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Research article

Evaluación de las propiedades físicas e hidrológicas de un Vertisol con diferentes usos de suelo

Evaluation of the physical and hydrological properties of a Vertisol with different land use

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Abstract

Land use changes can affect soil characteristics and ecosystem services such as the regulation of hydrological processes. The objective of this study was to evaluate the physical and hydrological properties of a Vertisol with different types of land use in the *El Salto*, *Durango* region. Three types were evaluated: forest, livestock and agriculture, carrying out infiltration tests using the double ring infiltrometer method. Likewise, in each land use, eight unaltered samples were extracted to determine permeability (*Ks*), eight samples for bulk density (*BD*) and total soil porosity (*P%*), all in two depth ranges (four from 0-10 cm and four from 10-20 cm). Results showed an increase of more than 100 % in initial infiltration (*Ii*), soil infiltration capacity (*Ib*) and total infiltrated layer (*Ia*) in agricultural use compared to forest use. Livestock use presented the lowest values in *Ii*, *Ib* and *Ia*. The two-factor ANOVA showed that all variables presented significant differences between land uses. The mean *BD* values ranged from 0.82 to 1.58 g cm^{-3}, while the average *P%* was 53 %. Agricultural and livestock uses presented the lowest and highest values of *BD* and *P%* of the soil respectively at both depths. The *Ks* of the forest area was 0.0011 cm s^{-1}, considered very low. The elimination of vegetation and the modifications of the physical properties of the soil due to changes in land use significantly influenced infiltration and permeability.

Key words: Bulk density, forest, infiltration, permeability, porosity, soil.

Resumen

Los cambios de uso de suelo afectan sus características y servicios ecosistémicos, como la regulación de los procesos hidrológicos. El objetivo del presente estudio fue evaluar las propiedades físicas e hidrológicas de un Vertisol con diferentes usos de suelo en la región El Salto, Durango. Se compararon tres tipos de uso: forestal, pecuario y agrícola mediante pruebas de infiltración por el método del infiltrómetro de doble anillo; en cada uso de suelo, se extrajeron ocho muestras inalteradas para determinar la permeabilidad (*Ks*), ocho para la densidad aparente (*DA*) y la porosidad total del suelo (*P%*); todo en dos intervalos de profundidad (cuatro de 0-10 cm y cuatro de 10-20 cm). Los resultados indican un incremento >100 % en la infiltración inicial (*Ii*), capacidad de infiltración del suelo (*Ib*) y lámina total infiltrada (*Ia*) en el uso agrícola, respecto al forestal. El uso pecuario registró los valores más bajos en *Ii*, *Ib* e *Ia*. El ANOVA bifactorial evidenció que todas las variables presentaron diferencias significativas entre usos de suelo. Los valores medios de *DA* fueron de 0.82 a 1.58 g cm^{-3}; la *P%* promedio fue de 53 %. Los usos agrícola y pecuario, en ambas profundidades, tuvieron los valores más bajos y altos de *DA* y *P%*, respectivamente. La *Ks* del área forestal fue de 0.0011 cm s^{-1} considerada como muy baja. La eliminación de la vegetación y las modificaciones de las propiedades físicas del suelo por los cambios de uso influyeron significativamente sobre la infiltración y permeabilidad.

Palabras clave: Densidad aparente, forestal, infiltración, permeabilidad, porosidad, suelo.

Introduction

Soil is a complex, diverse and dynamic natural resource, considered as the basis for the growth and development of organisms and microorganisms (Burbano-Orjuela, 2016; Kopittke *et al.*, 2019). It provides multiple ecosystem services that are essential to ensure the well-being of human beings, which can be classified into three main categories: regulatory, provision and maintenance, and cultural functions (Luna *et al.*, 2022). In this sense, the soil has different physical, hydrological, chemical and biological properties, which allow the quality and functioning of environmental systems to be indirectly assessed.

