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Soil quality and rehabilitation of tepetates using board-ditches

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ABSTRACT

Objective: Physical and chemical properties, as well as microbial respiration, were evaluated during the rainy and dry seasons in a vegetation-free *tepetate* treated with board-ditches and in a relic forest soil, in order to determine soil quality.

Design/methodology/approach: The study areas were: vegetation-free *tepetate*, *tepetate* with board-ditches, and relic forest soil. Within 625 m^2 of each area, a systematic sampling scheme was established to collect samples during the rainy and dry seasons. Data were analyzed under a randomized block experimental design with a 3×2 factorial arrangement. A Principal Component Analysis (PCA) was performed to determine the degree of association between soil properties and soil types by season.

Results: In tepetates treated with board-ditches, bulk density and electrical conductivity decreased, and a neutral pH was observed, with these effects being more evident during the rainy season. Cation exchange capacity, phosphorus, and inorganic nitrogen increased across all three soil types, particularly in the rainy season. PCA explained 75% of the total variation, accounted for by PC1 and PC2. The biplot graph showed that relic forest soil was associated with organic matter and calcium in both seasons, whereas *tepetate* with board-ditches, in both dry and rainy periods, was associated with the physical component.

Limitations of the study/implications: Physical and chemical properties in rehabilitated *tepetates* may take several years to exhibit significant changes compared to non-intervened sites.

Findings/conclusions: Three years after the establishment of the board-ditches, and together with the presence of herbaceous vegetation and grasses, a decrease in bulk density was observed during the rainy season, favoring increased porosity. Electrical conductivity also decreased, and the neutral pH indicates a reduction in soluble salts. PCA revealed that forest soil, in both seasons, is associated with organic matter and calcium; whereas tepetate with board-ditches, during the dry season, is associated with bulk density and sand content, and during the rainy season with particle density and silt, indicating that soil quality remains low.

Keywords: Soil degradation, soil conservation practices, physicochemical properties, volcanic soil.

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INTRODUCTION

Soil quality is fundamental to the functioning of terrestrial ecosystems, as it determines the soil's capacity to sustain essential ecological functions and provide ecosystem services

such as biodiversity conservation, biological productivity, water regulation, and nutrient cycling (FAO, 2023). However, the loss of vegetation cover caused by deforestation and forest fires has led to the formation of forest relics and extensive areas of degraded soil, such as *tepetates*, which have largely lost the functions associated with adequate soil quality (SEMARNAT, 2018).

Tepetates are characterized by low porosity, low organic matter content, and high compaction, which hinder root development and water infiltration (Velázquez-Rodríguez *et al.*, 2022). Their rehabilitation is therefore a challenge; however, various actions have been implemented, such as tillage, land leveling, terrace construction, contour furrows, crop rotation, and the incorporation of organic matter and fertilizers, all aimed at improving soil quality (Comisión Nacional Forestal, 2023). Nevertheless, one of the soil conservation practices that has proven successful in their rehabilitation is the use of board-ditches, which enhance moisture retention and thereby promote the establishment of native vegetation. Although they may induce changes in floristic composition, they also help stabilize and protect the bunds from erosion (Reyes Carrillo *et al.*, 2019; García Gallegos *et al.*, 2023). Doria Treviño *et al.* (2022) report that three years after establishing board-ditches as a soil conservation practice, increased water infiltration and higher organic matter content were observed, driven by the establishment of aboveground and root biomass of annual species, thereby improving soil quality. The latter is determined through the analysis of its physical, chemical, and biological properties (Quisimalin *et al.*, 2024), which is essential for assessing its potential for agricultural or forestry use.

In the state of Tlaxcala, 93.7% of the land area is recognized as being affected by erosion to varying degrees, with one of the main causes being soil erosion and the intensive use of soil resources (Alvarado Cardona *et al.*, 2007). Particularly on San Gregorio Hill, within the community of San Diego Metepec, Tlaxcala, significant ecosystem degradation is observed, mainly due to the loss of native vegetation and anthropogenic activities, resulting in the depletion of this resource and the exposure of *tepetates* (García Zepeda & López Corral, 2012). Therefore, alternatives have been sought, such as the construction of board-ditches as soil conservation practices to restore ecosystem functioning in the area. García Gallegos *et al.* (2023) analyzed *tepetate* soils with board-ditches at different sites in the state of Tlaxcala through their physical, chemical, and biological properties, finding that five years after the establishment of these conservation practices, there was a positive impact on organic matter content and bulk density. However, at another site where board-ditches had been established for more than 40 years, no significant changes were observed, with the type of established vegetation being a determining factor.

