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ROLE OF RUNOFF AND INTERFLOW IN CHEMICAL TRANSPORT FOR CLAYPAN SOILS

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ABSTRACT

No-tillage systems have been found to increase water runoff for some soils. This is a major concern because this increased runoff has the potential for increasing the runoff of dissolved herbicides in the spring since these chemicals are not incorporated into the soil with no-tillage systems. This study was conducted to evaluate the effects of seven long-term crop and tillage systems on runoff and saturated hydraulic conductivity. The study was conducted near Kingdom City, Missouri on a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualf). Runoff records from 1983 through 1993 were collected. The seven treatments consisted of no-tillage (NT), moldboard plow (MP), and chisel plow (CP) continuous corn (*Zea mays* L.) and continuous soybean (*Glycine max* L.) and fallow (F). Saturated hydraulic conductivity (Ksat), bulk density, organic matter, and water content were determined on soil cores removed from two interrow positions (trafficked and non-trafficked) and two soil depths (0 - 125 mm, 125 - 150 mm). Tillage had a small but significant effect on runoff, Ksat, bulk density, water content at sampling, and organic matter. The Fallow treatment produced the lowest values of Ksat (0.2 mm/h), bulk density (1.3 g cm^{-3}), and organic matter content (0.9%) for the surface 125 mm, as compared to the NT, MB and CP treatments. No differences in Ksat were found ($p=0.587$) among NT, MP and CP tillage treatments. Complex interaction effects of tillage vs. wheel traffic ($p=0.039$) and tillage vs. depth ($p=0.003$) suggested that tillage effects on Ksat vary with interrow position and soil depth. The NT (0.301 mm mm^{-3}) had significantly higher field volumetric water content than MP (0.285 mm mm^{-3}) and CP (0.282 mm mm^{-3}), when averaged across crops. Plots planted to corn had greater water content (0.297 mm mm^{-3}) compared to soybean plots (0.281 mm mm^{-3}). Runoff under F was the highest in each year from 1983 to 1993. The greatest amount of runoff occurred during Period 4 (harvest to planting). Runoff was lowest during Period 1 and 2. No-tillage had significantly higher runoff than MP and CP treatments during Period 4, spring ($p=0.006$); Period 4, fall ($p=0.011$); Fallow period ($p=0.005$); and Period 1 and 2 ($p=0.021$). Cumulative runoff with NT was significantly ($p=0.001$) higher compared to MP and CP, except from 1991 to 1993 in which differences were not significant ($p=0.374$). Corn produced lower runoff rates than soybean at the 0.05 level in Period 4, fall. Increased runoff in NT was attributed to higher water content and subsequently lower infiltration for this soil which had a nearly impermeable subsurface argillic horizon.

INTRODUCTION

Tillage is the mechanical application of force in the land for crop culture (Frederick et al., 1991). Tillage practices incorporate surface plant residue, alter surface soil porosity, loosen soil structure, and alter surface roughness. Tillage has been used since the dawn of civilization. Over the years, untimely tillage has led to soil erosion and decrease of soil fertility (Edwards, 1982).

The awareness of soil degradation and subsequent loss of soil productivity promoted the development of conservation tillage systems as an alternative to moldboard plowing or other conventional practices. In recent years, conservation tillage has been used to reduce soil erosion by maintaining residue. Conservation tillage practices may also reduce machinery, energy, and production costs (Frederick et al., 1991).

Broadly speaking, conservation tillage includes minimum tillage and no-tillage. No-tillage is a system that minimizes manipulation of the soil during the act of planting seeds in the soil. Investigations examining the relationship between tillage treatments and soil quality have been conducted under many different climatic and soil conditions. Results often show beneficial effects of reduced tillage and no-tillage on reducing soil erosion, increasing organic matter, and promoting biological activity (Smith et al., 1979; Edwards, 1982).

Despite beneficial aspects of conservation tillage, runoff amount and quality, saturated hydraulic conductivity (Ksat), and soil porosity have not always been improved with these practices. Some studies have found increased runoff from no-tillage (Smith et al., 1979; Lindstrom and Onstad, 1984; Alberts and Hjelmfelt, 1992). The Ksat may be higher, equal, or lower in no-tillage compared to conventional practices (Gantzer and Blake, 1978; Heard et al., 1988; Wu et al., 1995). No-tillage systems may also cause soil consolidation and, thus, decrease porosity (Tollner et al., 1984; Reynolds et al., 1994). Higher runoff and lower Ksat and porosity in no-tillage soil may cause greater loss of agricultural chemicals to streams and lakes.

These mixed findings underscore the need to better understand how tillage alters the hydraulic properties of soils in general, and specifically of the Mexico claypan soil associated with the runoff plots at the Midwest Claypan Experiment Farm (M^{c}Credie), Kingdom City, MO, where increased runoff in a no-tillage system has been observed (Smith et al., 1979;

Alberts and Hjelmfelt, 1992).

Attention has been focused on runoff and soil loss on these plots. Data on Ksat is limited. It would be useful to determine runoff behavior at McCredie and explain why the behavior occurs. A study of runoff by season and year is also needed to identify when differential runoff occurs.

The objectives of this study were to measure the effects of seven long-term crop and tillage treatments on saturated hydraulic conductivity of the surface soil horizon and determine the effects of the selected crop and tillage treatments on 11 years of runoff.

MATERIALS AND METHODS

Site Description

This study was conducted on the runoff plots at the Midwest Claypan Experiment Farm (McCredie) near Kingdom City, Missouri. The soil is a Mexico (fine, montmorillonitic, mesic Udollic Ochraqualf; Horn, 1992) with a near uniform slope of about 3%. The runoff plots have been in continuous operation for more than 50 years. These long-term experimental plots have served to quantify runoff amounts and erosion rates for use with the Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1978).

Runoff studies

Runoff records collected from the McCredie rainfall erosion plots from 1983 through 1993, were used in this study. A detailed description of runoff plot dimensions, instrumentation and procedures for runoff measurement on the plots is given by Jamison et al. (1968). Runoff was measured on four replicates from 1983 to 1990. From 1991 to 1993 two replicates were abandoned leaving only two replicates. Each replicate consisted of seven treatments: no-tillage, moldboard plow, and chisel plow continuous corn (*Zea mays* L.) and continuous soybean (*Glycine max* L.), and fallow.

Annual and seasonal runoff records of the no-tillage and conventional tillage plots were used. The goal of doing these analyses was to determine the structure of the runoff data, and characterize exactly when runoff differences occurred by tillage, season, and year.

An analysis of variance (ANOVA) was conducted to determine significance of the treatments. To determine when differential runoff occurred, selected periods of high runoff rates were evaluated. Precipitation data pertaining to precipitation were gathered to calculate runoff as a percent of annual and average annual precipitation. The precipitation record was obtained from an official National Oceanic & Atmospheric Administration (NOAA) weather station adjacent to the rainfall-erosion plots.

Annual and seasonal runoff rates were averaged by treatment, so comparison of differences could be readily assessed. Because successive runoff measurements were made from each plot, a factoral experiment of repeated measurements was used (Snedecor and Cochran, 1989).

Ksat Studies

This study focused on fourteen runoff-erosion plots in which two replicates of no-tillage (NT), moldboard plow (MP), and chisel plow (CP) had been planted to corn and soybean. Two additional plots were under continuous cultivated fallow (F). The experimental design of the plots was a randomized complete block with two replicates.

Undisturbed (76 x 76 mm) soil cores were collected from the fourteen runoff plots in June 1995. Samples were taken from trafficked and untrafficked interrow positions. Three replicate cores were collected vertically from two depths, 0 to 125 mm and 125 to 250 mm, within the Ap horizon.

Soil samples were taken in the upslope section of the plots to reduce the effects of sediment accumulation. A Uhland sampler was used to take samples (Uhland, 1950). Samples were labeled and sealed with polyethylene bags and closed with rubber bands. Soil cores were transported to the laboratory and stored in a refrigerator at about 4°C to minimize microbial and biological activity, for three days, before laboratory experiments were performed.

Laboratory tests were conducted for Ksat (Klute and Dirksen, 1986), bulk density (Blake and Hartge, 1986), organic matter content (Nelson and Sommers, 1982), and field volumetric water content (Gardner, 1986).

A split-split plot design was used to test the following hypotheses (Snedecor and Cochran, 1989): the Ksat in no-tillage plots was equal to that of tilled plots and the macro- (pore diam. > 0.5 mm) and meso-pore

(pore diam. 0.5 - 0.02 mm) soil porosity in untilled soil was equal to that in the tilled soil.

The experiment had tillage treatments as the main effect, wheel traffic as the first split treatment, and depth as the second split treatment. Six single degree of freedom contrasts of tillage treatments were tested: NT vs. MP and CP, MP vs. CP, Corn vs. Soybean, (NT vs. (MP+CP)) x Crop, (MP vs. CP) x Crop, and F vs. NT, MP, and CP.

RESULTS AND DISCUSSION

Bulk Density (ρ_b)

Means of ρ_b by tillage, crop, depth, and wheel traffic are presented in Table 1. A plot of the mean of ρ_b by depth is shown in Fig. 1. The ANOVA summary of the ρ_b data is given in Table 2. Differences in ρ_b were significant for all treatments (p=0.001). Mean ρ_b of NT was the highest (1.54 g cm^{-3} ± 0.004; Table 1) of all treatments, but the contrast between 'NT vs. (MP+CP)' was not significant. Figure 3 indicates that NT corn was 6% higher than MP and CP at both depths. Results are similar to those of Rhoton et al. (1993) who reported higher ρ_b in NT, compared to MP, in which tillage operations temporarily reduced ρ_b in MP and CP. Logsdon et al. (1990) demonstrated that NT soils are subject to compaction and increased strength resulting from the limited tillage operations over time. Differences in ρ_b for soybean among the NT, MP and CP were not significant at either depth.

The contrast of 'MP vs. CP' was not significant although Fig. 1 shows that MP corn was 7% higher compared to CP at the 100 to 200 m depth. Formation of a plow pan in the presence of compactive forces associated with wheel traffic may have accentuated the effect on ρ_b in the MP system.

The 'corn vs. soybean' contrast was significant (p=0.001) which reflected the higher ρ_b for corn (1.53 g cm^{-3} ± 0.004) than for soybean (1.49 g cm^{-3} ± 0.004). This indicates that soils under corn tend to be more compact than those under soybean. The contrast of 'F vs. (NT+MP+CP)' was significant (p=0.001). Table 1 indicates that F produced the lowest ρ_b values, when averaged across interrows, probably because of the continuous loosening of soil by tillage implements.

