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Modeling Water Retention Capacity and Hydraulic Properties of a Manure-amended Loam Soil and its Effect on Wheat and Maize Yield

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ABSTRACT

Water retention capacity and hydraulic conductivity of different soil layers is needed to quantify plant available water that may help determine irrigation water use efficiency (WUE_i) and yield of different crops. A field from Experimental Area of Soil and Environmental Sciences, University of Agriculture, Faisalabad was selected to quantify water retention curve (WRC) of the soil and other soil hydraulic properties and manure amendment under two irrigation levels was evaluated for this purpose. Soil water retention and hydraulic conductivity was measured at different suitable matric potentials using pressure membrane apparatus and tension infiltrometer, respectively. Curves of soil water retention and hydraulic conductivity were obtained by power function, Van Genuchten-Maulem and Durner-Maulem models. Durner-Maulem model was best in predicting the water retention and hydraulic conductivity of soil under field conditions. The highest available water capacity of soil with 14.2% increase at 0-35 cm soil depth was observed in manure amended soil, while least was recorded at 35-70 and 70-110 cm soil depths with lower soil organic carbon and increased sand proportion. Manure application increased the WUE_i of wheat and maize crop by 40.5 and 39.0% under deficit irrigation ($M_{50}I_1$), which ultimately increased the yield of these crops by 40.1 and 38.6%, when compared to "M_0I_2". Application of manure with deficit irrigation "$M_{50}I_1$" was better choice than applying heavy irrigation with no manure "M_0I_2". © 2012 Friends Science Publishers

Key Words: Manure; Soil water retention; Hydraulic conductivity; RETC-fit model; Crop yield

Abbreviations: S_e = the effective degree of saturation, θ = the volumetric water content, θ_r = residual water content, θ_s = saturated volumetric water content, θ_m, θ_{im}= mobile and immobile water content, respectively, θ_{FC} = volumetric water content of soil at field capacity ($cm^3\ cm^{-3}$); θ_{WP} = volumetric water content of soil at wilting point ($cm^3\ cm^{-3}$). θ_{AWC} = available water capacity of soil ($cm^3\ cm^{-3}$); b = slope of ln P vs $ln\ (\theta/\theta_s)$ water retention curve; α (cm^{-1}) = parameter related to pore size distribution/the inverse of the air-entry value; l = tortuosity factor/pore-connectivity parameter (0.5); w_i = weighting factors for the sub-curves of the overlapping subregions; a_i, n_i, m_i = empirical parameters of the sub-curves; n, m = shape parameters related to pore size distribution/pore size distribution index; SOC = soil organic carbon (%); B.D. = bulk density ($Mg\ m^{-3}$); SSQ = sum of squared residuals.

INTRODUCTION

Soil water retention curve (WRC) helps to determine the amount of water retained in a soil under equilibrium at a given matric potential (Gao & Liu, 2010). Soil water tension relationships with soil water content and hydraulic conductivity are necessary not only for quantifying plant available water but are used as tool for modeling of water and solute movement in or through soils (Rawls *et. al.*, 1982), which ultimately plays a critical role in the water management and in prediction of solute and contaminant transport in the unsaturated soil.

Typically a soil WRC is highly nonlinear and relatively difficult to obtain. Most of the researchers try to find equations describing the water retention curve using the simplest set of quantifiable parameters of soil such as texture, bulk density or organic matter content (Porebska *et al.*, 2006) such as described by Rosetta Lite v. 1.1 1999 (Schaap *et al.*, 2001). In laboratory, soil water retention is determined by measuring water contents at defined matric potential heads (Dane & Hopmans, 2002) using suction plates at several steps in the pressure range of 0.1 - 15 bar. The simplest empirical model for soil WRC is power function (Gao & Liu, 2010), which could be solved by a linear regression equation, taking $ln\ (h)$ verses $ln\ \theta/\theta_s$ to get water contents at permanent wilting point and field capacity (Williams *et al.,* 1983). On the other hand, According to Gardner model (Gardner, 1958), unsaturated hydraulic conductivity [$K(h)$] of the soil also varies with matric potential as a power function ($K(h) = K_s e^{-ah}$), where $K(h)$

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under field conditions is usually measured using Tension Infiltrometer and soil saturated hydraulic conductivity (K_s) by Guelph Permeameter.