Based on the above, the following objectives were established: 1) to evaluate, during the rainy and dry seasons, the soil quality of relic forest soil, vegetation-free *tepetate*, and *tepetate* rehabilitated with board-ditches, through the determination of their physical and chemical properties, as well as microbial respiration; and 2) to relate soil variables by area and season using Principal Component Analysis in order to identify the most relevant indicators of soil quality.

The hypothesis proposed is that relic forest soil exhibits more favorable soil properties, whereas *tepetate* with board-ditches will show significant recovery in comparison to vegetation-free *tepetate*. This difference is expected to be more evident during the rainy season due to increased moisture, vegetation establishment, higher organic matter content, and enhanced microbial activity.

MATERIALS AND METHODS

Study area

The study area is located within communal land on San Gregorio Hill, in the community of San Diego Metepec, south of the municipality of Tlaxcala. This site is important for the region and was originally characterized by a valuable forest ecosystem dominated by *Pinus*, *Quercus*, *Juniperus*, and *Cupressus*. However, decades of degradation driven by accelerated erosion, loss of vegetation cover, and land-use change have significantly compromised its capacity to provide ecosystem services. The site is located at 19° 16′47.443” N and 98° 15″25.574” W, at an altitude of 2,340 m above sea level. The dominant soil order is Cambisol, a young and weakly developed soil with evident changes in structure, color, and clay content. Land use is primarily rainfed agriculture. Mean annual precipitation ranges from 700 to 800 mm, the climate is temperate subhumid, and the mean annual temperature is 14 °C (INEGI, 2010).

Within the communal area, three sites were selected, each with specific conditions: 1) a tepetate area with complete absence of vegetation and the presence of surface stoniness, covering 2,070.02 m^2; 2) an area of 1,895.98 m^2 where, as part of the tepetate rehabilitation strategy, board-ditches were established in October 2021. These structures measured 2.64 m in length, 0.68 m in width, and 0.32 m in depth, providing a rainwater capture volume of 0.58 m^3 per season. A total of 28 board-ditches were constructed in this area. On each board, *Pinus leiophylla* and *Cupressus lusitanica* were planted, benefiting from increased moisture retention; at the time of sampling, survival exceeded 85%. In addition, herbaceous plants and grasses were observed on the boards and between ditches, predominantly from the families Asteraceae and Poaceae; and (3) a relic forest soil area covering 39,194.70 m^2, dominated by *Pinus*, *Cupressus*, and *Juniperus*, as well as plant species from the families Asteraceae, Cactaceae, Lamiaceae, Pteridaceae, and Rubiaceae.

Sampling and sample preparation

A systematic sampling approach, according to Schweizer (2011), was used in each study area to collect samples during both the rainy season (October 2024) and the dry season (February 2025). Based on the slope conditions of each area, 100 m^2 quadrats were established, covering a total surface area of 625 m^2. Within each quadrat, three simple random samples were collected at a depth of 0-20 cm. Subsequently, five composite samples per quadrat were obtained using the quartering method. In the conservation structures, *tepetate* soil samples were collected directly from the boards. According to the NOM-021-SEMARNAT-2000 (Semarnat, 2002), each sample was air-dried at room temperature in the shade on Kraft paper and subsequently sieved through a 2 mm mesh to obtain a homogeneous particle size.

Soil analyses

Bulk density, particle density, texture, porosity, pH, electrical conductivity, organic matter, calcium, magnesium, potassium, sodium, cation exchange capacity, extractable phosphorus, and inorganic nitrogen were determined for each sample, following the procedures specified in the NOM-021-SEMARNAT-2000 (Semarnat, 2002).

