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Water infiltration rate in Yellow Latosol under different soil management systems

Jorge L. X. L. Cunha[1], Maria E. H. Coelho[2], Abel W. de Albuquerque[1], Cicero A. Silva[1], Antônio B. da Silva Júnior[1] & Islan D. E. de Carvalho[1]

[1] Centro de Ciências Agrárias/Universidade Federal de Alagoas. Rio Largo, AL. E-mail: jorge.cunha.xavier@gmail.com; solosceca@gmail.com; iapa.alexandre@gmail.com; antonio.barbosa@ceca.ufal.br; islandiego@hotmail.com
[2] Instituto Federal do Ceará. Iguatu, CE. E-mail: mehcoelho@yahoo.com.br (Autora correspondente)

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A B S T R A C T

The management systems affect soil structure, causing changes in porosity that can influence soil water infiltration. In order to study the water infiltration rate in a Yellow Latosol under different tillage systems and different mathematical models, an experiment was conducted from October to December 2012, at the Center for Agricultural Sciences at the Federal University of Alagoas, using a randomized block design with five replicates, in a split-plot scheme. In the plots, the management systems were evaluated (conventional tillage, no-tillage and minimum tillage) and, in the sub-plots, the empirical mathematical models of Kostiakov, Kostiakov-Lewis and Horton, and the ring method. The method used to measure soil water infiltration rate was adapted from the classic double-ring infiltrometer method. The minimum tillage system provided better results compared with the others, with water infiltration rate of 167 mm h^{-1}, and the equation that best fitted the data of the ring infiltrometer was Kostiakov's, in the no-tillage system.

Palavras-chave:
irrigação
métodos de infiltração
sistemas de preparo do solo

Taxa de infiltração da água em um Latossolo Amarelo submetido a diferentes sistemas de manejo

R E S U M O

Os sistemas de manejo afetam a estrutura do solo ocasionando alterações na porosidade, passível de influenciar a infiltração de água no solo. Com o objetivo de estudar a taxa de infiltração de água em um Latossolo Amarelo, submetido a diferentes sistemas de manejo e diferentes modelos matemáticos, conduziu-se um experimento de outubro a dezembro de 2012, no Centro de Ciências Agrárias da Universidade Federal de Alagoas utilizando-se o delineamento estatístico em blocos casualizados com cinco repetições no esquema de parcelas. Nas parcelas foram avaliados os subdivididas sistemas de manejo convencional, plantio direto e cultivo mínimo e nas subparcelas os modelos matemáticos empíricos Kostiakov, Kostiakov-Lewis, Horton e o modelo prático do anel. O método adotado para medir a taxa de infiltração da água no solo foi adaptado do modelo clássico do infiltrômetro de anéis concêntricos. O sistema de cultivo mínimo proporcionou melhores resultados com valores da taxa de infiltração estável (T_{ie}) básica de água no solo de 167 mm h^{-1}, superando os demais tratamentos; a equação que mais se ajustou ao modelo do infiltrômetro de anel foi o de Kostiakov, no sistema de plantio direto.

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Introduction

Soil water infiltration is a dynamic process of entry of water into the soil through the soil surface as a function of the time elapsed. Initially, its value is high, decreasing over time until it becomes constant when the soil saturates, which can be called stable infiltration rate (T_{ie}) (Brandão et al., 2006).

Knowing the values of the stable infiltration rate is essential for the development of agricultural projects of irrigation, drainage and conservation of soil and water, the design of irrigation and drainage systems, as well as for the creation of a more real picture of water retention and soil aeration (Pott & Maria, 2003; Cunha et al., 2009). Errors in the calculation of the basic infiltration rate can cause failures in the dimensioning of irrigation projects, decrease the efficiency of the system, increase operation costs, energy expenditure and water consumption and maximize environmental impacts, such as soil erosion, nutrient leaching and salinization, among others (Calheiros et al., 2009).

Water infiltration rate is affected by the initial water content, soil surface conditions, saturated hydraulic conductivity, pore volume and size distribution, presence of stratified horizons, distance from water source to the wetting front, texture and type of clay (Paixão et al., 2009). Therefore, soil management systems influence water infiltration rates, since they change soil surface conditions.

