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Land Use and Soil Management Effects on Infiltration Model Parameters in Semi-arid Tropical Alfisols

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Abstract: Soil infiltration parameters for empirical and process-based models were evaluated in different land use systems, namely agriculture (farmers' and high management systems) and permanent fallow management system in two typical benchmark sites of Alfisol series (Hayathnagar and Kasireddipally) in Andhra Pradesh. Under permanent fallow, the soil series of Kasireddipally had four times higher steady state infiltration rate as compared to that in agricultural systems due to better soil physico-chemical properties. Among the agricultural systems, the steady state infiltration rate was higher by 78% under high management than in the farmers' management. Initial infiltration rate (B) and change in infiltration rate with time (n) in the permanent fallow and high management levels were considerably different than under agriculture and farmers' management. The different parameters of Horton model, i_o (the initial infiltration) and k (constant that determines the rate at which initial infiltration rate reaches steady state infiltration) were found to be higher in the permanent fallow as compared to agricultural land use. High management levels had beneficial influence on soil infiltration. Based on the coefficient of determination (R^2), percentage error (PE), coefficient of residual mass (CRM) and model efficiency (ME) parameters, the Horton's model gave the best representation of infiltration rate and time relationship in Alfisols.

Key words: Alfisol, infiltration, models, semi-arid tropics, land use management system.

Alfisols in semi-arid tropics generally possess inherently low water retention characteristics because of their particle size makeup and mineralogical composition. This is often aggravated by the shallow depth of the soil available for storage. Lack of water storage, combined with mechanical impedance in these hardening soils, tends to limit crop root proliferation. The structural instability and subsequent frequent failure in land surface configurations lead to a reduction in surface roughness (useful for maximizing infiltration) and enhancement of surface sealing and crusting (Weststeyn, 1983). These on the one hand induce excessive runoff even early in the season and, on the other directly affect seedling emergence. Localized droughts are also very likely in the seed environment, i.e. on ridges and in beds where water entry by infiltration is restricted by surface sealing. Infiltration rates of these soils play an important role in planning for *in-situ* moisture conservation during the pre-monsoon and monsoon season to ensure adequate water for crop production. Infiltration can be defined as the process of water entry into the soil through the soil surface (Hillel, 1980). The infiltration rate is most responsive to conditions near the soil surface and changes with management (Sarrantonio *et al.*, 1996). For instance, ploughing, as in conventional tillage, produces compaction (Allegre *et al.*, 1986; Hartge, 1988) which results in reduced soil porosity and huge runoff and nutrient leaching due to low infiltration rate (Hillel, 1982). Besides the predominant properties like soil structure, bulk density and soil organic carbon content, the land uses also considerably influence soil infiltration rate (Navar and Synnott, 2000). The infiltration models can serve as a valuable tool to predict soil infiltration behavior, which is otherwise a time consuming and cumbersome process. Not many efforts have been made so far to use infiltration models for land-use and soil management in semi-arid tropical Alfisol. The present study was conducted with the following objectives: (i) to determine the effect of land use and soil management on infiltration rate and model parameters, and (ii) to evaluate the infiltration

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models for their suitability in prediction of infiltration rate.

Materials and Methods

This work was carried out under National Agricultural Technology Project to identify potential carbon sequestering production systems in the semi-arid tropical benchmark sites of India. Two typical benchmark spots (i) ICRISAT Research farm at Patancheru representing permanent fallow, and (ii) Research Farm of Central Research Institute for Dryland Agriculture, at Hayathnagar representing agricultural system, both in Rangareddy district of Andhra Pradesh, were selected. The soils represented Typic Rhodustalf and were classified as Hayathnagar and Kasireddipally series, respectively (Bhattacharyya et *al*., 2003). Information on location, soil type, bio-climate, etc., of the study area is given in Table 1 (Bhattacharyya *et al*., 2003). The salient profile characteristics of the typifying pedons of the two soil series are as follows.

Kasireddipally: Located in a very gently sloping area (1-3%), the soils are derived from weathered granite and gneisses and are slightly acidic (pH 6.4) with good drainage properties. The surface horizon (Ap) has a strong brown color with sandy loam texture and granular structure, with abundance of earth worm casts, 3-5% fine gravels and an abrupt smooth boundary with the subsequent layer. It has well developed B (11-79 cm), BC (79-109 cm) and C (109-163 cm) horizons. The predominant land use is grassland with occurrence of many very fine and common fine roots in surface soil.

