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Article

Efecto de diferentes usos del suelo en las propiedades físicas e hidrológicas de un Luvisol en Oaxaca

Effect of different land use in the physical and hydrological properties of a Luvisol in the state of *Oaxaca*

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Resumen

Los cambios de uso del suelo en la Sierra Sur y Costa de Oaxaca han provocado el deterioro del ecosistema forestal. Así, ante la escasa información sobre su impacto en las propiedades del suelo, se planteó el objetivo de evaluar el efecto de distintos usos del suelo en las propiedades físicas e hidrológicas de un Luvisol. Los tratamientos evaluados fueron: pastizal, agrícola, plantación forestal, bosque de pino (control) y agropecuario; ubicados en la microcuenca Río La Venta, Copalita, Oaxaca. Los parámetros medidos en campo fueron: conductividad hidráulica (Ks), densidad aparente (DA), porosidad total (Po) que se obtuvieron en muestras inalteradas de suelo; además de, la resistencia mecánica a la penetración (RMP), infiltración inicial (Ia), infiltración acumulada (Ib) y capacidad de infiltración (Ic). La determinación de las partículas de arena (A), limo (L) y arcilla (Ar), capacidad de campo (CC), punto de marchitez permanente (PMP) y el agua disponible (Ad) se realizó en ocho muestras disturbadas (cuatro por profundidad) en cada uso, para un total de 40. Se registraron diferencias significativas en Po, RMP, DA, Ks, CC, PMP, Ad y en la proporción de arena entre usos de suelo. Ks presentó una correlación positiva significativa ($p \leq 0.05$) con PMP, Ad, A, Ia, Ib e Ic; las tres últimas tuvieron correlación positiva. Los usos agrícola, pastizal y agropecuario evidenciaron más impactos negativos en la infiltración y conductividad hidráulica; así como en la densidad aparente, porosidad, resistencia mecánica y disponibilidad del agua; la plantación forestal registró un efecto positivo en las propiedades evaluadas.

Palabras clave: Bosque de pino, infiltración, Luvisol, propiedades hidrológicas, suelo forestal, uso del suelo

Abstract

Changes in land use in the southern sierra and coast of Oaxaca have caused the deterioration of the forest ecosystem. Thus, given the scarce information on their impact on soil properties, the objective was to evaluate the effect of different land uses on the physical and hydrological properties of a Luvisol. The treatments evaluated were: pasture, agricultural, forest plantation, pine forest (control), and agricultural-livestock, located in the micro-watershed of the La Venta River, Copalita, Oaxaca. The parameters measured in the field were: hydraulic conductivity (K), bulk density (AD), total porosity (Po), which were obtained in undisturbed soil samples, mechanical resistance to penetration (MRP), initial infiltration (Ia), cumulative infiltration (Ib) and infiltration capacity (Ic). The determination of sand (S), silt (Si) and clay (Cl) particles, field capacity (FC), permanent wilting point (PWP), and available water (Aw) was performed on eight disturbed samples (four per depth) at each use, for a total of 40. Significant differences were observed in Po, MRP, AD, K, FC, PWP, Aw, and in the proportion of sand between land uses. K exhibited a significant positive correlation ($p \leq 0.05$) with PWP, Aw, S, Ia, Ib, and Ic; the last three were positively correlated. Agricultural, pasture and agricultural-livestock uses showed more negative impacts on infiltration and hydraulic conductivity, as well as on apparent density, porosity, mechanical resistance, and water availability; the forest plantation had a positive effect on the evaluated properties.

Key words: Pine forest, infiltration, Luvisol, hydrological properties, forest soil, land use.

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Introduction

Soil is an important natural resource on which society depends (George *et al*., 2016). However, the pressure exerted by man in recent years is degrading it (FAO-ITPS, 2015). Impacts on the soil begin with the removal of natural vegetation. In Mexico, the primary vegetation change rate is -0.6 % for the period 2000-2010, and -0.7 % from 1990 to 2015 (FAO, 2015). Likewise, the analysis conducted by Mas *et al*. (2009) indicates that the annual deforestation rate in the country ranges from -4.2 to -8.15 % for the high evergreen forest and is -10.1 % in the mesophilic mountain forest. In other words, the rate of deforestation varies with the type of ecosystem, but is generally higher in tropical ecosystems.

On the other hand, it is important to note that deforestation and forest degradation cause a significant loss of carbon stored in the aboveground and belowground biomass of terrestrial ecosystems (de Jong *et al*., 2018). Therefore, it is necessary to have information at an appropriate scale for the agricultural, forestry and other land use sectors to estimate the greenhouse gas emissions, as this data will serve as a basis for determining public policies on climate change (Paz *et al*., 2020).

Luvisols are soils that develop in temperate climates, have the highest clay content in the subsoil, and are very productive for agricultural and forestry use (IUSS-WRB-FAO 2015), as in the case of the upper part of the *Copalita* River sub-basin, *Oaxaca* (INEGI, 2013). Therefore, land use changes may result in changes in their physical and hydrological properties. Studying these changes will allow us to identify the main effects of land use and their relationship as a main factor in the loss of vegetation cover due to socioeconomic activities. The objective of this study was to evaluate the physical and hydrological properties of a Luvisol under agricultural, pasture, pine plantation, pine forest and agricultural-livestock land uses in the micro-watershed of the *La Venta* River*, in Copalita, Oaxaca, Mexico*. The hypothesis was that over time, the magnitude of the changes in the physical and hydrological properties of the researched Luvisol varies according to the type of land use.

