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Characterization of Tillage and Traffic Effects on Unconfined Infiltration Measurements

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ABSTRACT

Tillage and wheel-traffic compaction alter pore structure and hydraulic properties of agricultural soils. These alterations will affect root growth and movement of water and solutes. This study was conducted to develop new methods needed to characterize the effects of wheel traffic and tillage on pore structure as measured by water flow through macropores. Unconfined (three-dimensional) saturated and unsaturated infiltration measurements (0-, 30-, 60-, and 150-mm water tension) at the soil surface were taken sequentially at field sites to determine the steady-state rate of water flow through different pore-size classes on a Tama silty clay loam (fine-silty, mixed, mesic Typic Argiudoll). A tension infiltrometer was used to obtain the unsaturated infiltration rates. Sites were selected on trafficked and untrafficked interrow positions in two tillage systems (chisel plow and no-till). Steady-state infiltration rates from 2 to 300 μm s^{-1} were measured. Increasing the tension of applied water resulted in decreasing infiltration rates for both tillages and traffic treatments because, as tensions increased, larger pores emptied. Wheel traffic reduced infiltration rates in both tillages, but caused a greater decrease in infiltration rates in the chisel-plow system than in no-till. Increasing tension caused proportionately smaller decreases in infiltration rates for wheel-trafficked positions. This suggests that larger macropores were transporting a greater proportion of the total water flow in untrafficked soil than in trafficked soil and reinforces the concept that larger, as opposed to smaller, pores are more easily destroyed by wheel traffic. Unconfined infiltration measurements were shown to be useful in quantifying the effects of tillage and compaction on soil macropores.

INFILTRATION OF WATER INTO SOIL is directly related to soil macroporosity. Macropores are also important for root growth (Wang et al., 1986) and for solute movement (Beven and Germann, 1982). Tillage and compaction, however, can alter soil macroporosity. Thus, to elucidate the effects of tillage and compaction on soil macroporosity, we measured the rate of water infiltration into macropores for different tillage and wheel-traffic treatments.

Macropores have been defined in several ways (Luxmoore, 1981). In this study, we define macropores as pores than empty at <150 mm of water tension. The capillary-rise equation predicts that pores of $\geq$0.2 mm nominal diameter or larger will drain at 150 mm tension. This pore-size range was selected because it includes the pore sizes important for (i) root growth and (ii) preferential solute flow. Secondary laterals of cereal root tips have an average diameter of ~0.2 mm (Hackett, 1969). A root tip growing into a pore smaller than its own diameter undergoes mechanical stress (Russell, 1977). Therefore, an estimate of pores with diameter of $\geq$0.2 mm should be correlated with unrestricted root extension, in a soil of moderate strength. Preferential solute flow also occurs in large soil pores. Scotter (1978) calculated that significant preferential flow of both strongly and weakly absorbed solutes could occur in continuous macropores with diameters >0.2 mm.

Tension infiltrometers have been used to estimate soil pore and hydraulic properties. Clothier and White (1981) and Walker and Chong (1986) used tension infiltrometer measurements to estimate sorptivity. Moore et al. (1986) and Wilson and Luxmoore (1988) measured one-dimensional infiltration rates on forest soils to estimate macroporosity and unsaturated hydraulic conductivity. Control of tension at the soil surface by a tension infiltrometer limits the size of pores that are conducting water (Clothier and White, 1981) and allows measurement of unsaturated infiltration. Imposition of sequentially greater tensions leads to the incremental draining of smaller and smaller pores. Infiltration rates decrease as more of the water-conducting pores empty. Therefore, by comparing infiltration rates at increasing tensions, the relative contributions to water flow by various pore sizes can be evaluated. Greater relative water-flow rates are assumed to indicate more and/or better-connected pores within a pore-size class. This study was conducted to determine the effects of wheel traffic and tillage on pore structure as measured by water flow through macropores.

MATERIALS AND METHODS

Unconfined infiltration rates at selected tensions were measured, using a tension infiltrometer. Measurement at multiple tensions allowed evaluation of treatment effects on different pore sizes. Three-dimensional flow measurement avoids two problems inherent in one-dimensional measurement: (i) truncation or destruction of pores caused by driving a ring or isolating a soil monolith and (ii) wall flow along the edge of the soil sample.

