SOIL INFILTRATION AND LAND USE IN LINARES, N.L., MEXICO
Infiltración y Uso del Suelo en Linares, N.L., México

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SUMMARY

The aim of this study was to fit four infiltration models to 96 observed infiltration trials, as well as to determine the effect of four types of land use on the infiltration rate of vertisols in the northeastern part of Mexico. Infiltration tests were conducted using double ring constant-head infiltrometers during the period July to November 1985 on the property of the Universidad Autónoma de Nuevo León (UANL). The land use types tested were agricultural lands, grasslands, native scrub forests and forest plantations. The infiltration models of Green and Ampt, modified from Kostiakov, Horton, and Philip, were fitted to observed infiltration data. The statistical parameters of the infiltration models were estimated using non-linear least square techniques. A covariance analysis was conducted on the best fitting model to test for differences in the infiltration rate among the studied land uses. The results showed, based on the coefficients of determination, the standard errors, the probability of the fitted parameters and the independence, normality and common variance of errors, that the modified model of Kostiakov fitted the observed infiltration data best. The variance analysis indicated that the final infiltration rates were higher and more variable in vertisols of agricultural lands, grasslands, and forest plantations than in vertisols of native scrub forests. The likely explanation for this behavior was the differential dynamic contribution of soil cracks to the infiltration of water among land uses.

Index words: Tamaulipan thornscrub, agriculture, grasslands, forest plantations, Kostiakov model, plains of the northern Gulf of Mexico.

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RESUMEN

Los objetivos de este estudio fueron ajustar cuatro modelos no-lineales a 96 pruebas de infiltración y determinar el efecto del uso del suelo en la tasa de infiltración de vertisoles del nordeste de México. Las pruebas de infiltración se realizaron con el uso de infiltrometros dobles de carga constante durante el periodo de julio a noviembre de 1985 en la propiedad agrícola de la Universidad Autónoma de Nuevo León (UANL). Los usos del suelo probados fueron: terrenos agrícolas, pastizales, matorrales y plantaciones forestales. Los modelos de infiltración de Green and Ampt, modificado de Kostiakov, Horton y Philip fueron ajustados a los datos de infiltración. Los parámetros estadísticos de los modelos fueron estimados usando mínimos cuadrados en regresión no-lineal. Las diferencias en las tasas de infiltración fueron probadas por medio de un análisis de varianza realizado con las tasas finales de infiltración. Los resultados demostraron, basados en el coeficiente de determinación, el error estándar, la probabilidad de los parámetros ajustados y la independencia, normalidad y varianza común de los errores, que el modelo modificado de Kostiakov se ajustó mejor a las tasas de infiltración observadas. El análisis de varianza indicó que las tasas finales de infiltración fueron mayores y más variables en vertisoles con usos agrícolas, plantaciones forestales o pastizales que aquellas de los vertisoles de los matorrales. La explicación probable a este comportamiento fue la contribución dinámica diferencial de las grietas de desecación en la infiltración de suelos entre los usos del suelo.

Palabras clave: Matorral tamaulipeco, agricultura, pastizales, plantaciones forestales, modelo de Kostiakov, planicies del norte del Golfo de México.

INTRODUCTION

Infiltration is the process of water entry into the soil (Hillel, 1980). The rate of this process, relative to the rate of water supply, determines how much water...
will enter the unsaturated soil zone, and how much, if any, will runoff (Hillel, 1982). Therefore, this soil physical parameter is of paramount importance to the water economy of plant communities, recharge of aquifers, surface runoff, soil erosion, and the fate of pollutants in the environment.

Land use controls the infiltration of soils. Plowing agricultural lands produces soil compaction (Voorhes and Lindstrom, 1984; Blackwell et al., 1985; Allegre et al., 1986; Hartge, 1988), reducing soil porosity through the partial expulsion of permeating fluids, air and water. Because density of the largest soil pores is reduced by the compaction mechanism, the infiltration rate is also diminished (Hillel, 1982; Hartge, 1988).