This determination of soil WRC and hydraulic conductivity-matric potential relationship is time- and labor-consuming in addition to requirement of expensive and specific equipment. For these reasons, many semi-empirical and statistical equations (pedotransfer functions) describing the water retention curve have been developed (Kutilek & Nielsen, 1994). These equations contain parameters which, generally, have no direct physical logic and are mainly used as fitting parameters to match function to experimental points, some describe any property like Van Genuchten's parameter n and α show the impact content of small and large aggregates, respectively (Guber *et al.,* 2004).

As for as modeling of SWC and hydraulic properties is concerned, RETC-fit software is extensively used, which allows the six types of models for the soil hydraulic properties: (a) the Van Genuchten-Mualem model (Van Genuchten, 1980), (b) the Van Genuchten-Mualem model with an air-entry value of -2 cm, (c) modified Van Genuchten type equations (Vogel & Cislerova, 1988), (d) the equations of Brooks and Corey (1964), (e) the lognormal distribution model of Kosugi (1996) and (f) a dual-porosity model (Durner, 1994). In equilibrium conditions (single-porosity) one of the most popular is Van Genuchten's equation (Van Genuchten, 1980).

However, when water moves in structured field soils and even seemingly homogenous coarse-textured soils (Baker & Hillel, 1991), non-uniform flow occur which is referred to as preferential flow (Beven, 1991). It leads to an apparent non-equilibrium condition with respect to pressure head or solute concentration or both (Brusseau & Rao, 1990; Wang, 1991). In these conditions water flow is described by a dual porosity model. Durner (1994) divided the soil porous medium into two overlapping regions suggesting each of these regions a Van Genuchten-Mualem type function (Van Genuchten, 1980) of the soil hydraulic properties, where linear superposition of the functions for each region gives the functions for the entire multimodal pore system (Durner *et al*., 1999).

Manure application not only improves the soil physical properties (Fares *et al.,* 2008), it also increases the water holding capacity of soil due to increased surface area and ultimately enhances the water use efficiency (Gupta Gupta & Larson, 1979) and yield of crop.

Keeping in view the above discussion, soil water retention and hydraulic conductivity data of soil with and with out manure amendment were fitted to different models using RETC-fit software to find out relationships for predicting water retention volumes for particular tensions and hydraulic conductivities. Yield and WUE_i of wheat and maize receiving manure and no manure was observed under two irrigation levels.

MATERIALS AND METHODS

Experimental site and soil sampling: Experiments for determination of WRC and soil hydraulic parameters were laid out at the Research area, Institute of Soil and Environmental Sciences, University of Agriculture, Faisalabad. The site is in a semiarid region. The soil of the experimental field was loam (Table I), well-drained Hafizabad loam, mixed, semi-active, isohyperthermic Typic Calciargids (Iqbal *et al.,* 2012). Soil samples were collected from 0-35, 35-70 and 70-110 cm soil depth. From manure receiving plots soil samples were collected at 0-35 cm depth, 60 days after application (dairy manure was applied to field of wheat crop at the rate of 50 Mg ha^{-1}, having 68.4% moisture contents, 1.38% N, 0.50% P_2O_5, 1.20% K_2O & 48.6% organic carbon). Samples were run on pressure membrane apparatus within one month after sampling.

Wheat and maize trials: Wheat experiment was conducted with split plot arrangement using two manure levels, i.e., 0 and 50 mg ha^{-1} in main plots, while two irrigation levels (I_1=32.5 cm & I_2= 47.5 cm) maintained in subplots having 6.7 m × 13.3 m dimensions. Wheat variety AS-2002 was used as test crop. At the same layout, hybrid maize viz. Pioneer-3062 was grown with the residual manure i.e., 0 (M_0) and 50 Mg ha^{-1} (M_{50}), and two irrigation levels, i.e. 45.0 cm (I_1) and 60.0 cm (I_2). A basal dose of NPK to wheat and maize crop was applied at 105-85-62 and 195-140-105 kg N-P_2O_5-K_2O ha^{-1}, respectively. Wheat and maize crop was harvested after 141 and 115 days, respectively and grain yield was recorded.