Materials and Methods

Study area

The study area is located in the micro-watershed of the *La Venta* River, in *Copalita*, state of *Oaxaca*, Mexico (16°12′0” N, 96°25′30” W), at an average altitude of 2 850 m (Figure 1). According to the Köppen classification as modified by García (2004), the study area has a C (w) climate: semi-cold sub-humid, with a cool and long summer; winter rainfall less than 5 % of the annual rainfall, with an average annual precipitation above 1 300 mm, an average maximum of 215 mm during the month of July, and an average minimum of less than 10 mm in February. Average annual temperature of 18 to 20 °C, with a maximum of 24 °C in April and May and a minimum of 0 to 5 °C in December and January. The soil type is Luvisol; which have a high potential for agriculture, but also for temperate and tropical forests (INEGI, 2013).

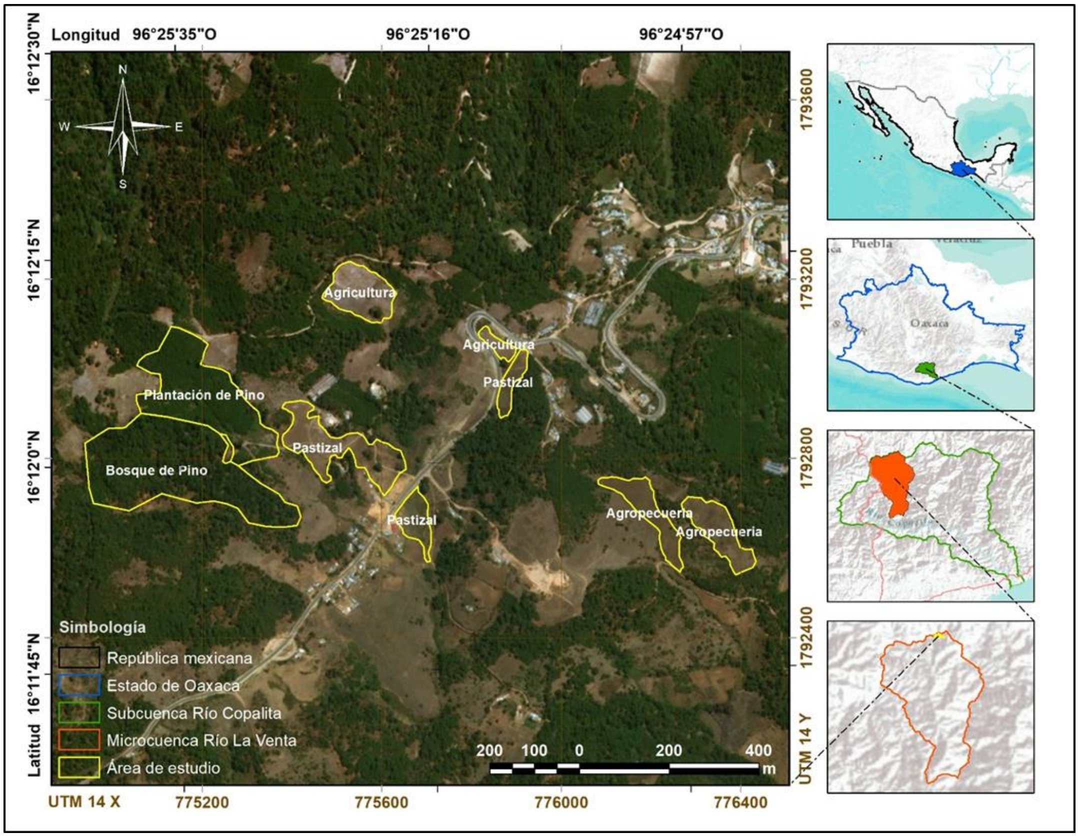


Figure 1. Location of the study area.

Description of the sampling sites

The present research was carried out in five land uses with the Luvisol soil type (INEGI, 2013):

a) Pasture. The area has different species of grasses —*Bouteloua repens* (Kunth) Scribn. & Merr., *Muhlenbergia robusta* (E. Fourn.) A. Hitchc., *Panicum bulbosum* Kunth, *Panicum mertensii* Roth., *P. parviglume* Hack., and *Paspalum convexum* Humb, *et* Bonpl. ex Flüggé (Pacheco-Rivera and Dávila-Aranda, 2004)— that were naturally established on plots used for agricultural production for about 10 years, which were later converted to grassland currently, they have 32 years with the same land use.

b) Agricultural use. This occurs in areas of no more than 5 ha, where rainfed agriculture is practiced, with corn crops associated with broad beans and sometimes interspersed with potato crops, as they are species adapted to these conditions; no change of land use has been recorded in 42 years.

c) Pine tree plantation. Established in agricultural areas that were 10 years old, subsequently used as grassland for 17 years. Currently, the plantation is around 15 years old; the planting was staggered, with a density of 1 111 trees per hectare and an equidistance of 3 m × 3 m, the species used were *Pinus ayacahuite* Ehrenb. ex Schltdl.*, P. douglasiana* Martínez and *Abies religiosa* (Kunth) Schltdl. *et* Cham.

d) Original pine forest (control). It consists of different taxa: *P. ayacahuite, P. douglasiana, P. patula* var. *longepedunculata* Loock. ex Martínez, *P. leiophylla* Schltdl. & Cham, and *Abies religiosa*.

e) Agricultural-livestock use. Farmers use these plots for grazing cattle, goats and sheep. These are agricultural areas that have been fallow for 1 to 2 years and have had intermittent agricultural activity for the last 20 years.