However, these characteristics are subject to climatic scenarios (rain and drought, mainly), type of ecosystem, as well as use and management practices, so an imbalance in any of them has an immediate impact on its condition and services associated ecosystems (Bai *et al.*, 2018).

Globally, the transformation of forests to land for agricultural use is one of the most serious concerns that negatively affects soil quality, and also contributes significantly to climate change processes at the regional level (Babin *et al.*, 2019; Lalthakimi *et al.*, 2023). In general, changes in land use modify the physical properties (bulk density, porosity, coverage, structure, texture, among others), and, therefore, the water contributions (recharge of aquifers) are altered, because these characteristics of the land soil regulates infiltration capacity, surface runoff and erosion processes (Yáñez-Díaz *et al.*, 2019).

According to Galicia *et al.* (2018), in Mexico, temperate forests are important for the recharge of aquifers, since they are located in 77 of the 110 main aquifer recharge and purification zones (total of 653), which coincides with locations of high concentration population (>30 million inhabitants), since they cover the metropolitan areas of Mexico City, *Guadalajara* and *Puebla* (INEGI, 2010). However, a large part of these ecosystems have fragmentation problems due to the change in land use and poor choices of management practices, which increases surface runoff, soil loss and the availability of water resources (Návar and Synnott, 2000).

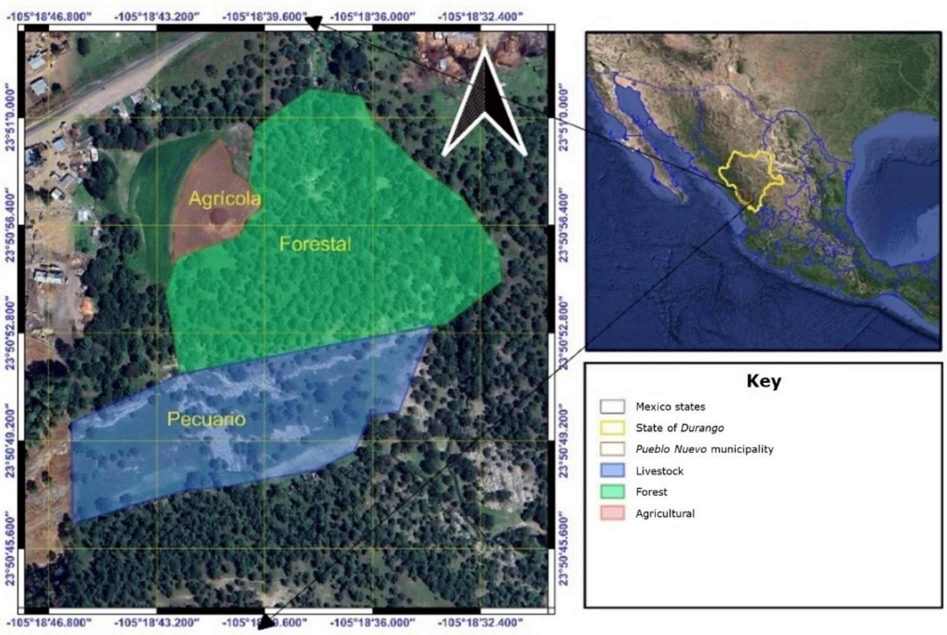
Dueñez-Alanís *et al.* (2006) point out that the soils of the state of *Durango* have a marked fragility or vulnerability from poor agricultural and livestock practices, which increase surface runoff, soil erosion and reduce infiltration capacity. In this sense, the transition from forest areas to extensive crop and livestock areas has progressively increased in the study region, which is located in the town of *José María Morelos*, in the of *El Salto*, *Durango* region; where the damage is already reflected in the infiltration capacity, water collection and productivity of the ecosystem.

The objective of this research was to determine the effect of land use change on the physical and hydrological properties of a Vertisol in two depth intervals in forests of *Durango*, Mexico, and thereby generate information that can be used in decision making and technical criteria for forestry, agricultural and livestock management in the region.

