Infiltration Rate of a Sandy Loam Soil: Effects of Traffic, Tillage, and Plant Roots

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ABSTRACT

Settling and trafficking of a soil after tillage causes rapid changes in the soil physical condition until a new equilibrium is reached. In the soil studied, a Wasco (coarse-loamy, mixed, nonacid, thermic Typic Torriorthent) sandy loam, soil compaction reduces infiltration rates, which under grower conditions could result in inadequate infiltration of irrigation water to supply crop requirements. Our objective was to evaluate important management practices as they relate to changes in the infiltration rate of a sandy loam soil. Factors evaluated were traffic, tillage between crops, and the formation of channels by roots of perennial crops. Tillage between crops increased the infiltration rate during the first part of the season in trafficked soils but decreased or had no effect on nontrafficked soil. Alfalfa (*Medicago sativa* L.) increased the infiltration rate fourfold during a 2-yr period in a heavily compacted soil. An increase in bulk density from 1.6 to 1.8 Mg m^{-3} decreased infiltration rate 54% in the field. Hydraulic conductivity of undisturbed cores was at least seven times larger than that measured in columns of disturbed soil (same bulk density). This difference is believed to be the result of natural channels in the undisturbed soil that are destroyed when the soil is disturbed. Under controlled traffic, when surface seal is not a problem, tillage will not be necessary to obtain adequate infiltration rates except in the wheel paths.

THE MAJOR EFFECT of soil compaction in an irrigated sandy loam soil may be the reduction in infiltration rate resulting in the infiltration of insufficient water (Goldhammer and Peterson, 1984). When a sandy loam soil is tilled, the infiltration rate will be increased because of the lower bulk density but decreased because large-pore continuity will be disrupted, and the importance of these two factors will depend on the level of compaction of the soil (Kooistra et al., 1984). Infiltration rate of a sandy loam soil that has been compacted will usually be correlated with bulk density (Agrawal et al., 1987). Infiltration rate of a tilled soil may improve with time when cropped if tillage is eliminated (Parker and Jenny, 1945). The proper use of tillage, control and timing of traffic, and selection of crops will allow a grower to maintain adequate infiltration levels so that adequate irrigation water can be applied.

Tillage may increase or decrease the infiltration rate depending on the degree of soil compaction. Allmaras et al. (1977) measured unsaturated hydraulic conductivity (K) values that were increased at least fourfold by chiseling 0.43 m deep compared with an untilled check. Burch et al. (1986) measured enhanced infiltration of simulated rain when the level of tillage disturbance was reduced and suggested that the increase may have been caused by changes in the surface seal. Lai (1978) measured infiltration rates of 480 mm h^{-1} for no-till and 150 mm h^{-1} for the plowed treatment after a field had been planted in maize (*Zea mays* L.) for 5 yr. They found that surface residues prevented surface seal in the no-till treatments. The manner in which recently tilled soil is settled may affect infiltration rate. Meek et al. (1989) measured a 17% increase in infiltration rate in the field when soil was packed lightly before the first flood irrigation compared with no packing.

Compacting loads of 335 kPa at field capacity on a sandy loam soil reduced infiltration rates to <1% of the rate obtained when the soil was compacted air dry (Akam and Kemper, 1979). Increases in bulk density usually result in large decreases in water flow through the soil. Patel and Singh (1981) reported that, if the bulk density in a course-textured soil was increased from 1.7 to 1.9 Mg m^{-3}, hydraulic conductivity decreased by a factor of 260. Meek et al. (1992), using the same soil, measured a decrease in infiltration rate of four times when traffic compacted a soil from a bulk density of 1.7 to 1.89 Mg m^{-3}. The soils studied by Patel and Singh (1981) and Meek et al. (1992) compact to high bulk densities since they are sandy with low organic matter.

Tillage disturbs natural channels that have formed in soil. The increase in porosity when soil is tilled may not result in an increase in infiltration rate because of disruption of the vertical continuity of the pores (Kooistra et al., 1984). Plant roots are important in forming new channels (Parker and Jenny, 1945). Root growth initially may decrease infiltration rates (Barley, 1954), but later decomposition of roots leaves channels that result in increased infiltration rates. Meek et al. (1989) measured increases in infiltration rate that were related to decreases in stand density under alfalfa. Disparte (1987) measured a positive correlation between increases in infiltration caused by the type of crop and size of tap root.

