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Evaluation of infiltration characteristics and models of an Alfisol under Tung (*Aleurites moluccana (L.) Wild*)-based cropping systems

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ABSTRACT: Infiltration is an important property that reflects the physical state, quality, as well as the structural stability of the soil. The objective of this study is to evaluate the infiltration characteristics and adequacy of some mathematical models in fitting the infiltration data in tung-based cropping systems in an Alfisol in southern Brasil. The treatments consisted of sole Tung (T); Tung-crambe-sunflower rotation + organic fertilizer (T-C-S+O); Tung-crambe-sunflower rotation + in-organic fertilizer (T-C-S+I) and Tung-oats-peanut rotation (T-Ot-P), with four replications in a randomized complete block design. Soil samples were collected from soil depths, 0-10, 10-20, 20-40, 40-60 and 60-80 cm for the determination of soil texture, organic matter, bulk density, total porosity and macroporosity. Infiltration tests were performed using double ring infiltrometers. The initial soil physical conditions did not show any impediment to water dynamics. Initial sorptivity and infiltration rate were highest in T-Ot-P and T-C-S+O. Horton model was the better of the empirical approaches while the Philip equation was better of the theoretically based models. In all, Philip's equation almost gave a perfect fit (NSE ≥ 0.98) of the data set, however the Green-Ampt model gave R^2 = 0 and NSE<0 in T-C-S+I treatments. This study affirmed the importance of cover crops and crop rotation for soil and water conservation and could enhance water availability and water use efficiency of the tung crop.

Keywords: Cover crops, soil water dynamics, model adequacy.

INTRODUCTION

Infiltration is an important property that reflects the physical state, quality, as well as the structural stability of the soil. However, this is a complex and dynamic process (Scott, 2000) governed by soil physical and hydraulic properties, as well as the crop and soil management practices (Urchei & Fietz, 2002). In the landscape, the most important factor that influences infiltration is the vegetation covering the soil surface during rain events because high rainfall intensity occurring in situations where the soil is not protected by vegetation or residue cover, promotes surface sealing as a result of raindrops impact and infiltration become reduced. Other factors include duration of rainfall or irrigation, hydraulic conductivity, soil depth and impervious layers (Reichert, 1992).

Numerous models, some entirely empirical and others theoretically based, have been proposed and employed to express and analyze infiltrability as a function of time or of the total quantity of water infiltrated into the soil. These widely used models include the Green-Ampt, Kostiakov, Horton, Philip, Modiffied Kostiakov or Kostiakov-Lewis, Smith equation, Holtan model and so on. However conclusions are not the same for different soils, climate and cropping conditions. For example, Jejurkar & Rajurkar (2012) found the Kostiakov equation as the best for analyzing infiltration for almost all the cultivated land cover they studied. On the other hand, Panachucki et al (2006) found Horton to be the most appropriate infiltration model in their studies.

Tung (*Aleurites moluccana (L.) Wild*) is one of the world's great domesticated multipurpose oil tree. It is native to the Indo-Malaysia region, and has been successful introduced to other regions including Brazil (Krisnawati et al., 2011).

Apart from studies on tung growth, medicinal attributes and ethnobotany, no or limited attempt has been made to evaluate the soil environment where it grows especially under different soil and crop management practices. Therefore, there is a need to evaluate the soil physico-hydric properties of the tung soil environment and more important, when grown with other crops. Thus, the objective of this study is to evaluate infiltration characteristics and the adequacy of some mathematical models in fitting the infiltration data in tung-based cropping systems in southern Brazil.

MATERIALS AND METHODS

Study site and climate

The experiment was conducted in a new tung field at the experimental station of the Department of Soils, Federal University of Santa Maria, Santa Maria, Rio Grande do Sul State, Brazil, latitude 29° 42' S, longitude 53° 48' W, and altitude of 90 meters. The climate is classified as "Cfa" by Köppen. The mean temperature of the warmest month is above 22°C, and the temperature of the coldest month is between -3°C and 18°C. Precipitation is well distributed, with annual rainfall ranging from 1300 to 1800 mm yr^{-1}. The main soil series of the study area is sandy loam, Dystrophic Paleudalf (Soil Survey Staff, 2006).