Field plots were established in the fall of 1984 on a Tama soil 12 km west of Marshalltown, IA. Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] were grown in rotation on the site beginning in 1985. Corn was grown in 1988 on the areas where infiltration measurements were taken. Three tillage systems (no-till, ridge, and chisel plow) with controlled wheel traffic and four replications had been established on the site. Infiltration measurements were taken only on the no-till (NT) and chisel-plow (CP) tillage systems. The NT plots received no primary tillage and were cultivated once a year; CP plots were chiseled in the fall, disked shortly before planting, and cultivated. Plots were arranged in a five-row configuration, with 76-cm rows. Foot traffic was confined to trafficked interrows throughout the year.

Infiltration measurements were made in mid-June, shortly before the 1988 cultivation. Infiltration measurements were taken in the center of trafficked and untrafficked interrows at two sites within each tillage replication. Thus, eight sites were measured in each tillage/traffic combination, for a total of 32 sites. At each of the 32 sites, steady-state (unconfined) infiltration rates were measured at four tensions: 0-, 30-, 60-, and 150-mm water tension.

At each infiltration site, an area approximately 25 to 30

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cm in diameter was cleared with a hand trowel to a depth of 20 to 30 mm, and leveled. Minimal compaction and smearing occurred, because of the dry initial conditions. Two layers of cheesecloth were placed on the soil surface before wetting, to minimize slaking of soil into the macropores. Flow measurements were taken from low to high tension (0 to 150 mm) on a 7.62-cm diameter circular area on the cleared soil surface. To delimit the surface infiltration area, a 7.62-cm diameter inner ring approximately 1.5 cm high was pushed 0.5 cm into the soil. The ring was sharpened to make insertion into the soil easier. A concentric outer ring, 1 cm high, and sleeved tightly on the inner ring, acted as a depth stop for the 1.5-cm ring, to attain a 0.5-cm deep insertion into the soil.

The 7.62-cm-diameter inner ring served as a single-ring infiltrometer for saturated-infiltration measurements (Bouwer, 1986). The infiltrometer consisted of a Mariotte bottle equipped with a pair of pressure transducers to measure infiltration rates (Ankeny et al., 1988) and a water outlet tube placed into the ring, to supply water to the soil surface. Water was ponded on the surface to a height of ~0.5 cm in the ring for at least 15 min before the start of measurements. After prewetting to obtain a steady-state rate, infiltration was monitored for 1000 s (250 measurements at 4-s intervals).

When the saturated measurements were complete, the supply tube from the Mariotte bottle was removed from the infiltrometer ring. The ring was filled with a fine sand and leveled with a straight edge. A tension infiltrometer, preset at 30 mm tension, was then gently placed in contact with the sand. The infiltrometer was anchored by pushing four sharpened, threaded rods at the corners of the base of the infiltrometer into the soil. The anchor rods prevented rocking of the infiltrometer by wind gusts. Unsaturated infiltration was monitored for 1000 s at 4-s intervals.

After data at 30 mm tension were recorded, the tension was increased (without moving the device) by closing the 30-mm-tension port and opening the 60-mm-tension port on the bubble tower of the infiltrometer. This procedure was then repeated for the 150-mm-tension setting. Recording of data (time = 0) did not begin until after the bubble tower bubbled. Bubbling indicated that the desired tension at the soil surface had been attained. The interval before bubbling at the increased tension varied from nearly zero for sites and tension settings with high infiltration rates to approximately 5 min for sites and setting with lower infiltration rates. After completion of infiltration measurements at all four tensions at a site, a 7.62-cm soil core was taken at the site of infiltration and visually examined for root growth and visible macropores. The design of the experiment was a split-split plot, with tillage as the main plot, wheel traffic the first split, and tension the second split. Tillage and traffic were class variables, and tension was used as a regression variable. Both infiltration rate and tension were log transformed to linearize their relationship.