Determinations: Oxidizable soil organic carbon (SOC) was analyzed using the procedure of Walkley and Black (1934). Soil bulk density from 0-35, 35-70 and 70-110 cm depths was determined by the core samplers (Black & Hartage, 1986). Percentage of sand, silt and clay was determined by Bouyoucos hydrometer method and textural class was determined by following the International Textural Triangle (Moodie *et al*., 1959). Field saturated hydraulic conductivity (K_s) was measured by Guelph Permeameter (Model 2800 KI), taking three steady-state readings. The K_s was then calculated from the following formula:

$$K_s = (0.0041)(X)(R_2) - (0.0054)(X)(R_1) \quad (1)$$

Where R_1 and R_2 are the steady-state rates of water fall (cm s^{-1}) in the reservoir at the first head (H_1) and second head (H_2) of water, respectively. H_1 and H_2 are the first and second head of water (cm) established in the well hole, and X (35.5 cm^2) is the reservoir constant, which relates to the cross sectional area of the combined reservoir (cm^2).

Unsaturated hydraulic conductivity was measured using Tension Infiltrometer (Eijkelkamp 09.09) by taking steady state readings at two matric potentials (h_1= -5 cm & h_2= -10 cm). The volume of water entering the soil per unit time through the porous membrane at two tensions, i.e. h_1 and h_2 was measured as follows:

$$Q = (\pi r^2 K\left[1 + \frac{4}{\pi r \alpha}\right] \quad (2)$$

Where, r is the radius of water reservoir of tension infiltrometer.

To find out K(h), the unknown parameter α was measured as follows:

$$\alpha = \frac{\ln[Q(h_2 / Q(h_1)}{h_2 - h_1} \quad (3)$$

Where, h_1 is -5 cm and h_2 is -10 cm matric potential.

Varying unsaturated hydraulic conductivity with matric potential was calculated after Gardner (1958) as follows:

$$K(h) = K_s e^{-ah} \quad (4)$$

To find out the WRC, water contents were determined at pre-defined matric potential using suction plates of 1 and 5 bar, at several steps in the pressure range of 0.3 - 4.5 bar i.e., 0.3, 0.6, 1.0, 3.0 and 4.5 bar. To solve the simplest empirical model "power function" for soil WRC (Gao & Liu, 2010), a following linear regression equation was developed by taking $\ln \theta/\theta_s$ verses $\ln(h)$ to get θ_{WP}, θ_{FC}, θ_{AWC} etc.

$$\ln P = \ln P_e + b \ln(\theta / \theta_s) \quad (5)$$

P is the matric potential (kPa), "Pe" (intercept) is air entry value/bubbling pressure which is inversely related to "*α*", and "*b*" is the slope of $\ln P$ vs $\ln \theta/\theta_s$ water retention curve.

RETC-fit description: RETC-fit version 6.02 software model was fitted to both retention and conductivity data using Van Genuchten- Mualem (Van Genuchten *et al.*, 1992) and Durner-Mualem (Durner *et al.,* 1999) model.

According to Van Genuchten (1980) single porosity (SP) model, matric potential water content relation was simulted as follows:

$$\theta(h) = \begin{cases} \theta_r + \dfrac{\theta_s - \theta_r}{[1 + |\alpha h|^n]^m} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \quad (6)$$

According to SP model, RETC-fit model simulated the effective saturation as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{1 + (\alpha|h|)^n}\right)^m \quad (7)$$

Hydraulic conductivity according to SP model was simulated as follows (Maulem, 1976):

$$K(h) = K_s S_e^l [1 - (1 - S_e^{1/m})^m]^2 \quad (8)$$

According to Durner (1994) dual porosity (DP) model,

a. effective saturation was simulated as follows:

$$S_e = w_1[1 + (\alpha_1 h)^{n_1}]^{-m_1} + w_2[1 + (\alpha_2 h)^{n_2}]^{-m_2} \quad (9)$$

b. Unsaturated hydraulic conductivity was simulated as follows:

$$K(S_e) = K_s \frac{\left(w_1 S_{e_1} + \omega_2 S_{e_2}\right)^l \left(w_1\alpha_1[1-(1-S_{e_1}^{1/m_1})^{m_1}] + w_2\alpha_2[1-(1-S_{e_2}^{1/m_2})^{m_2}]\right)^2}{(w_1\alpha_1 + w_1\alpha_1)^2} \quad (10)$$

Units for length and time selected were cm and days, respectively. Maximum number of iterations were 50, while number of retention and conductivity data points were 15 and 9, respectively. Default value for θ_r selected was 0.027 (Rawls *et al.*, 1982) and for α and *n* value of 0.012 and 1.43 predicted by pedotransfer function code with Rosetta Lite v. 1.1 1999. (Schaap *et al.*, 2001) were selected, respectively according to sand, silt and clay proportion. Then mean values of water fraction and hydraulic conductivity from recorded data were put again their respective matric potential to get results from the RETC-fit software. Model fitness was relied on R squared for regression of observed *vs* fitted values.