Experimental design, treatments and soil sampling

The experiment was a 4 x 4 randomized complete block design (RCBD). The treatments consisted of sole Tung (T); Tung-crambe-sunflower rotation + organic fertilizer (T-C-S+O); Tung-crambe-sunflower rotation + in-organic fertilizer (T-C-S+I) and Tung-oats-peanut rotation (T-Ot-P) with four replications. A total of eighty (80) undisturbed soil samples were collected using soil cores, 57 mm in diameter and 30 mm high, from soil depths, 0-10, 10-20, 20-40, 40-60 and 60-80 cm for the determination of bulk density (BD), total porosity (P_t), and macroporosity (Ma). Soil moisture content was determined with the aid of Time Domain Reflectometry (TDR) (Campbell Equipment Inc., USA). For granulometric analysis and textural classification, another set of disturbed samples were collected. The soil samples were stored in sealed plastic cans, transported to the laboratory and analyzed using Embrapa (1997) procedures.

Infiltration test

Infiltration tests were conducted using double ring infiltrometers (Bouwer, 1986), 20 and 40 cm diameter for the inner and outer rings, respectively. Initially, water was allowed to infiltrate at 1 min interval for the first 5 minutes, then 2, 5, 7 10 and 5 minutes intervals until steady rate was achieved.

The initial sorptivity of Philip equation was obtained using the equation derived by Amer (2012). The accumulated infiltration, initial and steady-state infiltration rates were determined.

The Kostiakov, Philip, Green-Ampt and Horton models (Table 1) were adjusted with the infiltration data and the parameters were obtained using the Gauss-Newton method, through DataFit program.

Model performance

The model performance was evaluated using the following statistical indices: coefficient of variation of the Root Mean Square difference (CV_{RMSD});

Table 1. Infiltration models evaluated.

S/No.	Name	Equation/Model
1	Kostiakov	$I(t) = mt^{\alpha}$ $i = \alpha\, mt^{\alpha-1}$
2	Horton	$i = i_f + (i_c - i_f)e^{-\beta t}$
3	Green-Ampt	$i = i_f + \frac{b}{\sum I}$
4	Philip	$I(t) = At^{1/2} + Kt$

I: cumulative infiltration, cm; *i*: infiltration rate, cm/hr; *t*: time, mins, i_o, i_f: initial and final infiltration rate, respectively, cm/hr; *α, m, β, b, A* and *K* are model parameters.

coefficient of determination (R^2) Kobayashi and Salam (2000) and the Nash Sutcliffe Efficiency, NSE, which indicates how well the plot of measured versus simulated values of infiltration fits the 1:1 line, where NSE = 1 shows a perfect fit, 0<NSE<1 as acceptable and NSE<0 as unacceptable, indicating measured results as better predictor than simulated values (Moriasi et al., 2007).

RESULTS AND DISCUSSION

Results

Soil physical properties

The results of some physical properties of the soil environment of the Tung-based cropping system are presented in table 2. The clay content increased down the profile and the soil texture changed from sandy loam to loam and clay loam. The BD ranged between 1.43 and 1.62 g cm^{-3}. This is less than the value of 1.75 g cm^{-3} considered as the critical limit to restrict water dynamics and root growth. Total porosity values were between 0.338 and 0.469 cm^3 cm^{-3} while the Ma ranged between 0.05 and 0.15 cm^3 cm^{-3}, the highest values being in the surface layer (Table 2). The test was conducted three weeks after rain, hence the low initial soil moisture content in comparison to the soil moisture content at field capacity (Table 3).

Table 2. Some physical properties of the study site at the beginning of the experiment in 2012.