RESULTS AND DISCUSSION

An example of unconfined-infiltration data from one field site is shown in Fig. 1. This figure shows cumulative water infiltration at four tensions into a chisel-plow untrafficked interrow site. Infiltration rates are almost constant throughout the 1000-s measurement period for all tensions, showing steady-state flow existed. Time zero usually started within five minutes after a switch in tension. Each increase in tension causes a decrease in infiltration rate, with the largest decrease in rate occurring between 0 and 30 mm tension. Steady-state infiltration rates were calculated from the slopes of the regression of cumulative infiltration vs. time for the last 500 s of infiltration at each tension. Mean rates varied from approximately 300 μm s^{-1} down to approximately 2 μm s^{-1} across the 16 treatment and tension combinations.

Table 1. Mean squares (MS) from the analysis of infiltration data from unconfined infiltration into a silty clay loam soil for natural-log transformed infiltration rates and tensions. Both linear (lin) and lack of fit (lof) components of the analysis are presented.

Source of variation	df	MS	*F*
Replication	3	0.0108	0.66NS
Tillage (Till)	1	0.1072	6.52NS
Error A	3	0.0163	–
Traffic (Trf)	1	14.786	219 **
Tillage × Traffic	1	0.4681	6.96*
Error B	6	0.0673	–
Tension$_{lin}$	1	8.6529	1055 **
Tension$_{lof}$	2	0.0565	0.70NS
Tension$_{lin}$ × Till	1	0.2944	35.9 **
Tension$_{lof}$ × Till	2	0.0028	0.34NS
Tension$_{lin}$ × Trf	1	0.7877	96.1 **
Tension$_{lof}$ × Trf	2	0.0384	4.68*
Tension$_{lin}$ × Trf × Till	1	0.0344	4.20*
Tension$_{lof}$ × Trf × Till	2	0.0078	0.95NS
Errors (residual)	36	0.0082	–

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

Both the main effect of wheel traffic and the interaction of tillage and wheel traffic were significant (Table 1). Wheel traffic reduced infiltration at all tensions in both tillages, but reduced infiltration more in the CP plots than in the NT plots (Table 2). Averaged across wheel-traffic treatments, however, the main effect of tillage on infiltration was not significant.

The response of infiltration rates to changes in water tension was analyzed by examining the linear regression of the natural log of infiltration rates on the natural log of tension (Fig. 2). Increasing tension decreases the infiltration rate because increasing tension reduces the size and number of pores conducting water. The ln–ln transformation, initially used by Wind (1955), was effective in linearizing treatment effects. Ahuja et al. (1980) and Schuh et al. (1984) also have used a similar transformation for tensions greater than the air-entry value. The largest pores visually observed on the infiltration surface in the field had a diameter of ~6 mm. From the capillary rise equation, the calculated nominal air-entry value for a

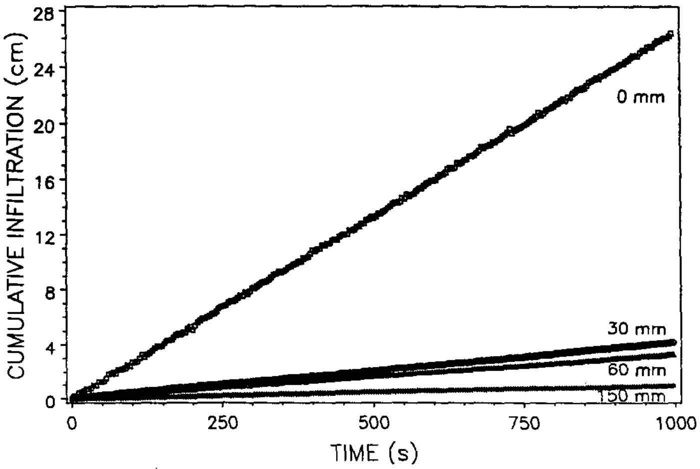

Fig. 1. Cumulative water infiltration at four tensions for a chisel-plow untrafficked interrow site on a silty clay loam.

Table 2. Summary of means and coefficients of variation for unconfined saturated and unsaturated infiltration rates into a silty clay loam, under various tillage and traffic treatments.