Hayathnagar: Located in a gently sloping to undulating area (3-8%), the soils are derived from weathered granite-gneiss and are strong to medium acidic (pH 5.2-5.6) and well drained. The surface horizon (Ap) is red to dark red with sandy loam to sandy clay loam texture and moderate medium subangular blocky structure. This layer has 30-35% gravels and a clear smooth boundary with well developed B (12-101 cm) and C (101+ cm) horizons. Agriculture is the predominant land use with occurrence of many very fine roots and few medium and coarse roots in surface soil. Information on certain physical and chemical properties of surface soils (0-15 cm) that influence the infiltration rate of experimental sites is presented in Table 2.

There are two agricultural management practices in the area: farmer's management (FM) and high input agricultural management (HM). The FM includes low application of NPK, rare application of manures, sole crop, removal of residues and biomass and no soil moisture conservation practices. The HM is characterized by application of high dose of NPK (location specific), regular application of manures, intercropping with legumes, incorporation of residues and adoption of soil moisture conservation practices.

The infiltration study was carried out in replicates using double ring infiltrometer with 27 cm outer diameter and 15 cm inner diameter (Bouwer, 1986). A constant water head of 8 cm was maintained in the inner ring and free water was kept in the outer ring at all the time. Infiltration rate was determined numerically from the depth of cumulative infiltration and the corresponding time interval data in each location until steady state infiltration rate was reached. The data generated on infiltration rates were fitted into two empirical models (Kostiakov, 1932; Horton, 1940) and two process based models (Green and Ampt, 1911; Phillip, 1957), using the following equations.

Table 1. Details of location, soil class and land use and management level of the study area

Details	Agriculture (HM)	Agriculture (FM)	Permanent fallow (PF)
Site	Hayathnagar, Hyderabad, Andhra Pradesh	Hayathnagar, Hyderabad, Andhra Pradesh	Patancheru, Andhra Pradesh
Latitude	17°20'26"N	17°21'26"N	17°21'36"N
Longitude	78°35'39"E	78°35'46"E	78°35'54"E
Soil classification	Loamy-skeletal, mixed, isohyperthermic, Typic Rhodustalf	Loamy-skeletal, mixed, isohyperthermic, Typic Rhodustalf	Fine, mixed, isohyperthermic, Typic Rhodustalf
Bio-climatic zone	Semi-arid (dry)	Semi-arid (dry)	Semi-arid (dry)
Land use	Agriculture (HM) Sorghum-castor	Agriculture (FM) Sorghum-castor	Permanent fallow

*PF = Permanent fallow; HM = High management; FM = Farmers' management.

Table 2. Some of the predominant physical and chemical properties of experimental soils

Details	Agriculture (HM)	Agriculture (FM)	Permanent fallow (PF)
Soil physical parameter			
Sand (%)	73.4	72.8	66.7
Clay (%)	23.2	17.4	17.9
Bulk density (Mg m^{-3})	1.5	1.6	nd
Soil chemical parameter			
Organic C (g kg^{-1})	6.2	5.3	31.0
$CaCO_3$ (%)	0.3	0.4	0.6
ESP^a (%)	4.0	3.0	4.0

a = Exchangeable sodium percentage; nd = not determined.

Kostiakov (1932) model

$$I = Bt^{-1}$$

$$i = B't^{-1(N+1)}$$

where, I = cumulative infiltration (cm); i = instantaneous infiltration rate (cm min^{-1}); t = time (min), 'B' and 'n' are empirical constants.

Horton (1940) model

$$I = i_c t + \frac{i_o - i_c}{k}(1-e^{-kt})$$

$$i = i_c + (i_o - i_c)e^{-kt}$$

where, i_o = Initial infiltration rate (cm min^{-1}) at t=0, i_c= steady state infiltration rate (cm min^{-1}) k= constant that determines the rate at which i_o reaches i_c, t = time (min).

Green and Ampt (1911) model

$$i = i_c + \frac{B}{I}$$

where, i = instantaneous infiltration rate of soil (cm min^{-1}), i_c = steady state infiltration rate (cm min^{-1}), B = constant.

Phillip (1957) model

$$I = St^{1/2} + At$$

$$i = \frac{1}{2}St^{-1/2} + A$$

where, S = sorptivity (cm $min^{-1/2}$), t = time (min), A = constant = saturated hydraulic conductivity for longer time intervals.