Although there is no standardization of systems for the measurement of water infiltration, it must be measured using techniques capable of adequately representing the natural conditions of the soil. According to Paixão et al. (2009), it is necessary to adopt methods and models with determinations based on conditions equal to those observed at field.

This study aimed to evaluate water infiltration rate in a soil subjected to different management systems using mathematical models, which were compared with the ring infiltrometer method at field conditions.

Material and Methods

The experiment was carried out from October to December 2012, at the Center for Agrarian Sciences of the Federal University of Alagoas (CECA/UFAL), located in the municipality of Rio Largo-AL (9º 29’ 45” S; 35º 49’ 54” W; 165 m) on a flat relief with good drainage. According to Köppen’s classification, the climate of the region is A's (tropical hot and humid, with dry season from spring to summer and rainy season from autumn to winter). The soil was classified as dystrophic cohesive Yellow Latosol, of sandy loam texture (EMBRAPA, 1999).

The experiment was set in a split-plot design with five replicates. In the plots, the following soil management systems were evaluated: conventional tillage (CT), no tillage (NT) and minimum tillage (MT). In the subplots, four empirical models for the determination of the water infiltration rate were evaluated, with five replicates.

The area under no-tillage had been cultivated for more than six years with *Brachiaria decumbens*, which was desiccated using 1.9 kg ha^{-1} of glyphosate, for the formation of straw. In the plots under conventional tillage, the area had been under fallow when the soil was plowed once and harrowed twice. In the area under minimum tillage, the soil was prepared through scarification and a light harrowing, revolving the soil as little as possible and maintaining plant residues on soil surface.

The method used to measure infiltration velocity and the later redistribution of water in the soil was adapted from the classic double-ring infiltrometer method, using only the cylinder of 50 cm of diameter and 40 cm of height.

The cylinder was inserted into the soil until the depth of 15 cm. Then, a ruler was fixed to the center of a wooden support from the upper edge of the cylinder until the soil surface, in order to measure the water level, which was kept at a maximum of 5 cm and minimum of 2 cm. After the readings for each determined time, a volume of water was poured into the cylinder until the height of 5 cm. At the end of each infiltration test, a soil pit was open in the area and the wetted perimeter was outlined for the collection of soil samples, which were sent to the Soil Physics Laboratory of the CECA/UFAL.

For the determination of T_{ie}, the empirical models of Kostiakov, Kostiakov-Lewis and Horton were used, which describe the volume of water entering the soil over time.

Kostiakov model:

$$I = aT^{n} \quad (1)$$

$$\frac{dI}{dT} = TI = anT^{n-1} \quad (2)$$

where:

I - cumulative infiltration;
a and n - constants depending on the soil (dimensionless);
TI - infiltration rate (cm h^{-1}); and
T - time.

Kostiakov-Lewis model:

$$I = aT^{n} + T_{ie}T \quad (3)$$

$$\frac{dI}{dT} = T_{ie} = anT^{n-1} + k \quad (4)$$

where:

I - cumulative infiltration;
a and n - constants depending on the soil (dimensionless);
TI - infiltration rate (cm h^{-1});
T - time; and
T_{ie} - stable infiltration rate.

Horton model:

$$I = i_f T = \left(i_i - i_f\right) e^{\beta t} \quad (5)$$

$$\frac{dI}{dT} = TI = i_f + \left(i_i - i_f\right) / \beta / \beta - e^{-\beta t} \quad (6)$$

where:

I - cumulative infiltration;
TI - infiltration rate;

a and n - constants depending on the soil (dimensionless);
i_f - final infiltration;
$_i$ - initial infiltration;
β - proportionality factor (dimensionless); and
T - time.

Eqs. 1, 3 and 5 represent the cumulative infiltration, while Eqs. 2, 4 and 6 represent water infiltration rate, for the empirical models of Kostiakov, Kostiakov-Lewis and Horton, respectively.

Results and Discussion

Soil bulk density varied between soil layers, from 1.30 to 1.33 kg dm^{-3} in the conventional tillage, from 1.28 to 1.31 kg dm^{-3} in the no-tillage and from 1.28 to 1.22 kg dm^{-3} for the minimum tillage in the layers of 0-40 and 40-60 cm (Table 1).