Significant wheel traffic effects on ρ_b occurred at both depths (p=0.0002; Table 2). On the average, ρ_b in the non-trafficked area was 24% higher than in the trafficked area, a reflection of the compactive effect of traffic. In the trafficked zone, NT corn produced the greatest ρ_b (1.60 g cm^{-3} ± 0.009), while F had the lowest ρ_b (1.47 g cm^{-3} ± 0.009). In the untrafficked zone, NT and MP corn had the highest ρ_b (1.50 g cm^{-3} ± 0.009), whereas, the lowest ρ_b (1.40 g cm^{-3} ± 0.009) corresponded to MP and NT soybean (Table 1).

Significant differences of ρ_b with depth (p=0.001) and 'tillage x depth' (p=0.036; Table 2) existed for all treatments. The 'tillage x depth' interaction suggested a study of the means. At the 0 to 100 mm depth, the mean NT corn was 4% higher than MP, but not at 100 to 200 mm in the trafficked positions. No differences in ρ_b were observed for MP and NT corn in the untrafficked zones (Table 1). For soybean, no significant differences in ρ_b existed in the 0 to 100 mm depth, but in the 100 to 200 mm depth, CP and MP were about 7% greater than NT. The increase of ρ_b in MP and CP in the 100 to 200 mm depth may be attributable to plow pan development.

At both depth intervals, F resulted in the lowest ρ_b with a mean of 1.41 g cm^{-3} ± 0.004 in the 0 to 100 mm and 1.46 g cm^{-3} ± 0.004 in the 100 to 200 mm, when averaged over wheel traffic. The maximum disturbance in the F treatment is thought to be the cause for the reduced ρ_b values. Burch et al. (1986) found that the ρ_b in tillage treatments with minimum disturbance (non-fallow) produced the highest ρ_b values, whereas, uniformly disturbed soils in the upper 50 mm surface gave the lowest ρ_b.

Organic Matter

Data were non-normally distributed (Pr<W=0.001), thus a logarithmic transformation on the data was performed to improve the normality (Pr<W=0.299). Table 3 shows the geometric means, averaged across depth and interrow positions. Geometric means are plotted in Fig. 2 by depth and wheel traffic. Analysis of variance is presented in Table 4.

The contrast between 'F vs. the average of (NT+MP+CP)' was significant (p=0.003; Table 4). The differences among treatments were nearly all due to the F, which yielded the lowest organic matter from all treatments, with a mean of 0.97 ± 0.06% (Table 3). The F reduced the soil organic matter content (Wischmeier and Smith, 1978). Mean organic matter, averaged over crop, depth, and wheel traffic, in F was 60% of that in NT, 68% of that in CP, and 66% of that in MP (Table 3). Interrow position, across depths, had no significant effect on the organic matter content. It should be noted that the mean for NT corn in the untrafficked position was 75% of that in the trafficked zone (Fig. 2). This may be attributed to the greater accumulation of corn residues in the trafficked soil zones, compared to that in the untrafficked positions (Soane and Van Ouwerkerk, 1994).

Differences in organic matter were significantly related to depth. The mean value for the 100 mm depth, averaged over crop and wheel traffic, was 1.2 times higher than for the 200 mm depth, agreeing with the fact that soil organic matter is mostly concentrated near the surface (Blevins et al., 1983). The response of organic matter to tillage treatment varied with crop type as shown by the significant interaction of '(NT vs. (MP+CP)) x Crop'.

No-tillage had significantly greater organic matter compared to MP and CP for corn. In contrast, no significant differences were reflected for soybean. The highest organic matter content in NT corn (1.86%) may be explained by the increased residue placement near the surface soil. Blevins et al. (1983) characterizing the tillage effects on a Maury silt loam soil, found that organic matter of NT was twice that of MP.

Field Water Content

Table 5 presents the arithmetic means, averaged over depth and wheel traffic, of field volumetric water content at sampling (June 1995). Figure 3 shows means of the seven tillage-crop treatments plotted by depth and wheel traffic. Table 6 shows the analyses of variance of the data.

Differences in soil water content among the treatments were significant ($p=0.029$). When NT was compared with the average of CP and MP, the differences were significant ($p=0.001$). No-tillage had the highest water content (0.313 $mm^3\ mm^{-3}$) for both crops. Means in Table 5 indicate that the water content was 10% higher in NT than in CP and 6% higher than in MP for corn plots. For soybean plots, NT had 4% and 5% higher water content compared with CP and MP, respectively.

Kitur et al. (1993) on a Grantsburg silt loam soil found that NT had significantly higher water content than CP and MP in the upper 0 to 150 mm surface at planting. Higher water content in NT was associated with residue cover which reduces the evaporation and increases the quantity of water stored. Dao (1993) measured the water storage on a Bethany silt loam soil managed under moldboard plowing, stubble-mulch tillage, and NT. Results showed that water content in NT was 3% higher than in MP and stubble-mulch tillage.

Differences in water content were not significant between these contrasts: 'MP vs. CP and F vs. (NT+MP+CP)' (Table 6). Water content in MP soybean was 90% of that in CP, and 89% of that in NT. This indicates that soils under MP soybean have less water storage capacity compared to CP and NT, due probably to soil inversion, deep plowing, and low quantity of residue.

'Corn vs. soybean' contrast was significant (p=0.009). Corn had 6% greater water content in comparison with soybean plots. Higher water content could be due to the greater residue cover in corn plots. Soybean residues are more easily decomposed compared to corn residues (Siemens and Oschwald, 1978).

Results showed that the differences in soil water content were significant with depth (p=0.001). Mean water content in the 0 to 100 mm depth was 13% lower than in the 100 to 200 mm depth, when averaged across crop and wheel traffic (Fig. 5). It should be noted that the magnitude of water content increased with depth, and was more noticeable in MP, CP, and F than in NT soybean. It is likely the higher evaporation in MP, CP and F resulted in lower water content in the upper 100 mm surface, compared with NT in which the remaining surface residue retained more water.

This is in agreement with Negi et al. (1982) who stated that water content in NT was twice the value of MP in the 0 to 300 mm depth on a Rosalie clay soil. An important point is that management induced changes in soil water storage. No-tillage had significantly greater water content compared to MP and CP, resulting from its greater ability to absorb water and larger amounts of decomposing crop residues near the soil surface (Table 6). The higher water content in NT may have important effects on field hydraulic conductivity and seasonal water infiltration in the runoff plots. A study to document the impact of higher water content in NT in precipitation storage, infiltration, and runoff on long-term data is required.

Ksat

Since the Ksat residuals were significantly non-normal (P=0.001), ANOVA and calculation of means were performed on log-transformed Ksat values. Data transformation showed that Ksat was log-normally distributed (Grossman and Harms, 1993). The ANOVA for Ksat is given in Table 7. A plot of geometric mean vs. tillage, crop, traffic and depth is displayed in Fig. 4.

The treatment effects on Ksat were similar to those of ρ_b in that both were significantly different with depth and traffic. Significant interactions were present for tillage vs. interrow position (p=0.041) and tillage vs. depth (p=0.003). The ANOVA indicated that the Ksat differences between blocks were not significant (p=0.184; Table 7). Significant differences (p=0.019) were found among tillage treatments. The differences were largely due to the F as shown by its contrast (p=0.002) to the rest of treatments.

As with bulk density, volumetric water content, and organic matter, the Ksat contrast between 'NT vs. MP and CP' was not significant (p=0.569). This result agrees with findings from Blevins et al. (1983) who found no differences in Ksat between NT and MP on a Maury silt loam. Wu et al. (1992) on a Rozetta silt loam, Seaton silt loam, and Nicollet clay loam also reported no differences in Ksat among NT, MP and CP.

However, a detailed comparison of means shows that for corn, at the 0 to 100 mm depth, Ksat for NT was about 6 and 2 times higher than that for MP and CP in both interrow positions, respectively. This suggests that, though 'NT vs. (MP+CP)' was not significant, Ksat under NT corn was higher, particularly in 0 to 100 mm depth, owing to the greater residue cover in interaction with the lack of soil disturbance. Conversely, Ksat in NT soybean was 3 times lower compared to that in MP and CP in the untrafficked interrows at the same depth (Fig. 4). Mixed Ksat results were observed in the 100 to 200 mm depth.

One might believe that the higher ρ_b observed in NT corn would reduce the Ksat; however, it is also possible that NT may have more water conducting macropores than MP and CP. Although water flow through those large pores open to the surface were minimized using a bentonite technique during Ksat measurements, it is likely that flow may have occurred in macropores not visibly connected to the core surface. Indeed, Phillips et al. (1989) stated that saturated and unsaturated water flux in the macropores apparently not open or continuous to the soil surface can be significant.

The contrast of '(MP vs. CP) x Crop' was significant (p=0.049; Table 7). For corn, at the 0 to 100 mm depth, Ksat in CP (6.1 mm/h) was about 2 times greater vs. MP (2.6 mm/h) in the untrafficked zone. For soybean, at the same depth, Ksat for CP (5.1 mm/h) was 2 times of that for MP (2.3 mm/h) in trafficked rows. At the 100 to 200 mm depth, Ksat of CP (13 mm/h) corn was 2 times of that in MP (7.8 mm/h) in untrafficked positions, while for soybean, CP (29.1 mm/h) was 1.5 times that of MP (25.6 mm/h) for both interrows. Lower Ksat in MP may be attributable to the change of soil structure in response to inversion tillage. In fact, Ksat in MP and CP corn was consistently lower in comparison with that in MP and CP soybean in untrafficked zones at both depths.

Differences in Ksat between corn and soybean for MP and CP were not significant in trafficked zones, where consolidation and closer packing of the aggregates altered the structure equally (Edwards, 1982). The Ksat differences with interrow position (p=0.001) and tillage x interrow interaction were significant (p=0.039; Table 7). Reduction in Ksat within the trafficked zone was attributed to soil compaction caused by wheel traffic (Rhoton et al., 1993).

At the 0 to 100 mm depth, the geometric mean, averaged across treatments, in the untrafficked (20.1 mm/h) was 7 times greater than in the trafficked interrow (2.73 mm/h) for soybean (Fig. 4). A difference was also noted for the corn in this depth, where the untrafficked Ksat values (7.73 mm/h) were thrice the value of the trafficked (2.6 mm/h). This is in agreement with Culley et al. (1987) who, studying the wheel traffic effects on Ksat on a Typic Haplaquoll in Minnesota, reported that the magnitude of Ksat determined on undisturbed 76 mm soil cores in untrafficked rows was about 17 times higher for NT and about 200 times higher for MP compared to that in trafficked positions in the 0 to 80 mm depth.