We carried out several infiltration studies on the same soil for several years. Our objectives were to: (i) evaluate the effect of timing of traffic and tillage on the infiltration rate of a sandy loam soil; (ii) determine the relationship between bulk density and infiltration rate; and (iii) evaluate the contribution to water flow of natural channels formed by plant roots.

MATERIALS AND METHODS

Plot Establishment and General Procedures

Wasco sandy loam has minimal shrink–swell characteristics and is not subjected to freezing. Unilateral compression at 200 kPa resulted in a bulk density of 1.72 Mg m^{-3} at a soil moisture of 0.131 g g^{-1}, which is equivalent to a matric potential of −10 kPa, and a bulk density of 1.65 Mg m^{-3} at a soil moisture of 0.058 g g^{-1}, which is

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Abbreviations: WTRV, wide tractive research vehicle; SD, standard deviation.

equivalent to a matric potential of −100 kPa. All field experiments were conducted within a 10-ha area.

Tillage was done in the same manner to start each of the experiments. This extensive tillage was done to remove the effects of previous cultural practices. All plots were chiseled to a depth of 0.54 m on 0.33-m centers using a WTRV that spans 10 m, so that no wheel traffic was applied in the plot. Wheel traffic was applied to traffic treatments using a wheel frame mounted on the WTRV that could be moved laterally along the frame to positions where the wheel tracks were to be located and on which the force on the wheel could be controlled to simulate tractor wheel loads up to 2900 kg. The WTRV allowed cultural operations to be conducted during the season without the requirement of applying wheel traffic to the plots.

Bulk density was measured using a two-probe density gauge (Model 2376, Troxler Lab., Triangle Park, NC)[1] in parallel 0.30-m-spaced Al access tubing. Equation [3] presented by Rawitz et al. (1982) was used to calculate bulk density using an unattenuated count rate (I_o = 316 000) and mass attenuation coefficients suggested by them for soil and water. Volumetric water content is part of the equation and was measured using a Troxler neutron probe.

Infiltration rates were measured, except for the furrow-irrigated experiment, by surrounding the complete plot with a border, flooding the plot rapidly, and measuring the decrease in water level with time using a hook gauge. Infiltration time was started when 50% of the soil surface was flooded and readings were taken at 16, 25, 36, 49, 64, 81, 100, 121, 144, 169, and 196 min or until the soil surface was no longer covered with water. Infiltration rates were plotted as a function of time and the rate 2 hr after water was applied was used.

Effect of Traffic and Tillage

The effects of traffic and annual tillage were evaluated in plots 9 by 30 m in a field that was tilled in 1983 to start the experiment. Cotton (*Gossypium hirsutum* L.) was grown in 1983, 1984, and 1985 on beds with 1-m centers. The cotton was furrow irrigated during the season. Infiltration was measured by the furrow advance method (DeTar, 1989). Traffic was applied in each furrow to the appropriate plots during the planting, cultivation, and harvesting operations. Weights were adjusted to reflect the weight of the equipment used for the different operations. Annual tillage was applied to the appropriate plots before the 1984 and 1985 crops. This tillage was done in the same manner as that done before starting each of the experiments. Treatments were replicated 10 times in a randomized complete block.