RESULTS AND DISCUSSION

Water retention capacity and hydraulic properties of the soil: Water retention capacity and hydraulic properties of soil for different soil depths are presented in Table I, while regression equations showing relations of $\ln \theta/\theta_s$ verses $\ln (P)$ are provided in Fig. 1. Soil was loam for all depths with almost similar clay contents, however an increase in sand fraction was observed with increasing depth, resulting in a decreased silt contents for that depth. Bulk density of soil also increased by 2.0 and 2.64 % for 35-70 cm (D_2) and 70-110 cm (D_3) soil depth when compared with 0-35 cm soil depth (D_1). However, application of manure to D1 (D_1M_{50}) resulted in 0.66% decrease in B.D. for D_1 depth. Manure application also increased the SOC from 0.35 to 0.50%, while a decreasing trend was observed with increasing depth. Soil saturated hydraulic conductivity increased with manure application, while decreased for lower depths that might be due to increased bulk density (Table I). Similarly, earlier on, at the same place, Khan *et al.* (2007) observed a significant increase in K_s (44%) and porosity of soil by the application of 20 Mg ha^{-1} manure, which may be due to its low bulk density and enhanced soil macro aggregation (Min *et al.,* 2003). Available water capacity of the soil increased from 0.135 cm^3 cm^{-3} to 0.142 cm^3 cm^{-3} for D_1M_{50}, while decreased to 0.127 cm^3 cm^{-3} and 0.126 cm^3 cm^{-3} for D_2 and D_3, respectively. Values of θ_{FC} were 0.265, 0.260, 0.256 and 0.254 cm^3 cm^{-3} for D_1M_{50}, D_1, D_2 and D_3, respectively, while respective values for θ_{WP} were 0.123, 0.125, 0.127 and 0.126 cm^3 cm^{-3}. Our findings are in line with Rawls *et al.* (1982) who stated almost similar values of θ_{FC} (0.27 cm^3 cm^{-3}), θ_{wp} (0.12 cm^3 cm^{-3}) and K_s (31.7 cm day^{-1}) for loam soil, A lower value of θ_{AWC} observed for D_2 and D_3

Fig. 1: Measured data of *ln* (θ/θ_s) vs ln *(P)* for the three main layers of the experimental site (data are average of three repeats)

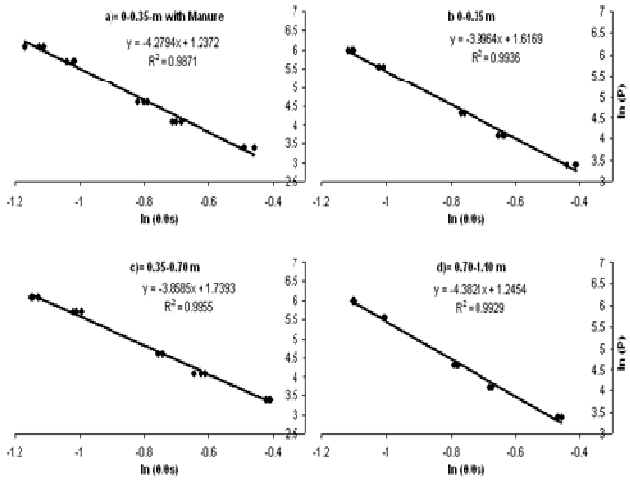


Fig. 2: WRC and hydraulic conductivity simulated according to single porosity model (SPM) using RETC-fit; Curves 1 to 4 (downward) representing D_1M_{50}, D1, D2 and D3, respectively