Significant Ksat differences with soil depth existed for all treatments (p=0.021); the tillage x depth interaction was also significant (p=0.003; Table 7). Values were consistently higher in the upper 100 mm in both untrafficked and trafficked interrows, except for the MP corn in which the Ksat was slightly higher in the 200 mm. It is possible that seasonal plowing in MP destroyed macropores only in the surface 100 mm and left stable and buried macropores below this depth (Logsdon, 1995). Buried macropores may be important in increasing Ksat (Phillips et al., 1989).

To investigate the nature of the 'tillage x interrow' and 'tillage x depth' interactions, orthogonal comparisons among the treatments were conducted by interrow position and depth (Table 7). 'Corn vs. soybean x wheel traffic' interaction (p=0.011) was significant.

The greatest combined effect of crop vs. row position occurred in the non-trafficked zone for soybean, where Ksat for the MP and CP was about 10 times (25.1 mm/h) of that for the MP and CP treatment (2.6 mm/h) in trafficked corn and soybean and untrafficked corn, at both depths (Fig. 4). This may be explained in part by the differences in ρ_b (Fig. 1). Corn plots had significantly higher ρ_b than soybean plots, suggesting that compactness and lower porosity in corn soils were, partially, responsible for the lower Ksat. A possible reason for decreased ρ_b in soybean is that decomposed soybean residues might be more effective at soil conditioning and improving the soil structure, compared to corn residues (Gantzer et al., 1987).

Differences in Ksat of the contrast of '[F vs. (NT+MP+CP)] x interrow' interaction were significant (p=0.029; Table 7). Figure 4 indicates that 'treatment vs. interrow' interaction, except for F, produced the highest Ksat values for both depths within the untrafficked positions. The Ksat under NT, MP and CP (13.95 mm/h) was about 4 times as high as of F (4.1 mm/h) in the untrafficked zone.

The lowest Ksat observed in F treatment is a reflection of the continuous cultivation that caused deterioration of soil structure, reducing the stability of soil aggregates and, thus, reducing macroporosity. Because of the continuous cultivation, the Ksat differences between rows and interrows in F is less compared to that under other treatments.

It is important to note that Ksat of F (2.6 mm/h) was 3 times higher than that of NT soybean (0.8 mm/h) in trafficked area at the 100 mm depth. This may indicate that trafficked interrows in NT soybeans became compacted with time in response to field traffic and this effect was more pronounced in reducing the Ksat than continuous cultivation.

The interaction of '[F vs. (NT+MP+CP)] x depth' was significant (p=0.001; Table 7). In this interaction with depth, F produced the lowest

Ksat of all treatments in the 100 to 200 mm depth (Fig. 4). This was likely caused by deterioration of subsurface layers by continuous tillage. Lower bulk density and organic matter in F found at this depth vs. NT, MP, and CP, support this analyses (Fig. 1 and 2). Radcliffe et al. (1988) stated that the combined effect of low organic matter, and frequent tillage in F reduces the soil hydraulic conductivity.

The interaction of '(crop vs. tillage) x depth' was significant (p=0.001) confirming that the depth effect on Ksat depends on both crop and tillage. The '(MP vs. CP) x depth' interaction was significant (p=0.017). At the 0 to 100 mm depth, Ksat under CP (3.1 mm/h) was about 3 times that under MP (1.1 mm/h) in any interrow position for both crops, with the only exception of untrafficked soybean. At the 100 to 200 mm, Ksat in CP corn was about 1.6 times greater in comparison to that in MP, except in trafficked corn. Non-inversion and reduced soil manipulation in CP were effective in increasing the Ksat compared to that in MP. Not only did the MP have lower Ksat values than CP, but it may be more susceptible to cracking than NT and CP as observed during soil sampling.

The management effects on Ksat are quite complex. It is difficult to conclusively state the nature and magnitude of the influence of management on Ksat. Acknowledgement of this complexity in discerning the full effects of tillage is corroborated by other studies (Tollner et al., 1984; Mahboubi et al., 1993). Although Ksat measured on small soil cores is not considered to be representative, the bentonite procedure used in this study minimized the macropore influence and interfacial flow between sample ring and soil.

Runoff Studies

Mean runoff by season for each treatment, averaged over an 11 year-period, is plotted in Fig. 5 to illustrate the runoff differences. Mean runoff by year, averaged over treatments, is found in Fig. 6. Annual total runoff for each treatment is plotted in Fig. 7. Runoff as percent of annual precipitation is given in Fig. 8. Cumulative annual runoff is presented in Fig. 9. The ANOVA by season of the runoff data is given in Table 8 and cumulative runoff is in Table 9.

Results indicate that runoff varied significantly among seasons and among treatments from year to year. Because of the significant tillage x year interaction effect (p=0.001), a more detailed approach by computing the mean seasonal runoff by year was performed as recommended by Snedecor and Cochran (1989).

Seasonal Effects on Runoff

Comparison of mean runoff by season, averaged over years, was conducted in spite of a significant tillage vs. year interaction. Inspection of mean runoff by season over the 11-year study indicated that F produced the highest runoff in Period 4 and Period 3 for both crops (Fig. 5).

The greatest amount of runoff occurred during Period 4 (harvest to spring tillage) and the lowest in Periods 1 and 2. Comparison of all possible means using Waller option test (SAS Institute, 1985) indicated that Period 4 was higher than Fallow period, Seedbed period, Period 3, and Periods 1 and 2. The mean runoff by season, averaged across years and treatments, was in this order: Period 4, fall (57.64 mm) = Period 4, spring (51.88 mm) > Fallow period (26.77 mm) = Seedbed (25.69 mm) = Period 3 (21.27 mm) = Period 1 and 2 (15.17 mm). Runoff in Period 4 was 7 times greater compared to that in Periods 1 and 2. The partitioning of means for Period 4 showed that the runoff in Fall was 11% times higher, compared to that in Spring.

Differences in runoff by season largely reflect surface soil conditions. The lowest runoff rates observed in Periods 1 and 2 were the result of the rough and loose plow layer created by the cultivation which increased infiltration and water storage. Recently plowed soils are efficient at reducing runoff by retaining rain water in the surface depressions, and increasing water intake in the soil profile (Edwards, 1982).

Detailed study of the mean seasonal runoff by year accounting for the tillage x year interaction confirmed the difficulty of summarizing behavior with the main effects of tillage and year. Figure 6 shows that Period 4, spring, which had the greatest precipitation, produced the largest runoff during 1984 and 1988, while the Fallow period in 1983, Seedbed period in 1990, Period 3 in 1989, 1991, and 1993, and Period 4, fall in 1985, 1986, 1987, and 1992, had the highest runoff. The largest recorded runoff over the 11 year period occurred in Period 3 which coincides with the year of the Great Flood of 1993.

Tillage Effects on Runoff

Tillage had mixed results over time. The F produced twice as much runoff as NT, MP, CP, particularly in Period 4, but not in the Fallow period, where runoff from F was 94% of that in NT for both crops. Runoff from NT corn was about 1.2 times the value of that from MP in all periods, except in Seedbed period and Period 3 (Fig. 5).

Mean runoff from continuous NT corn was 1.2 times of that from CP with the only exception being the Fallow period. No-tillage soybean had about 1.2 times greater runoff than MP and CP in all periods. For corn, MP was greater in runoff in Seedbed period, Period 1 and 2, and Period 3, and lower in Period 4 and Fallow period than CP. For soybean, runoff from MP was consistently higher than that from CP, except in the Fallow period.

Because there was a significant tillage x year interaction, annual total runoff was studied for each tillage treatment, as shown in Fig. 7. Tillage effects of NT, MP, and CP on runoff were mixed. Runoff in NT corn was higher compared to MP and CP, but not in 1989, 1990, 1992, and 1993. A similar pattern was observed for soybean; NT was higher than MP except in 1988, 1992, and 1993. The NT soybean was consistently greater than CP from year to year. Runoff, as percent of annual and average annual precipitation, shows, the same distribution by years, where no-tilled soils were responsible for 5 to 35% of precipitation loss by runoff (Fig. 8).

Cumulative runoff from NT was significantly (p=0.001) higher than from MP and CP in 1983 through 1990. Differences in cumulative runoff were not significant (p=0.374) from 1991 to 1993. The 11-year cumulative annual runoff shows that NT was about 10% higher compared to MP and CP for both crops, with the exception of NT soybean, which was 24% greater than CP soybean (Fig. 9).

The ANOVA by season in Table 8 indicates that runoff differences among the tillage treatments and years were significant at the 0.001 level for all seasons. The NT had significantly higher runoff than MP and CP treatments during Period 4, spring (p=0.006), Period 4, fall (p=0.011) Fallow period (p=0.005), and Period 1 and 2 (p=0.021).

Results indicate that runoff from NT was higher than that from MP and CP for most seasons and years. This supports the conclusion report by Alberts and Hjelmfelt (1992) indicating that the NT produced more runoff than conventionally tilled soils, for the M^{c}Credie rainfall erosion plots from 1983 to 1991. They also observed that the greatest runoff with NT occurred during Period 4 (harvest to planting). This study found lower annual runoff for NT compared to MP in 1988 for soybean, 1989 for corn, 1992 and 1993 for both crops, reflecting the complexity of runoff results of long-term NT systems.

The ANOVA in Table 9 shows that cumulative runoff from NT was significantly higher, compared to MP and CP at the 0.01 level for the following years and replicates: all four replicates (1983-1990) and (1983-1993), Replicates 1 and 2 (1983-1990) and (1983-1993). In contrast, no significant differences ($p=0.072$) in cumulative runoff were found for Replicates 3 and 4 from 1990 to 1993. This conflicting outcome indicates a significant replicate effect on runoff. This would not be expected to occur in a natural field situation. The reason for this difference may be linked to problems related to the experimental plots or runoff measuring equipment.

Higher runoff from NT systems in Replicates 1 and 2 may be associated with the higher antecedent water content and lower porosity of the surface layer, as shown in Fig. 1 and 3, especially for corn. The water content in NT, found during sampling in this study, was about 7% greater than in MP and CP. Higher water content in NT may reduce the water storage capacity. Consequently, NT soils would require less time to become saturated and initiate runoff compared to MP and CP systems (Wendt and Burwell, 1985). Increased residue cover or mulch in NT plots often reduces evaporation with consequent increase in stored water, reducing fillable porosity.