Livestock grazing on rangelands has the potential effect of reducing the infiltration of soils (Thurow et al., 1988; Wood et al., 1989; Takar et al., 1990) because of disturbances on soil and plant cover. Trampling promotes surface soil compaction and sealing (Warren et al., 1986). Grazing pressure removes shrubs, herbs, and grasses and controls the major input of organic matter to the soil surface. The exposure of bare soil to climate variations enhances soil crusting and slaking. Therefore, infiltration of soils is lower on bare soil than beneath trees and shrubs (Blackburn, 1984).

Land use frequently changes in vertisolic soils of northeastern Mexico. In the state of 'Nuevo Leon', the Undersecretary for Rural Development reported that 157 875 ha had been cleared for farming purposes between 1981 and 1986. Maldonado (1992) observed that 11.8 % of the land in the Coastal Plain of the northern Gulf of Mexico of the state of 'Nuevo Leon' was cleared between 1975 and 1986.

Considering the dynamic change in land use, it is of critical importance to study and forecast the infiltration rate of vertisols in the Coastal Plain of the northern Gulf of Mexico, where no research has been conducted on this issue. But forecasting infiltration in vertisols is complicated because of swelling and shrinking in response to soil moisture content. Swelling processes cause expansion of soil particles and close soil pores to water entry (Hillel, 1980). Soil shrinkage promotes cracks, changing the distribution of pore size, and increases water entry into the soil (Beven and Germann, 1982). Hence, physically-based models describing the infiltration rate of vertisols are scarce and complicated. However, several empirically-based equations describing the infiltration process, including Green & Ampt, Kostiakov, Horton, and Holtan, as well as the more physically-based equation of Philip (Hillel, 1982), are available to be fitted to observed infiltration data.

This study focused on: 1) fitting four infiltration models to observed infiltration data and 2) determining the effect of land use on the infiltration rate.

**MATERIALS AND METHODS**

**Characteristics of the Research Area**

The research was conducted on the property of the Faculty of Forest Sciences of the 'Universidad Autónoma de Nuevo León' (UANL), about 8 km south of Linares (24° 47’ N 99° 32’ W; 355 m above sea level) in the piedmont of the Sierra Madre Oriental in the northeastern of Mexico. The region is located on the Coastal Plain of the northern Gulf of Mexico. The region has a subtropical semi-arid climate, with hot summers and severe frosts in some winters. Mean annual rainfall in Linares is 805 mm (± s.d. = 260 mm) and mean annual temperature of 22.3 °C. A strong climatic gradient exists on the coastal plain due to the orographic effect of the Sierra and the gradual increase in elevation from East to West (Návar et al., 1994a). Of the total annual precipitation, 80 % falls during May-October. Annual potential evapotranspiration, estimated by the method of Thornthwaite, is 1150 mm (Návar et al., 1994b).

Approximately 80 % of the UANL-property (1500 ha) was cleared in 1980 for agriculture, grazing and forest plantations. *Sorghum vulgare*, *Leucaena leucocephalla*, and *Cenchrus ciliaris* are the main crops, in agricultural lands, experimental plantations, and introduced grasslands, respectively. *Sorghum vulgare* was growing in agricultural lands when the infiltration trials were conducted. Native grasses in cleared lands include the genera *Bautelova*, *Panicum*, *Setaria*, and *Chloris*.

The native scrub forest, named Tamaulipan thorn scrub, is a diverse, often dense vegetation, dominated by woody plants (Heiseke, 1986). Some 80 species of shrubs and trees, ranging in height from 1 to 5 m, are commonly encountered. Legume trees and shrubs constitute one third of the diverse woody flora (Reid et al., 1990).

The infiltration tests were conducted on vertisols of similar texture and content of organic matter (Table 1).
Table 1. Physical parameters measured in vertisols with four land uses in northeastern Mexico.