The 'S' parameter of Phillip (1957) model, 'B' parameter of Green and Ampt (1911) model and 'i_o' parameter of Horton (1940) model depend on the initial infiltration rate, whereas 'A' parameter of Phillip (1957) and 'i_c' parameter of Green and Ampt (1911) and Horton (1940) model govern the final steady state infiltration rate at large time (Shukla *et al.,* 2003). When logarithmic transformation of Kostiakov (1932) model is done, 'B' becomes the intercept and 'n' becomes the slope of the infiltration curve. So 'B' governs the initial infiltration rate and 'n' governs the rate of change of the infiltration rate with time. In case of Phillip (1957) model, the magnitude of value of sorptivity (S) indicates the capacity of a soil to adsorb water and controls the initial infiltration rate. When time increases, the transmissivity (A) becomes the important factor which controls the infiltration rate.

The infiltration model parameters were estimated by linear and nonlinear regression analysis (Gomez and Gomez, 1984). The performances of different models was evaluated using coefficient of determination (R^2),

Coefficient of determination (R^2) =

$$\left[\frac{\sum_{i=1}^{n}(O_i - \bar{O})\,(P_i - \bar{P})^2}{\left(\sum_{i=1}^{n}(O_i - \bar{O})^2\right.\left(\sum_{i=1}^{n}(P_i - \bar{P})^2\right.}\right]$$

Percentage error PE

$$\frac{100}{\bar{O}} \times \frac{\sqrt{1}}{n}\sum_{i=1}^{n}(P_iO_i)^2$$

where, $\sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_iO_i)^2}$ is Root Mean Square (RMSE)

Table 3. Effect of soil type and management on infiltration characteristics of SAT soils

Details	Land use		
	Agriculture (HM)	Agriculture (FM)	Permanent fallow (PF)
Initial infiltration (cm min^{-1})	1.60	0.90	3.07
Steady state infiltration rate (cm min^{-1})	0.05	0.01	0.12
Time to reach cumulative Infiltration (min)	150	235	180
Cumulative infiltration (cm)	13.66	9.98	18.29

Coefficient of residual mass (CRM) =

$$\frac{\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i}{\sum_{i=1}^{n} O_i}$$

Model efficiency (ME) =

$$1 - \frac{\sum_{i=1}^{n} (P_i - O_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$

where, O_i = observed value, P_i = predicted value, $\bar{O}$ = mean of observed value, $\bar{P}$ = mean of predicted values, and n = number of observations.

Higher values of coefficient of determination (R^2) and model efficiency (ME) imply better fitting of the model, whereas the lower values of PE and CRM indicate better performance of the model.

Results and Discussion

Influence of land use and management levels on soil infiltration

The temporal changes in the infiltration rate and the cumulative infiltration are depicted in Fig. 1 and the effects of different management practices on infiltration are given in Table 3. The initial infiltration (1.6 cm min^{-1}), steady state infiltration (0.05 cm min^{-1}) and cumulative infiltration (13.6 cm) values were higher under HM in Hayathnagar soil series than under FM (Table 3). However, when the effects of HM in Hayathnagar series was compared with the effects of permanent fallow in Kasireddipally series, it was observed that the initial infiltration and steady state infiltration rates in permanent fallow. were 92% and 140% higher, respectively, compared to HM in Hayathnagar series (Table 3). Permanent fallow provides almost the same benefits in terms of infiltration and soil and water conservation as no tillage or zero tillage with surface residue or surface cover. Permanent fallow also provides appropriate conditions for better microbial and earthworm activity and in turn influences soil organic matter. The higher soil organic carbon content (Table 2), high termite activity in the upper 65 cm of soil profile and abundance of earthworm casts (70-80% v/v) in the surface soil of permanent fallow in Kasireddipally series (Patancheru) could be the reasons for the higher infiltration. These factors have been viewed as important pathways for preferential flow of water in some soils (Shipitalo and Protz, 1987; Al-Addan *et al.*, 1991).

Unger (1990) observed that management practices such as surface residues, as with conservation tillage systems, reduce runoff and increase infiltration by dissipating the energy of falling rain drops, thereby reducing soil aggregate dispersion that results in surface sealing, and retarding of the flow rate of water across the surface, thus providing more time for water infiltration. Duley and Keley (1939) observed that management practices had a greater effect on infiltration than soil type, slope, antecedent water content, and rainfall intensity. Earlier, Berry *et al.* (1985), and Lang and Mallett (1984) observed that water infiltration increased with increasing amount of residue on the surface.

