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Research article

Indicadores de calidad para suelos forestales dentro de un Área Natural Protegida

Quality indicators for forest soils within a Protected Natural Area

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Abstract

The forest soil provides various ecosystem services; however, it does not escape the phenomenon of degradation, a situation that has repercussions on the structure of the forests. This has been particularly noticeable in the *La Malinche* National Park, a natural protected area in *Tlaxcala*, Mexico, which has large areas with a variety of disturbance conditions. The objective of this study was to determine the physical and chemical properties of forest soils to obtain quality indicators by means of a Principal Component Analysis (PCA). Two sites were selected (*San Francisco Tetlanohcan* and *Teolocholco*), and five points exhibited different disturbance and vegetation in each site. The results show a higher percentage of sand in all soils (>70 %) than of clay and silt; bulk density >1 g cm^{-3}, low organic matter content in all soils, and variability concerning nutrient content, except for phosphorus content, which was high at all sites, possibly depending on the type of vegetation and the condition at each of the sampling points. The Principal Component Analysis showed that bulk density, porosity, usable moisture, pH, cation exchange capacity, and concentrations of Mn, Na, Cu, B, Ca and K can be used to determine the physical and chemical quality of forest soils, which would support the design of rehabilitation strategies aimed at halting soil degradation within the protected natural area.

Key words: Soil quality, soil degradation, soil properties, soil resource, *Tlaxcala*, *La Malinche* volcano.

Resumen

El suelo forestal proporciona diferentes servicios ecosistémicos, pero que no escapan del fenómeno de la degradación, situación que repercute en la estructura de los bosques. Esto ha sido particularmente notable en el Parque Nacional La Malinche, área natural protegida de Tlaxcala, México, la cual tiene grandes superficies con diferentes condiciones de perturbación. El objetivo del presente estudio fue determinar las propiedades físicas y químicas de suelos forestales para obtener indicadores de calidad por medio de un Análisis de Componentes Principales (ACP). Se seleccionaron dos sitios (San Francisco Tetlanohcan y Teolocholco) y en cada sitio se establecieron cinco puntos, con diferente condición de perturbación y vegetación. Los resultados muestran un mayor porcentaje de arena en todos los suelos (> 70 %) que de arcilla y limo; densidad aparente >1 g cm^{-3}, contenido de materia orgánica bajo en todos los suelos y una variabilidad respecto a la parte nutrimental; a excepción del contenido de fósforo, que fue alto en todos los sitios, lo que posiblemente depende del tipo de vegetación y de la condición propia de cada uno de los puntos de muestreo. El Análisis de Componentes Principales evidenció que la densidad aparente, porosidad, humedad aprovechable, pH, capacidad de intercambio catiónico y las concentraciones de Mn, Na, Cu, B, Ca y K pueden emplearse para determinar la calidad física y química de los suelos forestales, lo cual apoyaría el diseño de estrategias de rehabilitación encaminadas a detener la degradación de los suelos dentro del área natural protegida.

Palabras clave: Calidad del suelo, degradación del suelo, propiedades edáficas, recurso suelo, Tlaxcala, volcán La Malinche.

Introduction

Soil is an important component of forest ecosystems, performing several functions such as decomposition of organic matter, nutrient cycling, ensuring water availability, as well as providing anchorage for trees and other vegetation (Corti *et al.*, 2020). However, disturbances, change of use and overexploitation can contribute to the degradation of this resource, which negatively affects the structure, size or function of forests, as well as reducing their capacity to provide environmental goods and services (Blum, 2020).

In Mexico, soil degradation is a serious problem that is accentuated in mountainous areas, particularly in the state of *Tlaxcala*, 92.9 % of whose surface area is recognized to suffer from water erosion (Bolaños *et al.*, 2016). This problem is observed in *La Malinche* National Park (a protected natural area), where the loss of soil and forest vegetation has led to an increase in temperature and changes in precipitation patterns that have favored an increase in the populations of the bark beetle, an insect that has eliminated a significant population of trees (López, 2023). This, together with the opening of land for agriculture, livestock, human settlements, deforestation, charcoal production and fires, has led to significant soil degradation (Blum, 2020).

Therefore, it is important to have a diagnosis and evaluation based on the study of the physical, chemical and biological properties of the soil to understand how they influence the growth of the vegetation cover and how they have been impacted by the various anthropic activities (Álvarez-Arteaga *et al.*, 2020). Soil characterization must be specific to each region, due to soil and climatic conditions, since they vary from one place to another; in addition to considering land use, this will contribute to an integrated management of the resource (Trujillo-González *et al.*, 2018).