Effect of Alfalfa Plants

The effect of alfalfa plants on infiltration rate of compacted soils was evaluated in field plots 9 by 20 m that were compacted to three levels and planted in alfalfa in April 1986. Compaction levels were (i) light (six plots), (ii) medium (six plots), and (iii) heavy (12 plots). Tire pressures for the three treatments were 41, 138, and 276 kPa, respectively and wheel weights were 1362, 2950, and 2770 kg respectivley. Traffic (1814-kg load) was applied during each harvest to half of the heavily compacted plots for a total of 24 plots (six replicates and 4 treatments). Soil was compacted at a soil moisture (0–2 m depth) of 0.09 g g^{-1} (SD = 0.008) for the light treatment (plots had received only winter rainfall) and a soil moisture of 0.12 g g^{-1} (SD = 0.006) for the other treatments. The alfalfa was harvested with the WTRV with no traffic applied to the plots except for the six plots receiving harvest traffic. Detailed cultural practices are given in Rechel et al. (1991). Bulk density was measured at three locations in each plot in April 1986 after alfalfa was planted, and in May 1988. Channels in the soil were measured by driving a 300 mm long by 200-mm-diam. steel cylinder into the soil to the 150-mm depth. One thousand milliliters of a 0.5% (w/w) aqueous solution of methylene blue was added to each cylinder and infiltrated in ≈20 min. The next day the cylinder was removed from the soil, inverted, and the number and diameter of the stained pores at the bottom of the cylinder were measured. One measurement was made in each of four replicates.

[1]References to brand names or companies is made for information purposes only and does not imply endorsement of these companies or brands over any other company or brand.

Bulk Density vs. Infiltration

The relationship between infiltration rate and bulk density for a rotation using annual crops was determined in 1986 in a field planted in cotton. Black-eyed pea [*Vigna unguiculata* (L.) Walp.] had been grown the previous year (1985), and no perennial crops had been grown in the previous 10 yr. The field was divided into 16 plots (four treatments and 4 replicates) each 9 by 20 m. The field was compacted to four levels before planting and no wheel traffic was applied to the plots during the season. Tire pressures for the four treatments were 48, 69, 172 and 276 kPa and wheel weights were 1293, 2297, 2906, and 2746 kg, respectively. Soil was compacted dry for the light treatment (plots had received only winter rainfall) and soil moisture was at field capacity for the other treatments. Cotton was grown flat, with the rows on 1-m centers. Bulk density was measured in June and November 1986. Infiltration rate was measured in July 1986.

The relationship between infiltration and bulk density for a cropping system that included a perennial crop was determined in a field where alfalfa was planted in the fall of 1982 and maintained until cotton was planted in 1988. No tillage was done from October 1982 until 1988. Shallow tillage to the 150-mm depth was done in one-half of the plots when the cotton was planted in 1988. Detailed procedures are given in Meek et al. (1990). Bulk density was measured in October 1988.

Bulk Density vs. Hydraulic Conductivity

The relationship between bulk density and hydraulic conductivity for undisturbed cores was determined on soil cores collected in 1985 from a field with 3-yr-old alfalfa that had been subjected to various levels of compaction (treatments given in Meek et al., 1989). Saturated hydraulic conductivity was determined on the cores after flushing the soil with CO_2. Hydraulic conductivity was determined for four treatments and six replicates on cores from the 0.02- to 0.11- and 0.20- to 29-m depths and the values averaged for the six replicates. Detailed procedures for the collection and treatment of the cores are given in Meek et al. (1989).

The relationship between bulk density and hydraulic conductivity for disturbed soil was determined in 0.18-m diam. soil columns. Soils were collected in 1988 from the same field as the undisturbed cores and adjusted to soil moisture contents ranging from 5.3 to 9.7% by weight. Sufficient soil was added to equal a 40-mm depth of packed soil, and it was packed with a 2.5-kg drop hammer falling 20 times from a height of 0.30 m. Additional layers of soil were added and packed until ≈0.26-m depth of soil was packed. The top 10 mm of each layer was broken up with a knife before soil was added for the next layer. The same force was used for packing each column, but the variation in moisture between columns resulted in a range of bulk densities from 1.52 to 1.88 Mg m^{-3}. To prevent surface seal, sand was added to the top of the column to form a layer 20 mm deep. The column was wet by flooding the soil surface and maintaining a constant head. During the constant-head permeameter tests, a 20-mm head of water was maintained above the surface of the sand and, after equilibrium, the outflow was measured and used to calculate hydraulic conductivity.