Soil sampling and analysis

In each soil use, four composite samples (from four subsamples) were collected at two depths (0-10 cm and 10-30 cm), for a total of 40, which were analyzed in the soil laboratory of the School of Forest Sciences of the *Universidad Autónoma de Nuevo León*. The samples were dried and sieved with a 2 mm metal mesh for the different analyses (Table 1).

Table 1. Methods for the determination of the physical and hydrological properties.

Property	**Unit**	**Method**
Physical		
$S^{1,2}$	%	AS-09 Method of the norm NOM-021-RECNAT-2000 (Semarnat, 2002).
$Cl^{1,2}$	%	
$Si^{1,2}$	%	
AD^{1}	g cm^{-3}	Gravimetric method (Woerner, 1989; Zhang *et al*., 2017).
MRP^{1}	Mpa	Hardness meter /penetrometer (Yamanaka type, 22110 Orion, MKK Co, Japan)
Po^{1}	%	The estimation was based on the apparent density values, assuming a particle density of 2.65 g cm^{-3} (McPhee *et al*., 2015).
Hydrological		
K^{1}	cm s^{-1}	Cylinder method (Das, 2002).
$I_a{}^{1}$	mm h^{-1}	Double ring method (Zhang *et al*. 2017).
$I_b{}^{1}$	mm	
$I_c{}^{1}$	mm h^{-1}	
$FC^{1,2}$ (0.033 MPa)	%	Pressure plate and membrane method, using pressure strippers (Soil Moisture Equipment Corp., Santa Barbara, CA) (Klute and Dirksen, 1986).
$PWP^{1,2}$ (1.5 MPa)	%	
$Aw^{1,2}$	%	

S = Sand; *Cl* = Clay; *Si* = Silt; *AD* = Bulk density; *MRP* = Mechanical resistance to penetration; *Po* = Porosity; *M* = Moisture; *K* = Hdraulic conductivity; I_a = Initial infiltration; I_b = Cumulative infiltration; I_c = Infiltration capacity; *FC* = Field capacity; *PWP* = Permanent wilting point; *Aw* = Available water; ^{1} = 0 to 10 cm; ^{2} = 10 to 30 cm.

Physical and hydrological properties

Table 1 shows the methodologies used to determine the physical and hydrological variables.

Statistical analyses

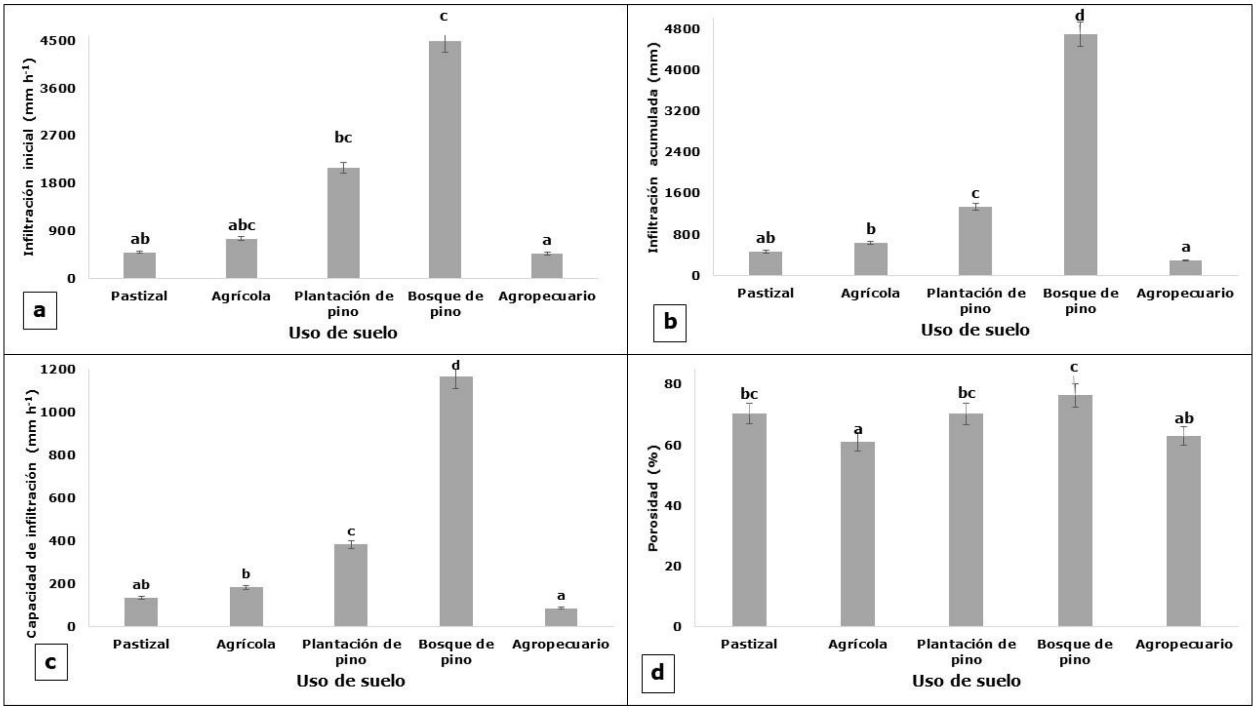
All variables were subjected to the Kolmogorov-Smirnov test with Liliefors and Levene's correction (Steel and Torrie, 1988) to determine whether the distribution was normal and the homogeneity of variance. A logarithmic transformation (Log_{10}) was applied to the cumulative infiltration (I_b), infiltration capacity (I_c) and hydraulic conductivity variables, and an arctangent transformation was used for the initial infiltration variable (I_a). In the end, only the variables *Po*, I_a, I_b, and I_c met the assumptions of normality and homoscedasticity. Subsequently, an analysis of variance (ANOVA) was performed for the different land uses. The Kruskal-Wallis test was used in the variables *K, AD, MRP, S, Cl, Si, FC, PWP,* and *Aw* at a depth of 0 to 10 cm, and in *S*, *Cl, Si, FC, PWP,* and *Aw* at a depth of 10 to 30 cm, as these do not meet the assumptions required for parametric analysis.