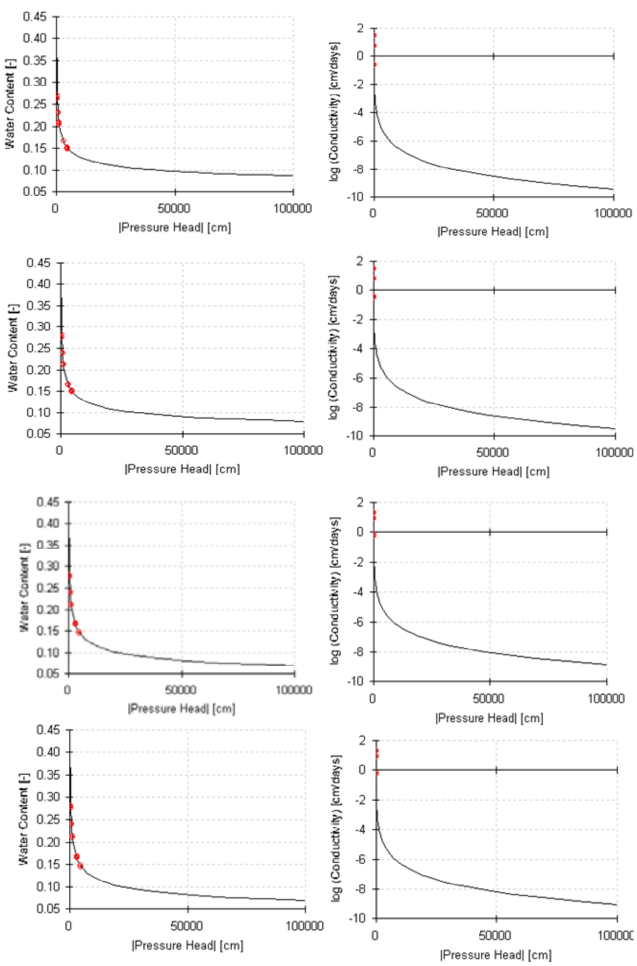
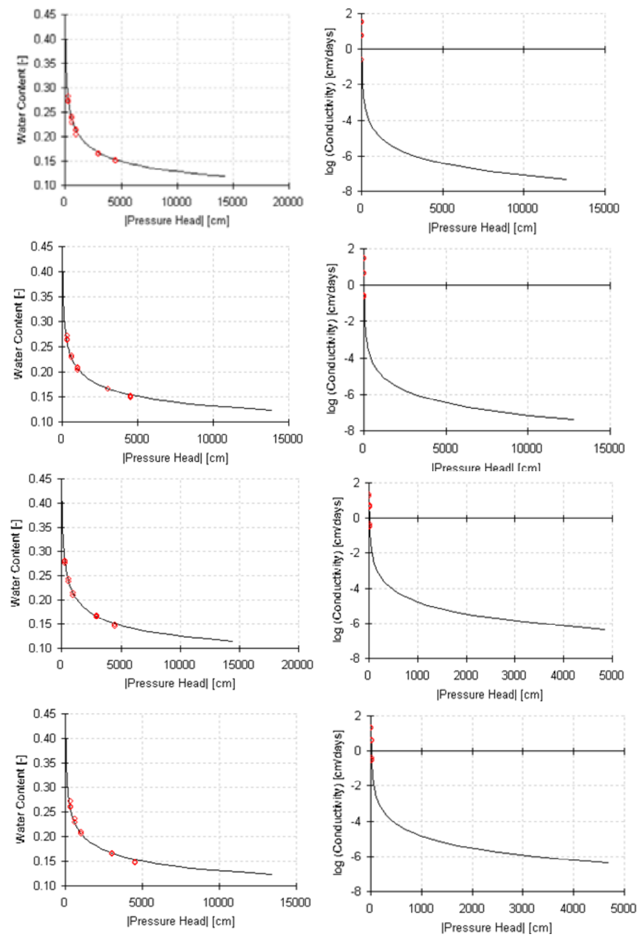


Fig. 3: WRC and hydraulic conductivity of soil simulated according to dual porosity model (DPM) using RETC-fit; Curves 1 to 4 (downward) representing D_1M_{50}, D1, D2 and D3, respectively



compared to D_1 soil depths might be due to an increased sand proportion in soil (Rawls *et al.,* 1982). A similar kind of correlation between soil water retention and particle size, soil organic matter and bulk density at a selected matric potential was observed by Gupta and Larson (1979).