RESULTS

Traffic Level and Annual Tillage

Traffic during the season and no tillage following the previous crop resulted in lower infiltration rates at the start of the season in 1984 and 1985, compared with other treatments (Fig. 1). Bulk-density levels at the end of the season in the furrow at the 0.25- to 0.35-m depth were 1.62 (no tillage, no traffic), 1.60 (tillage, no traffic), 1.80 (no tillage, traffic), and 1.68 Mg m^{-3} (tillage, traffic) (Meek et al., 1992). Tillage between crops increased the infiltration rate of soil receiving traffic during the first part of the season and this effect may be the result of the 0.12 Mg m^{-3} reduction in bulk density (0.25–0.35-m depth) compared with no tillage with traffic. The tillage effect was different for nontrafficked plots where bulk densities were not significantly affected by tillage. Tillage did not increase and sometimes decreased the infiltration rate during the season when the soil was not trafficked. Disruption of natural channels by tillage could explain this decrease in infiltration in the nontrafficked soil. The amount of water infiltrated and the differences between treatments became less with time during the season, with the data for 1984 and 1985 being similar. The reason for this seasonal decrease is probably surface seal development and consolidation, which would become more important with time. The infiltration rate of nontrafficked soil was not improved by tillage; therefore, tillage could be restricted to trafficked areas, which could be reduced by controlled traffic.

Effect of Alfalfa Plants on Infiltration Rate

Alfalfa growth increased the infiltration rate of both compacted and noncompacted soil with time (Fig. 2). Bulk-density levels measured in April 1986 were 1.76 for the low treatment, 1.88 for the medium treatment, and 1.92 Mg m^{-3} for the heavy treatment with or without harvest traffic, and the levels measured in May 1988 were similar. There was a significant increase in infiltration rate each year and the average rate for all treatments increased by 488% from July 1986 to October 1988. The increase in infiltration rate from 1986 to 1988 was 442% for the lightly compacted treatment compared with 534% for the heavily compacted treatment without harvest traffic. Traffic applied to the heavy compaction level had no significant effect on infiltration rate. Because of the debris left on the soil surface after alfalfa harvest, soil seal should not have been an important factor controlling infiltration rate. Bulk-density changes during the experiment were small and would have had minor effects on the infiltration rates. During the 2 yr, living crowns decreased from 247 to 43 crowns m^{-2}, which left many old root channels available for water flow which were observed after staining. Earthworm activity would not have contributed to the formation of channels because these soils have low populations. Pits were dug by hand to the 600-mm depth in each of 24 plots in the adjacent field and no earthworms were found. Meek et al. (1990) found that this increase in infiltration rate caused by alfalfa could result in a higher infiltration rate for the next crop under no-till or shallow tillage.

Pores that conducted the methylene blue solution past the 150-mm depth had an average diameter of 4 mm and many were partially filled with plant material (Table 1). The number of pores measured in this study (all data combined) was 40 m^{-2}, which was much less than those measured in the adjacent field (Meek et al. 1989), but the adjacent field measurements were made after 4 yr of alfalfa instead of 2 yr for this study.

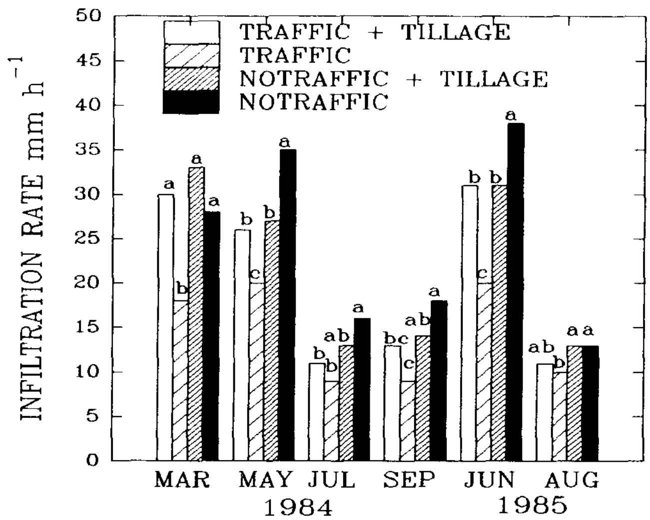

Fig. 1. Effect of tillage between crops and traffic applied during the season to the furrows on the infiltration rate 2 h after flooding in furrow-irrigated cotton. Values within one date followed by the same letter are not significantly different (Duncan's multiple-range test, 0.05 level).

