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Tension Infiltration for Estimating Pore Distribution of Alfisols under Different Land Management Systems

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Abstract: A field infiltration study was undertaken to evaluate near-surface pore characteristics under long-term land management systems in the semi-arid tropical Alfisols of India. Double ring and tension infiltrometer methods using tension equivalent to 3, 6 and 15 cm of water column were applied to soil under four land use systems; *viz.* cultivated field, under sorghum (*Sorghum bicolor* (L.)-castor [*Ricinus communis* (L.)] in two years rotation for last ten years; grassland, under *Cenchrus ciliaris* (L.) since 1991; forest soil, under *subabul* (*Leucaena leucocephala*) plantation since 1991; and an undisturbed bare soil within a micro-watershed. Ponded infiltration rates under forest, grassland and bare soil were 5.8, 2.2 and 1.4 times more than in cultivated field. At tension of 3 and 6 cm of water, maximum infiltration was found in the forest soil followed by grassland, cultivated field and bare soil and at 15-cm water tension, the trend was: grassland followed by forest soil, cultivated field and bare soil. The relatively large contribution of water flow in forest and grassland was probably due to combination of root chemicals, invertebrated burrows and the structural development of soil matrix materials. Lower bulk density, higher mean weight diameter of aggregates and higher organic carbon content were recorded in the forest and grassland soil compared to those of cultivated and undisturbed bare soils. Though number of macropores (diameter > 0.1 cm) were very less in all the soils except forest soil, nevertheless, nearly 77.5, 77.1, 72.5 and 64.5% of the saturated flux occurred in forest soil, bare soil, grassland, and in cultivated field, respectively through these macropores. ***(Key words: Macropore, forest soil, grassland, soil physical properties)***

Dynamics of soil moisture storage in the potential crop root zone is of primary importance to plant growth and agricultural production. Soil physical characteristics *e.g.*, hydraulic conductivity and infiltration rate co-determine the magnitude of rate of water flow in soil. Different land management practices like cultivation or tillage operation, cropping system, mulches and land use-land cover affect soil physical properties. Although tillage is undertaken to increase soil porosity, it is a short-term solution that has negative consequences on surface soil structural stability, residue accumulation, and soil organic carbon buildup, which are critical features that control water infiltration and subsequent water transmission and storage in soil (Franzluebbers 2002). Pores created by tillage operation are also more tortuous and less stable than faunal and root channels (Logsdon and Kaspar 1995). Even virgin soils have more cavities and burrows as well as more water-stable aggregates compared to cultivated soils (Abbott *et al.* 1979). Among various land use-land cover systems, forest cover greatly influences the infiltration rate. Storage of litter under the forest improved the water retention of soil and infiltration rate. Storage of litter under the forest improved the water retention of soil and infiltration rate (ZhangQing *et al.* 1998). Grass cover was also the key factor in improving soil structure, increasing infiltration rate by improving surface and subsurface macroporosity, assured regular additions of organic materials and primary productivity, thus, reducing surface runoff and controlling soil erosion in semi-arid and arid grazing lands in Africa (Obi and Nnabube 1988; Liniger and Thomas 1998; Obi 1999).

Recognition of the importance of biologically generated macropores and preferential flow paths to field infiltration and plant water uptake has led to a

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renewed interest in measurement techniques in which preferential water flow through macropores and soil cracks is selectivily-controlled (Perroux and White 1988). Since soil management practices and or environmental factors can dramatically change macroporosity, such techniques are valuable in quantifying alterations in soil properties, particularly those leading to changes in infiltration, time to ponding, run-off and erosion. Tension infiltrometers are rapidly becoming a standard tool for *in situ* determination of saturated and near-saturated soil hydraulic properties (Angulo-Jaramillo *et al.* 2000; Ankeny *et al.* 1990; Reynolds and Elrick 1991). This method provides the ability to exclude macropores of selected sizes from the infiltration process. Tension infiltrometer method has the advantage of estimating the porosity of the actively conducting macropores rather than the total quantity (Beven and Germann 1982).