Soil hydraulic properties according to Van Genuchten (VG) model: The parameters obtained from the fitting of the water retention curves are listed in Table II and the water retention curves are shown in Fig. 2. Values of r^2 for Pearson correlation show that observed data fitted well to the VG model. Data had values of "*n"* in the range of 1.16 (D_3) to 1.40 (D_1), while "α" ranged from 0.016 (D_1) to 0.025 (D_3) which is typical for loam soil. For D_2 and D_3 soil depths, lower values of "*n"* and higher values of *"α"* might be due to increase in sand proportion of the soil (Schaap *et al*., 2001). Data of soil water retention capacity of soil showed the similar trend for different depths as calculated by Equation-1 (Table I). Data show that (Table II) the residual water contents (θ_r) were in range of 0.045 (D_1M_{50}) to 0.035 (D_2). Curve fitting (Fig. 2) also showed that we can find out the water contents below 5000 cm pressure head

Table I: Measured soil physical and hydraulic parameters in the three main layers of the experimental site (data are average of three repeats)

Depth (cm)	Particle fraction (%)			Texture	B.D.	θ_s	θ_{FC}	θ_{PWP}	θ_{AWC}	K_s	SOC
	sand	silt	clay	(USDA)	(Mg m^{-3})	cm^3 cm^{-3}				(cm day^{-1})	(%)
0-35$^+$	38.0	37.5	24.5	Loam	1.50	0.43	0.265	0.123	0.142	30.4	0.50
0-35	38.0	37.0	25.0	Loam	1.51	0.43	0.260	0.125	0.135	27.3	0.35
35-70	40.0	34.5	25.5	Loam	1.55	0.42	0.256	0.127	0.129	19.5	0.28
70-110	42.5	32.5	25.0	Loam	1.54	0.42	0.254	0.126	0.128	20.0	0.22

$^+$Manure (50 Mg ha^{-1}) amended plots

Table II: Parameters of WRC measured using RETC-fit software according to single porosity-fit of retention (van Genuchten -Mualem model; average of three repeats)

Depth (cm)	α	*n*	*m*	θ_{FC}	θ_{PWP}	θ_r	θ_{AWC}	r^2	*SSQ (10^{-4})
	cm^{-1}			cm^3 cm^{-3}					
0-35$^+$	0.016	1.35	0.234	0.268	0.123	0.045	0.145	0.96	49.3
0-35	0.016	1.40	0.220	0.262	0.135	0.042	0.127	0.89	34.6
35-70	0.023	1.30	0.254	0.255	0.131	0.035	0.124	0.93	25.5
70-110	0.025	1.16	0.215	0.251	0.130	0.037	0.121	0.90	3.4

$^+$Manure (50 Mg ha^{-1}) amended plots

Table III: Parameters of WRC measured using RETC-fit software applying dual porosity - fit of retention (*Durner et al.*, 1999; average of three repeats)

Depth (cm)	*θ_r (-)	*α_m (cm^{-1})	*n_m	*α_{im} (cm^{-1})	ω_{im}	*n_{im}	θ_{FC}(-)	θ_{PWP} (-)	θ_{AWC} (-)	*SSQ (10^{-4})	*r^2
0-35$^+$	0.030	0.029	1.21	0.005	0.137	1.90	0.267	0.119	0.148	6.2	0.98
0-35	0.036	0.150	1.14	0.002	0.190	2.27	0.262	0.123	0.139	14.8	0.99
35-70	0.020	0.027	1.34	0.004	0.452	1.22	0.263	0.125	0.138	9.2	0.99
70-110	0.025	0.058	1.27	0.006	0.432	1.19	0.256	0.121	0.135	14.0	0.97

$^+$Manure (50 Mg ha^{-1}) amended plots

Table IV: Unsaturated hydraulic conductivity of soil (cm day^{-1}) at -5 and -10 cm matric potential by power function, van Genuchten-Mualem model (SPM) and Durner model (DPM); average of three repeats

Depth (cm)	Power function		Single-porosity*			Dual-porosity*		
	5 cm	10 cm	5 cm	10 cm	r^2	5 cm	10 cm	r^2
0-35$^+$	5.46	0.24	2.49	0.45	0.94	4.53	0.32	0.99
0-35	4.18	0.25	2.57	0.61	0.91	5.02	0.89	0.96
35-70	4.55	0.37	3.03	0.57	0.96	6. 21	1.29	0.96
70-110	4.02	0.34	2.53	0.49	0.96	5.94	0.89	0.97

*Measured using RETC-fit software

Table V: Effect of manure and irrigation on grain yield and WUE_i of wheat and maize