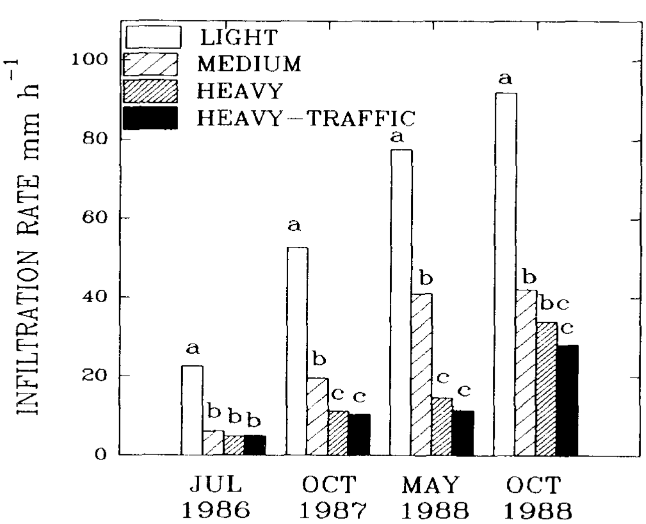

Fig. 2. Effect of alfalfa culture with time on the infiltration rate 2 h after flooding as influenced by compaction level and traffic. Values within one date followed by the same letter are not significantly different (Duncan's multiple-range test, 0.05 level).

Table 1. Effect of alfalfa plants on number and diameter of stained pores† at the 150-mm depth measured in February 1988 using methylene blue.

	Replicate 1			Replicate 2			Replicate 3			Replicate 4		
Compaction	Total pores	Diameter	Open‡ pores	Total pores	Diameter	Open pores	Total pores	Diameter	Open pores	Total pores	Diameter	Open pores
	no.	mm	%	no.	mm	%	no.	mm	%	no.	mm	%
Light	2	1	100	1	5	100	1	3	100	2	2	100
		2	50								5	20
Medium	2	4	100	1	10	10		none		4	1	20
		5	100								2	100
											3	100
											3	50
Heavy		none		1	2	50		none		2	2	100
											6	50
Heavy + traffic	3	2	50		none			none		1	2	50
		2	10									
		3	50									

† Pores were measured in an area of 31 400 mm^2 and were 1 mm in diam. or larger.
‡ Many of the pores had root material in them and the percentage give a visual estimation of the amount of the pore area that was open for water flow.

Relationship between Hydraulic Conductivity and Bulk Density

Hydraulic conductivity was correlated with bulk density in columns of disturbed soils (Fig. 3a) and in undisturbed cores collected in the field (Fig. 3b). The infiltration rate was much higher for the undisturbed cores than for the disturbed soil. At a bulk density of 1.6 Mg m^{-3}, the rate was 86 compared with 12 mm h^{-1} for the disturbed soil and, at a bulk density of 1.8 Mg m^{-3}, the rate was 36 compared with 1.7 mm h^{-1} for the disturbed soil.

An 86% decrease in hydraulic conductivity was measured when bulk density was increased from 1.6 to 1.8 Mg m^{-3} in the disturbed soils. In undisturbed cores, an increase in bulk density from 1.6 to 1.8 Mg m^{-3} resulted in a 58% decrease in hydraulic conductivity.

Relationship between Infiltration Rate and Bulk Density

There was a fair correlation (r^2 = 0.60) between bulk density and infiltration rate for the annual cropping system (Fig. 4a), but none (r^2 = 0.007) for the cropping system where alfalfa was grown (Fig. 4b). The minimum or no tillage plus the extensive tap-root system of the alfalfa would have promoted and protected the macropores, which would conduct water even in compacted soil. Blackwell et al. (1990) demonstrated that biopore channels formed by alfalfa roots can be very stable at diameters >4 mm under stresses up to 200 kPa.

Infiltration rate decreased by 53% when bulk density was increased from 1.6 to 1.8 Mg m^{-3} (Fig. 4a) by wheel packing. These slow infiltration rates resulting from the high bulk densities would make irrigation difficult because, at a soil bulk density of 1.90 Mg m^{-3}, it would be necessary to flood 24 h to infiltrate 78 mm of water. The long irrigation times would cause problems with crops that are sensitive to waterlogging and would require the application of small amounts of irrigation water at frequent intervals.