Materials and Methods

Study area

The study area is located in the *Sierra Madre Occidental* mountain massif in the state of *Durango*, in the *José María Morelos ejido* within the *Pueblo Nuevo* municipality, between 23°50'57” N and -105°18'41” W (Figure, 1).



Agrícola = Agricultural; *Forestal* = Forest; *Pecuario* = Livestock.

Figure 1. Location of area of study.

The dominant vegetation is made up of *Pinus cooperi* C. E. Blanco, *P. leiophylla* Schiede *ex* Schltdl. & Cham., *P. teocote* Schltdl. & Cham., *P. engelmannii* Carrière, *Juniperus deppeana* Steud., *Quercus sideroxyla* Bonpl. and *Q. durifolia* Seemen (González-Elizondo *et al.*, 2012).

The average annual precipitation varies from 600 to 1 000 mm in the driest to the most humid parts (INEGI, 2010; Inegi, 2017).

The dominant soil type corresponds to the Vertisol type, which are dark soils that lack distinctive horizons, with an average depth of 50 cm; they have 30 % or more clay, medium stoniness and cracks that open and close periodically; furthermore, these soils have high natural fertility, which is why they are commonly used for agricultural uses (Sotelo *et al.*, 2008).

Land use

Three land uses were considered, which are described below:

a) Forest use (7 ha): open pine-oak forest, with the presence of *P. cooperi*, *P. engelmannii*, *P. teocote*, *Quercus durifolia* and *Q. sideroxyla*. Individuals are of medium size with an average normal diameter of 30-35 cm and a height of 12-15 m. There is a lower stratum made up mainly of *Quercus striatula* Trel. and annual herbaceous species mainly *Muhlenbergia porteri* Scribn. former. The slope is very gentle, with a predominant Southeast exposure. Litter is scarce, located mainly in thin layers around the trees. There is a thin layer of mulch of 1 to 1.5 cm on average. The area is under management with the Mexican Method of Management of Irregular Forests (MMOBI, for its acronym in Spanish), where individual trees are selected. The presence of regeneration is scarce and occurs mainly in patches.

b) Livestock use (4 ha): area with extensive livestock farming for more than 50 years. The livestock is made up of 80 % dual-purpose cattle and 20 % horses.

c) Agricultural use (1.2 ha): area more than 50 years old with crops of oats, corn, pumpkin and, less frequently, beans. They are seasonal crops from May to November. It is customary to make a mechanized fallow field with an agricultural tractor or draft animals in January or February. The experiments were carried out in the first weeks of May 2023.

Bulk density and soil porosity

In each land use, eight unaltered soil samples were collected randomly at two depths (four samples from 0 to 10 cm and four from 10 to 20 cm), using metal cylinders of 5 cm in diameter by 5 cm in length. Subsequently, the samples were dried with forced air stove (model DNE910, Yamato Scientific America Inc.®) for 24 to 48 hours at 105 °C. For bulk density and porosity, the following equations were applied (Woerner, 1989; Yáñez-Díaz *et al.*, 2019):

a) Bulk density

$$BD = \frac{P}{VC} \quad (1)$$

Where:

BD = Bulk density (g cm^{-3})

P = Dry weight of sample with cylinder (g)

VC = Volume of the cylinder (cm^3)

b) Porosity

$$P\% = \left[1 - \left(\frac{BD}{2.65}\right)\right] \times 100 \qquad (2)$$

Where:

P% = Porosity expressed in percentage

BD = Soil bulk density (g cm^{-3})

2.65 = Assumed particle density

Permeability

Soil permeability (*Ks*) was determined by randomly extracting unaltered soil samples (four per depth) with two metal cylinders of equal size (5 cm in height and 3.7 cm in diameter) and volume (53.76 cm^{-3}); the samples were saturated for 24 hours, to then measure the time in which a column of water passes through the column of saturated soil. The permeability was obtained with the following formula (Sánchez, 2015; Yáñez-Díaz *et al.*, 2019):

$$Ks = \frac{3.46}{T} \qquad (3)$$

Where:

Ks = Soil permeability (cm s^{-1})

3.46 = Constant related to the volume of the cylinder (cm^{-3})

T = Time in seconds

Water infiltration into the soil

In each land use, three infiltration tests were applied with filler application for 150 minutes (2.5 hours); thus, a double ring (metal) infiltrometer (model M-0904E, Royal Eijkelkamp®) was used (Luna *et al.,* 2020).