The foregoing analysis is supported by Blevins et al. (1983) who found greater water content in NT (0.35 $m^3\ m^{-3}$) than in MP (0.29 $m^3\ m^{-3}$) in the plow layer during the growing season and suggested that the extra amount of water could be responsible for more runoff from no-tilled systems. Runoff from MP treatment was significantly ($p=0.003$) lower than that from CP only in Fallow period (Table 8). Mean runoff by season, averaged across crops, in Fig. 5 shows that CP (28.1 mm) was about 1.3 times greater than MP (21.2 mm) in Fallow period. A possible explanation for this is that the seasonal plowing in MP may have created greater surface roughness that increased detention storage and increased the time available for water infiltration.

Annual sums of runoff in Fig. 7 indicates that MP soybean, when compared to CP, tended to be greater in most years and lower in 1983 and 1990. The percentage of annual and average annual precipitation loss by runoff was from 5 to 35% in MP and CP (Fig. 8). This percentage was about 3% lower compared to that lost with NT. Cumulative runoff differences for corn between MP and CP were not significantly different, while for soybean, MP was 19% higher than CP. This is attributable to soil stirring in MP that buries all the crop residues, leaving virtually a bare surface more susceptible to runoff, in comparison with CP. Soil inversion is reduced by chiseling and thus greater amount of residue remains in CP near the soil surface compared to MP, slowing the runoff (Frederick et al., 1991). These results are supported by Burwell and Kramer (1983) who, in a 24-year study (1954-77) at the McCredie rainfall erosion plots, found that cumulative runoff for conservation tillage was 13% less than that for conventionally tilled corn.

The ANOVA showed that mean runoff from corn was significantly ($p=0.024$) lower than that from soybean plots in Period 4, fall (Table 8). This could be attributed to the amount of residue left near the soil surface (Gantzer et al., 1987). Mean runoff, averaged over seasons and years, indicate that runoff from corn was 90% of that from soybean, except for CP in which corn was 6% greater in runoff compared to soybean.

The F conclusively produced the highest runoff for all the years ($p=0.001$; Tables 8 and 9). F treatment also produced the highest runoff rates during all periods, but not in Fallow period and Seedbed period. Runoff from F plots was 40% greater for corn and 34% greater for soybean compared to that from NT treatments (Fig. 7). Cumulative runoff for F treatment was 45% greater than that for MP and CP corn, while for soybean, runoff from F was 55% and 50% higher than that from MP and CP, respectively. Highest runoff in F resulted from a combined effect of low Ksat and organic matter. Lower ρ_b suggests that F soils had more micropores than macropores. Macropore formation may be disrupted by the frequent stirring and inversion of soil, reducing the distribution and activity of earthworms.

The F plots without vegetation throughout the year, accompanied by frequent tillage, were highly prone to water loss by runoff patterns different from MP, CP and NT treatments. The F treatment, the extreme case of tillage used as a "standard" to compare and predict the soil loss in the Universal Soil Loss Equation (USLE), was expected to produce the greatest runoff (Wischmeier and Smith, 1978). Figures 7 and 8 indicate that 18% to 45% as annual precipitation, and 15% to 65% as average annual precipitation, were partitioned as runoff. The F surface, kept residue-free, reduces resistance to surface runoff and increases the runoff velocity (Siemens and Oschwald, 1978).

CONCLUSIONS

The Fallow (F) treatment produced the highest runoff in all years. Management induced alterations in soil physical properties, including low

Ksat and low organic matter were the main reasons for the increased runoff from the F plots. This analysis is supported by Bruce et al. (1992) who concluded that excessive tillage disturbance in F treatments leads to depletion of organic matter content, low Ksat, and increased susceptibility to runoff.

Runoff from NT soils was significantly higher compared to that from MP and CP during Period 4 (harvest to planting), Fallow period, and Period 1 and 2. A study of soil properties to determine the differential runoff showed that NT corn had higher water content at soil sampling and lower porosity compared to those in MP and CP as a result of the greater amount of crop residues remaining on the surface and less soil disturbance. No significant differences in Ksat were found among the treatments. This suggests that the antecedent water content may be the mechanism for the slightly increased runoff in no-tilled plots. The differential water content in NT plots could reduce the infiltration and water storage. More small pores in NT soil may be occupied with water (Blevins et al., 1983). Differential runoff from the plots can also be related to water movement through the argillic horizons (claypan). The Bt horizon represents a nearly complete barrier for downward water flow under saturated conditions and thus causes water to flow horizontally. Lower water content and roughened surface in MP are essential for water infiltration compared to more compact surface of NT soils (Singh et al., 1991). A significant increase in runoff from no-tilled plots may occur in part as a result of reduced disturbance.

This study shows a possible disadvantage in maintaining long-term NT systems in water infiltration and runoff. Indeed, NT may require some tillage to correct negative effects of compaction, low porosity, and higher water content. Tillage operations should temporarily increase soil porosity, but this would be expected to only make a small difference in Ksat. This study suggests that surface soil properties, especially water content may be important factors effecting runoff. A greater amount of plant residues is found on the NT surface soils, yet runoff is still higher compared to seasonally plowed soils with reduced residue because of higher water content.

Runoff from soybean plots was significantly higher than that from corn plots in Period 4, fall. This was presumably due to the amount of residue. Twice as much residue is produced by corn than soybean (Gantzer et al., 1987). Although residues are mixed with the soil during plowing and chiseling, larger leaves and stems resulting from corn remain partially unaltered for longer periods of time compared to soybean residues which may be easily decomposed and incorporated into the soil. This difference may improve the soil structure, slow the surface runoff and enhance the infiltration capacity in corn plots more effectively, compared to soybean residues. Similar results were stated by Siemens and Oschwald (1978) who compared corn and soybean tillage systems in terms of runoff and found that soybean residues were subject to greater disintegration in shorter time than corn residues.

Differences in runoff between MP and CP depend on the crop. Runoff from MP soybean was slightly higher than that from CP soybean. A possible reason for this is that deep plowing and soil inversion in MP increase runoff, compared to reduced tillage in CP. No significant differences were found between MP and CP corn.

A conclusive statement defining the causes of the runoff differences is complex because of the many interacting site-specific characteristics (Lindstrom et al., 1981). Knowledge of runoff suggests that a single physical factor to explain variation in runoff in NT systems is difficult to ascertain. Studies on claypan soils underscore the fact that the differential runoff is due to the interaction of factors inherent to local conditions. It is likely, however, that the significantly higher water content in NT would explain the increased runoff.

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Table 1. Mean ρ_b by tillage, crop, wheel traffic and depth for the McCredie rainfall erosion plots.

	Crop													
	Corn						Soybean						Fallow	
Depth	Trafficked			Untrafficked			Trafficked			Untrafficked			T†	U‡
	MP§	CP¶	NT#	MP	CP	NT	MP	CP	NT	MP	CP	NT		
mm	g cm^{-3}													
0-100	1.5	1.5	1.6	1.5	1.4	1.5	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.3
100-200	1.6	1.5	1.6	1.5	1.5	1.5	1.6	1.6	1.5	1.4	1.5	1.4	1.4	1.4
SE mean = ±0.02; n = 6														

† T=Trafficked interrow; ‡ U= Untrafficked interrow; § MP=Moldboard plow; ¶ CP=Chisel plow; # NT=No-tillage.

Table 2. Analysis of variance of ρ_b of the split-split plot of natural rainfall erosion plots at M^c^Credie, MO.

Source of variation	*df*	*F*	*P>F*
Blocks	1	0.19	0.680
Treatments, TRT	(6)	42.89	0.001**
• NT† vs. (MP‡ + CP§)	1	0.64	0.454
• MP vs. CP	1	0.08	0.782
• Crop	1	96.67	0.001**
• [NT vs. (MP+CP)] x Crop	1	39.34	0.001**
• (MP vs. CP) x Crop	1	21.57	0.001**
• Fallow vs. (NT + CP + MP)	1	108.32	0.001**
Error I	6		
Wheel traffic, WT	1	73.29	0.001**
TRT x WT	6	2.69	0.110
Error II	21		
Depth	1	59.68	0.001**
Depth x WT	1	0.11	0.741
TRT x Depth	6	1.20	0.036*
TRT x Depth x WT	6	2.16	0.110
Error III	112		
Total	167		

*, ** Significant at the 0.05 and 0.01 level, respectively. † NT=No-tillage; ‡ MP=Moldboard plow; § CP = Chisel plow.

Table 3. Geometric means of organic matter content averaged over depth and traffic for each tillage treatment.

Corn			Soybean					
MP†	CP‡	NT§	MP	CP	NT	F¶	SE mean†	
%								
1.44	1.47	1.86	1.48	1.40	1.40	0.97	± 0.057	n = 24

†SE mean corresponds to log-transformed values. † MP = Moldboard plow; ‡ CP = Chisel plow; § NT = No-tillage; ¶ F = Continuous cultivated fallow.

Table 4. Analysis of variance of organic matter content of the split-split plot of natural rainfall erosion plots at McCredie, MO.

Source of variation	*df*	*F*	*P>F*
Blocks	1	0.01	0.920
Treatments, TRT	(6)	11.28	0.005**
• NT† vs. (MP‡ + CP§)	1	5.18	0.063
• MP vs. CP	1	0.1	0.767
• Crop	1	4.97	0.067
• [NT vs. (MP+CP) x Crop]	1	7.36	0.035*
• (MP vs. CP) x Crop	1	0.07	0.807
• Fallow vs. (NT + CP + MP)	1	49.63	0.001**
Error I	6		
Wheel traffic, WT	1	0.29	0.607
TRT x WT	6	1.80	0.230
Error II	21		
Depth	1	13.39	0.001**
Depth x WT	1	2.38	0.145
TRT x Depth	6	1.68	0.198
TRT x Depth x WT	6	0.46	0.827
Error III	112		
Total	167		

*, ** Significant at the 0.05 and 0.01 levels, respectively. † NT=No-tillage; ‡ MP=Moldboard plow; § CP = Chisel plow.

Table 5. Mean of field volumetric water content, averaged across depth and wheel traffic, of the seven tillage-crop treatments.

Corn			Soybean				
MP†	CP‡	NT§	MP	CP	NT	F¶	SE mean
mm^3 mm^{-3}							
29.45	28.51	31.30	27.46	27.91	28.89	28.80	± 0.532
n = 24							

† MP = Moldboard plow; ‡ CP = Chisel plow; § NT = No-tillage; ¶ F = Continuous cultivated fallow.

Table 6. Analysis of variance of field volumetric water content of the split-split plot of natural rainfall erosion plots at McCredie, MO.