Microbial respiration was determined through closed-system incubation (CO_2) according to Paolini Gómez (2018). Soil samples were placed in 250 mL glass jars at 60% moisture content and incubated for 24 h at 22±2 °C. The released CO_2 was trapped using 0.2 N NaOH. At the end of the incubation period, CO_2 was precipitated with 2% $BaCl_2$ and titrated with 0.2 N HCl using phenolphthalein as an indicator. Microbial respiration was expressed as mg C-CO_2 kg^{-1} soil day^{-1} and calculated using Equation 1.

$$mg\,\mathrm{C}-\mathrm{CO}_2=\left(Vb-Vm\right)\times 6\times \mathrm{NHCl}$$

where: *Vb*=mL of HCl used for the blank, *Vm*=mL of HCl used for the soil sample, 6=equivalent weight of carbon, NHCl=normality of HCl.

Data analysis

The data were analyzed under a randomized block experimental design with a 3×2 factorial arrangement, where the first factor was soil type (vegetation-free *tepetate*, *tepetate* with board-ditches, and relic forest soil) and the second factor was season (rainy and dry). A total of six treatments with five blocks (replicates) were evaluated. Data were subjected to the Shapiro-Wilk normality test ($p>0.05$), followed by analysis of variance (ANOVA) and mean comparison using the John Tukey test ($p<0.05$). The statistical linear model used to analyze the data is presented in Equation 2.

$$Y_{ijk}=\mu+A_i+B_j+\left(AB\right)_{ij}+Ck+\varepsilon i_{jk}$$

where: Y_{ijk}=response variable, μ=overall mean, A_i=effect of the site factor, B_j=effect of the season factor, $\left(AB\right)_{ij}$ =site x season interaction, C_k=block effect and ε_{ijk}=experimental error.

Regarding microbial respiration data, the normality assumption was not met; therefore, the nonparametric Kruskal-Wallis test ($p<0.05$) was used. Subsequently, the Dunn test ($p<0.05$) was applied to identify which specific group pairs showed significant differences.

Finally, Pearson correlation and Principal Component Analysis (PCA) were performed to determine the degree of association between soil properties and sites by season. Prior to analysis, the data for each variable were standardized to ensure that all variables contributed equally regardless of their units. All analyses were performed using the free 2020 version of the statistical software InfoStat (Di Rienzo *et al.*, 2020).

RESULTS

Soil properties

The analysis of variance showed that the soil type factor was significantly different ($p<0.05$) for most variables, except for silt and potassium. Significant differences were observed for the season factor in clay, sand, magnesium, phosphorus, and nitrogen. The interaction between factors was significant ($p<0.05$) for magnesium and nitrogen (Table 1).

Among the physical properties, particle density showed the highest value in vegetation-free tepetate during the rainy season (2.62 g cm^{-3}), with significant differences ($p<0.05$) (Table 2). In contrast, the lowest values corresponded to relic forest soil during the dry season (2.38 g cm^{-3}) compared to vegetation-free *tepetate* and *tepetate* with board-ditches in both seasons. On the other hand, bulk density was significantly higher ($p<0.05$) in vegetation-free *tepetate* during the rainy season and in *tepetate* with board-ditches in both seasons. According to the NOM-021-SEMARNAT-2000 (Semarnat, 2002), bulk density values for volcanic soils should be lower than 1 g cm^{-3}, which was only observed in relic forest soil during the rainy season. Regarding porosity percentage, significantly higher values ($p<0.05$) were recorded in relic forest soil during the same season compared to vegetation-free *tepetate* and *tepetate* with board-ditches.

In both vegetation-free *tepetate* and *tepetate* with board-ditches, the sand fraction was predominant, with significant differences ($p<0.05$) observed during the dry season compared to the rainy season. Regarding clay percentage, statistically significant differences

Table 1. Significance values of the physical and chemical properties in the three soil types during the rainy and dry seasons.