Treatment	WUEi (kg ha-1 mm-1)¶		Grain yield (Mg ha^{-1})	
	Wheat	Maize	Wheat	Maize
M_0*	0.72	1.11	3.36	6.25
M_{50}	0.98	1.46	4.56	8.12
I_1**	0.97	1.31	3.86	6.42
I_2	0.80	1.05	4.41	6.72
$M_0 \times I_1$	0.79 b$^{\pm}$	1.18 bc	3.17 c	5.81 b
$M_0 \times I_2$	0.64 c	1.04 c	3.55 b	6.69 b
$M_{50} \times I_1$	1.11 a	1.64 a	4.44 a	8.05 a
$M_{50} \times I_2$	0.85 b	1.28 b	4.67 a	8.19 a
LSD P 0.05 M	0.08	0.16	0.34	0.89
I	0.05	0.17	0.20	NS
M x I	1.38, 1.32	0.25, 0.23	0.28, 0.39	0.07, 0.09

* M_0 and M_{50} correspond to dairy manure at 0, 50 Mg ha^{-1}; **I_1 and I_2 corresponds to 32.5 cm and 47.5 cm for wheat, and 45 and 60 cm for maize crop, respectively; ¶irrigation water use efficiency (kg of grain yield per mm of water applied); ¤ 1st LSD value is for same levels of Manure, while 2nd for different levels of manure; ±Means sharing the same letter (s) do not differ significantly at $P < 0.05$ according to Least Significance Difference Test

where pressure plates are no more reliable (Campbell, 1988). Curve fitting for hydraulic conductivity using Van Genuchten-Mualem model (VGM) are shown in Fig. 2 and unsaturated hydraulic conductivity predicted at -5 and -10 matric potential are presented in Table III, which show that model fitted well to observed data with r^2 value ranging from 0.91 to 0.96. Table IV also indicates that at -5 cm matric potential, a higher value of unsaturated hydraulic conductivity was observed by using power function after measuring α with tension infiltrometer when compared to VGM curve fitting.

Soil hydraulic properties according to Durner model: Table IV shows the hydraulic parameters of soil obtained by curve fitting of dual porosity model proposed by Durner-Maulem (DM), where as curve fitting is shown in Fig. 3. Dual porosity model fitted well with r^2 value ranging from 0.96 to 0.99, however no obvious difference in K(*h*) at -5 and -10 cm matric potential were observed for different soil layers and manure receiving treatment. Data also showed that r^2 observed in case of DM model was higher than VGM model, indicating that observed data of soil water retention and hydraulic conductivity fit better in dual porosity model under field conditions. Several authors have preferred DM model under field condition due to non-uniform water flow (Pruess & Wang, 1987; Gerke & Van Genuchten, 1993a; Jarvis, 1994; Kohne *et al.*, 2006).

Grain yield and WUE_i: Manure amendment improved the WUE_i of both crops by 37.1 (wheat) and 31.5% (maize) with a yield improvement of 36.6 and 29.9%, respectively (Table V). Heavy irrigation (I_2) also showed some increase in the yield of wheat (8.0%) and maize (7.4%) over deficit irrigation (I_1) but at the expense of 21.6 and 17.7% decrease in WUE_i for respective crops. Interactive results of manure and irrigation showed that "M_0I_2" had 12.0 and 15.1% increase in the yield of wheat and maize, respectively over "M_0I_1" but at the expense of 19.0 and 11.9% decrease in the WUE_i of these crops. However, "$M_{50}I_1$" showed an increase of 40.1 and 38.6% in the yield of wheat and maize, respectively over "M_0I_1" with 40.5 and 39.0% increase in WUE_i of respective crops. Results indicated that application of manure with deficit irrigation was better choice than applying heavy irrigation with no manure. This might be attributed to an enhanced water holding capacity of the manure amended soil (Table I) due to an increased surface area (Gupta & Larson, 1979). Weil and Kroontje (1979) also reported higher moisture contents in heavy manured plots when observed up to 5 years.

CONCLUSION

Soil water retention and hydraulic conductivity could be modeled for curve fitting by RETC-fit software using single or dual porosity model after getting a few inputs of soil suction pressure and hydraulic conductivity. Data fitted well to both models; however, Durner-Mualem (dual porosity) model better predicted the retention capacity and hydraulic conductivity of the soil under transient conditions of field. Manure improved the available water of the soil and led to increase in WUE_i and yield of wheat and maize crops under deficit irrigation.

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