Source of variation	*df*	*F*	*P>F*
Blocks	1	0.34	0.580
Treatments, TRT	(6)	5.47	0.029*
• NT† vs. (MP‡ + CP§)	1	14.65	0.001**
• MP vs. CP	1	0.22	0.657
• Crop	1	14.73	0.009**
• [NT vs. (MP+CP)] x Crop	1	1.48	0.269
• (MP vs. CP) x Crop	1	5.91	0.051
• Fallow vs. (NT + CP + MP)	1	0.03	0.869
Error I	6		
Wheel traffic, WT	1	1.94	0.206
TRT x WT	6	1.21	0.402
Error II	21		
Depth	1	146.83	0.001**
Depth x WT	1	0.28	0.605
TRT x Depth	6	2.09	0.120
TRT x Depth x WT	6	1.68	0.197
Error III	112		
Total	167		

*, ** Significant at the 0.05 and 0.01 levels, respectively. † NT=No-tillage; ‡ MP=Moldboard plow; § CP = Chisel plow.

Table 7. Analysis of variance of saturated hydraulic conductivity of the split-split plot of natural rainfall erosion plots at M^c^Credie, MO.

Source of variation	*df*	*F*	*P>F*
Blocks	1	2.26	0.184
Treatments, TRT	(6)	6.48	0.019*
• NT† vs. (MP‡ + CP§)	1	0.36	0.569
• MP vs. CP	1	3.11	0.128
• Crop	1	4.94	0.068
• [NT vs. (MP+CP)] x Crop	1	1.27	0.303
• (MP vs. CP) x Crop	1	6.07	0.049*
• Fallow vs. (NT + CP + MP)	1	28.50	0.002**
Error I	6		
Wheel traffic, WT	1	69.88	0.001**
TRT x WT	6	4.29	0.039*
• NT vs. (CP + MP) x WT	1	5.43	0.053
• MP vs. CP x WT	1	0.51	0.498
• Crop x WT	1	11.66	0.011*
• Tillage vs.Crop x WT	2	0.25	0.631
• Fallow vs. (NT + CP + MP) x WT	1	7.48	0.029*
Error II	21		
Depth	1	6.75	0.021*
Depth x WT	1	0.44	0.518
TRT x Depth	6	5.91	0.003**
• NT vs. (CP + MP) x Depth	1	0.27	0.614
• MP vs. CP x Depth	1	7.32	0.017*
• Crop x Depth	1	0.11	0.743
• Tillage vs. Crop x Depth	2	17.75	0.001**
• Fallow vs. (NT + CP + MP) x Depth	1	15.65	0.001**
TRT x Depth x WT	6	2.31	0.093
Error III	112		
Total	167		

*, ** Significant at the 0.05 and 0.01 levels, respectively. †NT=No-tillage; ‡ MP=Moldboard plow; § CP = Chisel plow.

Table 8. Analysis of variance summary of probabilities of the runoff data by season at the M^{c}Credie rainfall erosion plots over a 11 year-period.

		Cropstage periods †					
		P4sp	F	SB	P12	P3	P4fall
Source	*df*	*P>F*	*P>F*	*P>F*	*P>F*	*P>F*	*P>F*
Block	3	**<0.001****	0.073	**<0.001****	**<0.001****	<0.001**	**<0.001****
Tillage‡ (T)	6						
• NT vs. (MP+CP)	1	**<0.006****	<0.005**	0.332	**0.021***	0.368	**<0.011***
• MP vs. CP	1	0.493	**<0.003****	0.064	0.233	0.525	0.056
• Corn vs. Soybean (Crop)	1	0.688	0.732	0.309	0.160	0.575	**0.024***
• (NT vs. (MP+CP)) x Crop	1	0.365	0.136	0.400	0.140	0.345	0.642
• (MP vs. CP) x Crop	1	0.842	0.251	0.193	0.764	0.926	0.098
• Fallow vs. other	1	**<0.001****	0.418	0.533	**0.030***	**<0.001****	**<0.001****
Error I	18						

*, ** Significant at the 0.05 and 0.01 probability levels, respectively.

† Cropstage period (Wischmeier and Smith, 1978, p.18). P4sp = Period 4, spring, F = Rough fallow, SB = Seedbed, P12 = Rapid growth period, P3 = Maturing crop, P4fall = Period 4, fall.

‡ Tillage tmts under corn and soybean. NT = No-tillage, MP = Moldboard plow, CP = Chisel plow. The number of replicates were four from 1983 to 1990 and two from 1991 to 1993.

Table 9. Analysis of variance summary of cumulative runoff for the M^{c}Credie rainfall runoff plots, MO.

		10-year mean runoff				8-year mean runoff					
		Total		Rep 1 and 2 (1983-1993)		Total		Rep 1 and 2 (1983-1990)		Rep 3 and 4 (1983-1990)	
Source of variation	*df*	*F*	*P>F*	*F*	*P>F*	*F*	*P>F*	*F*	*P>F*	*F*	*P>F*
• NT† vs. (MP‡ + CP§)	1	10.6	**0.004***	13.80	**0.009***	20.40	**0.001***	31.44	**0.001***	4.75	0.072
• MP vs. CP	1	0.67	0.424	0.63	0.458	0.15	0.704	0.13	0.726	0.47	0.518
• Crop	1	0.97	0.339	0.04	0.840	3.51	0.077	1.48	0.269	2.43	0.170
• (NT vs. (MP+CP)) x Crop	1	0.83	0.375	3.75	0.101	1.04	0.322	6.60	**0.042***	0.08	0.789
• (MP vs. CP) x Crop	1	0.08	0.784	0.90	0.381	0.89	0.358	0.24	0.642	2.06	0.202
• Fallow vs. (NT+CP+MP)	1	147.6	**0.001***	183.56	**0.001***	243.77	**0.001***	318.35	**0.001***	71.29	**0.002***

† NT = No-tillage; ‡ MP = Moldboard plow; § CP = Chisel plow.

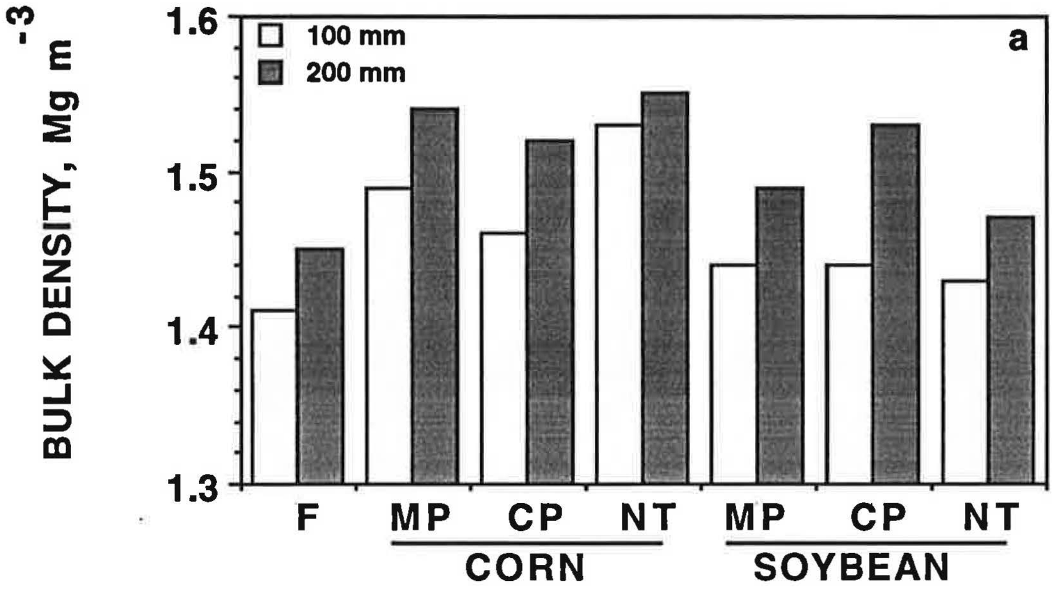


Fig. 1. Mean ρ_b of the seven tillage-crop treatments plotted by depth for a Mexico soil. F = Continuous cultivated fallow; MP = Moldboard plow; CP = Chisel plow; NT = No-tillage.

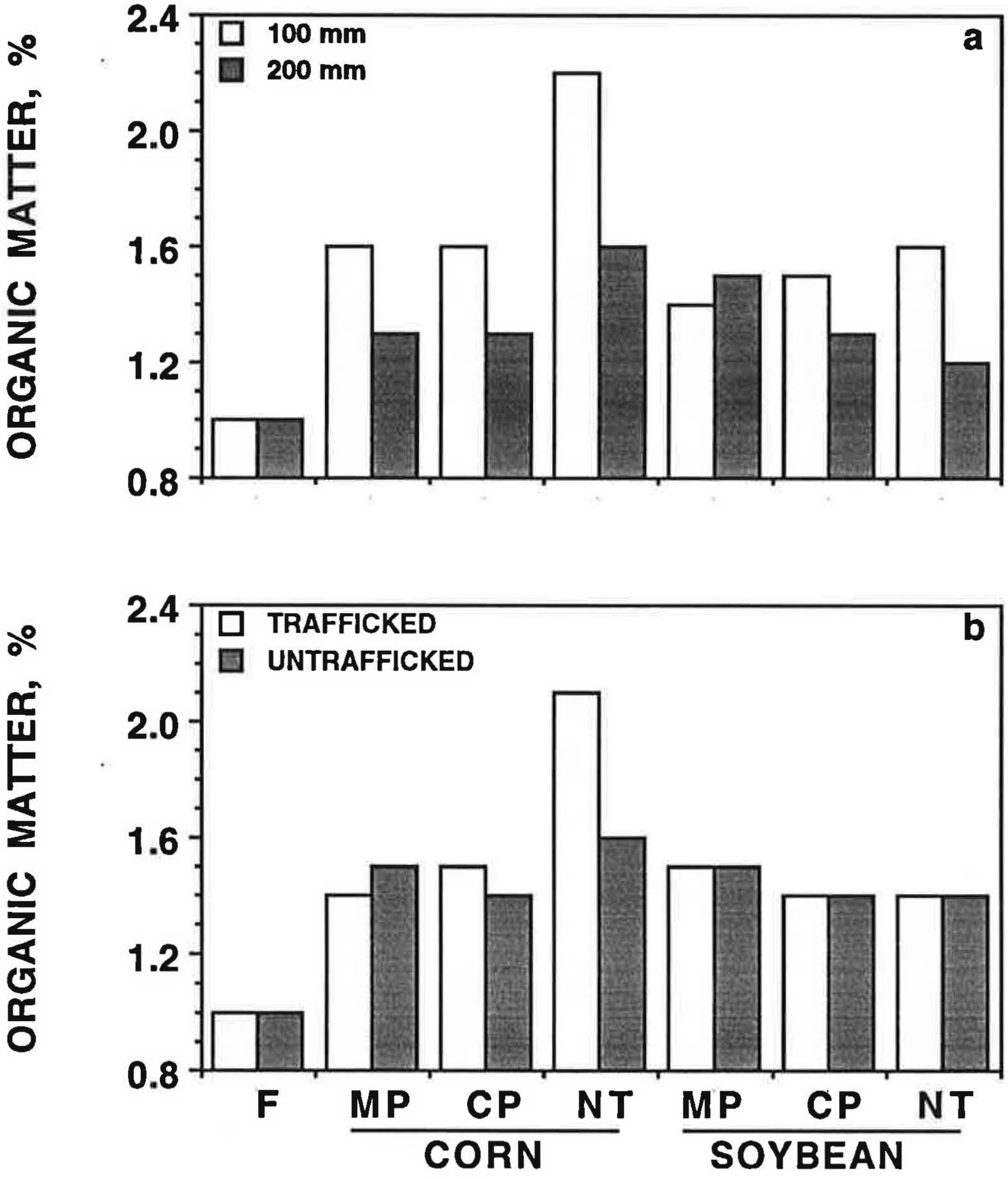


Fig. 2. Geometric mean of organic matter content of the seven tillage-crop treatments plotted by (a) depth and (b) wheel traffic for the M^cCredie rainfall erosion plots. F = Continuous cultivated fallow; MP = Moldboard plow; CP = Chisel plow; NT = No-tillage.