The Kruskal-Wallis Bonferroni post hoc test was also performed with pairwise comparisons for each land use. The relationship between the variables was analyzed using Spearman's correlation for the two depths sampled. Tukey's test (p=0.05) was used to compare means. Each of the statistical analyses was performed with a significance level (α) 0.05, in the statistical software *SPSS*® (Statistical Package for the Social Sciences) version 22.

Results and Discussion

Infiltration capacity and porosity

The results of Initial Infiltration (I_a), Cumulative Infiltration (I_b), and Infiltration Capacity (I_c) for each land use are illustrated in Figure 2.



The plotted values represent the mean (n=X), ± standard error. Means with different letters indicate statistical differences according to Tukey's test (p =0.05).

Figure 2. Initial infiltration (a), Cumulative infiltration (b), Infiltration capacity (c), and Porosity (d) for different soil uses at the depth of 0 to 10 cm.

The pine forest (control) exhibited the highest value of I_a (4 500 mm h^{-1}), followed by the pine plantation (2 100 mm h^{-1}), the agricultural area (760 mm h^{-1}), the grassland (500 mm h^{-1}) and the agricultural-livestock use (480 mm h^{-1}). The other components of infiltration (I_b and I_c) had a similar behavior according to the land use.

The results of the analysis of variance showed that the variables I_a, I_b, I_c, and *Po* exhibited significant differences ($p \leq 0.05$) between land uses (Table 2).

Table 2. One-way analysis of variance (land use), Levene's test and Kolmogorov Smirnov (K-S) test with Lilliefors correction.

Variables	F value (4,10)	*P* value	Levene's F test (4,10)	*P* value	*K-S*	*P* value
I_a (mm h^{-1})	6.31	0.008	3.06	0.068	0.18	0.186
I_b (mm)	51.93	0.001	2.97	0.074	0.20	0.077
I_c (mm h^{-1})	51.14	0.001	3.10	0.067	0.21	0.072
Po (%)	7.65	0.001	2.44	0.092	0.11	0.200

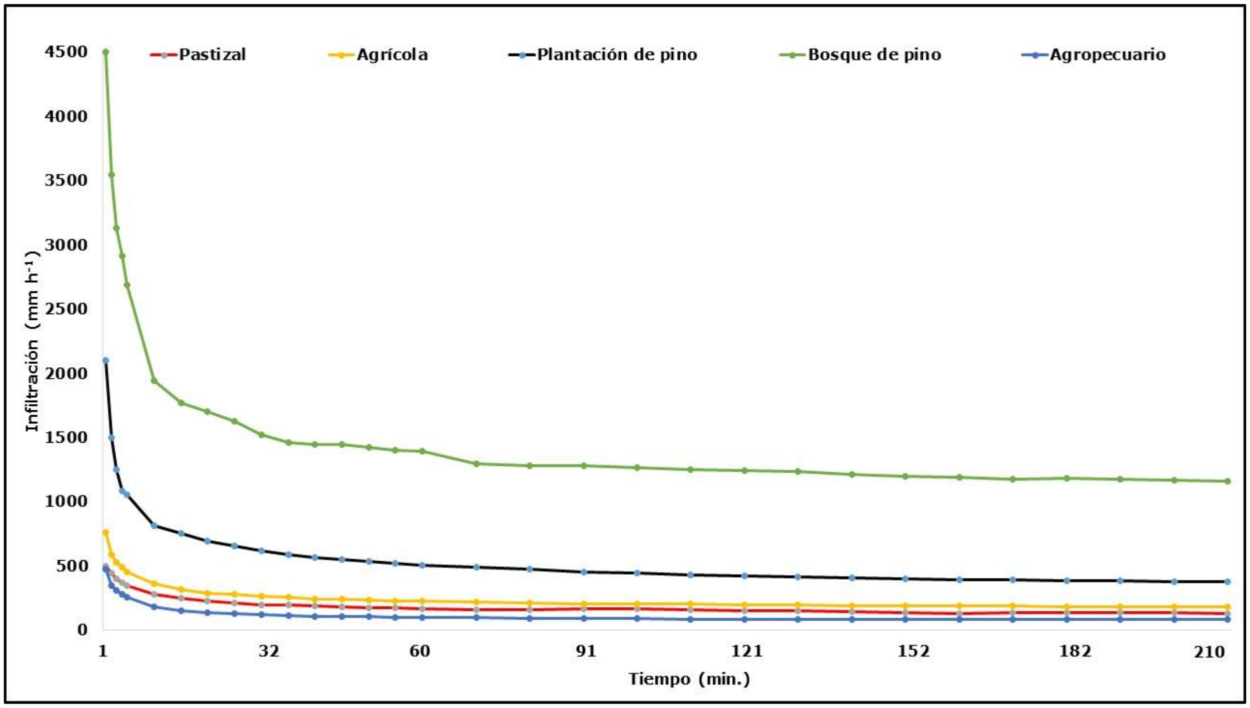
I_a = Initial infiltration; I_b = Cumulative infiltration; I_c = Infiltration capacity; *Po* = Porosity; *K-S = Kolmogorov-Smirnov* with Lilliefors correction. *P* value of 0.001, when the p-value is equal to or less than 0.001.