Infiltration variables

From the *in situ* readings, the variables of the infiltration process were calculated, which are presented below (Yáñez-Díaz *et al.*, 2019):

a) Infiltration speed

$$I = \frac{HL \times 10 \times 60}{T} \qquad (4)$$

Where:

I = Infiltration speed (mm h^{-1})

HL = Difference between readings (cm)

10 = Conversion factor from cm to mm

60 = Conversion factor from minutes to hours

T = Time lapse (min)

b) Initial infiltration

$$Ii = V_1 \qquad (5)$$

Where:

V_1 = Infiltration speed at minute (mm h^{-1})

c) Infiltration capacity

$$Ib = \frac{V120 + V135 + V150}{3} \qquad (6)$$

Where:

Ib = Infiltration capacity (mm h^{-1})

$V120$ = Infiltration speed at minute 120 (mm h^{-1})

$V135$ = Infiltration speed at minute 135 (mm h^{-1})

$V150$ = Infiltration speed at minute 150 (mm h^{-1})

d) Total infiltrated sheet

$$Ia = \sum L \qquad (7)$$

Where:

Ia = Total infiltrated sheet (mm)

$\sum L$ = Total sum of the volumes of water infiltrated in the time of 2.5 h

Statistical analysis

The data of all variables were subjected to normality and Kolmogorov-Smirnov goodness-of-fit tests, performing the necessary transformations (square root and Log10) and Levene's homogeneity of variances test (Rubio and Berlanga, 2012). Based on the results, the following analyzes were carried out: (A) Analysis of variance (ANOVA) of one factor ($P \leq 0.05$) to the variables initial infiltration, soil infiltration capacity and the total infiltrated sheet, (B) To detect differences between land uses and depths, a two-factor ANOVA ($P \leq 0.05$) was applied to the variables of bulk density (*BD*), porosity (*P*) and permeability (*Ks*), and (C) The *post hoc* test of Tukey ($P \leq 0.05$) for the comparison of means. All data were analyzed using the SPSS statistical package version 22.0 (IBM, 2013).

Results

The results of the normality and homogeneity of variance tests are presented in Table 1, which shows that all variables met both assumptions, for which one- and two-factor analysis of variance were used to detect significant differences between land uses, as well as between depth.

Table 1. Statistics of the Kolmogorov-Smirnov and Levene tests.

	Kolmogorov-Smirnov test	Levene test

	Statistic	*p* value	Statistic	*p* value
		N=9		
Ii (mm h^{-1})	0.226	0.200	0.486	0.638
Ib (mm h^{-1})	0.159	0.200	2.040	0.211
Ia (mm)	0.169	0.200	2.211	0.191
		N=24		
BD (g cm^{-3})	0.149	0.177	1.940	0.137
P (%)	0.149	0.177	1.940	0.137
Ks (cm s^{-1})	0.151	0.166	2.904	0.051

Ii = Initial infiltration; *Ib* = Soil infiltration capacity; *Ia* = Total infiltrated sheet; *BD* = Bulk density; *P* = Porosity; *Ks* = Permeability.

BD, *P%* and *Ks*

The results of the two-factor variance analysis are shown in Table 2, which shows the significant differences between land uses and not between depths.

Table 2. Two-factor analysis of variance for physical variables.

Origin		Sum of squares	*df*	Mean square	*F*	*Sig.*
Soil use	*BD*	1.333	2	0.667	47.980	<0.005
	Porosity	1 898.235	2	949.117	47.980	<0.005
	Ks	0.477	2	0.239	3.378	0.047
Depths	*BD*	0.009	1	0.009	0.626	0.439
	Porosity	12.388	1	12.388	0.626	0.439
	Ks	0.357	1	0.357	5.052	0.059

BD = Bulk density; *Ks* = Permeability; *Sig.* = Significance (*p* value).