Red soils (Inceptisols, Entisols and Alfisols) of the semi-arid tropics of Andhra Pradesh are shallow in depth, coarse in texture, have inherently low organic matter content and are prone to crusting and hard-setting, which ultimately influence the hydrological properties of soils. Proper land management systems need to be defined in this problematic soil that ultimately improves their hydrological behaviour.

The aim of this study was to evaluate near-surface pore characteristics of Alfisols in the semi-arid tropics of India under different long-term land management systems using ponded and tension infiltration measurements and to compare the soil hydrological properties with other soil physical properties in these systems.

Materials and Methods

Site Information and Treatments

Field infiltration measurements were conducted in a micro-watershed of three hectares at Hayatnagar Research Farm [17°20' N latitude and 78°35' E longitude and an elevation of 515 m above mean sea level (amsl)] of Central Research Institute for Dryland Agriculture, Hyderabad during January 2002. Farm situation represents semi-arid tropical environment with hot summers and mild winters. Mean maximum temperature during summer months (March, April and May) varies between 35.6 to 38.6 °C. Mean minimum temperature during winter months (December, January and February) ranges from 13.5 to 16.8 °C and mean annual rainfall is 746 mm. Soils in the experimental micro-watershed are light textured red Typic Haplustalfs.

Four land management systems *viz.* cultivated field, grassland, forest soil and undisturbed bare soil were chosen for the present infiltration study. In cultivated field, since 1993 onwards, sorghum-castor was taken in two years' rotation. The primary tillage, with tractor-drawn mould board plough followed by tractor-drawn cultivator was imposed after onset of rainfall during monsoon. Castor and sorghum were sown in latter half of June. Crops were grown under rainfed condition and no irrigation was applied. In grassland, *Anjan* (Buffel) grass (*Cenchrus ciliaris* L.), a perennial herbage, has been growing since 1991. Cutting of grass was done once every year in the month of September. *Subabul* (*Leucaena leucocephala*), a multipurpose tree was adapted in the forest land since 1991. Initially for two years the plants were allowed to grow without cutting. Subsequently cutting was undertaken once every year in January-February. The girth and height of *subabul* trees varied between 12-20 cm and 20-25 m, respectively at the time of study. A bare undisturbed plot, which was not at all under cultivation and less disturbed by human activity, was taken as undisturbed bare/fallow plot within the micro-watershed. Sparse weeds were there during the study in the bare/fallow plot.

Soil Hydraulic Properties

The infiltration study was carried out using both a double ring as well as a tension infiltrometer. Water was ponded to a depth of about 15 cm initially in both the inner and outer rings of double ring infiltrometer until a constant rate of infiltration was achieved. It took 45 to 60 minutes to reach a constant infiltration rate. Additional infiltration measurements were determined by using a tension-infiltration device (manufactured by Soil Measurement Systems, Tucson, Arizona, USA). Tension levels of 3, 6, and 15 cm were applied to exclude pores more than 0.05, 0.025 and 0.01 cm in radius, respectively, using the capillary equation given below.

$$r = \frac{-2\sigma \cos c}{\rho g h} = \frac{-0.15}{h} \quad \ldots(1)$$

where h = the pressure height of water (cm) in the tension infiltrometer, r = radius of the tube (cm), ρ= density of water (1 g cm^{-3}), σ = surface tension of water (72 dynes cm^{-1} at 25 °C, c = contact angle between the water and the pore wall assumed 0, g = acceleration due to gravity (980 cm s^{-2}). Tension was regulated by opening the appropriate air-entry valves in the tension-control tube. Readings were noted at every minute interval by using a stopwatch for 45 to 60 minutes until a constant rate of infiltration is reached at each tension. Since both ponded and tension-infiltration measurements were determined under approximately steady-state condition, a unit hydraulic gradient was assumed. Macropore flow was determined as the dfference between the ponded infiltration rate and the infiltration rate at 3 cm of water tension (Watson and Luxmoore 1988) by

$$\theta = (8\mu Im)/(g\rho r^2) \qquad \ldots(2)$$

where μ is the viscosity of water, (0.0089 gm cm^{-1} s^{-1} for 25 °C) and g, ρ, r are same as in equation (1) and Im is macropore flow. Since the effective porosity, q equals the number of pores per unit area times the area of the corresponding size pores, the number of effective pores N, per unit area for each size class of pores is given by