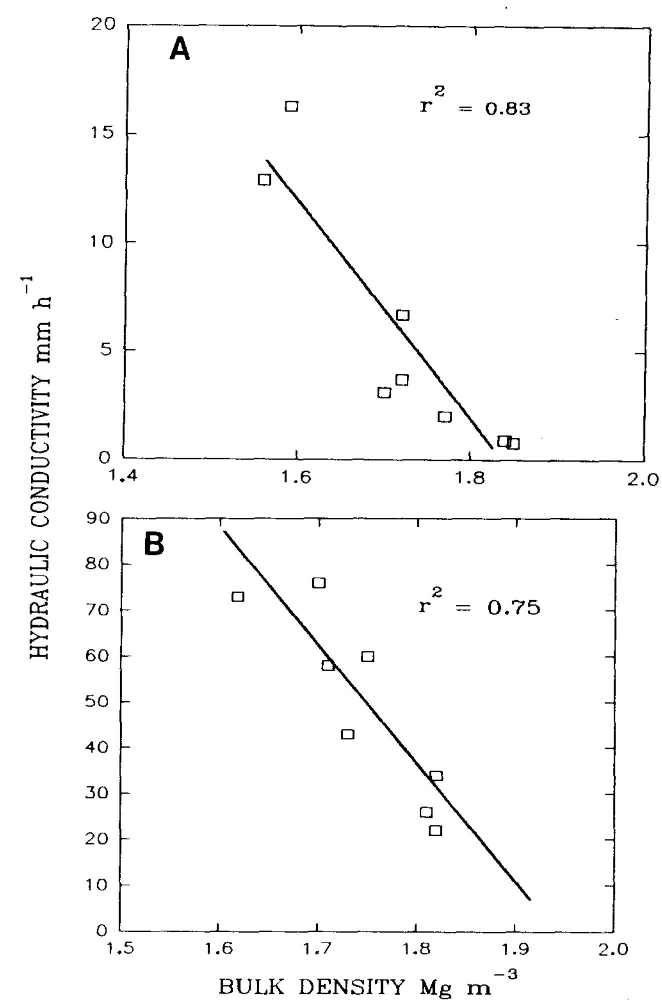

Fig. 3. Relationship between bulk density and hydraulic conductivity (a) in columns using disturbed soil; and (b) for undisturbed cores collected under 3-yr-old alfalfa subjected to various traffic levels.

DISCUSSION

Channels formed by roots of perennial crops are important in increasing the infiltration rate of soil where the channels are stable. In this study, alfalfa roots were important in increasing the infiltration rate by reforming channels that were destroyed by tillage. Measurements with methylene blue in February 1988