Influence of land use and management levels on soil infiltration model parameters

The infiltration model parameters for two empirical models and two process-based models were estimated by fitting the observed data (Table 4).

Empirical models: The value of B in Kostiakov model, in FM of Hayathnagar soil series, was 127% higher than the observed value, while the predicted value of B under HM closely matched the observed

Table 4. The parameters and coefficients of various infiltration models for various land use and management systems

Soil series (Management)	Kostiakov		Horton		Green and Ampt			Phillip	
	B	n	i_0 (cm min^{-1})	i_c	k	B (cm)	i_c (cm min^{-1})	S (cm $min^{-1/2}$)	A
Patancheru (PF)*	1.736	-0.414	15.662	0.174	0.839	7.260	-0.595	7.418	-0.427
Hayatnagar (HM)	1.541	-0.313	4.219	0.109	0.516	2.104	-0.163	3.907	-0.188
Hayatnagar (FM)	2.040	-0.094	4.111	0.060	0.525	0.536	-0.081	2.883	-0.125

*PF = Permanent fallow; HM = High management; FM = Farmers' management.

value of 1.60. There was considerable difference in 'n' values (Table 4). In Horton (1940) model, the parameters i_o, i_c and k were found to be highest in the soils of Patancheru as seen from the observed and predicted values. The parameters i_o and k had a significant difference between the land uses only. Similarly, i_c values reflected the differences among the land uses and management levels.

Process-based models: In Green and Ampt (1911), the 'B' value of Patancheru soils was found to be 245% more than that of HM soils of Hayathnagar. This parameter and i_c values of the model had considerable difference between the land uses and also among the management levels. In Philip model, there was considerable difference in S and A values among the land uses and management levels. The negative values of i_c and A in Green and Ampt and in Phillip models can be attributed to the truncation errors or errors caused by the mathematical approximations (Lal and Van Doren, 1990).

The above results indicate that both land use and management levels considerably influenced different infiltration parameters, as reasonably predicted by the models. However, to understand the relative performance of each model from the estimated values with respect to R^2, PE, CRM and ME parameters, regression studies were carried out. From the R^2 values, it was understood that Kostiakov (1932) model could explain 81-97% variations in the infiltration rate, whereas Horton (1940) model accounted for 96-99% variation (Table 5). The variation in infiltration rates explained by Green and Ampt (1911) model and Phillip (1957)

Table 5. Evaluation of different infiltration models under different

Details	Agriculture (HM)	Agriculture (FM)	Permanent fallow (PF)
Kostiakov (1932)			
R^2	0.965	0.965	0.808
PE	17.405	13.067	34.883
CRM	0.109	0.014	0.259
ME	0.803	0.923	0.516
Horton (1940)			
R^2	0.965	0.960	0.995
PE	7.475	9.565	3.574
CRM	2.36E-16	0.006	0.007
ME	0.964	0.959	0.995
Green and Ampt (1911)			
R^2	0.808	0.626	0.582
PE	17.195	28.882	32.404
CRM	0.0001	-9.4E-05	7.49E-05
ME	0.808	0.626	0.626
Philip (1957)			
R^2	0.832	0.846	0.743
PE	16.085	18.559	25.398
CRM	-11.98E-05	1.69E-05	1.69E-05
ME	0.832	0.846	0.846