The contents of total sand and silt decreased along the soil layers (Table 1), and the opposite occurred for total clay and porosity, which increased in the layer of 40-60 cm, while the silt/clay ratio noticeably decreased as depth increased. Soil porosity ranged from 49,98 to 51,38, 51,74 to 52,09 and 51,86 to 54,27 for the treatments CT, NT and MT, respectively.

The mean values of the infiltration rate decreased over time for the different soil management systems studied (Table 2). This indicates that, for all treatments, the results became progressively constant, trending to the infiltration rate (T_{ie}). In this case, the T_{ie} is stabilized from 164 min on, with the rates of 14.88, 16.32 and 25.44 cm h^{-1}, for CT, NT and MT, respectively. These values agree with those obtained by Hillel (1980).

The mean values of T_{ie} (14.88, 16.32 and 25.44 cm h^{-1}) of the studied areas were obtained using as a reference the curves of the equations of the mean values of infiltration rates.

Table 1. Physical attributes of the soil subjected to conventional tillage, no-tillage and minimum tillage, in the layers of 0-20, 20-40 and 40-60 cm

	Units	Soil management systems								
		Conventional tillage			No-tillage			Minimum tillage		
		0-20	20-40	40-60	0-20	20-40	40-60	0-20	20-40	40-60
		cm								
Total sand	g kg^{-1}	616.00	577.60	509.40	583.80	588.60	553.00	577.80	549.80	486.40
Coarse sand	g kg^{-1}	442.40	422.20	633.60	421.20	440.00	412.80	411.80	390.20	346.00
Fine sand	g kg^{-1}	173.60	155.40	142.40	162.60	148.60	140.20	166.00	159.60	140.40
Silt	g kg^{-1}	179.64	108.04	96.24	161.34	97.04	92.64	167.84	115.84	99.24
Total clay	g kg^{-1}	204.36	314.36	394.36	254.36	314.36	354.36	254.36	334.36	414.36
Soil bulk density	kg dm^{-3}	1.33	1.33	1.30	1.28	1.31	1.28	1.28	1.28	1.22
Soil particle density	kg dm^{-3}	2.66	2.65	2.67	2.66	2.65	2.67	2.66	2.65	2.67
Total Porosity	%	49.98	49.72	51.38	51.74	50.51	52.09	51.86	51.87	54.27
Silt/Clay	-	0.88	0.34	0.24	0.64	0.31	0.26	0.66	0.35	0.24

Table 2. Mean values of infiltration rates, standard deviation and correlation coefficient for water infiltration tests in a soil under conventional tillage, no-tillage and minimum tillage over time

Time (min)	Water height – cm								
	Conventional tillage			No-tillage			Minimum tillage		
	Mean IV	Standard deviation	CV (%)	Mean	Standard deviation	CV (%)	Mean	Standard deviation	CV (%)
001	67.20	0.22	19.36	68.40	0.11	10.00	75.60	0.15	12.04
002	48.00	0.34	42.39	48.00	0.23	29.32	69.60	0.05	4.72
004	36.00	0.16	13.18	43.80	0.36	24.98	57.00	0.19	9.85
006	34.80	0.15	13.07	35.40	0.29	25.00	55.80	0.17	9.00
008	33.00	0.16	14.37	31.20	0.24	25.98	51.60	0.13	7.58
012	24.00	0.24	15.31	27.90	0.13	7.21	47.70	0.77	24.20
016	23.10	0.24	15.64	27.60	0.15	8.24	44.40	0.65	22.10
020	22.50	0.23	15.63	25.80	0.08	4.86	42.90	0.61	21.21
024	20.70	0.24	17.30	24.90	0.11	6.87	42.00	0.58	20.82
029	21.12	0.27	15.35	22.08	0.24	13.09	39.84	0.63	18.98
034	20.88	0.31	17.99	22.08	0.13	7.29	39.60	0.64	19.52
039	19.92	0.32	19.33	21.60	0.16	8.78	38.88	0.60	18.47
044	19.68	0.25	15.30	21.12	0.11	6.48	38.16	0.58	18.26
049	18.96	0.22	13.72	20.88	0.11	6.55	37.68	0.60	19.06
054	18.96	0.22	13.72	21.12	0.09	5.08	36.48	0.60	19.68
064	17.76	0.42	14.05	20.16	0.21	6.17	30.84	0.61	11.88
074	17.04	0.38	13.32	19.32	0.19	5.97	29.76	0.58	11.63
084	16.92	0.36	12.98	19.08	0.20	6.44	28.68	0.42	8.80
094	16.32	0.37	13.61	18.00	0.24	8.16	28.68	0.41	8.66
104	15.84	0.39	14.82	18.00	0.24	8.16	28.08	0.49	10.40
119	15.92	0.33	8.22	17.76	0.38	8.52	27.28	0.75	10.99
134	15.44	0.31	8.11	17.60	0.19	4.25	26.72	0.64	9.61
142	15.12	0.29	7.80	16.72	0.24	5.71	25.84	0.34	5.20
164	14.88	0.30	8.15	16.32	0.16	4.03	25.60	0.38	5.95
179	14.88	0.30	8.15	16.32	0.16	4.03	25.62	0.38	5.91
194	14.88	0.29	7.88	16.32	0.16	4.03	25.44	0.39	6.15