Parameter	Factor A Soil Type	Factor B Period	Interaction A×B
PD (g cm^{-3})	0.0001	0.0294	0.7127
BD (g cm^{-3})	0.0008	0.3608	0.1714
Porosity (%)	0.0065	0.0665	0.0768
Clay (%)	0.0001	0.0001	0.9994
Silt (%)	0.3322	0.3657	0.3582
Sand (%)	0.0388	0.0003	0.3067
pH	0.0001	0.0890	0.4030
EC (dS m^{-1})	0.0001	0.6504	0.8416
OM (%)	0.0003	0.8336	0.6999
CEC [Cmo(+) kg^{-1}]	0.0009	0.0649	0.3055
Ca (mg kg^{-1})	0.0001	0.6008	0.5860
Mg (mg kg^{-1})	0.0005	0.0247	0.0093
K (mg kg^{-1})	0.1564	0.2924	0.6201
Na (mg kg^{-1})	0.0001	0.4278	0.7288
P (mg kg^{-1})	0.0001	0.0001	0.5916
Inorg. N (mg kg^{-1})	0.0001	0.0001	0.0001

Table 2. Physical and chemical properties in the three study sites during the rainy and dry seasons.

Parameter	Board ditch *Tepetate*		Vegetation-free *Tepetate*		Relic forest soil	
	Rainy	Dry	Rainy	Dry	Rainy	Dry
PD (g cm^{-3})	2.57 ab	2.49 abc	2.62 a	2.59 ab	2.45 bc	2.38 c
BD (g cm^{-3})	1.21 a	1.26 a	1.21 a	1.15 ab	0.97 b	1.09 ab
Porosity (%)	53.14 ab	49.31 b	53.76 ab	55.63 ab	60.42 a	54.3 ab
Clay (%)	12.00 ab	6.95 bc	10.07 bc	4.95 c	17.11 a	12.08 ab
Silt (%)	20.36 a	18.00 a	23.49 a	19.6 a	17.85 a	19.6 a
Sand (%)	67.64 ab	75.05 a	66.44 b	75.45 a	65.04 b	68.32 ab
pH	6.73 a	6.48 ab	5.82 c	5.81 c	6.37 ab	6.25 b
EC (dS m^{-1})	0.02 b	0.04 b	0.27 a	0.26 a	0.07 b	0.11 ab
OM (%)	1.28 b	1.30 b	0.69 b	1.52 b	8.34 a	6.72 ab
CEC [Cmol(+) kg^{-1}]	10.01 b	7.78 b	11.68 ab	11.51 ab	18.52 a	13.37 ab
Ca (mg kg^{-1})	1232 b	1254.63 b	1234.18 b	1336.15 b	3285.52 a	2677.1 ab
Mg (mg kg^{-1})	1702.01 a	1075.87 b	1852.92 a	1933.25 a	1771.35 a	1681.84 a
K (mg kg^{-1})	452 a	386.4 a	509.87 a	358.40 a	562.40 a	568.40 a
Na (mg kg^{-1})	83.6 a	66.8 ab	61.87 abc	58.8 abc	20.40 bc	19.20 c
P (mg kg^{-1})	19.84 b	5.63 c	20.44 b	7.03 c	25.68 a	10.17 c
Inorg. N (mg kg^{-1})	0.78 b	0.13 c	2.50 a	0.07 c	0.60 bc	0.35 bc

Different letters within each row indicate significant differences (Tukey, $p<0.05$). PD=Particle density, BD=Bulk density, EC=Electrical conductivity, OM=Organic matter, CEC=Cation exchange capacity.

($p<0.05$) were found, with the highest values recorded in relic forest soil during the rainy season. Silt percentage was significant in the three soil types analyzed and in both seasons. Regarding pH, values were classified as moderately acidic (5.1-6.5), according to the NOM-021-SEMARNAT-2000 (Semarnat, 2002), in all soil types analyzed, except for tepetate with board-ditches during the rainy season, where a significantly higher value ($p<0.05$) classified as neutral (6.6-7.3) was recorded. Electrical conductivity showed significant values ($p<0.05$) in vegetation-free *tepetate* during both seasons, whereas lower values were observed in tepetate with board-ditches and relic forest soil in both periods. Mexican regulations indicate that values <1 dS m^{-1} reflect the absence of effects associated with salt accumulation.