The infiltration observed in the different kinds of land use, when compared to that of the pine forest (control), clearly shows the effect of the change in land use on this characteristic. Properties such as porosity, apparent density, mechanical resistance to penetration, and soil management practices cause modifications in the infiltration rates.

Luna *et al*. (2020) evaluated infiltration in an Umbrisol type soil, subjected to different forestry treatments in a pine forest, and registered values below those obtained in the present research for the pine forest and in the pine plantation; the same applies to the study by Chagoya *et al*. (2015).

Pine forest had the highest porosity (76 %), followed by grassland and pine plantation (70 %), agricultural-livestock (63 %), and the use with the lowest value was agricultural (61 %). The former data indicate the difference in infiltration and porosity between the pine forest (control) and the other evaluated uses. This shows that changing the use of forest land affects the different physical and hydrological variables. Soil porosity in the pine forest and pine plantation is associated with the incorporation of organic matter, while that of the grassland is associated with the large number of roots of herbaceous plants and grasses that are added each year and penetrate the surface, promoting aeration and infiltration of water into the soil.

Figure 3 shows the average infiltration behavior for each assessed land use during 210 minutes; it shows the difference between pine forest and pine plantation in relation to agricultural, grassland and agricultural-livestock uses. From the 90th minute on, infiltration stability was observed for all kinds of land use.



The plotted values represent the average (*n*=x).

Figure 3. Average infiltration curves for different land uses.

According to the Kruskal-Wallis test for the *K*, *AD*, *MRP*, *S*, *FC*, *PWP* and *Aw* variables, the null hypothesis of equality of centrality parameters for the different kinds of land use in the 0 to 10 cm depth was rejected (Table 3); while, at soil 10 to

30 cm deep, only the variable *Aw* registered significant differences ($p \leq 0.05$) between kinds of land use (Table 4).

Table 3. Kruskal-Wallis test to detect significant differences in soil physical and hydrological properties among the analyzed soil uses (depth from 0 to 10 cm).

Statistic	***K*** **cm s^{-1}**	***AD*** **g cm^{-3}**	***MRP*** **Mpa**	***S*** **(%)**	***Cl*** **(%)**	***Si*** **(%)**	***FC*** **(%)**	***PWP*** **(%)**	***Aw*** **(%)**
N	20	20	20	20	20	20	20	20	20
Mean	0.007	0.84	2.30	67.05	6.65	26.35	42.22	25.63	16.56
Median	0.002	0.90	1.75	68.00	6.00	26.00	40.62	21.85	16.77
$X^2_{(4)}$	15.44	12.57	12.27	12.21	4.16	8.95	13.10	17.17	14.64
Asymptotic significance	**0.004**	**0.014**	**0.015**	**0.016**	0.385	0.062	**0.011**	**0.002**	**0.006**

K = Hydraulic conductivity; *AD* = Bulk density; *MRP* = Mechanical resistance to penetration; S = Sand; Cl = Clay; Si = Silt; *FC* = Field capacity; *PWP* = Permanent wilting point; *Aw* = Available water. Bold numbers indicate the variables that exhibited significance.

Table 4. Kruskal-Wallis test to detect significant differences in physical and hydrological properties between the analyzed soil uses (depth from 10 to 30 cm).

Statistic	***S*** **(%)**	***Cl*** **(%)**	***Si*** **(%)**	***FC*** **(%)**	***PWP*** **(%)**	***Aw*** **(%)**
N	20	20	20	20	20	20
Mean	69.60	5.30	25.10	38.43	24.12	14.31
Median	70.00	6.00	25.00	38.14	22.15	14.43
$X^2_{(4)}$	7.78	5.60	6.47	5.64	8.94	13.21
Asymtotic significance	0.100	0.231	0.167	0.227	0.063	**0.010**

S = Sand; *Cl* = Clay; *Si* = Silt; *FC* = Field capacity; *PWP* = Permanent wilting point; *Aw* = available water. Bold numbers indicate the variables that showed significance.