The T_{ie} in the minimum tillage system was higher compared with no-tillage and conventional tillage systems. According to Holanda et al. (2003), the little or no soil disturbance, combined with the incorporation of residues from previous crops, improves soil physical attributes.

Many other studies have also evidenced the higher infiltration rate in the minimum tillage system (Souza & Alves, 2003; Llanillo et al., 2006; Zwirtes et al., 2011). Different results were obtained by Netto & Fernandes (2005), in which the conventional tillage system showed higher T_{ie}. These authors attributed this result to the soil disturbance, which broke the sealed layer and increased the volume of macropores in the superficial layer, responsible for higher water flows in the beginning of the infiltration process. Franzluebbers (2002), Zwirtes et al. (2011) and Gonçalves & Moraes (2012) observed higher T_{ie} in the no-tillage system and explained that factors like the lack of soil disturbance and the presence of residues on the soil surface are determinant in the process of soil water infiltration, since the residues absorb the impact of raindrops and thus reduce superficial sealing. In addition, water infiltration is also influenced by the presence of biological channels, formed by the soil fauna and by the decomposition of roots.

The curves of soil water infiltration were obtained using the mean values of infiltration rates and cumulative infiltration (Table 2) and can be seen by analyzing the opposite behavior of the infiltration rates (Figure 1A)

High determination coefficients were observed for the studied models, which ranged from 0.96 to 1.00 (Table 3). The Kostiakov model was the best one for the calculation of the infiltration rate (R^2 = 1.00). The values of the determination coefficients of model Horton, were 0.87, 0.86 and 0.79 to conventional tillage, no-tillage and minimum tillage, respectively, being lower than those obtained by ring. High coefficients of determination were also obtained for Kostiakov-Lewis model (0.99) being higher than those by ring. High coefficients of determination for Kostiakov-Lewis model were also obtained for all soil management systems.

The stable infiltration rates were 12.97, 14.81 and 23.37 cm h^{-1} for the empirical model of Kostiakov, in the conventional tillage, no-tillage and minimum tillage, respectively. The greatest infiltration rate, final velocity and mean velocity infiltration values were obtained for the minimum cultivation.

Table 3. Mean values of the parameters, determination coefficients, non-linear regressions for the ring method and Horton, Kostiakov and Kostiakov-Lewis models