<table>
<thead>
<tr>
<th>Soil physical parameter</th>
<th>Native scrub forest</th>
<th>Grasslands</th>
<th>Plantations</th>
<th>Agriculture</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand (%)</td>
<td>16.00</td>
<td>20.00</td>
<td>16.00</td>
<td>18.00</td>
</tr>
<tr>
<td>Fine sand (%)</td>
<td>11.70</td>
<td>09.80</td>
<td>07.40</td>
<td>08.20</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>53.00</td>
<td>54.00</td>
<td>58.00</td>
<td>51.00</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>31.00</td>
<td>26.00</td>
<td>26.00</td>
<td>31.00</td>
</tr>
<tr>
<td>Field capacity (%)</td>
<td>33.00</td>
<td>33.00</td>
<td>36.00</td>
<td>45.00</td>
</tr>
<tr>
<td>Wilting point (%)</td>
<td>24.00</td>
<td>26.00</td>
<td>28.00</td>
<td>24.00</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>02.90</td>
<td>01.70</td>
<td>01.60</td>
<td>01.50</td>
</tr>
<tr>
<td>Slope (%)</td>
<td>04.00</td>
<td>03.50</td>
<td>03.50</td>
<td>04.00</td>
</tr>
<tr>
<td>Bulk density (0 to 15 cm) (g cm⁻³)</td>
<td>01.14</td>
<td>01.10</td>
<td>01.04</td>
<td>01.07</td>
</tr>
<tr>
<td>Bulk density (25 to 40 cm) (g cm⁻³)</td>
<td>01.20</td>
<td>01.22</td>
<td>01.11</td>
<td>01.47</td>
</tr>
</tbody>
</table>

In an area with a radius of approximately 200 m, where the four major types of land use converge. Infiltration tests were carried out on gentle plains with 2 to 4% of average slope. Soils of the plains and lower slopes are mainly dark gray, deep, silty clay vertisols with smectite, which shrink and swell noticeably in response to changes in soil moisture content (Woerner, 1991), and present structure of the prismatic type.

Experimental Design

Infiltration tests were conducted using double ring, constant head, infiltrometers. The sizes of the inner and outer infiltrometer rings were 20.5 and 31.0 cm in diameter and 23 and 39 cm in height, respectively. The water depth above the soil surface was kept constant, approximately between 7 and 13 cm, during the infiltration tests. In total, 96 infiltration tests; four treatments, eight trials, and three replicates, were conducted from July to November, 1985. Land uses, considered as treatments, tested were the following: 1) native scrub forests, 2) agricultural lands, 3) native grasslands, and 4) forest plantations. Trials were considered the different dates when infiltration tests were conducted. Three replicates were conducted in each of eight dates in each of four treatments.

Procedure

The depth of water in the inner infiltrometer ring and the depth of added water were recorded every minute during the first 20 minutes and every two to five minutes thereafter for 125 minutes. Readings of water depth were taken using a ruler attached to the inner infiltrometer ring. Antecedent soil moisture content was measured weekly from volumetric soil samples and neutron probes from June to December of 1985. Volumetric soil samples and neutron probe readings were taken at 0.30, 0.60, and 0.90 m of soil depths.

Statistical Analysis

Fitting four infiltration models. The infiltration models of Green and Ampt, the modified Kostiakov, Horton, and Philip were fitted to the collected infiltration data. The model proposed by Green and Ampt (Hillel, 1980) is:

\[ i = ic + \frac{b}{I} \]

The model of Kostiakov has been subsequently modified to predict the vertical infiltration rate as follows:

\[ i = Br^n + ic \]

The third infiltration model is due to Horton (1940),

\[ i = (i_o - ic)e^{kt} + ic \]

The fourth equation is a truncated form of the series presented by Philip (1957),

\[ i = ic + \frac{s}{2t^{1/2}} \]

Where: \( i = \) the infiltration rate (LT⁻¹), \( ic = \) the asymptotic steady infiltration flux (LT⁻¹), \( I = \) the
cumulative infiltration rate: \( I = \sum i dt \), \( t = \text{time (T)} \), \( i_0 = \text{the initial infiltration rate (LT}^{-1}) \), \( b, B, n, k, \) and \( s \) are characterizing constants.