Depth, cm	OM	Sand	Silt	Clay	Texture
	-----------------------	%	----------------------		
0-10	1.5	61.25	25.97	12.79	SL
10-20	1.3	60.57	25.30	14.15	SL
20-40	1.2	55.29	26.44	18.27	SL
40-60	0.9	46.79	29.61	23.59	L
60-80	0.8	38.29	24.08	37.63	CL
	T-C-S+I		T-C-S+O	T-Ot-P	T
			BD, g cm^{-3}		
0-10	1.50a		1.62a	1.57a	1.50a
10-20	1.61a		1.53a	1.61a	1.57a
20-40	1.56a		1.58a	1.52a	1.53a
			Pt, cm^3 cm^{-3}		
0-10	0.38a		0.35a	0.36a	0.39a

10-20	0.38a	0.38a	0.33a	0.35a
20-40	0.35a	0.35a	0.36a	0.36a
	Ma, $cm^3\ cm^{-3}$			
0-10	0.13a	0.07a	0.09a	0.15a
10-20	0.06a	0.12a	0.08a	0.08a
20-40	0.05a	0.06a	0.06a	0.07a

SL: sandy loam; L: loam; CL: clay loam; OM: organic matter; T-C-S+O: Tung-crambe-sunflower rotation + organic fertilizer; T-C-S+I: Tung-crambe-sunflower rotation + inorganic fertilizer; T-Ot-P: Tung-Oats-Peanut rotation; BD: bulk density; Pt: total porosity; Ma: macroporosity. Trts: treatments; Values with the same letter within columns do not differ at 5% probability level by Tukey test.

Table 3. Field capacity, initial soil moisture content and infiltration characteristics of the Tung-based cropping systems.

Treatments	T-C-S+I	T-C-S+O	T-Ot-P	T
FC, %	29.86	27.96	28.40	27.81
θ_i, %	22.64	23.86	22.40	22.43
S_i, $cmmin^{0.5}$	0.52	0.86	0.87	0.69
I, mm	100.18	117.33	75.81	75.13
i_o, mm/hr	108.30	230.70	243.70	216.60
i_f, mm/hr	25.00	25.70	17.60	12.20

FC: soil moisture content at field capacity; θ_i: initial soil moisture content before the test, S: sorptivity ($S_i = m^{0.5}/\ \alpha$) (Amer, 2012); I: accumulated infiltration; i_o, i_f: initial & final infiltration rates.

Sorptivity and infiltration

At the beginning of infiltration (unsaturated condition), the initial sorptivity, S_i, was highest (0.87 $cm/min^{0.5}$) in T-Ot-P plots and lowest (0.52 $cm/min^{0.5}$) in T-C-S+I (Table 3). At the end of infiltration, the accumulated infiltration was highest (117.33 mm) in T-C-S+O treatments and least (75.13 mm) in sole tung. At the onset of infiltration, the initial infiltration rate was greatest (243.7 mm/hr) for the T-Ot-P and the least (108.3 mm/hr) was for the T-C-S+I. The final infiltration rate was between 12.2 and 25.7 mm/hr, the greatest value from T-C-S+O plots and the least for the sole tung treatments.

Model parameters and performance

The fitting parameters, *α, m, β, b, A* and *K,* and performance evaluation of the various models are presented in table 4. The R^2 was least for Green-Ampt. Similarly, the CV was highest for Green-Ampt model. However, the least and the best R^2 and CV were obtained for Philip equation. For all the models, the NSE values were between 0 and 1 except in T-C-S+I where it was less than zero (0) for Green-Ampt model. The highest and best NSE was from Philip equation while the lowest NSE values were also obtained from Green-Ampt model.

Discussion

Infiltration is a surface phenomenon and is greatly influenced by soil surface conditions. The initial

Table 4. Model parameters and adequacy of the various infiltration models.