Treatment	Model	Empirical Parameters				
		IV	Vf	N	Y	R^2
		cm h^{-1}				
Conventional tillage	Ring	67.20	14.80	0.74	54.62 $T^{-0.26}$	0.96
	Horton	61.09	14.80	0.70	57.11 $T^{-0.30}$	0.87
	Kostiakov	49.41	12.93	0.74	49.40 $T^{-0.26}$	1.00
	Kostiakov – Lewis	64.21	27.73	0.74	61.35 $T^{-0.26}$	0.99
No-tillage	Ring	68.90	16.32	0.75	57.31 $T^{-0.25}$	0.97
	Horton	62.09	16.32	0.72	56.81 $T^{-0.28}$	0.86
	Kostiakov	52.11	14.81	0.77	52.11 $T^{-0.23}$	1.00
	Kostiakov – Lewis	68.43	31.13	0.86	65.74 $T^{-0.14}$	0.99
Minimum tillage	Ring	75.60	25.44	0.72	81.64 $T^{-0.22}$	0.97
	Horton	67.14	25.44	0.83	55.16 $T^{-0.17}$	0.79
	Kostiakov	68.91	27.37	0.83	68.90 $T^{-0.17}$	1.00
	Kostiakov – Lewis	94.35	52.81	0.90	92.30 $T^{-0.10}$	0.99

IV- infiltration rate, Vf - final velocity, N - mean velocity infiltration

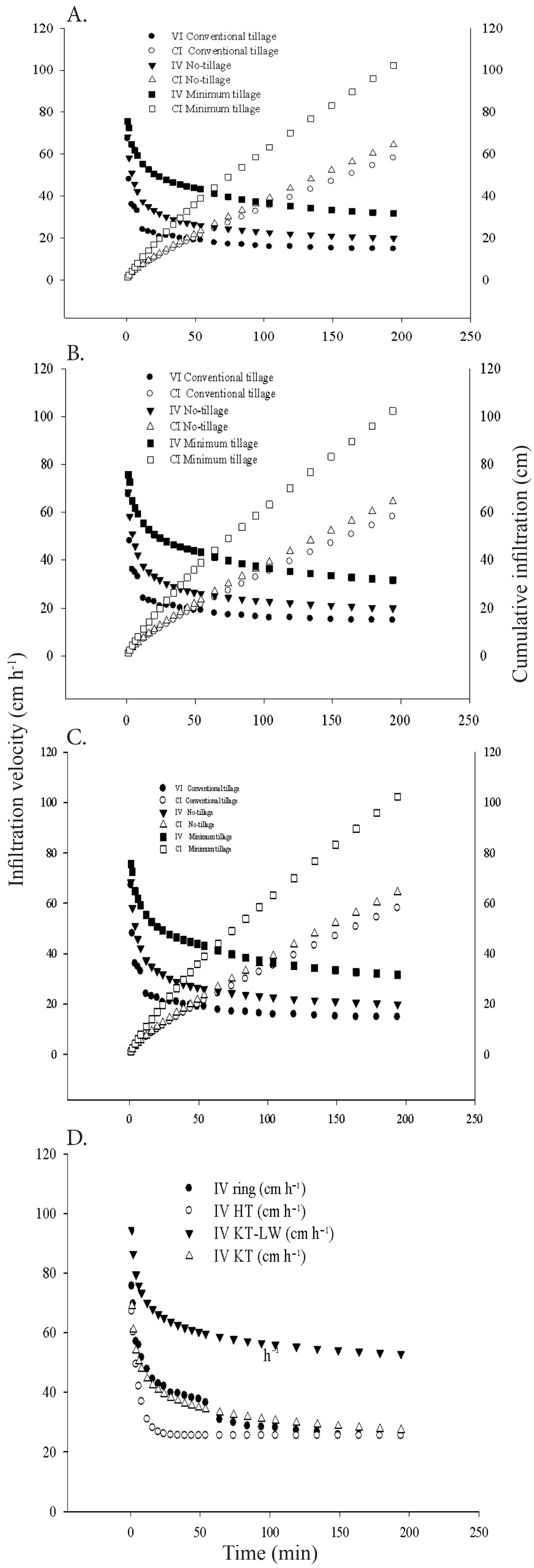

Figure 1. Infiltration velocity (IV) and cumulative infiltration (CI) of the mathematical models of Kostiakov (KT), Kostiakov-Lewis (KT-LW) and Horton (HT) (D); mean infiltration rates in field by ring infiltrometer and calculated by the mathematical models of HT, KT and KT-LW (D)

This occurred probably due to scarification. The results were similar to those obtained by Sidiras & Roth (1984) in a Dusky Red Latosol, who observed a T_{ie} of 12.9 cm h^{-1}, and different from those obtained by Wilson & Oduro (2004), who used double-ring infiltrometer in a Latosol, applying water depths of 0.5 and 1.0 cm h^{-1}, and obtained T_{ie} of 40.0 and 48.2 mm h^{-1}, respectively.