Organic matter in relic forest soil showed a significant value ($p<0.05$) during the rainy season. According to the NOM-021-SEMARNAT-2000 (Semarnat, 2002), values between 6.1 and 10.9% are classified as medium concentration. In contrast, organic matter content in *tepetate* with board-ditches and vegetation-free *tepetate* was classified as very low (<4%).

Similarly, relic forest soil during the rainy season showed the highest cation exchange capacity, with significant differences ($p<0.05$), classified as medium [15-25 cmol(+) kg^{-1}]. In the dry season, cation exchange capacity was classified as low [5-15 cmol(+) kg^{-1}] in relic forest soil, vegetation-free *tepetate*, and *tepetate* with board-ditches.

Regarding nutrient content, calcium showed a significantly higher value ($p<0.05$) in relic forest soil during the rainy season, being classified as rich (2500-5000 mg kg^{-1}), whereas in both *tepetate* conditions the concentrations were classified as medium (1000-2500 mg kg^{-1}).

As for magnesium, concentrations in the three soil types and both seasons were classified as very rich (>120 mg kg^{-1}). This nutrient showed significant values ($p<0.05$) in relic forest soil and vegetation-free *tepetate* during both seasons, except that the significance of *tepetate* with board-ditches was only observed during the dry season.

Potassium was significantly higher ($p<0.05$) in the three soil types and during both seasons. Concentrations were classified as very rich (>320 mg kg^{-1}), according to the classification proposed by Vázquez (1997).

Regarding sodium, *tepetate* with board-ditches showed a significant value ($p<0.05$) during the rainy season compared to the dry season, vegetation-free *tepetate*, and relic forest soil. Phosphorus content in relic forest soil during the rainy season was significantly higher ($p<0.05$). According to the NOM-021-SEMARNAT-2000 (Semarnat, 2002), the value is classified as medium (15-30 mg kg^{-1}), as was also observed in vegetation-free *tepetate* and *tepetate* with board-ditches during the same season. Finally, inorganic nitrogen content was classified as very low (0-10 mg kg^{-1}) in all cases according to Mexican regulations. However, vegetation-free *tepetate* showed a significant value ($p<0.05$) during the rainy season compared to *tepetate* with board-ditches and relic forest soil in both seasons.

Microbial respiration, determined through C-CO_2 content, did not show statistically significant differences according to the medians ($p<0.05$). However, the highest values were observed in vegetation-free tepetate during the rainy season, followed by relic forest soil and tepetate with board-ditches, whereas during the dry season an increase was observed in relic forest soil (Table 3).

Relationship among soil properties

Correlation analysis showed that bulk density was the variable with the highest number of significant and negative interactions, particularly with cation exchange capacity ($r=-0.97$), porosity ($r=-0.92$), organic matter ($r=-0.92$), and calcium ($r=-0.94$). Porosity was positively correlated with cation exchange capacity ($r=0.95$). Sand content showed a significant negative correlation with phosphorus content ($r=-0.90$). Soil pH was negatively correlated with electrical conductivity ($r=-0.98$). Organic matter was negatively correlated with sodium content ($r=-0.93$), which in turn was also negatively correlated with calcium ($r=-0.93$).

Table 3. Median values of microbial respiration in the three study sites by season.

Sites	Period	Microbial respiration (mg C-CO_2 kg^{-1} soil day^{-1})
Board dith Tepetate	Rainy	7.3
Vegetation-free Tepetate		14.6
Relic forest soil		11
Board dith Tepetate	Dry	11
Vegetation-free Tepetate		11
Relic forest soil		14.6

According to the Principal Component Analysis (PCA), the different variables were grouped into three components, all with eigenvalues >1, which together explained 75% of the total system variability. PC1 accounted for 47% of the variability, whereas PC2 explained 27% (Table 4).

PC1 was explained by the positive loadings of calcium, organic matter, cation exchange capacity, and clay content, indicating that higher PC1 values are associated with increased nutrient availability and clay content. In contrast, the negative loading of bulk density indicates an inverse relationship. This component was associated with the organic and physical fractions of the soil. PC2 was explained by the positive loadings of silt, magnesium, inorganic nitrogen, electrical conductivity, and particle density, as well as by the negative loading of microbial respiration. This indicates that as this component increases, microbial respiration decreases, highlighting the importance of the physical and nutrient related components in relation to biological activity.