Within this context, the objective of this study was to determine the physical and chemical properties of forest soils with different conditions of disturbance at the *La Malinche* National Park, and, through a principal component analysis (PCA), to obtain quality indicators for the implementation of conservation strategies for this natural resource by monitoring changes in its quality.

Materials and Methods

Study area

The study area is located Southwest of the *La Malinche* National Park in the state of *Tlaxcala*, Mexico. Two sites were selected during the dry season: *Teolocholco* (TL) and *San Francisco Tetlanohcan* (SFT), and five points were established in each of them, separated by 500 m and surrounded by environments disturbed by erosion, deforestation, fires, and land use change (Table 1); in addition, preserved sites were included.

Table 1. Location and condition of each sampling point in the sites of *La Malinche* National Park, *Tlaxcala*, Mexico.

Point	Latitude	Longitude	Altitude (masl)	Dominant vegetation	Condition
			San Francisco Tetlanohcan		
1	19°14'19.26''	98°04'18.38''	3 242	*Pinus* sp., *Alnus* sp., herbs	Preserved
2	19°14'22.97''	98°04'34.32''	3 189	*Pinus* sp., *Alnus* sp., herbs	Preserved
3	19°14'29.79''	98°04'51.42''	3 121	*Pinus* sp., ferns, herbs	Deforestation, erosion
4	19°14'36.02''	98°05'08.43''	3 031	*Pinus* sp., *Quercus* sp., herbs	Forest fire, deforestation, erosion
5	19°14'40.61''	98°05'39.27''	2 925	*Pinus* sp., *Quercus* sp., herbs	Forest fire, deforestation, erosion
			Teolocholco		
1	19°14'06.95''	98°05'05.29''	3 117	*Pinus* sp., ferns, herbs	Preserved
2	19°14'07.05''	98°05'15.77''	3 060	*Pinus* sp., ferns, herbs	Preserved
3	19°14'03.93''	98°05'31.25''	3 004	*Pinus* sp., herbs	Deforestation, erosion
4	19°14'06.33''	98°05'51.41''	2 920	*Pinus* sp., *Quercus* sp., herbs	Forest fire, deforestation, erosion
5	19°14'13.12''	98°06'08.58''	2 890	*Zea mays* L., *Phaseolus vulgaris* L., herbs	Change of land use

The climate in the area is temperate sub-humid, and the vegetation is characteristic of a temperate forest. Rainfall occurs from May to September; the average annual minimum temperature varies from 6.4 to 6.9 °C and the maximum from 22.7 to 24.3 °C; the average rainfall range is from 100 to 165 mm, and the predominant soil corresponds to the Regosol order (young soils, which develop on unconsolidated material) with a presence of 74 % in TL and 43 % in SFT (INEGI, 2010a, b).

Soil sampling and sample preparation

At each sampling point, a 400 m^2 quadrant was drawn where three simple samples were collected at 0-30 cm deep, following a zig-zag trajectory to eliminate the shore effect. Subsequently, each sample was dried on *Kraft* paper at room temperature and in the shade, and then sieved on a 2 mm mesh to obtain a homogeneous particle size, in accordance with NOM-021-RECNAT-2000 (Semarnat, 2002).

Soil analysis

The textural class was determined in each sample once the percentage of sand, silt and clay particles was obtained by the Bouyoucos hydrometer method; the field capacity (*FC*) and the permanent wilting point (*PWP*) were evaluated by the pressure pot and membrane method; the porosity and usable moisture (*UM*), according to Rodríguez and Rodríguez (2011); the bulk density (*BD*) by the test tube method as indicated in NMX-FF-109-SCFI-2007 (SE, 2008); the pH at a 1:2 soil to water ratio (w/v); the organic matter (OM) with the Walkley and Black method; the electrical conductivity (*EC*) in a 1:5 soil to water suspension (w/v); the cation exchange capacity (*CEC*), and K, Ca, Mg and Na, with 1 N pH 7 ammonium acetate; the total N with the semi-micro Kjeldahl method; the available K with modified No. 1 Bray and Kurtz test; the micronutrients (Cu, Fe, Mn, Zn), with the DTPA complexing solution, and B with the azomethine-H method (NOM-021-RECNAT-2000) (Semarnat, 2002).