The values observed at field through the ring method (Figure 1B), when compared with the Kostiakov-Lewis model, showed different behavior between the curves, with 100% of the value obtained using the ring method, with T_{ie} of 14.8 and 27.7 cm h^{-1} at the end of the test. Similar results were obtained by Alves Sobrinho et al. (2003), who studied the use of Horton and Kostiakov-Lewis equations under conditions of a simulated rainfall of 14.6 cm h^{-1}, and concluded that the latter would be the least adequate to estimate soil water infiltration rate.

The results were different from those obtained by Alves Sobrinho et al. (2003), who studied the applicability of Horton's equation for a simulated rainfall of 60 mm h^{-1} in areas under conventional tillage and concluded that this was the most adequate equation for the estimation of the water infiltration rate.

The best performance of the Kostiakov model is due to its similarity with the equation used by the ring method (Table 4). The Kostiakov model underestimates the results for the high values (initial velocity) and overestimates the low values, i.e., close to the infiltration rate.

The no-tillage treatment was statistically similar to the model of conventional tillage and both differed statistically from the model of minimum tillage (Table 4) by Tukey test at 0.05 probability level.

The results that originated the curves, which were compared with the Kostiakov model, are shown in Figure 1C. Therefore, it was observed that the model can be safely applied for the cohesive Yellow Latosol and that the results of T_{ie} were 16.32 and 14.80 cm h^{-1}, respectively (Table 3). In addition, the curves showed a similar behavior throughout the experiment (Figure 1C); during the initial time, the infiltration rate was higher, but during the rest of the test, there was almost no difference between the curves. Simões et al. (2005) observed approximate T_{ie} values of 10.4 and 14.3 cm h^{-1} for Cambisols using the model (IAC), with hydraulic heads of 5 and 10 cm.

Table 4. Equations and correlation coefficients of the interactions of the infiltration rates for the treatments x adopted models

Management system	Means	Mathematical models	Means	IV (cm h^{-1})	R^2
Conventional tillage	17,59 a	Kostiakov	12,97 a	$VI = 49,40T^{-0,26}$	1,00
		Ring	14,80 a	$VI = 54,62T^{-0,26}$	0,96
		Kostiakov-Lewis	27,77 b	$VI = 61,35T^{-0,26}$	0,99
		Horton	14,80 a	$VI = 57,11T^{-0}$	0,87
No-tillage	19,68 a	Kostiakov	14,87 a	$VI = 41,11T^{-0,23}$	1,00
		Ring	16,82 a	$VI = 57,31T^{-0,25}$	0,97
		Kostiakov-Lewis	31,19 b	$VI = 61,74T^{-0,14}$	0,99
		Horton	16,32 a	$VI = 56,81T^{-0,28}$	0,86
Minimum tillage	32,81 b	Kostiakov	27,49 a	$VI = 68,90T^{-0,17}$	1,00
		Ring	25,44 a	$VI = 81,64T^{-0,22}$	0,97
		Kostiakov-Lewis	52,90 b	$VI = 92,30T^{-0,10}$	0,99
		Horton	25,44 a	$VI = 55,16T^{-0,17}$	0,79

Means followed by the same letter in the column do not differ statistically by Tukey test at 0.05 probability level

The values obtained using the Kostiakov–Lewis (Kv-Lw) equation and the values from the infiltration tests, which originated the curves in Figure 1C, were similar only at the beginning. However, as time passed, the distance between the curves progressively increased.

The statistical analysis (Table 4 and 5) indicated a significant difference by Tukey test at 0.05 probability level between the means of the treatments of the ring and Kostiakov-Lewis. These results differed from those obtained by Lisboa et al. (2007), who observed basic infiltration rate of 41.0 cm h^{-1} in a Gray Argisol, while in Haplic Luvisol and Humic Cambisol the values corresponded to 18.4 and 16.0 cm h^{-1}, respectively.