The biplot graph shows the variables associated with each soil type by season. In the case of relic forest soil during the rainy and dry seasons, similar characteristics were shared in terms of organic matter and calcium content. In contrast, during the dry season, tepetate rehabilitated with board-ditches was directly associated with bulk density and

Table 4. Proportion of variance explained by each principal component.

Component	Value	% Total variance	% Cumulative variance
1	8.07	0.47	0.47
2	4.61	0.27	0.75
Loadings			
Parameter		**CP1**	**CP2**
Particle density		−0.21	0.34
Bulk density		−0.33	0.01
Porosity		0.29	0.15
Clay		0.31	0.01
Silt		−0.09	0.39
Sand		−0.26	−0.18
pH		0.05	−0.28
Electrical conductivity		−0.07	0.34
Organic matter		0.33	−0.14
Calcium		0.34	−0.12
Magnesium		0.13	0.37
Potassium		0.30	0.05
Sodium		−0.29	0.10
Cation exchange capacity		0.33	0.08
Phosphorus		0.22	0.23
Inorganic nitrogen		−0.001	0.36
Microbial respiration		−0.07	−0.32

sand percentage, whereas during the rainy season it showed an association with particle density and silt content (Figure 1).

Soil properties

Volcanic soils exhibit physical characteristics that promote adequate structural stability and considerable resistance to degradation. However, these characteristics are affected by anthropogenic activities, as is the case for soil particle and bulk density. The particle density values obtained in both relic forest soil and *tepetates* were lower than the 2.65 g cm^{-3} established by the FAO (2025), indicating the absence of highly dense materials (Tolimir *et al*., 2020). On the other hand, bulk density values are associated with high organic matter content, mainly in relic forest soil during both seasons (Semarnat, 2002). Pérez Hernández *et al*. (2023) reported that in conserved temperate soils with pine-oak forest for 50 years, bulk density was 0.32 g cm^{-3}, whereas in recently disturbed soils, where all vegetation had been removed, an increase in bulk density (0.62 g cm^{-3}) was observed. Therefore, this property may increase in the short term if soil conservation practices are not implemented.

Bulk density values in the *tepetates* under study were lower than those reported by Gama-Castro *et al*. (2007), who found values ranging from 1.70 to 1.96 g cm^{-3} for hardened materials. This influenced porosity, which according to Kaurichev (1984), cited by Jaramillo (2002), is classified as satisfactory (50-55%) in the soil types analyzed, except for *tepetate* with board-ditches during the dry season. On the other hand, in disturbed soils of Tlaxcala, García Gallegos and Hernández Acosta (2024) reported porosity values ranging from 42.6 to 44.4%. Therefore, it can be inferred that three years after establishing conservation practices for *tepetate* rehabilitation, a slight decrease in bulk density has occurred due to vegetation establishment during the rainy season. Regarding particle proportions, sand percentage was predominant in both *tepetates* and relic forest soil. Feifel *et al*. (2024) mention that soils dominated by the sand fraction tend to exhibit increased water retention in surface layers; however, this also implies greater evaporation and reduced water availability, thereby limiting vegetation growth.