Treatment	Tension	Infiltration rate	CV_{rate}
	mm water	μm s^{-1}	%
Untrafficked, no till	0	232.5	47
	30	53.2	46
	60	31.5	35
	150	9.6	35
Trafficked, no till	0	22.5	53
	30	6.7	35
	60	4.7	37
	150	3.1	31
Untrafficked, chisel plow	0	292.6	44
	30	53.8	21
	60	34.4	16
	150	12.5	28
Trafficked, chisel plow	0	9.8	65
	30	4.4	46
	60	2.9	37
	150	2.2	32

Table 3. Slopes and intercepts for regression of ln infiltration rates (μm s^{-1}) vs. ln tension (mm water).

Treatment	Slope (m)	Intercept (ln b)	SE of slope
No-till, no traffic	−.881	4.95	0.062
No-till, trafficked	−.566	3.67	0.045
Chiseled, no traffic	−.887	5.05	0.045
Chiseled, trafficked	−.425	3.22	0.052

6-mm-diameter pore is 5 mm water tension. This value was used in place of zero for the ln transformation of tension. Although the largest pores observed in the field were ~6 mm, the placement of the ponded rates on Fig. 2 is still rather arbitrary. However, whether these points are moved higher or lower on the x axis or omitted altogether, the conclusions are the same, as can be seen by inspection of Fig. 2 with the saturated values omitted. The linearity obtained by the ln-ln transformation indicates that the relationship between infiltration and tension can be expressed in the form $y = bx^m$, where y is the infiltration rate and x is tension. The ln b and m (Table 3) are the intercept and slope, respectively, of the linear regression equation for the ln-ln transformed data. Because infiltration rates decrease with increasing tensions, the m slopes are negative.

The significant interaction between wheel traffic and linear component of the sums of squares for log tension (tension_{lin}) in Table 2 indicates that wheel traffic altered the pore structure. Infiltration rates in untrafficked rows decreased more dramatically with increasing tension than infiltration rates in trafficked interrows (Table 2). Evidently, larger pores (i.e., those that drain at lower tensions) were conducting a greater percentage of water in untrafficked interrows than in trafficked interrows. Therefore, wheel traffic preferentially destroyed and/or prevented the formation of the large macropores that would conduct water at tensions of less than 150-mm water tension. Although infiltration rates declined more rapidly with increased tension in untrafficked sites, the absolute rate was still higher than in trafficked sites. Thus, although traffic reduced the number of water-conducting pores at all measured tensions, traffic destroyed a smaller percentage of the smaller water-conducting pores and a larger percentage of the larger pores. Culley et al. (1987) reported saturated hydraulic conductivity values of undisturbed cores from both trafficked and untrafficked interrows on both a conventional-tillage and a no-tillage treatment. They obtained the same saturated-flow-treatment ranking as this experiment. The highest flow rates were in the conventionally tilled, untrafficked interrows, followed by the no-till, untrafficked interrows, followed by no-till, trafficked interrows. The conventionally tilled, trafficked interrows had the lowest infiltration rates in both studies.

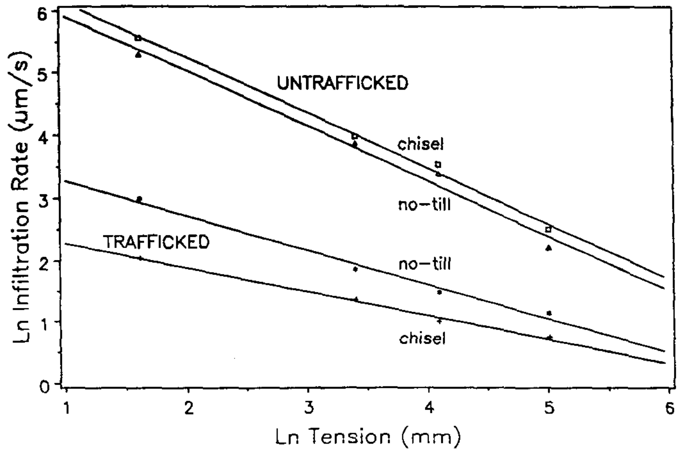

Fig. 2. Plot of the natural log of the unconfined infiltration rate means ($n = 8$) vs. the natural log of tension for traffic and tillage combinations on a silty clay loam.

