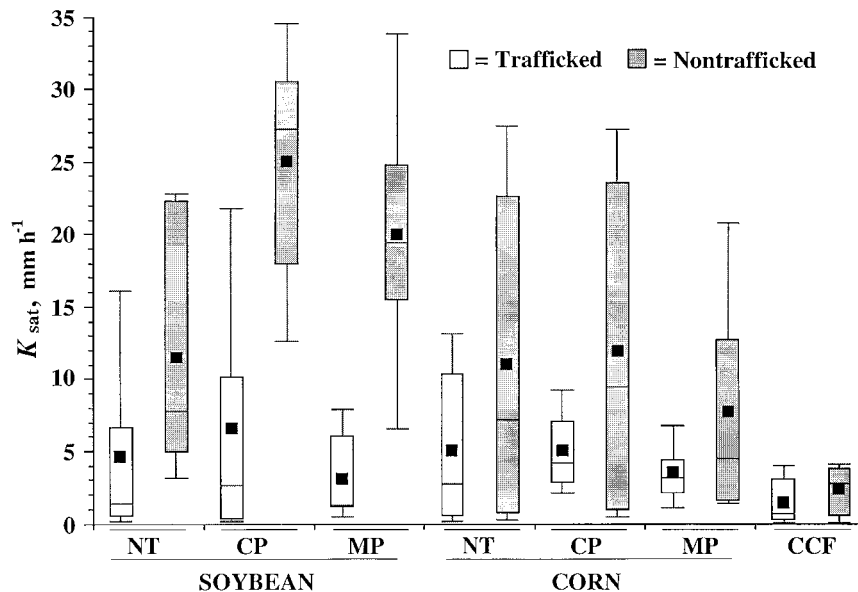
Fig. 4. Geometric means of saturated hydraulic conductivity (K_{sat}) of the tillage-crop treatments for trafficked and nontrafficked interrows averaged across depths for the runoff-erosion plots at the Midwest Claypan Farm near Kingdom City, MO. NT = No-tillage; CP = Chisel plow; MP = Moldboard plow; CCF = Continuous cultivated fallow.

1991 through 1995 (r^2 = 0.10). For medium rainstorms (between 13 and 54 mm), the linear regression r^2 increased but was not significant (r^2 = 0.15; Fig. 5).

Results showed that the runoff vs. K_{eff} relationship was highly influenced by higher runoff produced in the CCF treatment, which was 36% more than the next highest runoff amount found in other plots (P < 0.01). The highest runoff for the CCF treatment was probably a result of surface sealing of the bare soils inhibiting water infiltration and thus increasing runoff. Our results

indicate that K_{eff} values from continuously tilled soils are related to runoff suggesting that K_{eff} can be a significant predictor of runoff only for excessively tilled soils. This is supported by Bruce et al. (1992) who concluded excessive tillage leads to low K_{sat} and increased runoff.

The limited relationship between runoff vs. K_{eff} in NT, CP, and MP agrees with Edwards (1982) who reported that K_{sat} is not as sensitive a variable as precipitation, and antecedent soil moisture for predicting runoff. The reasons for the limited relationship in this study
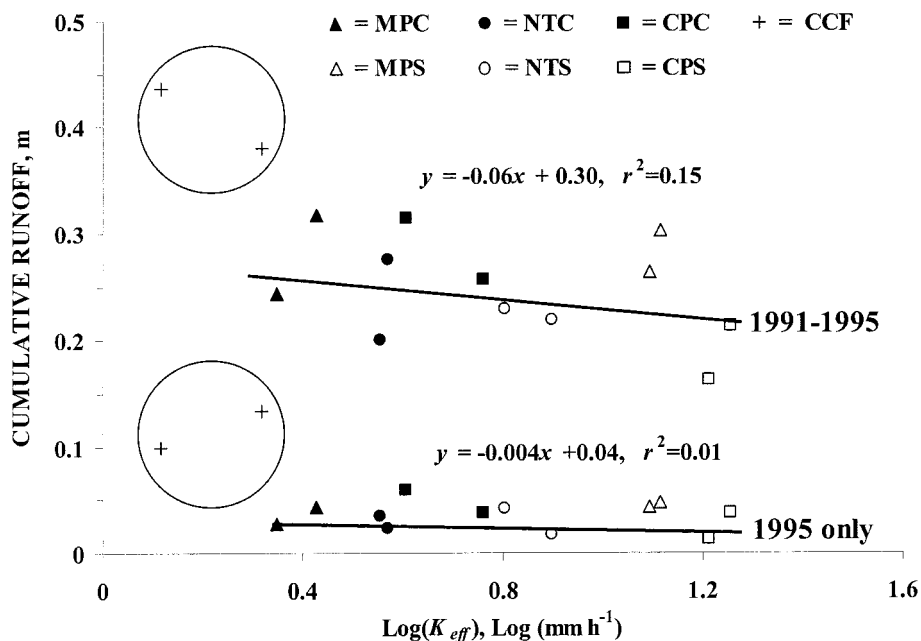