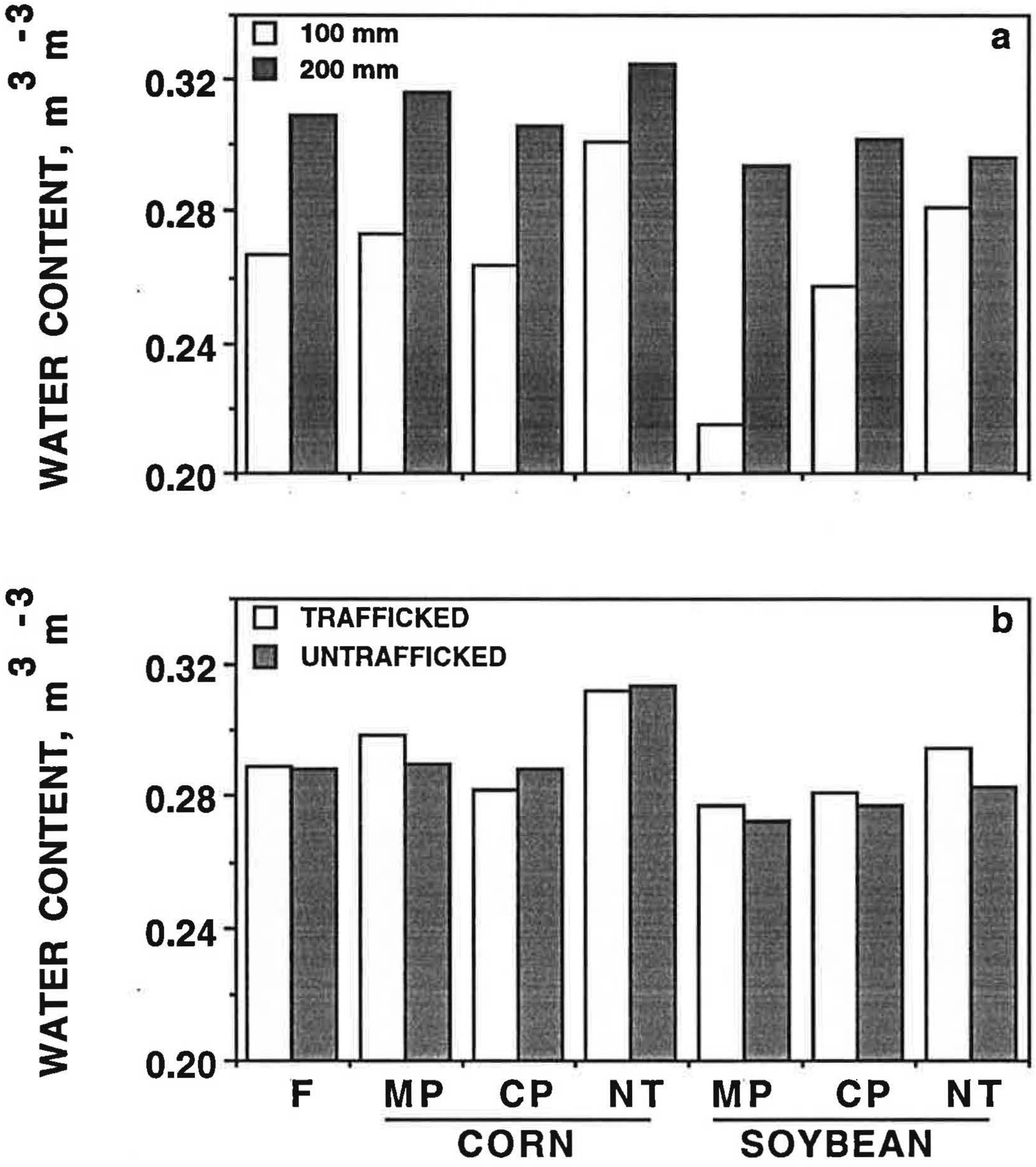


Fig. 3. Mean of field volumetric water content of the seven tillage-crop treatments plotted by (a) depth and (b) wheel traffic at the McCredie rainfall erosion plots. F = Continuous cultivated fallow; MP = Moldboard plow; CP = Chisel plow; NT = No-tillage.

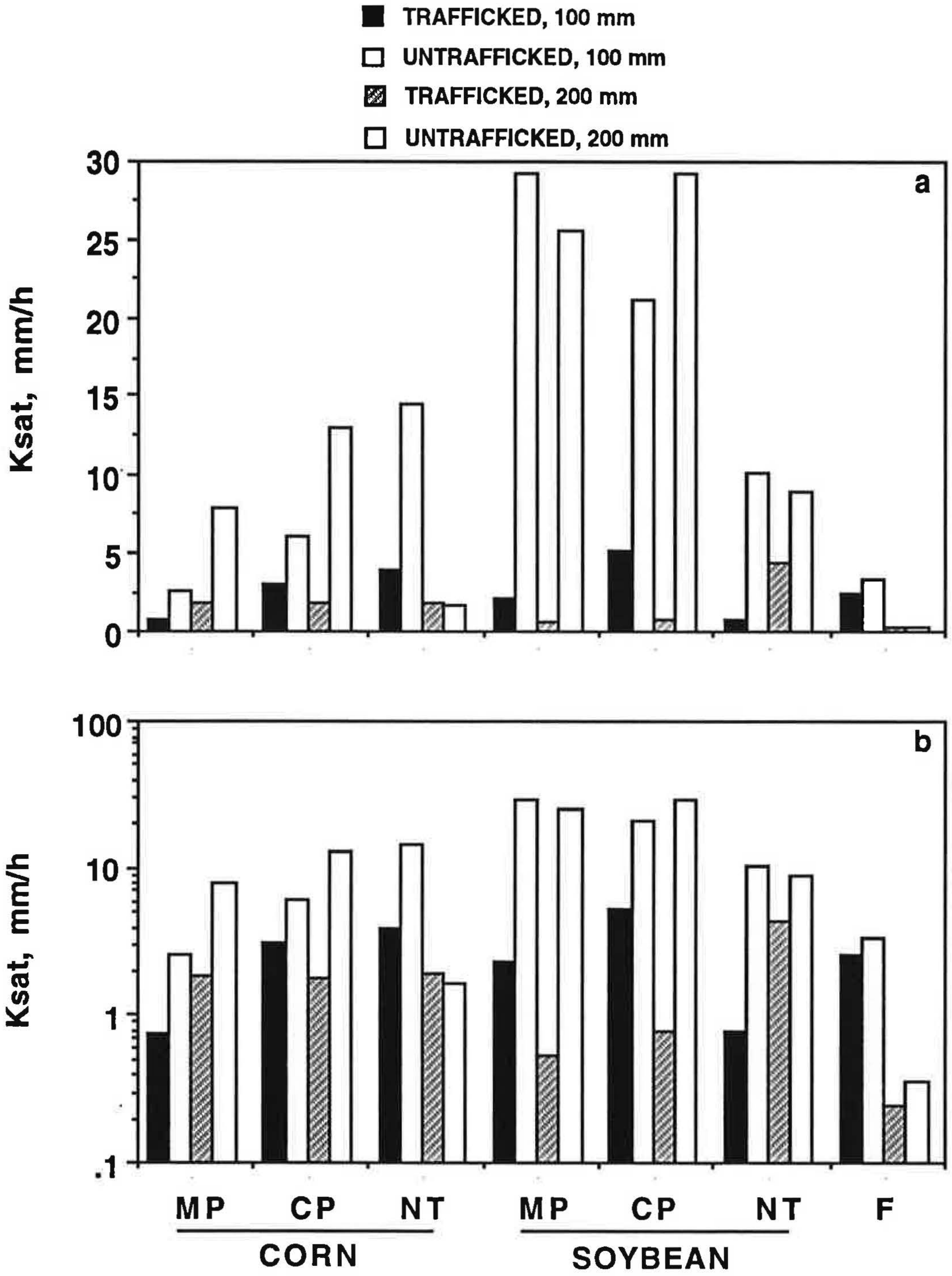
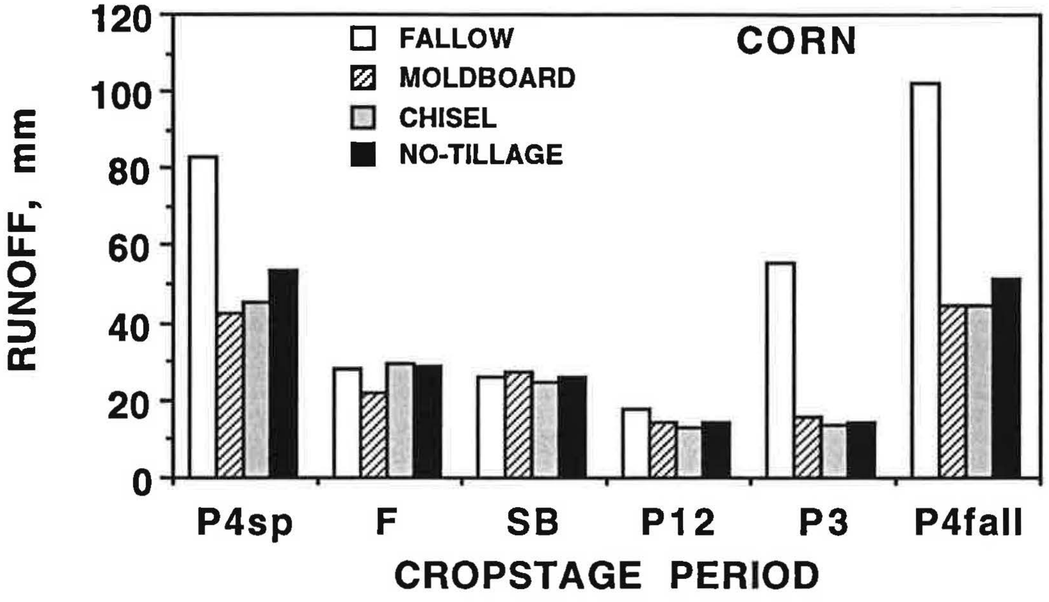


Fig. 4. Geometric mean of Ksat of the seven tillage-crop treatments plotted by depth and wheel traffic for a Mexico soil (a) normal scale and (b) log scale. F = Continuous cultivated fallow; MP = Moldboard plow; CP = Chisel plow; NT = No-tillage.