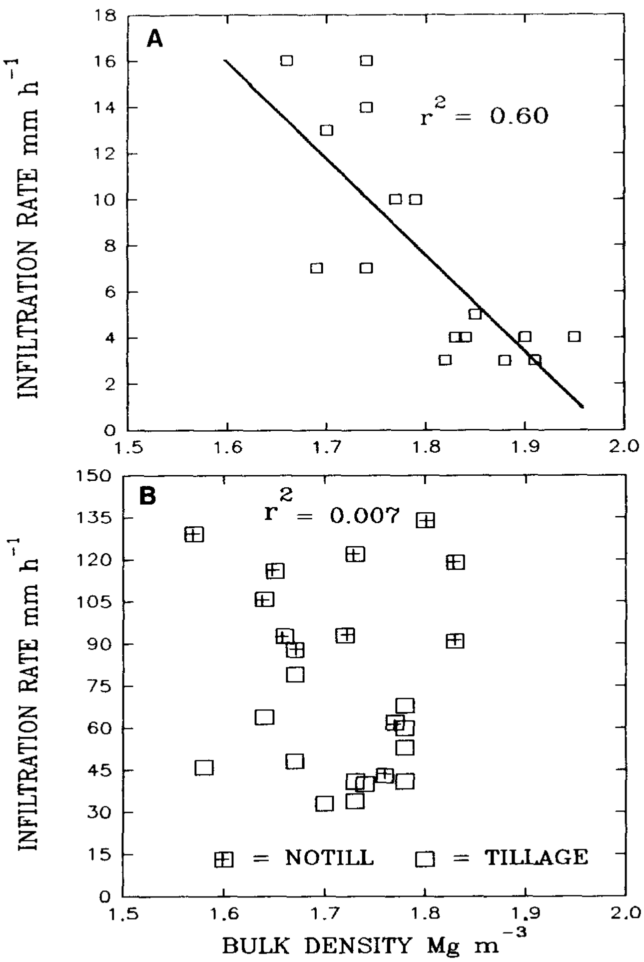

Fig. 4. Relationship between bulk density (150–300-mm depth) and infiltration 2 h after flooding determined in July in the field under (a) an annual cropping system where cotton followed black-eyed peas and (b) cotton culture following alfalfa.

found 40 pores m^{-2} (average diameter of 4 mm) conducting dye to the 150-mm depth. Because of additional death and decomposition of alfalfa tap roots during the season in 1988, this number would have increased. Using flow rates found by Ehlers (1975) for 4-mm-diam. pores, this would give a macropore flow rate for this study (40 pores m^{-2}) of 14.3 mm h^{-1}. The hypothetical flow rates through pores of this size would be about two orders of magnitude greater than those measured by Ehlers. The formation of channels by alfalfa roots should be the main factor explaining the large increases in infiltration under alfalfa culture, although only a few measurements were made of channels in the soil using methylene blue. Other factors that may contribute to increases in infiltration rate, such as swelling–shrinking, earthworm activity, or freezing–thawing (Carter, 1988), are not important factors in these soils. Gish and Jury (1983) also found that plant roots were important in regard to water flow through the soil. When the plants were actually growing, they found that the infiltration rate was reduced because root growth blocked channels. Later, when the roots decayed, channels were open for water flow.

The much higher K measured in undisturbed soil than in a column of disturbed soil is attributed to flow through channels that would increase flow but would not be influenced by the bulk density of the core. Large differences were also measured by Potter et al. (1988), who found that the hydraulic conductivity of disturbed soil was 25% in the topsoil and 10% in the subsoil, compared with the undisturbed soil.

The relationship between bulk density and infiltration was measured in two experiments as part of this study. In the system where annual crops were grown with extensive tillage, $r^2 = 0.60$ (Fig. 4a); but, in a system where alfalfa promoted channel formation and there was minimum or no tillage, $r^2 = 0.007$ (Fig. 4b). The 5-yr period when the field was in alfalfa was sufficient to allow channels to form and increase the infiltration rate to an averge of 75 mm h^{-1} (Fig. 4b), compared with a much lower rate for the annual cropping system (Fig. 4a). Beven and Germann (1982) found that decaying corn roots were important channels for water movement when corn was grown without tillage.

In this study, an increase in bulk density from 1.6 to 1.8 Mg m^{-3} decreased the infiltration rate measured in the field at 120 min by 53% and hydraulic conductivity by 58% (determined using undisturbed soil cores). Similar results were measured by Agrawal et al. (1987) in a sandy soil, with an increase in bulk density of 0.15 Mg m^{-3} (10.0–30-m depth) resulting in a decrease in infiltration rate of 42% and a decrease in hydraulic conductivity (0.10–0.30-m depth) of 56%.

These results may only apply to sandy soils low in organic matter. Measured bulk densities would be different on another soil with a different texture or higher organic-matter content or a soil subjected to freezing and thawing.

CONCLUSIONS

The results of this study are:

1. Tillage increased the infiltration rate of compacted soil but did not change or decrease the rate of uncompacted soil because of disruption of channels.
2. Alfalfa culture resulted in large increases in the infiltration rate for both compacted and uncompacted soil. An explanation for this increase would be the death and decomposition of alfalfa tap roots.
3. The disruption of soil structure and channels resulted in a lower infiltration rate for disturbed soil than for undisturbed cores (same bulk density).
4. There was a fair correlation between bulk density and infiltration rate in fields under an annual cropping system, but none when cotton was grown following alfalfa.

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