DOI: 10.29298/rmcf.v16i89.1522

Research article

Evaluación física y química de un Vertisol en dos usos de suelo en el noreste de México

Physica and chemical evaluation of a Vertisol in two land uses in Northeastern Mexico

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Fecha de recepción/Reception date: 6 de octubre de 2024.
Fecha de aceptación/Acceptance date: 19 de marzo de 2025.

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Abstract

The conversion of forest areas into agricultural and livestock lands, as well as intensive practices can cause soil degradation. The objective of this study was to analyze the effects of land use change on the physical (Bulk Density [*BD*], Porosity [*P*], Texture, Mechanical Resistance to Penetration [*MRP*]) and chemical properties (Organic Matter [*SOM*], Organic Carbon [*%C*], *pH* and Electrical Conductivity [*EC*]) of a Vertisol at different depths (0-5, 5-15, 15-30, 30-60 and 60-100 cm); considering that most research focuses only on the evaluation of the first centimeters of soil, so there is lack of knowledge and uncertainty about the behavior of edaphic variables in greater depth ranges. In each land use, four soil samples composed of depth (n=40) were collected. The chemical variables did not present significant differences between land uses, but between depths. The *SOM* and *%C* decreased significantly as depth increased, where the highest values were recorded at 0-5 cm in both land uses. The *pH* was moderately alkaline, while the *EC* was below salinity levels. In regard to physical properties, only *BD* and porosity showed significant differences between land uses (p<0.05); between depths, only the contents of sand and silt varied. MRP only presented differences between land uses (p<0.01). Vertisol presented greater sensitivity in the physical properties of the soil after the conversion of the Tamaulipan Thorny Scrub to Grassland.

Key words: Organic Carbon, Organic matter, Tamaulipan Thorny Scrub, Grassland, intensive practices, soil degradation.

Resumen

La conversión de áreas forestales a tierras de uso agrícola y pecuario, así como sus prácticas intensivas pueden provocar la degradación del suelo. El objetivo del presente estudio fue analizar los efectos del cambio de uso de suelo sobre las propiedades físicas (densidad aparente [*DA*], porosidad [*P*], textura, resistencia mecánica a la penetración [*RMP*]) y químicas (materia orgánica [*MOS*], Carbono orgánico [*%C*], pH y conductividad eléctrica [*CE*]) de un Vertisol en diferentes profundidades (0-5, 5-15, 15-30, 30-60 y 60-100 cm); a partir de que diversos estudios se enfocan solo en la evaluación de los primeros centímetros del suelo, existe desconocimiento e incertidumbre acerca del comportamiento de las variables edáficas en intervalos de profundidad mayores. En cada uso de suelo, se recolectaron cuatro muestras de suelo compuestas por profundidad (n=40). Los resultados indican que las variables químicas no presentaron diferencias significativas entre usos de suelo, pero sí entre profundidades. La *MOS* y *%C* disminuyeron significativamente conforme aumentó la profundidad; en 0-5 cm se registraron los valores más altos en ambos usos. El pH fue medianamente alcalino, mientras que la *CE* se registró por debajo de los niveles de salinidad. En cuanto a las propiedades físicas solo *DA* y la porosidad presentaron diferencias significativas entre usos de suelo ($p<0.05$); entre profundidades unicamente variaron los contenidos de arenas y limos. La *RMP* solo presentó diferencias entre usos de suelo ($p<0.01$). El Vertisol tiene mayor sensibilidad en sus propiedades físicas tras la conversión del Matorral Espinoso Tamaulipeco a Pastizal.

Palabras clave: Carbono orgánico, materia orgánica, Matorral Espinoso Tamaulipeco, Pastizal, prácticas intensivas, degradación del suelo.

Introduction

Soil is considered a multifunctional dynamic system that originates from biotic and abiotic interactions and is a key component in the functioning of ecosystems. Its importance lies in its ability to provide ecosystem goods and services necessary to meet the multiple demands and needs of humans, which can be classified as provisioning, regulating, supporting, and cultural services (Avendaño-Leadem et al., 2020). In addition, soil properties are considered indicators of its health, which, in turn, are directly reflected in the quality of its ecosystem services (Rodríguez et al., 2024).