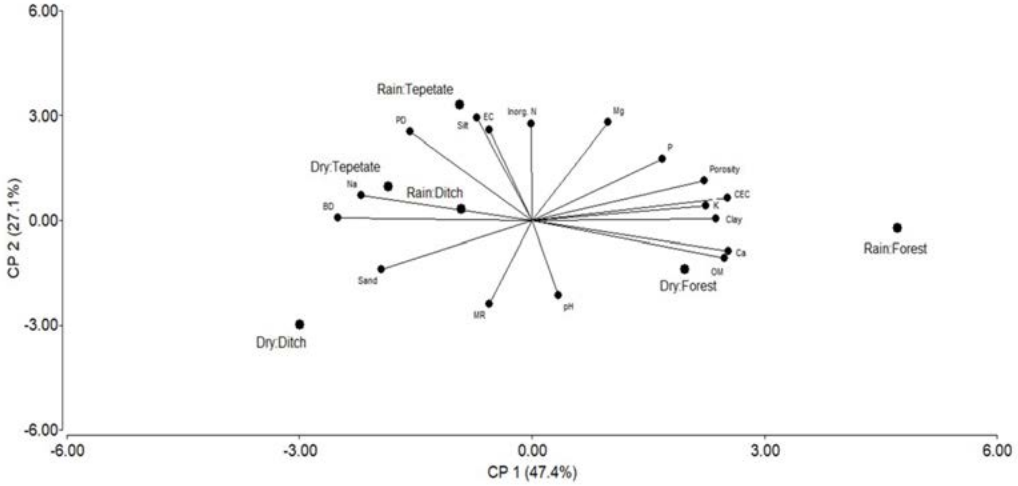

Figure 1. Biplot graph of soil properties in relic forest soil, vegetation-free tepetate, and tepetate rehabilitated with board-ditches on San Gregorio Hill, Metepec, Tlaxcala.

According to the chemical properties, the pH values obtained indicated favorable conditions for nutrient availability, as reported by Estrada-Herrera *et al.* (2017), who found pH values ranging from 5.7 to 7.2 in relic forest and degraded soils, respectively. Acidity is associated with organic matter decomposition and the release of organic acids (Hong *et al.*, 2019), whereas an increase in pH during the rainy season reflects a buffering effect associated with soil moisture (Manirakiza *et al.*, 2025). Electrical conductivity values in vegetation-free tepetate during both seasons agree with those reported by Navarro-Garza *et al.* (2004) for tepetates in eastern Tlaxcala (0.29 dS m^{-1}), considered low, with even lower values observed in *tepetate* with board-ditches and in the relic forest soil analyzed in this study.

Regarding organic matter content, values in the *tepetates* were higher than those reported by Munive-Martínez *et al.* (2018), who recorded 0.30% organic matter in a *tepetate* from Atlangatepec, Tlaxcala. In contrast, the percentage of organic matter was higher in relic forest soil, which is characteristic of this type of soil. Cation exchange capacity was also higher in the same soil. Litter accumulation, the formation of organo-mineral complexes, and biological activity contribute to soils with greater exchange capacity and availability of exchangeable bases, as mentioned by Nsengimana *et al.* (2024).

The high concentrations of calcium, magnesium, and potassium in the three soil types are related to the volcanic parent material from which these soils originated, which is rich in feldspars and other calcium, magnesium, and potassium rich minerals. In particular, magnesium content increases due to the presence of ferromagnesian minerals or feldspars rich in this element (Rodríguez-Valdivia *et al.*, 2021).

Lower concentrations than those found in this study have been reported in other areas of the state of Tlaxcala. Munive-Martínez *et al.* (2018), in vegetation-free *tepetate*, reported potassium, calcium, and magnesium contents of 2.15, 13.63, and 7.90 mg kg^{-1}, respectively. García Gallegos *et al.* (2023), in *tepetates* with board-ditches established in 2012, reported 1,510 mg kg^{-1} of calcium, 288 mg kg^{-1} of magnesium, and 156 mg kg^{-1} of potassium. However, sodium content reached 5,370.5 mg kg^{-1}, a value considerably higher than that obtained in the *tepetates* analyzed in this study.

In contrast, the high phosphorus values in relic forest soil may be attributed to the greater input of litter and plant residues, which release nutrients through decomposition, as mentioned by Lemanowicz (2018). In *tepetates*, García Gallegos and Hernández Acosta (2024) obtained an average phosphorus content of 37.2 mg kg^{-1} in degraded soils where *tepetate* outcrops occur at some sites within La Malinche National Park during the dry season, a value higher than the phosphorus concentrations recorded in the *tepetate* study sites during both seasons.