$$N = \theta/(\pi r^2) = (8\mu Im)/(\pi g \pi r^4) \qquad \ldots(3)$$

Effective macropores are those that are actively conducting. Using the 'minimum' pore radius of 0.05 cm between 0 to 3 cm tension and applying equation (3) in conjunction with Poiseulle's equation, the 'maximum' number of effective macropores (in short number of pores) per unit area are given by

$$N = (8\mu Im)/[\pi g\rho(0.05)^4] \qquad \ldots(4)$$

The above calculations were repeated for the 3 to 6 and 6 to 15-cm tension ranges using a minimum pore radius of 0.025 and 0.01 cm, respetively. The water level in the reservoir of the tension infiltrometer was read directly on the centimetre scale attached to the water reservoir. Since the inside diameter of the water supply tube was 5.1 cm and the disc diameter was 20 cm, a multiplication factor of 0.065 (5.1 × 5.1)/(20 × 20) was used to multiply with readings of water level in the reservoir to get the final value.

Soil Physical Properties and Organic Carbon

The surface soil samples of 0-15 cm depth were collected for analysis of soil physical properties and organic carbon. Bulk density and soil texture were measured by the core method (Blake and Hartge 1986) and Bouyoucos hydrometer method (Gee and Bauder 1986), respectively. Soil water retention at permanent wilting point and field capacity was measured at 1.5 MPa and 0.033 MPa in a pressure plate apparatus (Cassel and Nielsen 1986). The organic carbon was determined by Walkley and Black's method (Jackson 1967). The aggregate size distribution was determined using wet sieving method (Yoder 1936) and the values were expressed as mean weight diameter (MWD) after oven drying (van Bavel 1949). The results were corrected for the coarse primary particles retained on each sieve by dispersing them. Weight of sand retained after the second sieving was then subtracted from the total weight of undispersed material retained after the first sieving. The percentage of water stable aggregates (%SA) was calculated using the relationship given by Hillel (1980), which is as follows:

$$\%SA = 100 \times [\{(\text{Weight retained}) - (\text{weight of sand})\}/\{(\text{Total sample weight}) - (\text{Total weight of sand})\}] \qquad \ldots(7)$$

Water stable mean weight diameter (WSMWD) was calculated in the same way as MWD from %SA.

Data Analysis

Four sets of observations or analyses were recorded for each land use system for soil physical properties and organic carbon. Both, tension and ponded infiltration study was undertaken at six locations chosen randomly under each land use treatment. The data sets for variables were evaluated using a one-way analysis of variance (ANOVA) and Student's comparison of means at p = 0.05.

Results and Discussion

Infiltration

The study revealed that forest and grassland soils had significantly higher infiltration rate (Table 1) when compared with bare and cultivated field. Amount of water that infiltrated through forest and grassland soils under ponding was 5.8 and 2.2 times higher than that of cultivated field. Even the undisturbed fallow showed higher ponded infiltration rate when compared to cultivated field. When infiltration was recorded under tension of 3 and 6 cm of water, the maximum infiltration was found under forest soil followed by grassland, cultivated field and bare soil. Infiltration rate under 3 cm of water tension for forest soil was 1.3 times higher than ponded infiltration of cultivated field. At 15 cm water tension, highest infiltration was observed under grassland followed by forest soil, cultivated field and lowest value was registered under bare plots. Canopy cover, faunal activity, and/or undisturbed old root channels might have contributed to higher conductivity observed in forest soil, as well as, in grassland. In forest land, profuse faunal activity, mainly earthworm casts, were visu-

Table 1. Infiltration rates (cm hr^{-1}) at 0, 3, 6 and 15 cm water tension under different land management systems

Different land management systems	Water tension (cm) 0	3	6	15
Undisturbed bare soil	6.75	1.55	0.82	0.29
Cultivated field	5.00	1.8	0.89	0.32
Grassland	10.92	3.00	1.25	0.55
Forest soil	29.00	6.53	1.57	0.49
CD (P=0.05)	1.51	1.04	0.31	0.10

Table 2. Physical and chemical properties of soil under different land management systems