Soil represents the largest terrestrial Carbon (C) reservoir, storing approximately three times more than the atmosphere and 4.5 times more than the biosphere (Veni et al., 2020; Wang et al., 2021). This makes it a potential contributor to climate change mitigation, considered one of the most important global problems affecting humanity (El-Ghamry et al., 2024). In a similar way, it is worth mentioning that Organic Carbon is a key element determining soil quality, fertility, productivity, and profitability, as it intervenes in various physical, hydrological, chemical, and biological processes, ranging from defining the degree of soil structure to retaining and circulating water and nutrients (Kumar et al., 2022). However, all these capacities are dynamic and subject to land use, management practices, and disturbances (Cantú & Bejar, 2024).

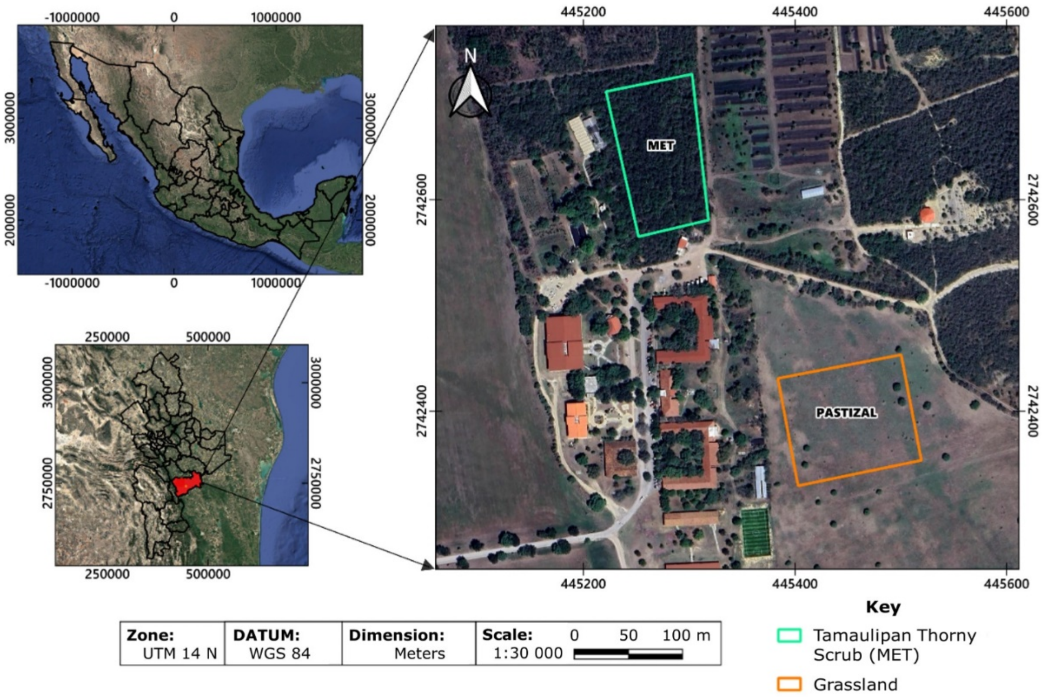
In this sense, land use change is considered one of the main factors in its degradation, due to the recurrent and excessive transformation for production purposes (agriculture, livestock, industrialization and urbanization). The constant population increase increases human demands, which leads to greater pressure on the soil and impacts environmental, economic, and social aspects (Dumas et al., 2022; Escandón et al., 2018; Kouassi et al., 2021).