Lastly, the interaction between wheel traffic and tillage and tension also was significant (Table 1). Trafficked interrows in NT had greater decreases in infiltration rates with increased tension than did trafficked interrows in CP plots. These data indicate that larger pores were conducting relatively more water in trafficked interrows in NT than in CP plots. Both tillage systems had been cultivated for weed control in the previous summer, but the CP treatment was also chisel-plowed in the fall and disked before planting. Wheel traffic at planting caused deeper ruts in CP interrows than in NT interrows. Neither tillage treatment was disturbed between planting and the infiltration measurements. Thus, the reduction in large water-conducting pores in the trafficked interrows of the CP treatment probably resulted from greater soil compaction by wheel traffic of the tilled soil than of the untilled soil at planting. Culley et al. (1987) reached the same conclusion for a more poorly drained soil.

Measurements could be taken from high to low tension as well as from low to high tension. However, in the initially dry conditions that we encountered, prewetting at 150 mm tension would have required a longer time to wet the soil and minimize the effect of the antecedent water potential.

Visual observations of macroporosity (primarily root channels, with some wormholes and cracks) related well to observed infiltration rates. Roots were just beginning to reach the middle of the interrow when measurements were made. In general, soil samples with many roots had higher infiltration rates and lower bulk densities than samples with few roots. The sample with the most roots, however, had a fairly low infiltration rate, probably because the macropores were filled with roots. This observation suggests that, over a growing season, changes in water infiltration patterns through macropores caused by root occlusion may be important. If these changes are large, then both sampling schemes and infiltration models may need to account for this temporal variation in infiltration.

There are two sources of error in the estimation of steady-state infiltration rates (Elrick et al., 1988): (i) not reaching a final steady-state rate and (ii) errors in rate measurement (instrument error). Elrick et al. (1988) suggested, based on a simulated flow, that the approach to a steady-state infiltration rate for a well permeameter may take less than 30 min in a permeable soil but could require 6 h or more in a slowly permeable soil. We therefore determined infiltration rates for time subsets of each infiltration run, to see if rates were still decreasing with time. The rate obtained from the 500- to 750-s data subset was compared with the rate from the 750- to 1000-s subset. Only some trafficked sites at zero tension showed a rate decrease that could be detected beyond measurement error, indicating that saturated infiltration rates of those sites were overestimated. Longer prewetting of less-permeable sites seems necessary to obtain more accurate steady-state rates. Errors in rate measurement (e.g., the noise around each line in Fig. 1) are small, relative to rates measured on different sites. The CVs for individual rate measurements at a given site and tension were typically about 0.5 to 5.0%.

Wilson and Luxmoore (1988) suggested that the variability of infiltration rates did not decrease at higher tensions, and they concluded that smaller macropores are as variable as larger pores. This is inconsistent with the conclusions of Clothier and White (1981). The extent of errors in rate measurement, however, are unknown in these studies. Therefore, without knowledge of both rate measurement variability and site variability, the cause of variability in infiltration rates when comparing pore-size classes cannot be determined. At this particular location, we found that infiltration variation due to sites is approximately an order of magnitude larger than the variation due to imprecision in a rate estimate. The CV of the treatment mean slopes (Table 3) varied from 19 to 34%, while the CV of steady-state infiltration for an individual tension within a treatment varied from 16 to 65%.

CONCLUSIONS

Unconfined infiltration measurements proved useful in quantifying the effects of tillage systems and wheel traffic on soil structure. The new field methods are capable of measuring infiltration across the tension range of primary interest for root growth and preferential solute movement. Separation of measurement error from experimental error allows comparisons of variability and should improve the efficiency of future experiments.

Tillage had little effect on infiltration rates per se. Wheel traffic greatly reduced infiltration in both tillages. The CP tillage, however, was more susceptible to wheel-traffic compaction than was NT. Compaction destroys a larger percentage of pores carrying water at low tension (large pores) than of pores carrying water at higher tensions (smaller pores). Wheel traffic at planting caused compaction that minimized any soil loosening from tillage.

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