Data analysis

The data analysis is based on a nested experimental design with two factors (TL and SFT sites) using the points as levels, each with three replicates. The data were subjected to the Shapiro-Wilk normality test and Levene's test for homogeneity of variances ($p>0.05$). Once the assumptions of normality were met, an analysis of variance and subsequently a Tukey mean comparison test ($p<0.05$) were performed to identify whether there are differences between the sites (TL and SFT) and between the points within each site. Equation 1 represents the statistical model for the experimental design used (InfoStat, 2008).

$$Y_{ijk} = \mu + S_i + P_{j(i)} + \varepsilon_{(ij)k} \qquad (1)$$

Where:

Y_{ijk} = Response variable

μ = Overall mean

S_i = Value of the i^{th} factor site

$P_{j(i)}$ = Value of the j^{th} value of the point within the i^{th} site

$\varepsilon_{(ij)k}$ = Random error associated with the response variable Y_{ijk}

Subsequently, a Principal Component Analysis (PCA) was performed to estimate the soil quality indicators. The statistical software InfoStat, free 2008 version, was utilized for all of the above (InfoStat, 2008).

Results and Discussion

Differences between the various physical and chemical properties of the soils were found only in *EC* (*p*=0.0349), with higher values at the *Teolocholco* site (TL) than at *San Francisco Tetlanohcan* (SFT). At least one point within each of these two sites registered significant values, except for the B content (*p*=0.0676). These results may be because the soils of the *La Malinche* National Park were formed from the weathering of volcanic ash, and, therefore, their physical and chemical characteristics tend to be similar; although the type of vegetation, as well as its condition, influences its edaphic properties (Vela-Correa *et al.*, 2007).

As for the physical properties, all soils had a higher proportion of the sand fraction >70 % in relation to clay and silt content. Table 2 shows the significant differences of the variables between points per site. At SFT, the *BD* was significantly higher at

Point 2, close values were recorded at site points TL. Porosity in all samples was >40 %, with a significant value at Point 4 of the SFT.

Table 2. Physical properties of the soils at two sites in the *La Malinche* National Park, *Tlaxcala*, Mexico.

Point	***BD*** **(g cm^{-3})**	**Porosity**	***FC*** **(%)**	***PWP***	***UM***
			San Francisco Tetlanohcan		
1	1.51 b	43.0 ab	17.9 g	6.3 f	11.5 g
2	1.55 a	41.0 c	18.5 f	6.6 e	11.8 f
3	1.46 c	44.5 b	20.7 d	7.3 d	13.4 e
4	1.27 d	51.6 a	31.2 a	9.3 a	22.5 a
5	1.51 b	43.0 ab	20.9 d	6.2 f	14.2 c
			Teolocholco		
1	1.46 c	43.7 b	18.4 f	7.5 d	10.9 i
2	1.51 b	42.6 ab	21.8 c	8.0 c	13.8 d
3	1.51 b	43.1 b	19.1 e	7.4 d	11.6 fg
4	1.47 c	44.1 b	17.9 g	6.7 e	11.2 h
5	1.47 c	44.4 b	23.5 b	8.4e	15.0 b

Different letters per column indicate significant differences ($p<0.05$). Tukey's mean. *BD* = Bulk density; *FC* = Field capacity; *PWP* = Permanent wilting point; *UM* = Usable moisture.

At this same Point, the FC and PWP provided by the UM of the soils at the time of the sample collection were significant and decreased at the rest of the points in the two studied sites (Table 2).

In soils with a higher proportion of sand, mineralization processes are favored as a result of increased aeration, but they reduce the *FC* (Huang and Hartemink, 2020).

The *PWP* increases if there is a larger amount of clay; however, given that the soils under study are sandy, the value of this variable was lower at the SFT Point 5, where there is disturbance due to fires, deforestation, and erosion problems.

In an agroforestry system, Murray *et al.* (2014) cite a *FC* of 36 %; on the other hand, in forest soils of *Cofre de Perote*, state of *Veracruz*, Meza and Geissert (2003) calculated a *FC* of 43 %, a *PWP* of 21 %, and a *UM* of 22 %, values higher than those estimated in SFT and TL. The above responds to the texture and organic matter, together with the vegetation present and its condition and management (Table 1).