Particularly in *Linares*, state of *Nuevo León*, Mexico, grasslands are currently the type of land use with the largest area in the municipality (Hernández-Cavazos et al., 2023). Vertisols are the dominant soil in the area, characterized by their depth and clay content of more than 30 %. These soils have the greatest agricultural and grazing potential in the country (International Union of Soil Sciences [IUSS], 2015; Torres et al., 2016). However, these soils exhibit physical degradation due to surface compaction and sealing, as well as chemical degradation due to nutrient loss or fertility decline resulting from poor practices such as excessive use of organic and inorganic chemicals in agricultural activities, conventional (intensive) tillage, use of heavy machinery, overgrazing, fires, and irrigation (Luna et al., 2022a; Salamanca et al., 2004; Torres et al., 2016).

Based on the above and the dominance and transformation of grazing systems in scrubland areas in the state of *Nuevo León*, the objective of this study was to analyze the effects of this land use on the physical and chemical characteristics of a Vertisol along a 0 to 100 cm depth gradient. The above is based on the fact that many of the studies focus only on the evaluation of the first few centimeters, so there is a lack of knowledge and uncertainty about the behavior of the physical and chemical variables of the soil at greater depth ranges.

Materials and Methods

The study was conducted in the *Linares* municipality, *Nuevo León*, on the campus of the Graduate School of Forest Sciences of the Autonomous University of *Nuevo León* (*Universidad Autónoma de Nuevo León*), at an altitude of 380 m, with an average monthly temperature of 22.4 °C and an average annual rainfall of 805 mm. It has vegetation of the Tamaulipan Thorny Scrub and a grassland area of *Dichanthium annulatum* (Forssk.) Stapf (Yáñez et al., 2018) (Figure 1).



MET = Tamaulipan Thorny Scrub; *Pastizal* = Grassland.

Figure 1. Location of the study area in Linares, Nuevo León, Mexico.

Field sampling

Sample collection was carried out in two plots, described below:

(a) Control area, characteristic of the region's native vegetation and undisturbed in the last 20 years, known as the Tamaulipan Thorny Scrub (MET).

(b) Grassland land use, 20 years old, corresponding to an intensive grazing system with rotation cycles in pastures and a stocking rate of 8 AU ha^{-1}, with rest periods of 8 and 5 weeks during the dry and rainy seasons, respectively.

For each land use, four composite soil samples weighing 1 to 1.5 kg were collected at five depths (0-5, 5-15, 15-30, 30-60, and 60-100 cm) (Comisión Nacional Forestal [Conafor], 2017), yielding a total of 40 composite soil samples. Forty undisturbed samples were also extracted using metal cylinders measuring 5 cm in diameter by 5 cm in length to determine Bulk density. These samples were then sent to the Soil and Forest Nutrition Laboratory of the Graduate School of Forest Sciences of the Autonomous University of *Nuevo León* (*Universidad Autónoma de Nuevo León*), for subsequent laboratory analysis.

Table 1 shows the different physical and chemical properties, as well as the method and units of measurement used for their determination.

Table 1. Methods for determining physical and chemical properties.

Properties		Metodology
Physical	*BD* (g cm^3)	Gravimetric method (Woerner, 1989)
	P (%)	Estimation by *BD* and particle size ratio (Luna-Robles et al., 2021)
	MRP (kg cm^2)	Penetrometer (Herrick & Jones, 2002)
	Texture (%)	AS-09 NOM-021-RECNAT-2000 (NOM-021-RECNAT-2000, 2001; Silva et al., 2020)

Chemical	*SOM* (%)	Wet combustion according to Walkley-Black (Cantú & Yáñez, 2018; Woerner, 1989)
	C (%)	Estimation by *SOM* (Cantú & Luna, 2022; Woerner, 1989)
	pH (%)	AS-23 NOM-021-RECNAT-2000 (NOM-021-RECNAT-2000, 2001)
	EC (μS cm^{-1})	Rapid soil-water determination (Woerner, 1989)

BD = Bulk density; *P* = Porosity; *MRP* = Mechanical resistance penetration; *SOM* = Soil organic matter; *C* = Organic Carbon content; *EC* = Electric conductivity.