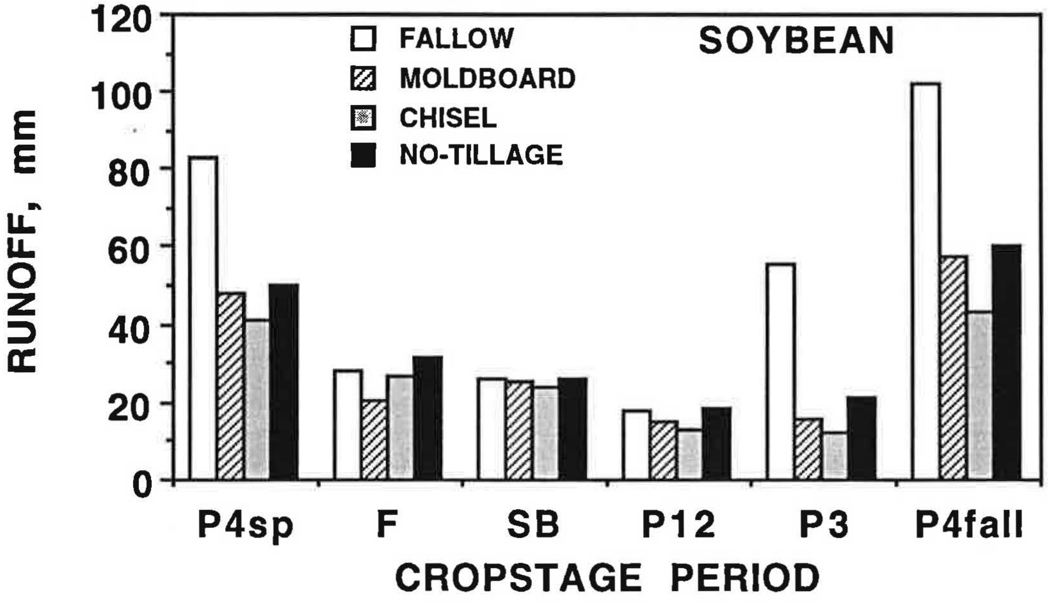


Fig. 5. Mean runoff for corn and soybean by season at the M^{c}Credie rainfall erosion plots during 1983 to 1993. P4sp = Period 4, spring; F= Rough fallow; SB = Seedbed period; P12 = Period 1 and 2; P3 = Period 3; P4fall = Period 4, fall.

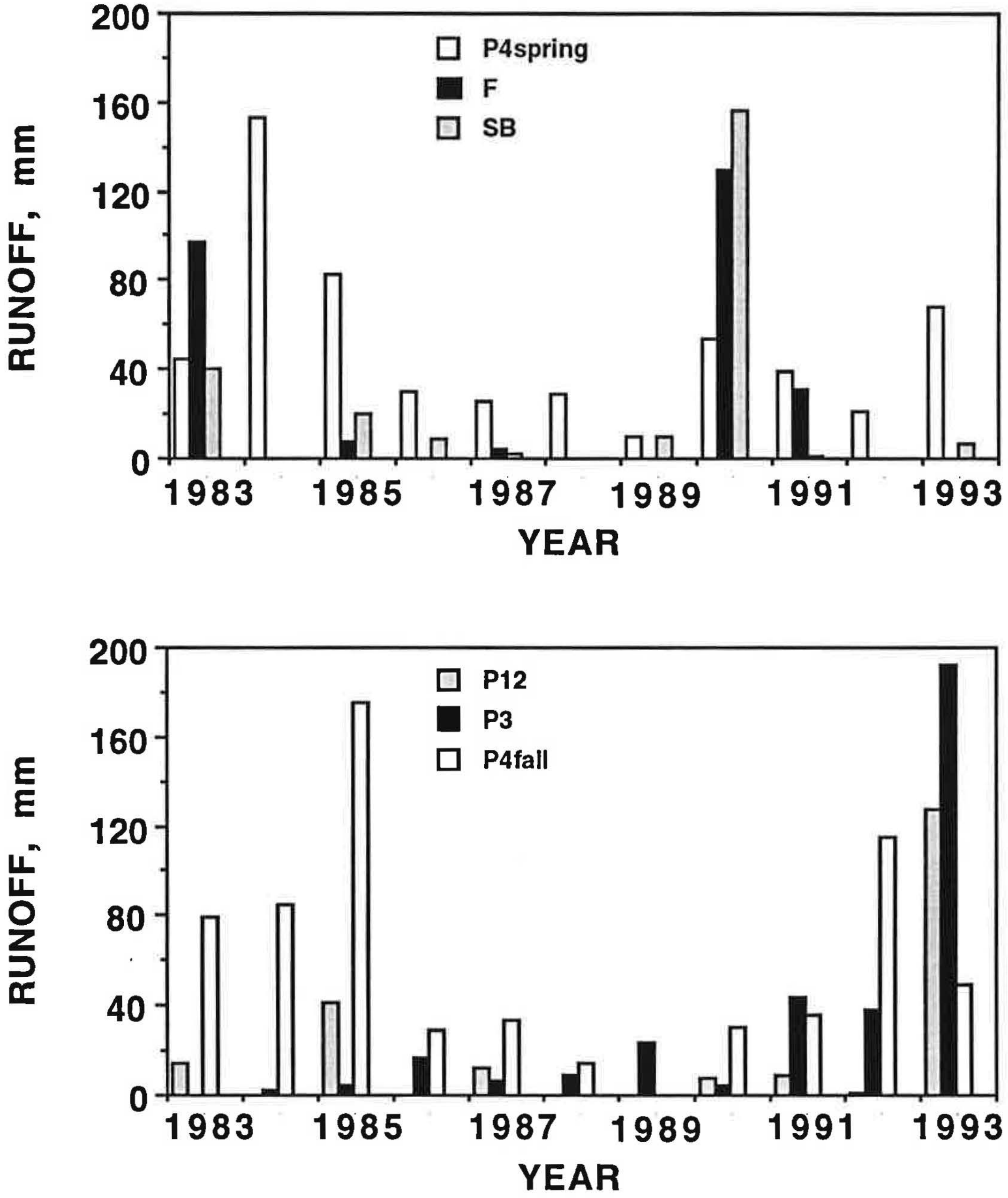


Fig. 6. Comparison of mean seasonal runoff by year for the M^{c}Credie rainfall erosion plots during 1983 to 1993. P4sp = Period 4, spring; F = Rough fallow; SB = Seedbed period; P12 = Period 1 and 2; P3 = Period 3; P4fall = Period 4, fall.