Post Hoc Kruskal-Wallis tests were also performed for independent samples with pairwise comparisons and Bonferroni correction for land use. These showed significant differences for the variables *K*, *AD*, *FC*, *PWP*, *S* in the kinds of use of the Agriculture-Forest combination, as well as for *K*, *PWP*, and *Aw* the Forest-Agricultural-Livestock use at a depth 0-10 cm, while Aw had differences between Pine Plantation and the Agricultural-Livestock use at a depth 10-30 cm (Table 5).

Table 5. Kruskal-Wallis *post hoc* test with Bonferroni correction to detect significant differences for the physical and hydrological variables at the depth of 0 to 10 cm and 10-30 cm for the variable *Aw*.

Soil uses 1 and 2	**Variables**							
	MRP	***K***	***AD***	***FC***	***PWP***	***Aw^1***	***Aw^2***	***S***
	Adjusted significance							
Agricultural-Pine plantation	1.000	0.168	0.786	0.198	0.168	1.000	1.000	0.223
Agricultural-Forest	1.000	**0.050**	**0.024**	**0.004**	**0.002**	0.831	1.000	**0.009**
Agricultural-Agricultural-livestock	1.000	1.000	1.000	1.000	1.000	0.558	0.486	1.000
Agricultural-grassland	0.070	1.000	0.560	0.639	0.232	1.000	0.070	1.000
Pine plantation-forest	1.000	1.000	1.000	1.000	1.000	0.270	1.000	1.000
Pine plantation-Agricultural-livestock	1.000	0.168	1.000	1.000	1.000	1.000	**0.013**	1.000
Pine plantation-pasture	1.000	1.000	1.000	1.000	1.000	1.000	.486	1.000
Forest-Agricultural-livestock	1.000	0**.008**	0.068	0.486	**0.034**	**0.003**	0**.050**	0.666
Forest-grassland	0.070	0.163	1.000	0.943	1.000	1.000	0.070	0.353
Agricultural-livestock-grassland	1.000	1.000	1.000	1.000	1.000	0.102	1.000	1.000

Each row tests the null hypothesis that land use distributions 1 and 2 are equal.

Each row tests the null hypothesis that land use distributions 1 and 2 are equal. *MRP* = Mechanical resistance to penetration; *K* = Hydraulic conductivity; *AD* = Apparent density; Aw^1 = Available water (0-10 cm); Aw^2 = Available water (10-30 cm); *FC* = Field capacity; *PWP* = Permanent wilting point; *S* = Sand. Asymptotic significances (bilateral tests) are shown. The significance level is 0.05.

Hydraulic conductivity

The saturated hydraulic conductivity (*K*) showed significant differences among the kinds of land use that were analyzed. The mean *K* values were 0.001 cm s^{-1} for agricultural and agricultural-livestock uses; 0.002 cm s^{-1} for pasture; 0.008 cm s^{-1} for pine plantation, and 0.022 cm s^{-1} for pine forest. The low value of *K* for agricultural-livestock use is due to the increase in apparent density and the decrease in porosity. The static and dynamic pressure exerted by livestock on the surface soil causes compaction and mechanical resistance. The results for K are similar to those obtained in other studies (Quichimbo *et al*., 2012; Jaurixje *et al*., 2013; Novillo-Espinosa *et al*., 2018).

Bulk density

The mean AD values for depth 0 to 10 cm were 0.63 g cm^{-3} for pine forest, 0.78 g cm^{-3} for pasture, 0.79 g cm^{-3} for pine plantation, 0.98 g cm^{-3} for agricultural-livestock, and 1.03 g cm^{-3} for agricultural use. The low *DA* in the pine forest is due to its porosity and mechanical resistance, in addition to its sandy loam textural class. This shows that land use change increases *DA*, which also results in an increase in *RMP* and a decrease in *K.* Cruz-Ruiz *et al*. (2012), Carlos-Gómez *et al*. (2014), Chagoya *et al*. (2015) and Alejandro-Martínez *et al*. (2019) document similar values of bulk density and porosity, and also indicate that *AD* tends to increase at greater depths and Po decreases in loam, sandy loam and clay textures.

Mechanical resistance to penetration of the soil

The *MRP* of the soil at a depth of 0 to 10 cm exhibited significant differences between kinds of land use. Grassland recorded the highest value for hardness (0.42 Mpa), followed by the agricultural-livestock use (0.27 Mpa). While, agricultural uses, pine plantation and pine forest had a *MRP* (0.15 Mpa). The high *MRP* value observed in the grassland is due to soil compaction caused mainly by livestock, in addition to increased *AD* and decreased *Po*; the exposure and lack of cover favored a greater loss of soil moisture. Yáñez-Díaz *et al*. (2019) cited similar results for mechanical resistance to penetration in a Vertisol soil, in which hardness is common when it loses moisture. Conversely, Medina-Guillén *et al*. (2017) indicated lower *MRP* values that may vary according to the type of vegetation, management and stocking rate present.

Soil Texture

At the 0-10 cm depth, only the proportion of sand had significant differences between land uses, ranging from 62 to 72 %. The proportion of clay and silt was in the range of 5 to 8 % and 22 to 30 %, respectively. For these two variables, no significant differences were observed between the kinds of land use.