Soils of volcanic origin have physical characteristics that favor good structural stability and a high resistance to degradation. However, they are affected by anthropogenic activities, as is the case of the *BD*. SFT and TL soils had values higher than those established by NOM-021-RECNAT-2000 (Semarnat, 2002) for volcanic soils (<1 g cm^{-3}). A *BD* of 0.8 g cm^{-3} was registered in soils located at an altitude of 2 700 m with *Pinus ayacahuite* C. Ehrenb. *ex* Schltdl. and at 3 000 m with *P. patula* Schltdl. & Cham. (Vázquez-Cuecuecha *et al.*, 2015): this value is value lower than that determined in the soils under study. In forest soils with harvesting of *P. radiata* D. Don, the *BD* was 1.35 g cm^{-3} (Acevedo-Sandoval *et al.*, 2010). Only at Point 4 of the SFT site, the fire caused a mineralization of the organic residues, which resulted in a decrease of the *BD* (Table 2).

The pH was moderately acidic in all soils sampled, with Point 1 at site TL having the highest significant value (Table 3). The pH is considered adequate for its forest condition, which may be due to the mineralization of the *OM* and to the presence of aluminum and the needles of trees of the genus *Pinus* sp., which are potentially acidifying due to the production of organic acids and H_2CO_3 that influence the formation of Al-humus complexes (Martínez-Cruz *et al.*, 2002).

Table 3. Chemical properties: total N, P, and K of soils sampled in the *La Malinche* National Park, *Tlaxcala*, Mexico.

Point	pH	*OM* (%)	*EC* (dS m^{-1})	*CEC* (Cmol$^{(+)}$ kg^{-1})	Total N (%)	P (mg kg^{-1})	K
				San Francisco Tetlanohcan			
1	5.9 b	3.10 c	0.35 fg	14.10 a	0.14 de	37.80 e	5.0 b
2	5.7 bc	2.50 f	0.35 fg	8.10 i	0.12 e	36.56 f	2.9 d
3	5.5 c	3.10 e	0.37 ef	9.02 g	0.15 cd	39.13 b	3.0 d
4	5.5 c	5.20 b	0.34 g	9.03 g	0.25 a	39.43 a	3.8 c
5	5.8 b	1.70 g	0.29 h	12.10 c	0.08 f	35.13 g	4.9 b
				Teolocholco			
1	6.2 a	3.20 e	0.90 a	12.86 b	0.17 c	33.70 i	3.9 c
2	5.7 bc	4.30 d	0.39 e	10.13 e	0.21 b	34.60 h	5.9 a
3	5.9 b	4.36 d	0.42 d	9.76 f	0.21 b	38.30 f	3.0 d
4	5.8 b	4.66 c	0.75 b	8.70 h	0.21 b	39.20 d	5.0 b
5	5.9 b	5.66 a	0.51 c	11.33 d	0.27 a	38.70 c	6.0 a

Different letters per column indicate significant differences ($p<0.05$). Tukey's mean. *OM* = Organic matter; *EC* = Electrical conductivity; *CEC* = Cation exchange capacity.

Regarding the *OM* content, Point 5 of the TL site had the most significant value in relation to the other points; however, it was low (4.1-6.0 %) in accordance with NOM-021-RECNAT-2000 (Semarnat, 2002). Particularly, the soils of the TL site showed a tendency to reduce the *OM* content at higher altitudes; this behavior was not observed in the SFT soils, where there was variability in their content, which can probably be attributed to the condition of each of the points of the soil (Table 1).

According to Bhardwaj *et al.* (2022), the amount of leaf litter that is incorporated into the soil in a temperate forest varies according to the plant species, which generates various organic compounds that determine the quality of the *OM* and therefore, the availability of nutrients for the plants; thus, litterfall is one of the most dynamic fractions of forest soil *OM* (Tapia-Coronado *et al.*, 2023). Jiménez-Hereida *et al.* (2010) recorded 5.3 % *OM* in secondary forest soils with shrub vegetation, a similar amount to that of Point 5 of the TL site. The *OM* content depends on the type of vegetation, soil use and management, among other factors (Rodríguez-Yon *et al.*, 2020).

In the soils of the two sites there were no salt issues, and the *CEC* was high and significant in Point 1 of SFT with respect to the other points. However, cation exchange was low in all soils (5-15 $Cmol^{(+)}$ kg^{-1}), according to the norm NOM-021-RECNAT-2000 (Semarnat, 2002), due to the low percentage of *OM* (Table 3) and the predominance of the sand fraction, which leads to the inference that the soils have a low cation exchange capacity. In the soils of *La Malinche* National Park, Vela-Correa *et al.* (2007) report a low *CEC* in the superficial horizons (0-20 cm), decreasing with depth, in agreement with the findings of the present study.