Figure 2 shows the values by depth and land use for *BD*. The forest area had a value of 1.24 g cm^{-3} from 0 to 10 cm, while agricultural and livestock uses recorded lower and higher *BD* values (34 and 24 %) compared to the forest area. For the 10-20 cm depth the trend was similar; the forest area presented an *BD* of 1.31 g cm^{-3} and the agricultural and livestock uses 14 and 17 % higher and lower values, respectively.

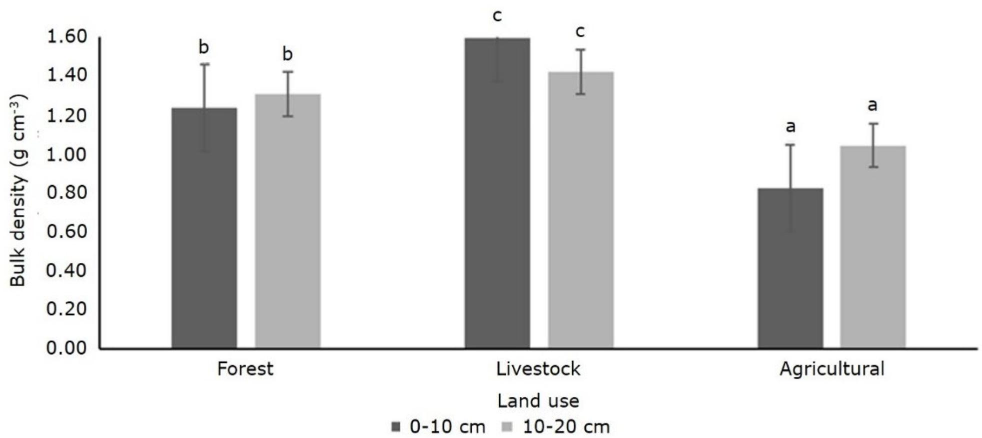


Figure 2. Average *BD* values by land use and depth.

On the other hand, the *P%* values are presented in Figure 3; in which the forest area decreased from 53 *P%* to 40 *P%* in livestock use for the first depth. From 10-20 cm, the average *P%* was 53 % for forestry with significant increases and decreases in agricultural (62 *P%*) and livestock (44 *P%*) use, respectively.

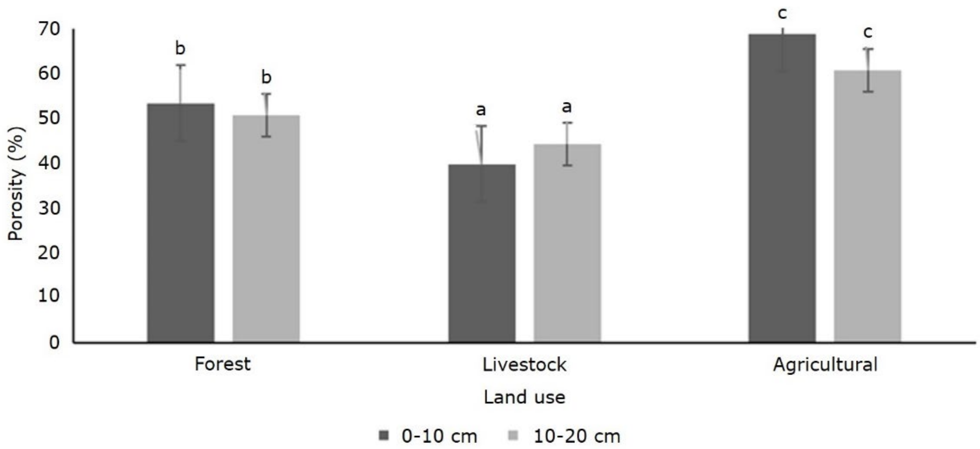


Figure 3. Average values of *P%* by land use and depth.