At the depth of 10 to 30 cm, none of the texture variables showed significant differences, and the percentages of sand ranged from 67 to 73 %; silt ranged from 23 to 27 %, and clay, from 4 to 6 %. The texture assessment for the 0-10 cm depth corresponded to the classifications sandy loam (grassland, agricultural, pine plantation, and agricultural-livestock) and loamy sand (pine forest). The 10-30 cm depth corresponded to sandy loam (pasture, agricultural, agricultural-livestock) and loamy sand (pine plantation and pine forest). This means that the pine plantation and forest have lower apparent density and mechanical resistance to penetration but higher porosity; this favors the hydraulic conductivity and infiltration of the soil, which contribute to the recharging of aquifers and reduces the risk of erosion.

The results of the present research coincide with those obtained by Lozano-Trejo *et al.* (2020), who evaluated a Luvisol soil in the *Copalita* River sub-basin.

Soil water characteristics

Field capacity (*FC*). The *FC* at a soil depth of 0 to 10 cm exhibited significant differences between the kinds of uses under study; values ranged from 33.59 to 51.86 % water; the pine forest (51.86 %) and the agricultural use (33.59 %) had the highest and lowest percentage, respectively, of water retention at field capacity. The *FC* of the remaining uses were: agricultural-livestock (39.64 %), grassland (42.77 %) and pine plantation (43.57 %).

No significant differences between kinds of use were detected at a depth of 10 to 30 cm. The FC ranged from 32.81 to 42.70 %, with agricultural use having the lowest value (32.81 %), and grassland, the highest (42.77 %); pine plantation registered 36.44 %; the agricultural-livestock use, 39.49 %, and pine forest, 40.22 %.

Pine forest was the land use with the highest *FC* value, probably because the organic matter content in the soil favors moisture retention, and due to its low density and mechanical resistance to penetration, all of which allows water infiltration.

Field capacity is affected by the change of use; thus, agricultural use had the lowest FC*.* This is due to its porosity and texture (FAO, 2005); in addition, the high apparent density, lower organic matter content, lack of cover, low hydraulic conductivity and soil compaction increase the mechanical resistance to penetration, which, therefore, does not allow a larger amount of water to be retained (FAO, 2009).

Permanent Wilting Point (*PWP*). The *PWP* of the 0 to 10 cm depth of the Luvisol showed significant differences between the kinds of land use, with a variation between 16.77 % and 39.72 %. Agricultural use had the lowest value (16.77 %), and the highest value corresponded to pine forest (39.72 %). The agricultural-livestock, pine plantation and grassland types of use registered: 19.02, 25.94, and 26.76 %, respectively. The *PWP* range for the depth of 10 to 30 cm was 18.70 % to 29.15 %; the agricultural sector had the lowest value (18.70 %), followed by agricultural-livestock (20.76 %), pine plantation (24.91 %), and grassland (27.09 %); the highest value, of 29.15 %, was determined in the pine forest. In general, a low clay content was observed in the Luvisol, which consequently exhibited lower moisture retention.

These results are similar to those obtained by Muñoz-Iniestra *et al*. (2013). Silva *et al*. (2011) state that, by maintaining a cover, an agroforestry system allows for greater soil moisture.

Available water (*Aw*). The *Aw* content exhibited significant differences between the land uses at the two sampling depths (0-10 cm and 10-30 cm). At the depth of 0 to 10 cm, it ranged between 12.14 and 20.62 %; pine forest exhibited a lower percentage of *Aw* (12.14 %), followed by pasture (15.71 %), agricultural (16.83 %) and pine plantation (17.66 %) and agricultural-livestock use registered the highest percentage (20.62 %). The Aw at the depth of 10 to 30 cm fluctuated between 11.08 and 19.13 %; likewise, the pine forest had the lowest percentage, of 11.08 %, followed by pine plantation, with 11.54 %; agriculture, with 12.13 %, and grassland, with 15.69 %; while the agricultural-livestock use had the highest percentage, of 19.13 %.

The lowest percentage of available water was obtained in the pine forest and pine plantation, since these were the uses with a textural class (loamy sand) with a high percentage of sand, mainly at the depth of 10-30 cm. The higher the number of macropores, the faster the water seeps into the subsoil, as gravitational water.

These available water values are higher than those documented by González-Nivia (2014) and La Manna *et al*. (2018), but lower than those indicated by Béjar-Pulido *et al*. (2020) in andosols in *Uruapan,* state of *Michoacán*, because sandy soil has a higher water infiltration, and, therefore, the percentage of available water there is lower. Bachmair *et al*. (2009) point out that land use change has an impact on the vertical and horizontal movement of water.

Correlation of physical and hydrological variables

Table 6 shows Spearman's correlations (r_s) for the physical and hydrological variables evaluated at the 0 to 10 cm depth interval. The *AD* correlated significantly, but negatively, with the *Po*, *FC*, and *PWP*. The *MRP* exhibited a negative and highly significant correlation with I_a and I_b. At the depth of 10-30 cm, only the field capacity (*FC*) had a significant positive correlation with *S*, *Aw*, and *PWP*

Table 6. Spearman's correlation coefficients (r_s) for the physical and hydrological variables evaluated at the depth of 0-10 cm.