The nutritional part is important in forest soils. In the sampled sites, the concentration of total N was significantly higher in Point 4 of SFT and 5 of TL, compared to the rest of the points, possibly due to the effect of the fire and the incorporation of organic amendments (Table 1). P concentration was high (30 mg kg^{-1}) in all soils (Semarnat, 2002). Zhu *et al.* (2021) report high amounts of P under tree that may be caused by the higher acidity, high inputs, and decay of leaf litter, conditions that favor greater microbial activity, specifically fungal activity responsible for the solubilization of inorganic phosphorus, and also for the mineralization of organic phosphorus. Soils with *Pinus radiata* and *P. halepensis* Mill. have P concentrations of 62 and 94 mg kg^{-1}, respectively (Zalba and Peinemann, 1987), values even higher than those estimated in this work.

The K concentration at TL points 2 and 5 was low (<150 mg kg^{-1}) according to Aguilar *et al.* (1987), but more significant ($p<0.05$) (Table 3) with respect to the other TL and SFT points.

Table 4 shows the Ca content, which was significantly higher and was present in a mean concentration (5-10 $Cmol^{(+)}$ kg^{-1}) in Point 1 of SFT; whereas, at Point 5 of this site, the Mg concentration was high (>3 $Cmol^{(+)}$ kg^{-1}), like that of Cu, although deficient in all soils (<0.2 mg kg^{-1}); on the other hand, Fe and Mn concentrations —2.5 to 4.5 mg kg^{-1} and >1.0 mg kg^{-1}, respectively— were mostly significant and adequate at Point 4 (Semarnat, 2002).

Table 4. Nutrients of soils sampled in *La Malinche* National Park, *Tlaxcala*, Mexico.

Point	Ca	Mg	Na	Cu	Zn	B	Fe	Mn
	(Cmol$^{(+)}$ kg^{-1})		(%)		(mg kg^{-1})			
				San Francisco Tetlanohcan				
1	11.6 a	0.00 f	0.00016 a	0.13 ab	0.27 b	0.32 b	3.44 d	0.96 d
2	5.2 f	1.56 d	0.00012 cd	0.11 bc	0.17 de	0.33 ab	1.97 i	0.53 i
3	8.0 cd	0.00 f	0.00013 bcd	0.13 ab	0.19 d	0.34 ab	3.49 c	1.15 b
4	8.1 cd	0.00 f	0.00015 ab	0.12 abc	0.19 d	0.34 ab	3.98 a	1.83 a
5	6.0 ef	4.10 a	0.00015 ab	0.14 a	0.14 fg	0.32 b	3.30 f	0.90 e
				Teolocholco				
1	10.0 b	1.13 b	0.00014 abc	0.10 c	0.13 g	0.33 ab	1.86 j	0.52 i
2	8.3 c	0.00 f	0.00012 cd	0.10 c	0.23 c	0.34 ab	3.52 b	0.77 g
3	6.1 e	2.06 c	0.00011 d	0.11 bc	0.16 ef	0.35 a	2.28 h	0.58 h
4	5.8 ef	1.46 e	0.00016 a	0.12 abc	0.23 c	0.34 ab	3.35 e	0.99 c
5	7.2 d	2.26 b	0.00015 ab	0.12 abc	0.32 a	0.34 ab	2.77 g	0.83 f

Different letters per column indicate significant differences ($p<0.05$). Tukey's mean.

At TL Point 5, the Zn concentration reached a more significant value ($p<0.05$), but was deficient (<0.5 mg kg^{-1}) as in all TL and SFT soils. B concentration was low (<0.39 mg kg^{-1}) (Semarnat, 2002), but significantly higher in Point 3, and the Na content was not an issue (Table 4).

The analysis of the exchangeable bases in the different soils showed a variation in the K, Ca, Mg, Na contents. Murga-Orrillo *et al.* (2021) document that K, Ca, Mg and Fe contents decrease with increasing altitude due to the influence of low temperatures and humidity, which did not occur in this study.

Principal Component Analysis

The correlation analysis showed that *BD* was the variable with the most significant negative interactions, especially with Mn (*r*=-0.86), *FC* (*r*=-0.85), *PWP* (*r*=-0.75), and *UM* (*r*=-0.85). This indicates that the higher the *BD*, the lower the usable water and the more compacted the soils will be. Therefore, the pore space will decrease, which will affect plant root growth, *OM* dynamics, and soil biological activity (Díaz *et al.*, 2018). On the other hand, the *OM* was significantly and positively correlated with the total N content (*r*=0.99) and with the B content (*r*=0.72). The results indicate that the condition of forest soils is based on the relationship between the decrease in organic carbon content, total N, pH, and porosity with the increase in *BD* (Álvarez-Arteaga *et al.*, 2020), a situation that is observed in the soils under study.