Soil permeability (*K*s) changed significantly between land uses (Table 3). The average *Ks* values of the forest area were 0.0013 cm s^{-1}, with a slight reduction in livestock use (0.0011 cm s^{-1}) and significant increases in agricultural use (0.0019 cm s^{-1}).

Table 3. Average permeability values by land use.

Land use	Depth	*Ks* (cm s^{-1})
Forest	0-10 cm	0.0013
	10-20 cm	0.0012
	Average	0.0013a
Livestock	0-10 cm	0.0016
	10-20 cm	0.0006
	Average	0.0011a
Agricultural	0-10 cm	0.0019
	10-20 cm	0.0019
	Average	0.0019b

Infiltration

Table 4 shows the results of the analysis of variance of land use for the variables that make up the infiltration process; all variables presented significant differences.

Table 4. Analysis of variance for infiltration variables.

Variable	Sum of squares	*df*	Square mean	*F*	*Sig.*
Ii (mm h^{-1})	2 565 600	2	1 282 800	36.034	<0.001
Ib (mm h^{-1})	0.952	2	0.476	7.006	0.027
Ia (mm)	0.922	2	0.461	6.609	0.030

Ii = Initial infiltration; *Ib* = Soil infiltration capacity; *Ia* = Total infiltrated sheet; *Sig.* = Significance (*p* value).

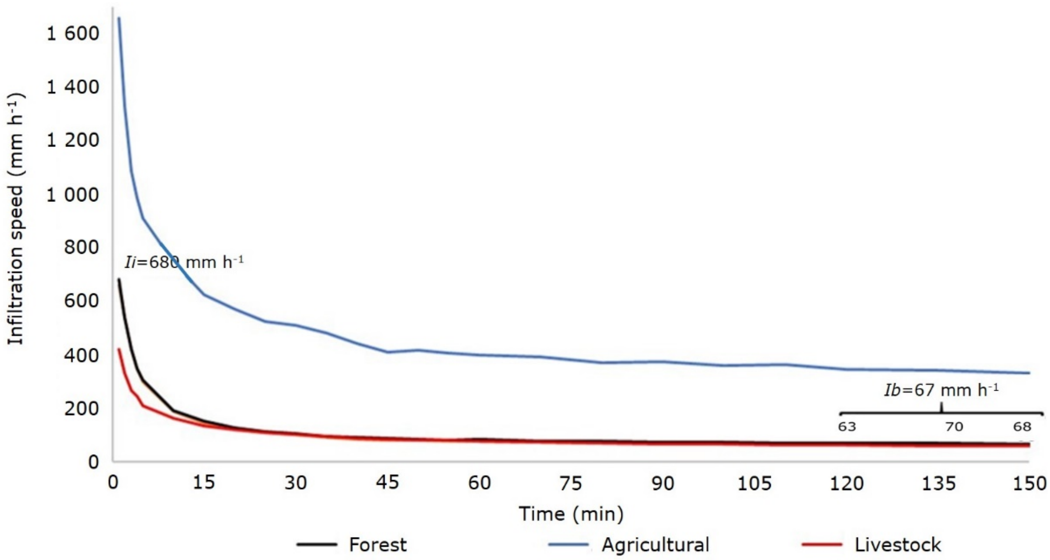
Variable *Ii* was 680 mm h^{-1} in the forest area, with an increase of 145 % in the agricultural area and a decrease of 40 % in livestock use. The *Ib* was similar between the forest area and livestock use, however, it increased by 500 % in the agricultural area. While the *Ia* presented the following order of descending: agricultural>forest>livestock (Table 5).

Table 5. Average values of infiltration variables by land use.

Land use	*Ii* (mm h^{-1})	*Ib* (mm h^{-1})	*Ia* (mm)
Agrícultural	1 660^{b}±242	338.96^{b}±190	830^{b}±500
Forest	680^{a}±150	67.31^{a}±10	182.33^{a}±22
Livestock	420^{a}±160	59.72^{a}±40	145.33^{a}±108

Ii = Initial infiltration; *Ib* = Soil infiltration capacity; *Ia* = Total infiltrated sheet; ± Standard desviation.