Two characterizing constants, to carry out the appropriate comparisons, were statistically estimated using least square technique in nonlinear models by the simplex methodology (Wilkinson, 1989). These were: \( i_c \) and \( b \), \( B \) and \( n \), \( i_c \) and \( k \), and \( i_c \) and \( s \) for the Green & Ampt, Kostiakov, Horton and Philip infiltration models, respectively. The other parameters were graphically estimated from the observed data. The goodness of fit tests were conducted by comparing the coefficients of determination, \( r^2 \), standard error, \( S_x \), and the probability of the estimated parameters, as well as by revising the errors for normality, independence, and common variance. Normality tests were conducted using the Shapiro-Wilks test in SAS (1985), whereas independence and common variance were studied by checking plots of predicted versus observed infiltration rates.

To test the differences on the infiltration rates of vertisols among land uses, a covariance analysis was conducted on the best fitting infiltration model. This statistical procedure was conducted in SAS using the GLM procedure. Because \( i_c \) was graphically estimated on the best fitted model of Kostiakov, a variance analysis was conducted to test the effect of land uses on the final infiltration rate. The analysis was conducted with the log transformed \( i_c \) data because it distributed log-normally. The abbreviations used in this report are: \( \bar{X}_p = \text{mean}, \bar{X}_g = \text{geometric mean}, \text{S.D} = \text{standard deviation}, \text{C.V} = \text{coefficient of variation}, P>F = \text{probability of a larger value than } F \).

**RESULTS AND DISCUSSION**

The infiltration rates of studied vertisols for all land uses for four trials are displayed herein for observation (Figure 1). However, the discussion focuses on all 24 infiltration tests for all four treatments. The infiltration rates were highly variable and declined at different rates between and within treatments. Infiltration curves decayed and attained a steady final infiltration rate quickly, in less than 10 minutes, for vertisols of native scrub forest. Vertisols of agricultural lands, forest plantations, and grasslands achieved the final steady infiltration rate in less than 35 minutes. In the latter treatments, the infiltration curves also declined quickly but only when the antecedent soil moisture content was high.

**Fitting the Infiltration Models**

An example of the four models fitted to infiltration data for all treatments is reported in Figure 2. The average statistics, \( r^2 \) and \( S_x \), for the four infiltration models for all 96 infiltration tests showed that Kostiakov’s model fitted best the infiltration data (Table 2). The average coefficients of determination were: 0.79, 0.87, 0.86, and 0.84 for the infiltration models of Green and Ampt, Kostiakov, Horton, and Philip, respectively. The average standard errors due to the model prediction were: 123, 85, 116, and 127 mm h\(^{-1}\) for the Green and Ampt, modified Kostiakov, Horton, and Philip, respectively. The deviations between observed and predicted infiltration rates distributed more normally and showed themselves to be more independent in the model of Kostiakov than those of the other infiltration models.

The number of estimated parameters with no statistical significance (\( P>F>0.05 \)) for the infiltration models of Green and Ampt, modified Kostiakov, Horton, and Philip were: 18, 26, 6, and 23, or the 9.3%, 13.5%, 3.2%, and 11.5% of the number of parameters estimated, respectively. That is, the Horton’s infiltration model consistently showed statistically significant estimated parameters.

Fitted parameters \( i_c \), \( n \), \( i_c \), and \( i_c \) for the infiltration models of Green and Ampt, Kostiakov, Horton, and Philip, respectively, showed the least statistical significance. The final steady infiltration rate, \( i_c \), estimated by the infiltration model of Horton, approached more closely the observed final infiltration rate. Estimated and observed average figures were 154 and 158 mm h\(^{-1}\) with standard deviations of 180 and 120 mm h\(^{-1}\), respectively. Estimated final infiltration rates estimated by the Green and Ampt or Philip infiltration models were sometimes positive and sometimes negative, indicating the inappropriateness of the statistical estimation.

Problems in fitting the modified Kostiakov parameters, \( B \) and \( n \), to observed infiltration data arose when infiltration trials were conducted on dry antecedent soil moisture contents, where the final infiltration rates took more time to attain a steady infiltration rate. It was also more problematic to fit this
model to infiltration rates of vertisols of grasslands and forests plantations than to infiltration rates of vertisols of agricultural lands and native scrub forests. Problems in fitting the models of Green and Ampt and Philip to observed infiltration data became apparent when the final infiltration data did not attain a steady, final constant value.