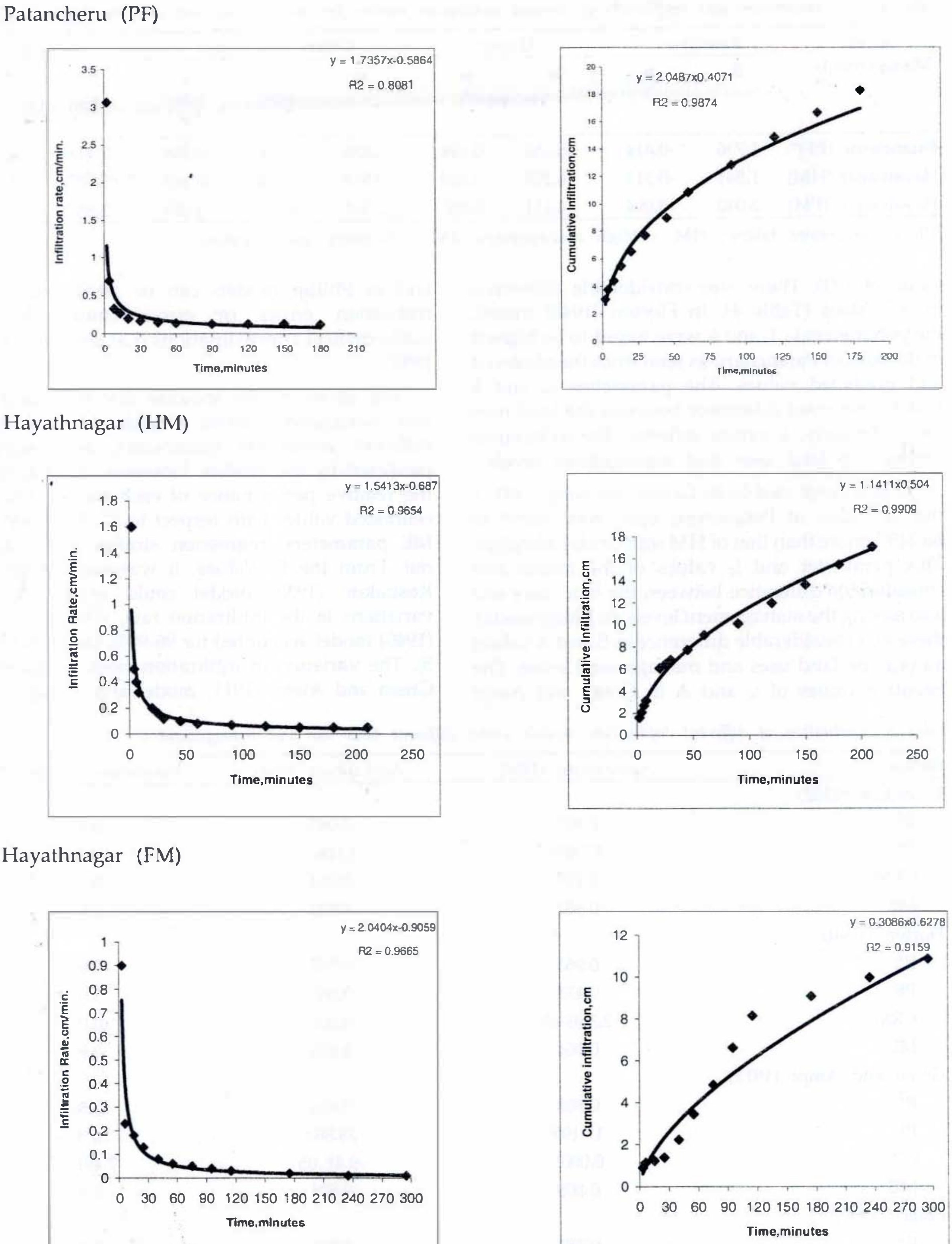

Fig. 1. Mean values of observed infiltration rate and cumulative infiltration of various land use and management levels in two soil series representing Alfisols.

model was to the extent of 58-81% and 74-84%, respectively. From the goodness of fit analysis, it was found that about 80% and 97% of the variation in soil infiltration rate was explained by the observed infiltration data (Fig. 1) in case of Patancheru and Hayathnagar soil series, respectively. Thus, the overall performance of the infiltration models tested in relation to the field observed values in the semi-arid tropical Alfisols in India can be ranked as follows, Horton (1940)> Kostiakov (1932)> Phillip (1957)> Green and Ampt (1911).

The results of the present study could be used to understand the infiltration behavior and to predict the infiltration rates for the Alfisol soil series.

Conclusions

High management systems with suitable land uses in the Alfisols of semi-arid tropical region of India may be helpful in positively influencing the soil organic carbon, which in turn may result in higher infiltration with less runoff. Patancheru (Kasireddipally) had four times higher steady state infiltration rate under permanent fallow as compared to agricultural systems. Further, among the agricultural systems, the steady state infiltration rate under high management was more than under farmers' management by 78%. Among the empirical models, Kostiakov (1932) model performed better and among the process-based models, Phillip (1957) model performed better than the Green and Ampt (1911) model. However, considering the overall performance, simple infiltration models based on Horton (1940) provided best representation of the infiltration rate and time relationship and represented a best fit with experimental infiltration data in the semi-arid tropical Alfisols.

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