Statistical analysis

All data variables were subjected to Kolmogorov-Smirnov normality tests and Levene's homogeneity of variance tests (Flores & Flores, 2021). Variables that met both assumptions (*%C*, *SOM*, *EC*, *pH*, *BD*, *P*, sand and silt) underwent a two-way analysis of variance to determine significant differences between land uses (Scrub and Grassland), depths (0-5, 5-15, 15-30, 30-60, and 60-100 cm), as well as their interactions with their respective Tukey tests (p=0.05). Meanwhile, for *MRP* and clay, the Mann-Whitney *U* test (Berlanga & Rubio, 2012) and the Kruskal-Wallis test were applied to determine significant differences between land uses and depth ranges. All statistical analyses were performed using SPSS version 22.0 (International Business Machines [IBM], 2020).

Results

Chemical properties

According to the results of the two-way ANOVA, none of the chemical variables showed significant differences between land uses (p>0.05); however, there were significant differences between depths, as well as between their interaction (p<0.01) (Table 2).

Table 2. Two-way ANOVA for land uses (MET and Grassland), depths (0-5, 5-15, 15-30, 30-60, and 60-100 cm), and their interaction on the chemical properties of a Vertisol.

Variable	Land uses *F*-Value	Depth *F*-Value	Uses * Depth *F*-Value	Levene
SOM (%)	1.21ns (0.06)	109.46** (<0.01)	4.54** (<0.01)	0.431
%C	1.87ns (0.28)	105.03** (<0.01)	4.71** (<0.01)	0.830
pH	6.05 (0.18)ns	32.44** (<0.01)	7.59** (<0.01)	0.062
EC (μS cm^{-1})	0.16 (0.68)ns	71.23** (<0.01)	3.02* (<0.05)	0.111

SOM = Soil organic matter; *%C* = Organic Carbon content; *EC* = Electric conductivity; ns = Non-significant differences (p>0.05); ** Highly significant differences (p≤0.01); * Significant differences (p≤0.05); p-values are indicated in parentheses.

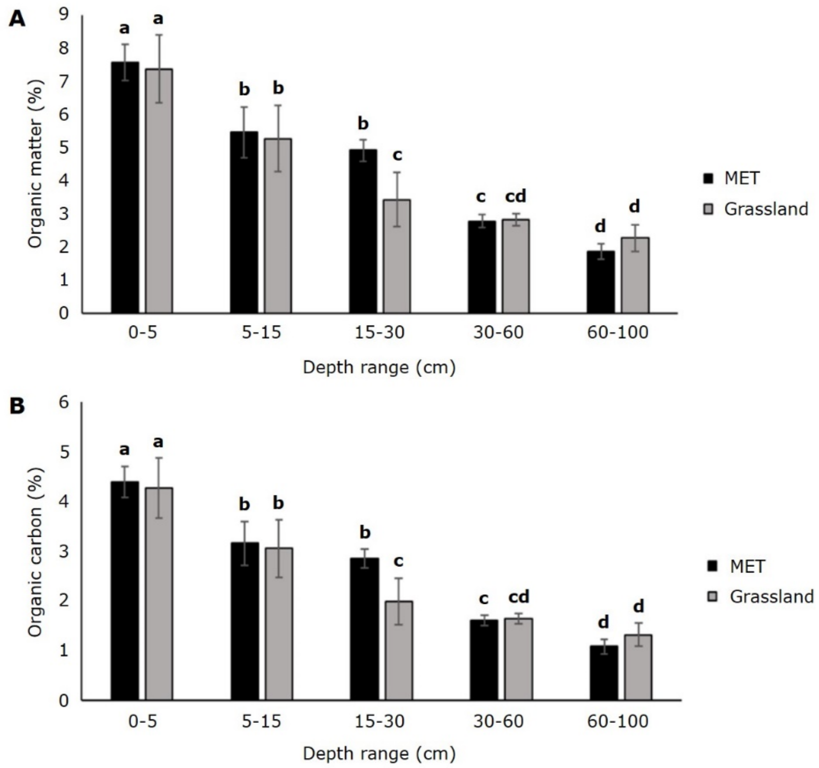
Specifically, the organic matter (*SOM*) content was 4.52 and 4.24 % in the MET and Grassland, respectively, while the corresponding Organic Carbon values were 2.62 % in the MET and 2.42 % in the Grassland. Furthermore, the *pH* for both land uses was considered moderately alkaline, while the *EC* was recorded below salinity levels considered very low (<500 μS cm^{-1}) (Table 3).