Fig. 5. Relationship between cumulative runoff and log of the effective saturated hydraulic conductivity (K_{eff}) for all rainstorms in January through April 1995 and for the Universal Soil Loss Equation (USLE) crop stage period "P4 Residue or Stubble," for medium rainstorms (between 13 and 54 mm) from 1991 to 1995. NTC = No-tillage in corn (*Zea mays* L.); CPC = Chisel plow in corn; MP = Moldboard plow in corn; NTS = No-tillage in soybean (*Glycine max* L.); CPS = Chisel plow in soybean; MPS = Moldboard plow in soybean; CCF = Continuous cultivated fallow.

may be attributed to (i) temporal variability of K_{eff} in tillage systems, and (ii) low claypan conductivity. The dynamic temporal variability of tilled soils may create difficulties in establishing a surface runoff vs. K_{eff} relationship. The K_{eff} may be more related to runoff immediately after tillage when differences in surface physical properties between tilled and no-till soils are great. Tillage loosens the soil and creates unstable structure increasing the K_{eff} and reducing runoff after tillage relative to no-tillage that remains consolidated over time. However, tillage effects on soil surface conditions dissipate rapidly with time as external forces (traffic, overburden pressure, rainfall-induced consolidation, and surface sealing) take place. Tilled soils may thus be physically similar to no-till, as the residual effects of tillage diminish within 21 to 28 d. Or et al. (2000) and Leij et al. (2002) affirmed that soil immediately after tillage is highly unstable and undergoes dynamic changes in the interaggregate porosity significantly altering the hydraulic properties. The K_{sat} after plowing can be one or two orders of magnitude higher compared with K_{sat} measured before tillage. Such K_{sat} changes diminish with time as the natural structural pore system gradually evolves. Our soil samples were collected almost a year after primary tillage, and thus differences in initial soil conditions among NT, CP, and MP would have diminished.

An understanding of the K_{eff} variations by crop-stage period, and seasonal variations induced by management would be desirable. An important factor reducing differences in runoff among treatments is related to the claypan soil that has a nearly impermeable claypan at approximately 230 mm ($K_{sat} \leq 0.003$ mm h^{-1}). The low claypan K_{sat} limits downward water movement and redirects the flow laterally into interflow (Blanco-Canqui et al., 2002). Indeed, runoff rates are equal to precipitation when these soils are saturated particularly in spring (Saxton and Whitaker, 1970). Thus, claypan K_{sat} is the main control that inhibits vertical water flow. This would be expected to have a significant influence on the surface runoff vs. K_{eff} relationship. Assessment of soil parameters that are sensitive to tillage and crop management changes in soil structure such as least limiting water range may help to evaluate tillage management impact effects on hydraulic properties (Da Silva et al., 1994).

CONCLUSIONS

This 13-yr study on the effects of tillage-crop management on soil physical properties for an Aeric Epiaqualf shows that only small changes in ρ_b, OM, soil–water retention, and K_{sat} occurred from the NT, CP, and MP treatment under corn and soybean management. Results suggest that the tillage systems are of little importance to soil properties in claypan soils, and thus would not greatly affect crop production. However, the CCF treatment had a major effect on soil properties decreasing K_{sat}, ρ_b, and OM in contrast to NT, CP, and MP. This confirms the idea that excessive tillage has a deleterious effect on soil properties.

The kind of crop (corn vs. soybean) had a greater effect on soil properties compared to tillage. Soils in corn had decreased K_{sat}, and increased ρ_b and OM as compared with soils in soybean. Increased compactness of soils in corn may significantly reduce saturated water flow while increasing OM in claypan soils. Tractor WT caused soil consolidation and reduced saturated water flow. No consistent relationship between runoff and effective K_{sat} for NT, CP, and MP treatments was identified. Thus, K_{sat} determined on small intact cores was not a significant predictor of runoff. However, runoff from excessively tilled plots (CCF) was related to effective K_{sat} where runoff increased. The ρ_b was a significant predictor of log K_{sat} for NT, CP, and MP but not in CCF because of excessive soil disturbance that lowered K_{sat}, ρ_b, and OM. While conservation tillage is beneficial for soil and water conservation and for reduced tillage costs, changes in topsoil physical properties due to conservation tillage management are small.

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