The covariance analysis conducted on the modified model of Kostiakov showed that the intercepts and slopes did not show a statistical difference ($P>F = 0.25$; $P>F = 0.18$, respectively). However, the analysis of variance on the final infiltration rates presented statistical differences among the various land uses. Vertisols of native scrub forest showed a lower mean final infiltration rate than vertisols with the other types of land use ($P>F = 0.021$). The final infiltration rates of the studied vertisols suited a log-normal distribution better. Thus, the geometric mean for each type of land use decreased in the following order: agricultural lands ($X_g = 257.3 \text{ mm h}^{-1} \text{ s.d} = 102 \text{ mm h}^{-1}$), grasslands ($X_g = 215.7 \text{ mm h}^{-1} \text{ s.d} = 139 \text{ mm h}^{-1}$), forest plantations ($X_g = 201.4 \text{ mm h}^{-1} \text{ s.d} = 131 \text{ mm h}^{-1}$) and native scrub forest ($X_g = 112.8 \text{ mm h}^{-1} \text{ s.d} = 73 \text{ mm h}^{-1}$).

Figure 1. Infiltration curves for four trials and four land uses in vertisols of northeastern Mexico.
Figure 2. The models of Green and Ampt, Kostiakov, Horton and Philip fitted to observed infiltration data for one trial in vertisolic soils of Linares, NL, Mexico.

Fitting the modified version of Kostiakov’s model has the disadvantage of statistically estimating three parameters. Parameters B and n, which describes the initial infiltration rate, at times t=1 and the rate of decay, fitted a lognormal distribution better with a geometric average of 1575 mm h\(^{-1}\) and -0.9513 mm h\(^{-1}\) sec\(^{-1}\) with a standard deviation of 1491 mm h\(^{-1}\) and 0.61 mm h\(^{-1}\) sec\(^{-1}\), respectively. The mean observed and estimated final infiltration rate appeared to fit a bimodal probabilistic distribution function. It could have been the result of soil shrinkage cracks on dry soils contributing to the infiltration of water beneath the infiltrometers. In general, this version of Kostiakov's model describes physically better the vertical infiltration rate of the vertisols studied than the two parameter empirical equation of Kostiakov used by Naeth et al. (1991) in Alberta.

The final infiltration rates were smaller and less variable in vertisols of native scrub forest than those of grasslands, forest plantations and agricultural lands. This presents a strong contrast to previous experience in this field. Lower final infiltration rates in soils of native scrub forests may be partially explained by the organic matter content of the vertisols studied (Table 1). Fewer or smaller soil cracks of desiccation, which dominate the infiltration rate, develop in vertisols with higher contents of organic matter. Dadvidson and Page (1956), El-Swaify and Emerson (1975), and Kimmer and Greenland (1976) associated the magnitude of the potential volume change of...
vertisols to their organic matter content. Changes in pore size distribution have been associated to the potential volume of soils (Blake et al., 1973; Kissel et al., 1973). That is, dry vertisols with high contents of organic matter would have a more rigid soil matrix with fewer and/or smaller soil desiccation cracks. Therefore, the final infiltration rate would be less dependent on antecedent soil moisture content (there was statistical evidence on this relation for vertisols of native scrub forest). The rate of closing soil desiccation cracks during the wetting process may also be different in vertisols with different land uses. Therefore, soil desiccation cracks may not have closed during the 125 minutes of having conducted the infiltration tests. This probably explains the large final infiltration rates observed in this study for antecedent soil moisture contents below field capacity.

CONCLUSIONS

This report showed that the infiltration rate can be predicted by using the modified model of Kostiakov and that there was statistical evidence that land use plays a key role on the infiltration process in the UANL property. Higher and more variable final infiltration rates were observed in vertisols of agricultural lands, grasslands and forest plantations than in vertisols of native scrub forests. The differential development of desiccation cracks among land use could have resulted in differential infiltration rates in vertisolic soils.

ACKNOWLEDGMENTS

This research was funded by Facultad de Ciencias Forestales and UANL through the PAICyT program under grant No CT 99-203. The authors of this study would like to thank Mr. Crecencio Reyna for their help in the data collection.

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