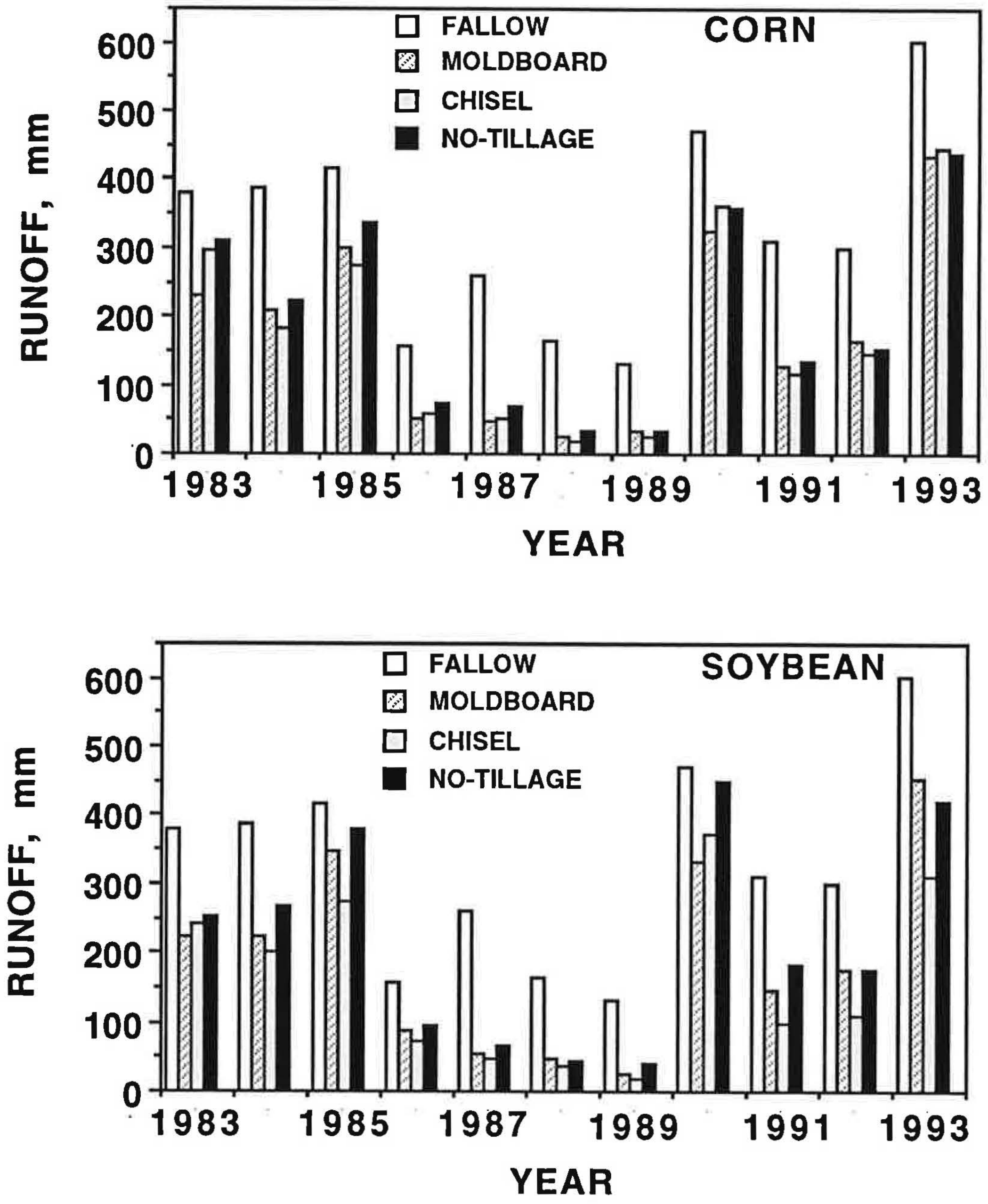
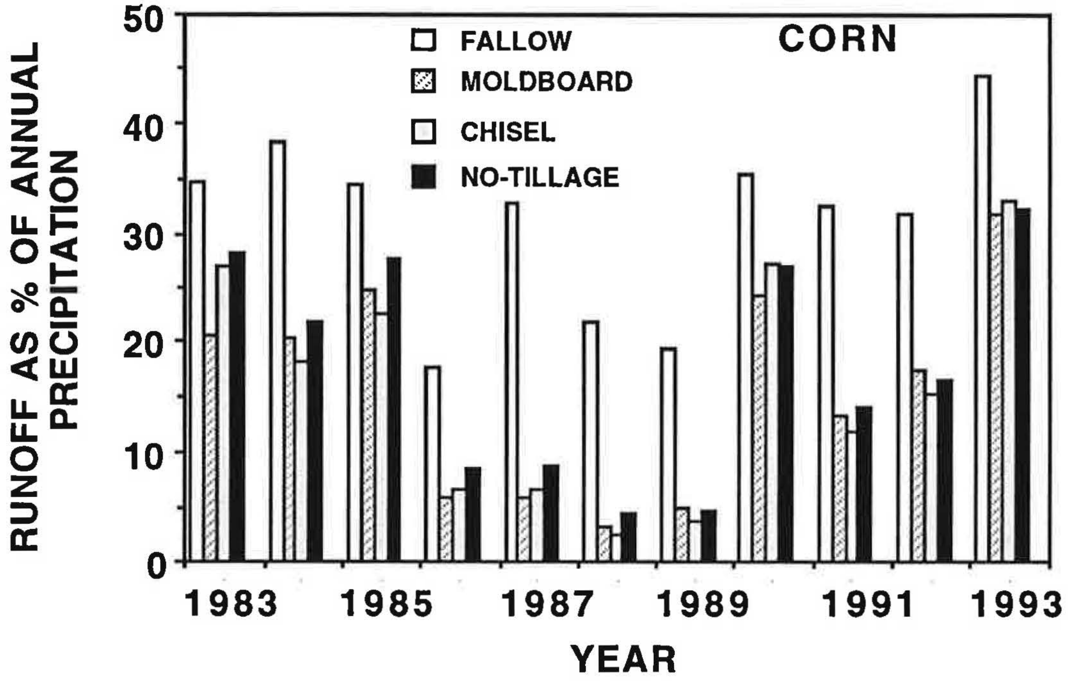


Fig. 7. Annual total runoff from corn and soybean plots for tillage treatments of moldboard plow, chisel, no-tillage, and fallow at the McCredie rainfall erosion plots.



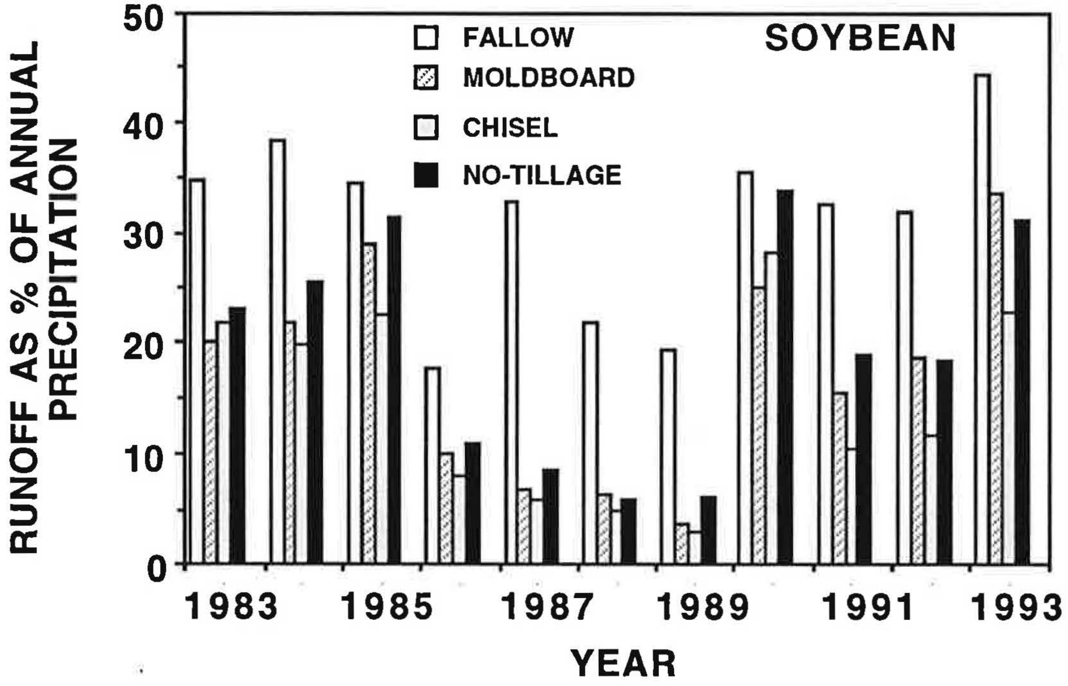


Fig. 8. Runoff as a percent of annual precipitation from corn and soybean plots for tillage treatments of moldboard plow, chisel, no-tillage, and fallow.

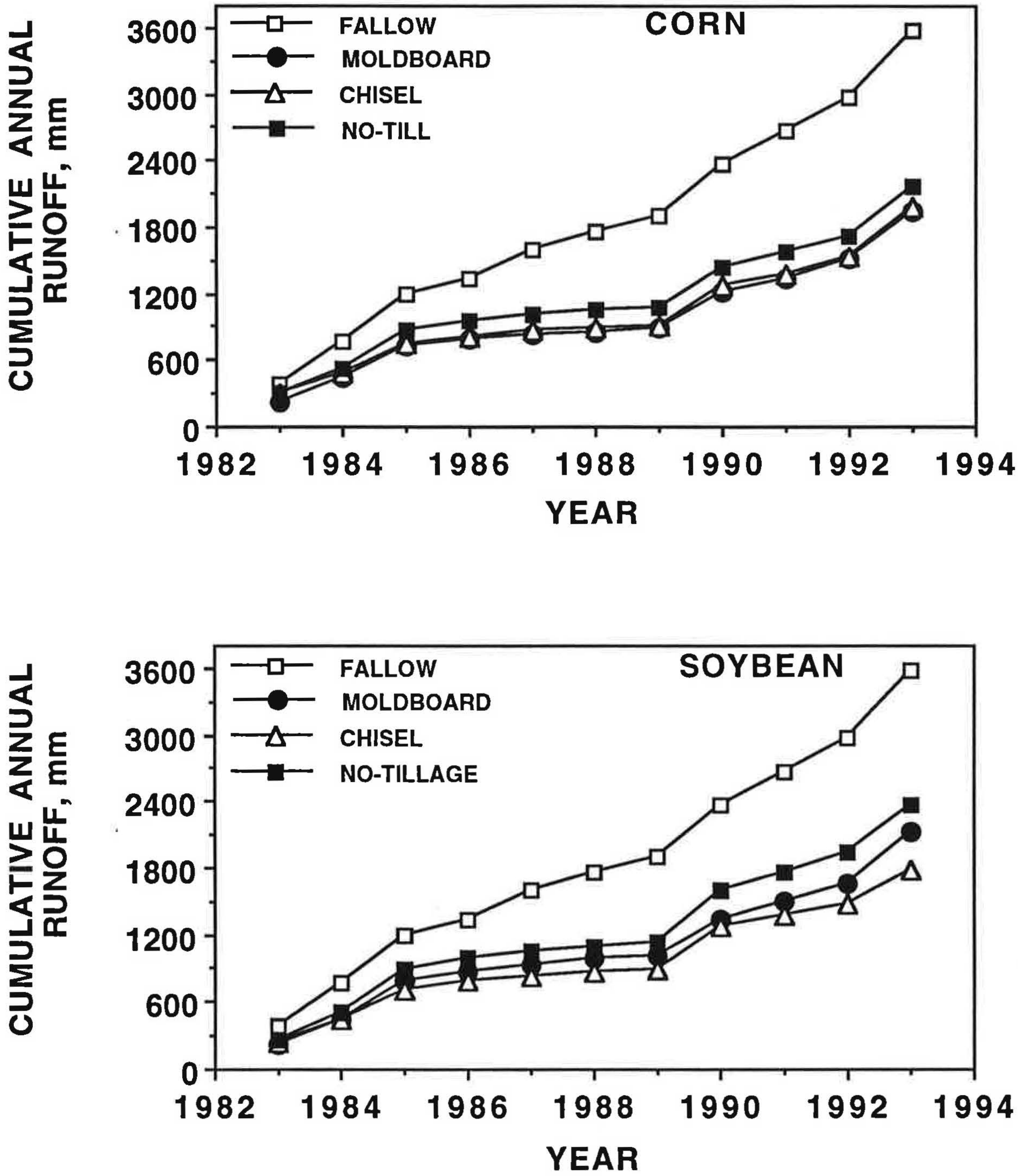


Fig. 9. Cumulative annual runoff from corn and soybean plots for tillage treatments of moldboard plow, chisel, no-tillage, and fallow at the M^cCredie rainfall erosion plots.

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November 30, 1996

Melissa Peterson, Admin. Assistant
Missouri Water Resources Research Center
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University of Missouri
Columbia, Missouri 65211

Dear Melissa:

I have enclosed the “Final Report” of my Missouri Water Resources Research Grant. Please let me know if you have any questions regarding these items.

Sincerely,

Stephen H. Anderson

Stephen H. Anderson
Associate Professor

Enclosure