Table 3. Average values of chemical variables among land uses (*n*=20).

Variable	MET	Grassland
SOM (%)	4.52±2.11	4.24±2.03
%C	2.62±1.23	2.42±1.15
pH	7.45±0.11	7.50±0.16
EC (μS cm^{-1})	73.72±11.8	74.08±17.98

SOM = Soil organic matter; *%C* = Organic Carbon content; *EC* = Electric conductivity; MET = Tamaulipan Thorny Scrub.

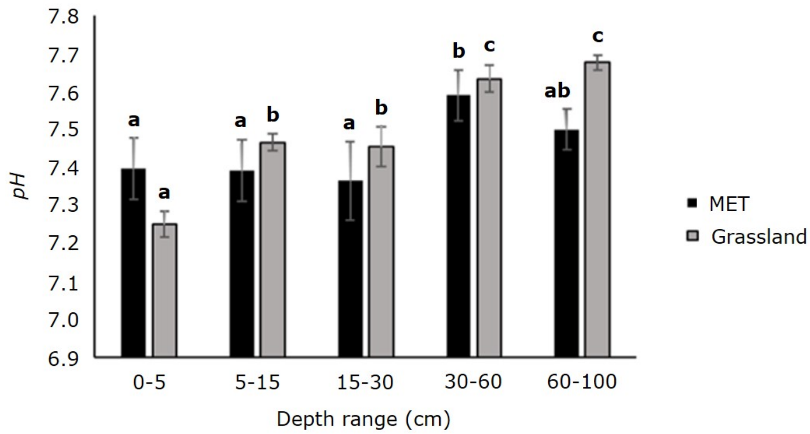
Figure 2 illustrates the variables by depth range, where it is evident that organic matter (*SOM*) and Organic Carbon (*%C*) showed a uniform downward trend with increasing depth in both land uses. In the MET, in particular, the highest levels of *SOM* and *%C* were recorded at depths of 0-5 cm, reaching values of 7.6 and 4.4 %, respectively, while the lowest values were found at depths of 60-100 cm, with 1.9 % for *SOM* and 1.1 % for *%C*. On the other hand, in the Grassland the *SOM* contents ranged between 2.3 and 7.4 % and the *%C* contents fluctuated between 1.3 and 4.3 %.



A = Organic matter; B = Organic Carbon. MET = Tamaulipan Thorny Scrub. Different letters represent significant differences.

Figure 1. Organic matter and Organic Carbon contents by depth, in the two land uses.

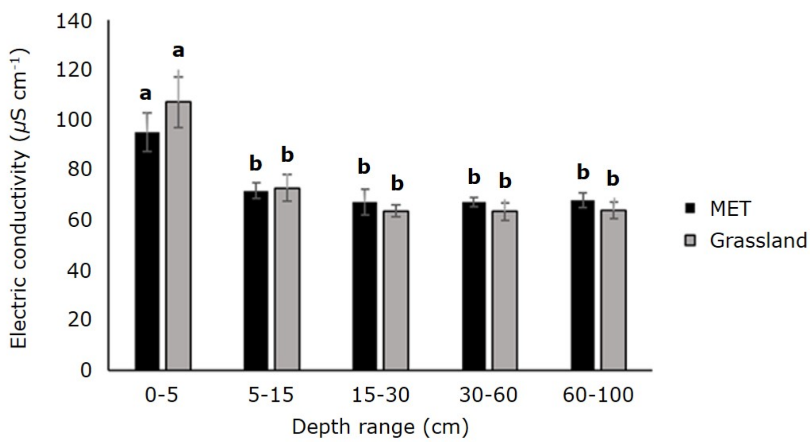
Regarding pH levels, in the MET the lowest values were recorded in the 15-30 cm depth range (7.4), while the highest values were observed in the 30-60 cm range (7.6). In contrast, in the Grassland, a practically upward trend was recognized as the depth increased, with figures between 7.3 and 7.7, which, according to its assessment, are moderately alkaline soils (Figure 3).