Regarding inorganic nitrogen content, values were low in both relic forest soil and tepetates. Febles-Díaz *et al.* (2023) indicate that this may be related to the geological origin of these soils, since *tepetates*, when non-rehabilitated, exhibit low availability of this element, resulting in poor plant growth and a lack of essential nutrients. Therefore, three years after the establishment of board-ditches, there is still no significant increase in phosphorus and nitrogen content, which is reflected in the biological component. García Gallegos *et al.* (2023) reported microbial respiration values of 23.3 and 23.7 mg C-CO_2 kg^{-1} soil for soils rehabilitated with board-ditches established in 2012 and 2015, respectively, values higher than those observed in the three soil types and during both periods in the present study. For *tepetates*, Álvares-Solís *et al.* (2000) mention that the incorporation of organic residues together with plant establishment promotes an increase in microbial activity, thereby contributing to the rehabilitation process of this substrate.

Relationship among soil properties

Bulk density was negatively correlated with porosity, organic matter, cation exchange capacity, and calcium content. This indicates that a decrease in bulk density promotes an increase in pore space and greater humification of organic matter, which in turn provides higher exchange capacity due to the presence of humus and promotes mineralization processes that enhance nutrient availability, ultimately favoring vegetation establishment (Barajas Guzmán *et al.*, 2020). On the other hand, García Gallegos and Hernández Acosta (2024) found that bulk density was the variable with the highest number of significant negative interactions, particularly with manganese ($r=0.85$), field capacity ($r=-0.85$), permanent wilting point ($r=-0.75$), and available water content ($r=-0.85$). This indicates that an increase in bulk density reduces plant-available water and, consequently, leads to greater soil compaction.

Principal Component Analysis (PCA) (Table 4) showed that PC1 and PC2 accounted for 75% of the total variation, and the biplot graph indicated that relic forest soil in both seasons exhibited a stronger association with organic matter and calcium (Figure 1). In contrast, during the dry season, sand content and bulk density were the variables associated with tepetate under conservation practices, suggesting a sandy texture and an increase in porosity (Table 2), whereas during the rainy season, tepetate was associated with particle density and silt content, indicating that seasonality influences the rehabilitation process of tepetate. Rosero *et al.* (2019) reported that in forest, grassland, and silvopastoral system soils, PC1 explained 48.48% of the total variability and was determined by cation exchange capacity and calcium, whereas PC2 explained 21.69% through the sand and clay fractions, pH, and total N. This allowed the identification of soil properties that significantly influence soil quality. García Gallegos *et al.* (2023), with the establishment of board-ditches for *tepetate* rehabilitation, obtained that PC1, with 52.1%, showed the greatest total variability of the data and was explained by cation exchange capacity, calcium, organic carbon, and organic matter. PC2, with 22.4%, was determined by the sand and clay fractions, pH, and total N, which differs from what was obtained in the present study. Hence, soil variables depend on the specific conditions of each study site, the time since the establishment of conservation practices, and the type of vegetation present (García Gallegos *et al.*, 2023).

Reyes Carrillo *et al.* (2019) mention that the construction of board-ditches increases water capture during the rainy season and consequently promotes the establishment of herbaceous plants and grasses during the initial stages. This was observed three years after the rehabilitation of *tepetate* with board-ditches, which agrees with Doria Treviño *et al.* (2022), who mentioned that after the same number of years following the establishment of soil conservation practices, herbaceous cover was observed, favoring moisture retention and an increase in organic matter accumulation, as well as a decrease in bulk density, which in turn increases porosity. This situation was also observed in the *tepetates* rehabilitated with board-ditches.

CONCLUSIONS

In the three soil types, an increase in cation exchange capacity, phosphorus, and inorganic nitrogen was observed during the rainy season. Particularly, three years after the establishment of board-ditches as a conservation practice for tepetate rehabilitation, the presence of herbaceous plants and grasses, a decrease in bulk density, neutral pH, and a reduction in electrical conductivity were observed, indicating an improvement in edaphic quality compared to vegetation-free *tepetate*, with this effect being more evident during the rainy season.

Principal Component Analysis showed that two components (PC1 and PC2) accounted for 75% of the total variation produced. Bulk density and sand content during the dry season were the variables influencing the rehabilitation process, whereas silt content and bulk density were associated with the rainy season. On the other hand, organic matter and calcium in relic forest soil showed no changes during either season.

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