Parameters	Undisturbed bare soil	Cultivated field	Grassland	Forest soil	*CD (P = 0.05)*
Coarse sand % (2-0.2 mm)	58.1	48.7	43.7	51.5	
Fine sand % (0.2-0.02 mm)	14.4	12.6	24.8	23.6	
Silt % (0.02-0.002 mm)	2.7	5.3	3.7	3.0	
Clay % (< 0.002 mm)	24.8	33.4	27.8	21.9	
Soil textrue (ISSS)	Sandy clay loam	Sandy clay loam	Sandy clay loam	Sandy clay loam	
Bulk density (Mg m^{-3})	1.56	1.62	1.41	1.37	0.065
Water retention at 0.033 MPa (m^3 m^{-3})	0.127	0.189	0.139	0.159	0.013
Water retention at 1.5 MPa (m^3 m^{-3})	0.068	0.099	0.069	0.083	0.010
MWD (mm)	0.723	0.568	0.803	0.894	0.071
Water stable-MWD (mm)	0.275	0.226	0.622	0.484	0.166
Soil organic carbon (g kg^{-1})	6.84	6.25	8.89	17.82	1.08

ally noticed, which might have contributed to increased ponded conductivity. Earthworm casts were also noticed in grassland to a limited extent. However, no cast was noticed in case of fallow or cultivated field. A clear correlation between soil infiltration and earthworm activity was illustrated by Al-Addan *et al.* (1991). At the same time, the cultivated land was visually compacted which might have contributed to decreased ponded conductivity. Though tillage increased the porosity of surface soil, it remained a short-term solution. Logsdon and Kaspar (1995) also noticed that tillage created pores near the surface, but these pores were more tortuous and less stable than faunal and root channels. The macropores developed by tillage collapsed quickly due to rainfall impact (Logsdon *et al.* 1993; Franzuluebbers 2002). Seal formation was the major factor reducing infiltration rate in undisturbed bare soil (Moore 1981; Connolly *et al.* 1998). The infiltration studies were conducted after seven months of tillage operation in cultivated field. As the last crop was harvested in October 2001 the field remained bare for over three months before the commencement of infiltration study. Crusting or surface seal as well as hardsetting are the major problems associated with red soils of Andhra Pradesh (locally known as *chalka* soil) in India (Mullins *et al.* 1990; El-Swaify *et al.* 1985).

Soil Physical Properties and Organic Carbon

Leucaena plantation as well as *Anjan* grass had a distinct advantage in maintaining soil physical properties and organic matter (Table 2). Organic carbon content in forest, grassland and bare soils were 2.9, 1.4 and 1.4 times than that of the cultivated field. The soil colour was also reported to be dark grey in case of forest land, while it was reddish in other three soil types. The increase in organic carbon resulted in reduction in bulk density of forest and grassland sites. The extent of reduction in bulk density in forest, grassland and bare soils was 0.25, 0.21 and 0.06 Mg m^{-3} over cultivated field. Leaf litter as well as root decay increased the total space, which in turn decreased bulk density of the soil. Total pore space, calculated from bulk density and particle density, was 48.3, 46.8, 41.1 and 38.9% in case of forest soil, grassland, bare soil and cultivated field, respectively. The organic matter accumulation improved the soil structure as was evident from higher values of MWD of aggregates in forest and grassland. There was significant difference (P=0.05 level) in MWD among the four land use systems. The MWD, when calculated without dispersing the soil was highest under forest soil followed by grassland, bare soil and least in cultivated field. However, water stable MWD calculated after dispersing the soil was highest under grassland condition followed by forest, bare soil and cultivated field, respectively. The primary particles might have contributed more towards the MWD when determined without using dispersing agent, in forest soil than grassland. Similarly, fibrous roots of grassland might have contributed towards granular structure, and that increased the water stable MWD. Water retention at field capacity (0.033 MPa) and permanent wilting point (1.5 MPa) was maximum under cultivated land followed by forest land, grassland and bare soil, respectively. Soil texture played a dominant factor in controlling the water retention characteristics. Cultivated soil was texturally more fine with higher clay content than other three types of soils. The second higher values of water retention properties in forest soil may be due to higher organic matter in the soils.