MET = Tamaulipan Thorny Scrub. Different letters represent significant differences.

Figure 3. *pH* values by depth in the two land uses.

Figure 4 describes the *EC* behavior across the five depth ranges. It can be seen that the highest values were recorded at 0-5 cm, with 95 μS cm^{-1} for the MET and 106.96 μS cm^{-1} for the Grassland. However, as depth increases, the *EC* decreases significantly, and remained in more stable ranges between 66.98 and 67.94 μS cm^{-1} for the MET and between 63.33 and 63.75 μS cm^{-1} for the Grassland, which is considered a very low *EC*.



MET = Tamaulipan Thorny Scrub. Different letters represent significant differences.

Figure 2. *EC v*alues by depth in the two land uses.

Physical properties

The two-way ANOVA for the variables indicated that only *BD* and *P* had significant differences between land uses ($p<0.05$); only sand and silt contents varied between depth ranges; and in their interaction, no variable showed significant differences ($p>0.05$) (Table 4). The Mann-Whitney *U* test indicated that only *MRP* presented highly significant differences between land uses ($p<0.01$).

Table 4. Two-way ANOVA for land uses (MET and Grassland), depths (0-5, 5-15, 15-30, 30-60, and 60-100 cm), and their interaction on the physical properties of a Vertisol.

Variable	Uses	Depth	Uses* Depth	Levene
BD (g cm^{-3})	29.10** (<0.01)	0.67ns (>0.05)	1.56ns (>0.05)	0.487
P (%)	29.10 (<0.01)**	0.67ns (>0.05)	1.56ns (>0.05	0.487
Sand (%)	1.05 (0.58)ns	0.87** (<0.01)	2.76ns (>0.05)	0.126
Silt (%)	0.01 (0.68)ns	7.74** (<0.01)	1.54ns (>0.05)	0.107

BD = Bulk density; *P* = Porosity; ns = Non-significant differences ($p>0.05$); ** Highly significant differences ($p\leq0.01$); the *p*-value is indicated in parentheses.

The *BD* and *MRP* values of the Grassland, in particular, increased significantly compared to the Scrubland, while *P* decreased by 7 % on average. Both land uses are similar in particle size distribution and were classified as clay-loamy (Table 5).

Table 5. Average values of the physical variables among land uses (*n*=20).

Variable	MET	Grassland
BD (g cm^{-3})	1.09±0.15	1.34±0.14
P (%)	57.40±5.99	47.84±5.34
MRP (kg cm^{2})*	3.31±1.84	15.73±14.9
Sand (%)	24.57±4.66	23.40±2.98
Clay (%)*	32.01±3.14	33.05±5.68
Silt (%)	43.42±4.99	43.55±3.69

BD = Bulk density; *P* = Porosity; *MRP* = Mechanical resistance penetration.

Table 6 shows the results of the Kruskal-Wallis test for *MRP* and clay percentage. Only the latter was similar in terms of MET across the different depth ranges (p>0.05); while in the Grassland, both variables were significant across depths (p<0.05).

Table 6. Statistics from the analysis of variance and Kruskal-Wallis test for the physical variables across depths (*n*=4).

Use	Variable	***Chi*-square**	p-value
MET	*MRP*	16.473	0.002
	Clay	9.073	0.059
Grassland	*MRP*	10.497	0.033
	Clay	13.234	0.010

MET = Tamaulipan Thorny Scrub; *MRP* = Mechanical resistance penetration.