Figure 4 shows the infiltration curves for each land use. Three different periods can be seen: first, the initial infiltration rate is high and remains constant for a short time (<10 min) in the three land uses; subsequently it drops considerably, with agricultural use being the one that manages to last intensely until before minute 45, while that in forestry and livestock it is observed before minute 15; finally, a third moment of stabilization can be seen (where the curve becomes more asymptotic) called soil infiltration capacity, which is seen before 120 minutes in agricultural use, while in forestry and livestock use it is observed about 105 minutes.



Ii = Initial infiltration of the forest area; *Ib* = Soil infiltration capacity of the forest area.

Figure 4. Average infiltration speed by land use.

Discussion

The results of this study showed significant differences in infiltration, permeability and physical properties between land uses and the forest area, which can accelerate soil degradation processes and directly impact the multiple ecosystem services offered by the forest soil (Béjar-Pulido *et al.*, 2021).

The value of the infiltration capacity of the forest soil is similar to those reported by Pérez-Hernández *et al.* (2023) for temperate forests (Mean: 1 600±1 100 mm h^{-1}). On the other hand, Woerner's (1989) assessment for the average bulk density indicates that for the forest area and livestock use it was low class (1.27 cm^{-3}) and medium class (1.51 g cm^{-3}), respectively, while agricultural use was considered very low (0.93 g cm^{-3}).

Zemke *et al.* (2019) point out that in forest soils, aerial cover and soil cover (woody material, leaf litter and humus) play an important role since they regulate the entry of water into the soil, so its elimination can cause variations that are reflected in increases and decreases significantly. Specifically, Landini *et al.* (2007) mention that trees play an important role in the infiltration of water into the soil since it defines the levels of precipitation interception, moisture content and amount of organic matter in the soil, variables that significantly influence the infiltration, as well as its permeability.

According to the observed values of infiltration in the different land uses, the agricultural area caused a more significant effect on this hydrological property, particularly it recorded increases of more than 100 % on the variables of *Ii* (mm h^{-1}), *Ib* (mm h^{-1}) and *Ia* (mm) with respect to livestock and forestry uses. The results of the present study are similar to the values by Yáñez-Díaz *et al.* (2019), who evaluated the response of a Vertisol soil with different management systems (agriculture, forest plantation, *Tamaulipas* thorn scrub and grasslands), where agriculture stood out as the change in land use that caused the most significant modifications on physical soil properties and water availability.

Martínez *et al.* (2015), Torres *et al.* (2016), Lozano-Trejo *et al.* (2020) and Béjar-Pulido *et al.* (2021) point out that the infiltration capacity and permeability of the soil may be higher in agricultural uses compared to forest areas, because the soil structure is constantly altered by tillage activities and crop rotations, which favors the formation of cracks, the increase in pores and low bulk density, which increases the movement of water in the soil; however, the degree of water movement depends on the nature of the soil type. However, Gómez *et al.* (2014) mention that, as infiltration increases in agricultural areas, they demand a greater amount of water to keep crop production, which is why they suggest incorporating organic matter such as fertilizers, to optimize the infiltration capacity of the soil, which should range between 40 and 70 mm h^{-1}; in this sense, the infiltration capacity of the soil for agricultural use evaluated was greater than 300 mm h^{-1}.

In a similar way, Villagra-Mendoza *et al.* (2023) determined that increased infiltration in agricultural use is common in Vertisols, in which, being bare and subject to continuous subsoiling, soil moisture and bulk density are reduced, while porosity and permeability increase, and, therefore, its saturation and infiltration capacity can increase too; in contrast to forest soil, where by maintaining its organic layer (litter and humus) and vegetation, soil evaporation is lower and moisture levels remain in a good condition; with rainfall, these components raise the retention time of soil water, which, afterwards, slowly incorporates to the ground (Lozano-Trejo *et al.*, 2020).