The different variables were grouped into three principal components (Table 5), all with an eigenvalue >1, which together accounted for 70 % of the total variance. The first principal component (8.01) was responsible for 38 % of the variance; it consisted of porosity, *BD*, *FC*, *UM*, and Mn content and was associated with the pore space.

Table 5. Proportion of variation accounted for by each principal component.

Component	Value	% Total variance	% Cumulative variance
1	8.01	0.38	0.38
2	3.53	0.17	0.55
3	3.18	0.15	0.70
Variable	Autovectors		
	CP1	CP2	CP3
Porosity	0.32	0.05	0.05

Bulk density	-0.31	-0.03	-0.07
Field capacity	0.32	0.04	-0.01
Permanent wilting point	0.29	-0.21	0.13
Usable moisture	0.31	0.09	-0.05
pH	-0.21	-0.11	0.38
Organic matter	0.25	-0.23	0.22
Electrical conductivity	-0.08	-0.23	0.34
Cation Exchange Capacity	-0.13	0.25	0.38
Total N	0.25	-0.26	0.23
P	0.22	0.04	-0.14
Ca	0.01	0.16	0.36
K	0.02	0.16	0.36
Na	0.08	0.36	0.28
Cu	0.01	0.43	-0.17
Zn	0.11	0.10	0.24
B	0.17	-0.40	-0.09
Fe	0.22	0.32	-0.04
Mn	0.31	0.22	-0.06

The second component (3.53) with 17 % of the variance, was related to the nutrient condition of the soil, which is accounted for by Na, Cu and B; the latter correlated positively with the *OM*. The third component (3.18) with 15 % of the total variance, was related to soil carrying capacity and was defined by the pH, *CEC* and Ca and K content (Table 5).

The Principal Component Analysis showed that the greatest variation (first component) involves porosity, *FC*, *UM*, Mn, and *BD*, which implies that, the more it increases, the more degradation problems will exist. Bolaños *et al.* (2016) point out that the erosion exhibited by the area of *La Malinche* is extreme in 16.76 % of its surface, strong in 16.28 %, mild in 15.55 %, and moderate in 44.39 %, percentages that may increase, because *La Malinche* is losing, in its lower gradient, much of its vegetation cover as a result of climate change (López, 2023). Pérez-Hernández *et al.* (2023) cite that the process of harvesting a temperate forest causes an increase in *BD* and a reduction in infiltration due to the loss of vegetation, cutting, and dragging of wood.

The second component is represented by Na, Cu, and B, although in all soils the concentrations of these elements were low (Table 4). Das and Purkait (2020) report that B is deficient in forest soils derived from volcanic ash, and its content depends on the degradation of existing *OM*. In this sense, the positive correlation with *OM* (r=0.72) means that the higher the *OM* content, the higher the concentration of B, which is important for the growth of the roots of tree species. Finally, the third component was associated with pH, *CEC*, Ca, and K. At five sites with presence of *P. montezumae* Lamb., located at an altitudinal range of 2 900 to 3 600 m within *La Malinche* National Park, Vela-Correa *et al.* (2007) registered soils with a very acid pH, rich in *OM*, and exhibiting a medium *CEC* and a base saturation above 50 %, dominated by Ca^{2+}, and found a lower degree of disturbance by thinning, logging or burning at 3 600 m above sea level. The indicators obtained through Principal Component Analysis are very helpful for determining the effect of disturbances on certain physical and chemical properties of the soil, which is important for its conservation.

Conclusions

A decrease in pore space is observed in the soils of *Teolocholco* and *San Francisco Tetlanohcan*, with different levels of disturbance attributed to an increase in bulk density and a low organic matter content.

The Principal Component Analysis identified that bulk density, porosity, usable moisture, pH, cation exchange capacity, and essential nutrients —particularly K, Ca, Cu, and B—, can be used as indicators for monitoring the physical and chemical quality of soils in *La Malinche* National Park. These findings suggest the importance of implementing rehabilitation strategies aimed at stopping the degradation of forest soils in the Protected Natural Area studied.

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Conflict of interest

The authors declare that they have no conflict of interest.

Contribution by author

Elizabeth García-Gallegos and Elizabeth Hernández-Acosta: determination of variables, analysis of data, structuring of the manuscript.

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