BD values were slightly higher in the Grassland area than in the MET for all depths analyzed; in the Grassland, they ranged from 1.26 (5-15 cm) to 1.45 g cm^{-3} (0-5 cm), while in the MET, they ranged from 1.02 (0-5 cm) to 1.19 g cm^{-3} (30-60 cm). *P* in the MET ranged from 53.65 to 60.15 %, and in the Grassland, it ranged from 43.41 to 50.74 % (Table 7).

Table 7. Mean values of soil Bulk density and Porosity across the depth ranges and land uses analyzed.

Depth range (cm)	MET		Grassland	
	BD **(g cm^{-3})**	***P*** **(%)**	***BD*** **(g cm^{-3})**	***P*** **(%)**
0-5	1.02	60.15	1.45	43.41
5-15	1.17	54.45	1.26	50.74
15-30	1.04	59.31	1.29	49.65
30-60	1.19	53.65	1.35	47.17
60-100	1.04	59.44	1.33	48.22
Average	1.09	57.4	1.33	47.83

MET= Tamaulipan Thorny Scrub; *BD* = Bulk density; *P* = Porosity.

The granulometric compositions of sand, clay, and silt are shown in Table 8 for each depth range in both land uses, as well as their corresponding textural class.

Table 8. Texture classification in each depth range by land use.

Depth range (cm)	MET				Grassland			
	% Sand	**% Clay**	**% Silt**	**Texture Class**	**% Sand**	**% Clay**	**% Silt**	**Texture Class**
0-5	21.76	28.29	49.95	Clay loamy	26.58	26.42	47	Loam
5-15	22.35	31.56	46.09	Clay loamy	23.99	32.51	43.5	Clay loamy

15-30	26.58	32.56	40.86	Clay loamy	23.4	32.51	44.09	Clay loamy
30-60	27.08	34.06	38.86	Clay loamy	23.31	35.01	41.68	Clay loamy
60-100	26.51	33.92	39.57	Clay loamy	19.72	38.78	41.5	Silty clay loamy

MET = Tamaulipan Thorny Scrub.

Discussion

Globally, changes in forest cover for livestock use are considered one of the factors with the greatest impact on soil conditions (Lalthakimi et al., 2023); however, these changes are dependent on soil type, land use, and management practices. In this sense, the results of this study suggest that the conversion of scrubland to grassland does not cause a significant change in the chemical properties of Vertisols. This has already been reported in previous studies, which have indicated that the conversion of ecosystems to grassland is one of the land uses with little or no effect on soil Organic matter, Carbon, *pH*, and *EC* content (Martínez et al., 2023; Yáñez et al., 2018).

Specifically, the *SOM* results of the present study were 5.98 and 5.36 % up to 30 cm depth for the MET and the Grassland, respectively, which is considered high; this is attributed to the incorporation of crop residues and mineralization and humification rates in the soil up to this depth, which, in turn, impacts the *%C* contents (Montoya-Jasso et al., 2022). This has already been discussed by Yáñez et al. (2018) with the same type and land uses (6.1 % in MET and 4.6 % in Grassland). It should be noted that, although livestock on site consume a large part of the source of soil Organic matter (grasses and shrubs), these variables did not reveal differences between the land uses evaluated; since to some extent compensation may be occurring due to the accumulation of urine and livestock feces in the soil (Martínez et al., 2023; Tácuna et al., 2015). In a similar way, Yáñez et al. (2018) mention that Vertisol, having a soil texture rich in clays, tends to retain more Organic matter and *%C*, which is reflected in both land uses.

The highest soil Organic Carbon contents in both land uses (4.39 and 4.27 % for MET and Grassland, respectively) were recorded at 0-5 cm deep. This is explained by the fact that this depth accounts for the greatest accumulation of soil Organic matter and, therefore, the greatest mineralization (Cantú & Luna, 2022).

However, the dynamics of *%C* can be determined by other environmental factors such as vegetation type and livestock management (Conforti et al., 2016; Luna et al., 2022b). In this regard, Bautista-García et al. (2022) point out that controlled rotational grazing ensures the restoration of soil fertility and site productivity over time, as this management system promotes vegetation cover, which leads to constant inputs of Organic matter into the soil and, in turn, maintains stable soil mineralization rates.