On the other hand, Hidalgo *et al.* (2019) highlight the importance of soil organic matter for the formation and stability of soil aggregates; regardless of the type of land use, they consider that any imbalance in the soil organic matter content (gains or losses) will have a direct impact on the physical and hydrological processes of the soil.

Sánchez *et al.* (2003) and Yáñez-Díaz *et al.* (2019) mention that in agricultural uses two scenarios can occur, the first during the beginning of cultivation and the second during the harvest process. During the harvest period, the soil tends to increase compaction and reduce water flow significantly; however, these characteristics are partially restored by subsoils and crops; in this sense, the response of the physical and hydrological variables of Vertisol coincide with the aforementioned aspects.

The results of the physical and hydrological variables of livestock use with respect to those obtained in the forest can be attributed to the effect of trampling by livestock, which has already been recorded in several studies at a global level, in which it is described that the compaction of the soil can affect the first 20 cm of its depth (Karlin *et al.*, 2019), which agrees with the depths analyzed in the present study. Gómez *et al.* (2014) mention that in these areas, livestock extensively take advantage of the plant cover made up, to a large extent, of grasses, which causes the soil structure to weaken; this considerably reduces the proportion of soil pores due to animal load and, therefore, the levels of water entry into the profile decrease significantly.

In this study, the variability of infiltration and permeability between land uses and the forest area can be associated with changes in its physical characteristics, mainly the bulk density and total porosity, which were affected by the compaction of the soil due to trampling and movement of livestock, the elimination of cover and subsoil (Torres *et al.*, 2016; Martínez *et al.*, 2023). Therefore, these soils with abundant rainfall are more susceptible to developing some degree of degradation compared to forested areas where all tree strata, as well as ground cover and roots, function as agents that moderate the entry speed and circulation of water in the ground (Muñoz-Villers *et al.*, 2015; Lozano-Trejo *et al.*, 2020).

The *Ks* values can be considered low for the forest area and livestock use, and moderately low for agricultural use. The above agrees with Kumar *et al.* (2017), who recorded higher *Ks* values for soils with agricultural management compared to forest, where bulk density and porosity of the soil are the variables responsible for marking significant differences. It should be noted that this variable is influenced by vegetation cover, depth, slope, texture and errors in its determination (Figueroa *et al.*, 2018; Nuñez-Peñaloza *et al.*, 2022).

The trends of soil permeability results have already been published in other investigations for the Vertisol type, in which it is pointed out that a change from forest to agricultural land use can significantly increase the permeability of the substrate. In contrast, when the change in land use is from forest to livestock, there are slower flows derived from the loss of cover and trampling of livestock (Yáñez-Díaz *et al.*, 2019).

Conclusions

Land use changes modify the physical and hydrological properties of the soil and, therefore, its ecosystem services, such as water infiltration, are significantly altered.

From the conservation perspective, the forest area remained in-between the assessment of physical and hydrological properties, which made it possible to clearly distinguish the effects specifically of each land use. The vegetation present, as well as the soil cover, play an important role in regulating the physical and hydrological processes of the soil.

Infiltration varied significantly in agricultural use, with increases greater than 100 % compared to the forest use. The initial infiltration, the infiltration capacity and the total infiltrated sheet followed the same trend in descending order (agricultural>forest>livestock).

Livestock use recorded the highest values of the physical properties of the soil (bulk density and porosity) and the lowest values of the hydrological properties of the soil (infiltration and permeability), which can be attributed to the constant trampling of livestock that considerably modifies the structure of the soil.

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Conflict of interests

The authors declare no conflict of interest.

Contribution by author

Isaac Rodríguez Reta: field work, review and correction of the manuscript; Erik Orlando Luna Robles: field work and preparation of the manuscript; Carlos Enrique Aguirre Calderón: review and correction of the manuscript; Silvia Janeth Bejar Pulido: field work and correction of the manuscript; David Orlando Álvarez Favela: field work and correction of the manuscript.

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