The means of the values of ring cylinder and Horton's model (Figure 1C) were similar at the beginning and at the end, with T_{ie} of 16.32 cm h^{-1} (Table 3). However, in the interval from 10 to 15 min, the difference increased, which shows that the model can be used for this type of treatment. According to the Tukey test at 0.05 probability level, there was no significant difference between the two curves (Table 5). These results do not agree with those obtained by Simões et al. (2005), who studied T_{ie} in Cambisols with hydraulic head of 5 cm and observed infiltration rates of 10.44 and 14.43 cm h^{-1}, respectively, for the same type of soil.

The no-tillage system, considered as a conservation practice, promotes profound changes in the relations between soil, water and plant, improving soil physical and chemical attributes and contributing to the improvement of porosity, soil density and, consequently, water infiltration (Klein & Libardi, 2002). Many studies have concluded that, in the no-tillage system, water infiltration values tend to increase due to the improvement in soil structure and consequent increases in organic matter content and porosity caused by the accumulation of plant material (Gonçalves & Moraes, 2012), besides the improvement of soil water storage and reduction of soil losses (Marouelli et al., 2010; Carvalho et al., 2011, Coelho et al., 2013).

The minimum tillage system showed higher infiltration rate compared with conventional tillage and no-tillage systems (Table 5), with significant difference between the mathematical models, by Tukey test at 0.05 probability level.

The curve with the results obtained in an area subjected to minimum tillage, with two harrowings and one subsoiling until the depth of 40 cm, is shown in Figure 1D. The Kostiakov model can be used safely in this type of soil, in which T_{ie} values corresponded to 25.44 and 27.37 cm h^{-1} (Table 3).

Table 5. Summary of the analysis of variance for the soil management systems versus mathematical models in the municipality of Rio Largo, AL, 2008

Source of variation	DF	Mean square
Management System (MS)	2	1361.7560**
Residue (A)	8	11.9709
Equation model (EM)	3	1294.4008**
MS x EM	6	69.1695**
Residue (3)	40	3.9417
Total	59	
CV (%) MS	14.81	
CV (%) EM	8.50	

** Highly significant

The Kostiakov model can be used safely in this type of soil, in which T_{ie} values corresponded to 25.44 and 27.37 cm h^{-1} (Table 3).

According to the Figure 1D, the model indicated that the curves, from the beginning to the end of the test, showed consistent behavior and distribution of all the theoretical values, virtually identical to those obtained through the ring infiltrometer, as the other previously studied soil managements, which explains why the means were equal between the treatments according to Tukey test at 0.05 probability level (Table 5). These results do not agree with those obtained by Lisboa et al. (2007), who studied infiltration rates in soils with more sandy textures and observed T_{ie} values of 40.00 cm h^{-1}, as well as Ottoni Filho (2003), who observed values higher than 26.00 cm h^{-1} in four Cambisols.

The treatment in which the ring cylinder method was used, which was compared with Kostiakov-Lewis model (Figure 1D), that the values obtained by the equation were consistent, but cannot be considered as the ideal model in comparison to the ring cylinder method; this model shows an increasing difference from the beginning of the study, showing a difference of 103.26% between the curves with T_{ie} of 25.4 and 52.8 cm h^{-1}.

After 150 min, the curves for the water infiltration rate through the ring method and Horton's model, for the area under minimum tillage (Figure 1D), became virtually identical. This means that Horton's model is consistent when the infiltration time becomes closer to the time that defines T_{ie}, with values of 25.4 and 25.4 cm h^{-1} (Table 3) According to the statistical analysis (Table 5), there was significant difference at 0.05 probability level between the model of Horton and the ring infiltrometer method.

Conclusions

1. The management systems (conventional tillage, no-tillage and minimum tillage) showed different infiltration rates.

2. The highest basic infiltration rate was observed in the minimum tillage system, followed by conventional tillage and no-tillage.

3. The empirical model of Kostiakov was the best model to express mathematically the ring infiltrometer method.

4. The empirical model of Kostiakov can be used to determine water infiltration rates in the three tillage systems, for this type of soil and soils with similar physical attributes.

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