Regarding *pH* values, on average in both land uses they ranged from 7.3 to 7.7, indicating that it is a moderately alkaline soil; this is consistent with the results of Córdova-Sánchez et al. (2023), who determined the same classification for a Vertisol. According to the assessment of NOM-021-RECNAT-2000 (2001) and Woerner (1989), the soil's Electrical conductivity was very low.

On the other hand, physical properties such as Bulk density, Porosity, and Mechanical resistance to penetration are considered the most sensitive to the presence of livestock, as this factor can significantly increase these variables compared to forest use, which is attributed to the constant trampling of livestock (Rodríguez et al., 2024). This coincides with the findings of the present study, in which these variables were affected after the conversion of scrubland to grassland.

Likewise, Bellora et al. (2023), Villazón et al. (2015) and Zemke et al. (2019) indicate that aerial and soil cover play an important role in soil moisture, Bulk density, Porosity, and soil hardness, which is reflected in the results of the Grassland. Without sufficient vegetation cover, there is no protection to cushion the effects of livestock trampling, resulting in significant changes in soil physics. In particular, in both land uses, the highest values for Mechanical resistance penetration and soil Bulk density were recorded in the first five centimeters. According to Woerner (1989), these values went from very low in the Scrubland (<1.20 g cm^{-3}) to moderately low in the Grassland (>1.30 g cm^{-3}). These values also do not significantly limit plant establishment.

However, Cid-Lazo et al. (2021) mention that the removal of vegetation directly impacts Vertisol moisture and generates immediate changes in soil Bulk density, Porosity and *MRP*. In addition, Álvarez et al. (2012) determined that the use of machinery in grasslands may be another factor determining the dynamics of soil characteristics. Cherubin et al. (2016) and Mitchell et al. (2017) indicate that these variables can be improved through cover management, increased rotation cycles, and decreased animal density. Furthermore, an alternative for improving properties may be the use and management of organic fertilizers (Bolo et al., 2020).

Regarding soil texture, Valdez-Galvez et al. (2023) describe it as a property that is difficult to modify in the short and medium term due to changes in land use under different low-intensive management practices. Therefore, in this context, it can be inferred that Vertisol maintains its granulometric stability (Loam-Clay loam) under a pasture system. However, the first few centimeters of soil are subject to alteration due to erosion resulting from the lack of cover and livestock trampling.

Soil analyses are commonly conducted within the first 40 cm because these ranges are considered to be the most susceptible to vegetation changes and land-use changes (Gómez et al., 2021; Gross & Harrison, 2019; Guevara & Vargas, 2021). However, a more in-depth analysis of these soil analyses allows for the identification of the response of the soil's physical and chemical properties to any disturbance and a more precise determination of its degree and depth of impact.

Conclusions

In this study, the physical properties of the Vertisol were those that showed the greatest impact after the conversion of the Tamaulipan Thorny Scrub to Grassland, while the chemical properties did not show significant changes between land uses but did change between depths.

BD, *P* and *MRP* were more susceptible to the conversion from Scrub to Grassland; *BD* and *MRP*, in particular, increased by 23 and >400 %, respectively, and *P* decreased by 13 %. These changes may be related to the presence of livestock in the Grassland area, where constant trampling has significantly modified the soil structure.

The *SOM* and *%C* contents in both land uses showed a downward trend with increasing depth.

Acknowledgments

The authors express their gratitude to the National Council of Humanities, Sciences, and Technologies (*Consejo Nacional de Humanidades*, *Ciencias y Tecnologías*) for the grant awarded to the first author to conduct this research.

Conflict of interest

The authors declare no conflict of interest.

Contribution by author

Jorge Alexis Luna Robles: field and desk research; Israel Cantú Silva: revisions and corrections of the manuscript and statistical analysis; Erik Orlando Luna Robles: reviews and corrections of the manuscript and statistical analysis; Silvia Janeth Bejar Pulido: reviews and corrections of the manuscript.

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