	AD (n=20)	***MRP*** (n=20)	***Po*** (n=20)	***K*** (n=20)	I_a (n=15)	I_b (n=15)	I_c (n=15)	***FC*** (n=20)	***PWP*** (n=20)	***Aw*** (n=20)	***S*** (n=20)	***Cl*** (n=20)	***Si*** (n=20)
AD	-	0.730	0.000	0.015	0.146	0.086	0.071	0.000	0.000	0.033	0.031	0.363	0.279
MRP	0.082	-	0.762	0.130	0.003	0.001	0.003	0.586	0.824	0.336	0.551	0.542	0.982
Po	-0.988^{**}	-0.072	-	0.009	0.124	0.079	0.060	0.000	0.000	0.035	0.041	0.367	0.319
K	-0.536^{*}	-0.350	0.565^{**}	-	0.000	0.001	0.001	0.018	0.000	0.008	0.001	0.138	0.015
I_a	-0.394	-0.712^{**}	0.415	0.789^{**}	-	0.000	0.000	0.085	0.044	0.121	0.011	0.498	0.045
I_b	-0.458	-0.764^{**}	0.468	0.779^{**}	0.927^{**}	-	0.000	0.071	0.025	0.022	0.025	0.604	0.069
I_c	-0.300	-0.603^{*}	0.325	0.690^{**}	0.774^{**}	0.692^{**}	-	0.063	0.049	0.634	0.002	0.105	0.045
FC	-0.760^{**}	0.130	0.785^{**}	0.523^{*}	0.459	0.479	0.524^{*}	-	0.000	0.420	0.006	0.859	0.010
PWP	-0.861^{**}	0.053	0.883^{**}	0.720^{**}	0.525^{*}	0.575^{*}	0.602^{*}	0.916^{**}	-	0.028	0.002	0.464	0.013
Aw	0.478^{*}	0.227	-0.473^{*}	-0.577^{**}	-0.418	-0.586^{*}	-0.570^{*}	-0.191	-0.490^{*}	-	0.204	0.813	0.291
S	-0.484^{*}	-0.142	0.461^{*}	0.692^{**}	0.637^{*}	0.575^{*}	0.569^{*}	0.595^{**}	0.645^{**}	-0.523	-	0.010	0.661
Cl	0.215	0.145	-0.213	-0.344	-0.190	-0.146	-0.075	-0.042	-0.174	-0.481	0.927^{**}	-	0.000
Si	0.254	0.005	-0.235	-0.534^{*}	-0.523^{*}	-0.481	-0.500	-0.561^{*}	-0.546^{*}	-0.480	0.925^{**}	0.999^{**}	-

r_s values in the lower triangular matrix, *p* values in the upper triangular matrix; *MRP* = Mechanical resistance to penetration; *K* = Hydraulic conductivity; *AD* = Bulk density; *Po* = Porosity; *FC* = Field capacity; *PWP* = Permanent wilting point; *Aw* = Available water; *S*= Sand; *Cl*= Clay; *Si*= Silt; I_a = Initial infiltration; I_b = Cumulative infiltration; I_c = Infiltration capacity; * = Significant correlation with ($p \leq 0.05$); ** = Highly significant correlation ($p \leq 0.01$).

Conclusions

The results indicate that Luvisol subjected to different land uses undergoes modifications in its physical and hydrological properties as a consequence of the changes in land use, mainly, when it occurs from forest to agricultural use, where the variables hydraulic conductivity, bulk density, field capacity, permanent wilting point, and sand are significantly different. The variables hydraulic conductivity, permanent wilting point and available water exhibit significant differences with the change from forest to agricultural-livestock use.

Pine forests were shown to have a greater infiltration capacity and, in this respect, they are superior to the rest of the researched land uses, which accounts for their high capacity to provide hydrological environmental services. When the land use changes, there is a significant decrease in this variable, as observed in the case of agricultural-livestock use and grassland which have the lowest infiltration capacity.

Low apparent density of the soil in the pine forest is the result of low compaction. On the contrary, the agricultural-livestock use exhibits a high apparent density, due to the compaction caused by grazing.

The hydraulic conductivity is clearly dependent on the type of land use; therefore, the pine forest exhibits a high value compared to the other uses, which have a lower permeability.

The variables with most differences due to change of land use are infiltration capacity, hydraulic conductivity, bulk density, and mechanical resistance to penetration, resulting in the modification of the field capacity, permanent wilting point, and available water.

The results obtained from the present investigation show the impact caused by land use change in the micro-watershed of the *La Venta* River, *Copalita*; and we conclude that it is important to conserve the tree vegetation, since this will help to maintain the recharge of the aquifers, as well as the environmental functions of the ecosystem.

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Conflict of Interest

The authors declare no conflict of interest.

Contribution by author

Celestino Sandoval García: research development, structure and design of the manuscript; Israel Cantú Silva: design of the experiment and correction of the manuscript; Humberto González Rodríguez: review and corrections of the manuscript; María Inés Yáñez Díaz: statistical analysis and correction of the manuscript; José Guadalupe Marmolejo Monsiváis: review of the manuscript; Marco Vinicio Gómez Meza: statistical analysis and review of the manuscript.

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