	T-C-S+I	T-C-S+O	T-Ot-P	T
	Kostiakov model			
α	0.67	0.55	0.45	0.51
m	0.42	0.85	0.88	0.69
R^2	0.77	0.96	0.91	0.94
CV	0.34	0.28	0.32	0.31
NSE	0.47	0.88	0.90	0.90
	Horton model			
β	0.025	0.052	0.092	0.090
R^2	0.91	0.97	0.96	0.90
CV	0.14	0.15	0.20	0.31
NSE	0.91	0.97	0.96	0.90
	Green-Ampt			
b	2.27	12.47	11.34	9.69
R^2	0.00	0.57	0.84	0.82
CV	0.49	0.53	0.41	0.42
NSE	-0.12	0.57	0.84	0.82
	Philip equation			
A	0.53	0.95	0.86	0.73
K	0.037	0.012	-0.015	-0.002
R^2	0.99	0.99	0.99	0.99
CV	0.067	0.044	0.050	0.046
NSE	0.98	0.99	0.99	0.99

α, m, β, b, A and *K:* fitting parameters of the models; R^2: coefficient of determination; CV: coefficient of variation; NSE: Nash Sutcliffe Efficiency

physical conditions of the surface layers are considered adequate for water entry as the BD values were less than the value of 1.75 g cm^{-3} considered as the critical limit to restrict water dynamics and root growth (Reinert et al., 2008) and the macroporosity values were almost equal to and greater than 0.10 $cm^3\ cm^{-3}$ as the limit for optimum water flow and gas exchange (Drewry et al, 2008).

Infiltration was high at the beginning and over time, slowed down and reached the steady-state, or final infiltration. The effect of initial soil water content and sorptive forces were predominant among the stages of unsaturated and transition water flow during the initial infiltration process. Sorptivity is the ability of the soil to suck or absorb water and a relatively dry soil will suck up more water (Hallet, 2008). Since the initial soil moisture content was less than the field capacity, there is the tendency for high initial absorption of water. However, as the soil wets up and approaches the steady state, gravitational forces and hydraulic conductivity come into play and the infiltration is governed by the shape, volume and tortuosity of pores. The high sorptivity in T-C-S+O and T-Ot-P plots can also be related to the low macropore volume. This is because soils with smaller pores have higher sorptivity than those with greater pores (Hallet, 2008), and consequently, the high infiltration rates. This can be attributed to the importance of cover crops which capture the energy of raindrops and eliminates surface sealing, addition of organic matter which promotes aggregation and porosity as well as the extensive root system that create pores which favours water flow. This result corroborates the findings of Panachuki et al (2006) who found highest infiltration rate in no-tillage with winter oats.

The coefficient of determination, R^2, is an indicative of explained variability of a given model. Comparing the theoretically based models, the CV was higher in Green-Ampt, confirmed the low R^2 values. The low R^2 (as low as 0) obtained from Green-Ampt model is reflected in the very high CV values (40.5-53.5 %). The zero (0) R^2 value obtained in T-C-S+I plots is an indication that the Green-Ampt model failed to accurately simulate the dataset. However, for the empirical models, the low CV (4.4-6.7 %) from the Horton model is an indication of high R^2 of not less than 90 %.

In this study, Philip's equation gave almost a perfect fit (NSE $\geq$ 0.98) of the data set whereas it was less than zero in T-C-S+I treatments. This is unacceptable and showed that the measured results were better predictor than the simulated values. Based on these results, it can be affirmed that the Horton model was the better of the empirical approaches while the Philip equation was the better of the theoretically based models. Alve Sobrinho et al. (2003) and Panachuki et al. (2006) evaluated the adequacy of Horton and Kostiakov-Lewis models and concluded that the Horton model was more adequate to estimate infiltration rate whereas Jejurkar and Rajurkar (2012) found Kostiakov model as the best among the various models evaluated.

Conclusions

Initial sorptivity and infiltration rate were highest in Tung and oats-peanut cover crop rotation and Tung-crambe-sunflower + organic fertilizer.

Horton model was the better of the empirical approaches while the Philip equation was better of the theoretically based models.

This study affirmed the importance of cover crops and crop rotation for soil and water conservation and could enhance water availability and water use efficiency of the tung crop.

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