Soil Pore Distribution

A steep decrease in infiltration rate from 0 to 3-cm water tension indicates the dominance of large pores under saturated flow condition in all the land use systems. Though pore size distribution indicated fewer number of macropores (pores >0.1 cm diam-

Table 3. Porosity parameters estimated from the ponded and tension infiltrometer data under different land management systems

Different land management	Number of pores m^{-2} Tension, cm water			Per cent of soil volume (10^{-3}) Tension, cm water			Per cent of flux Tension, cm water		
	0-3	3-6	6-15	0-3	3-6	6-15	0-3	3-6	6-15
	Pore radius, cm			Pore radius, cm			Pore radius, cm		
	>0.05	0.025-0.05	0.01-0.025	>0.05	0.025-0.05	0.01-0.025	>0.05	0.025-0.05	0.01-0.025
Undisturbed bare soil	53	120	3432	4.2 (3.9-4.4)	2.4 (1.6-2.9)	10.8 (9.0-12.0)	77.05 (74.07-81.72)	10.79 (7.51-12.38)	7.91 (6.74-9.34)
Cultivated field	33	146	3644	2.6 (2.0-2.9)	2.9 (2.4-3.6)	11.5 (11.0-12.0)	64.46 (60.70-68.11)	17.76 (15.70-19.80)	11.34 (10.09-14.31)
Grassland	81	288	4538	6.4 (6.2-6.7)	5.7 (5.3-5.9)	14.3 (11.5-17.7)	72.51 (71.61-73.78)	16.03 (15.79-16.42)	6.47 (5.45-7.55)
Forest soil	231	816	6941	18.2 (17.5-19.4)	16.0 (15.2-17.5)	21.8 (16.9-24.3)	77.50 (77.11-78.13)	17.09 (16.70-17.36)	3.72 (3.02-4.27)
CD (P=0.05)	26	99	201						

Values in the parentheses are the percent range

eter associated with 0 to 3 cm water tension) in all soil types with the exception of forest soil, nearly 77.5, 77.1, 72.5 and 64.5% of the saturated flux (Table 3) occurred in forest soil, bare soil, grassland, and in cultivated field, respectively through these macropores. The large measured infiltration rates were associated with exceedingly small macroporosities of 3×10^{-5}, 4×10^{-5}, 6×10^{-5} and 20×10^{-5} m^3 m^{-3} in cultivated field, bare undisturbed soil, grassland, and forest soil, respectively. Pore distribution at 0.05-0.1 cm diameter (associated with 3-6 cm water tension) and at 0.02-0.05 cm diameter (associated with 6-15 cm water tension) was maximum under forest soil followed by grassland, cultivated field and least under fallow undisturbed soil. Relatively large contribution of macropores to water flow in forest and grassland soils is probably due to a combination of root channels, invertebrate burrows and the structural development of the soil matrix materials. In cultivated field, infiltration study was conducted after seven months of tillage operation and three months of harvesting of crop. By that time the contribution of macropores developed by tillage had subsided but the micropores (associated with 3-15 cm water tension) contribution might be still there which provided higher infiltration than the fallow plots. An estimated water flux of 94, 95, 96 and 98% of the ponded flow was transmitted through only 0.02, 0.03, 0.02 and 0.06% of soil volume under cultivated, grassland, bare soil and forest soil, respectively between 0-15 cm of water tension. At tension >15 cm of water, the infiltration rate was reduced to <6, <5, <4 and <2% of the ponded-flow rate under cultivated, grassland, bare soil and forest soil, respectively.

Conclusions

Tension infiltrometer provides a rapid and convenient method for obtaining a large amount of hydrological data, which can be useful for transport models. Ponded infiltration rates decreased from forest soil, grassland, undisturbed bare soil and was least in case of cultivated/agricultural field. The trend of tension infiltration rates was: Forest soil > grassland > cultivated/agricultural field > undisturbed bare soil. Relatively large contribution of macropores to water flow in the forest and grassland soils was probably due to a combination of root channels, invertebrate burrows and the structural development of the soil matrix materials. Though tillage is used to improve hydrological properties in soil, it is a short-term solution. Keeping the cultivated field fallow for more than 2nd/3rd year is a major cause for soil degradation in red soil regions of semi-arid tropics of India.

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