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Soil quality in volcanic soils in a forest biosphere reserve in Mexico

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Abstract: Forest soils respond dramatically to management changes compared to other soils influenced by different land-use forms. This work aimed to compare the soil conditions in four different zones in a temperate forest in a biosphere reserve in Mexico, using a minimum data set (MDS) based on volcanic soils properties to develop a soil quality index (SQI). For this purpose, two different MDSs were used, one obtained from an expert opinion and the other through a multivariate principal component analysis (PCA). The soil quality assessment was conducted in a biosphere reserve in Mexico, where volcanic soils predominate. Four different areas were studied. Overall, six different types of SQI were calculated for each area, for which linear and nonlinear functions were used and the additive and weighted method. The six SQI showed a significant difference between the four areas of study. The zone with the highest SQI values was the zone with a preserved pine forest, followed by the zone with a pine forest managed by the population, and the zones with a pine forest and grassland in recovery showed the lowest SQI. The linear score indices obtained by the PCA indicated the better ability to differentiate the calculated SQI values, which would provide information to contribute to the stakeholder management and decision making in the protection, conservation and management of the ecosystems present in the biosphere reserve.

Keywords: Andisol; forest soil; land use and management

Forest soils help maintain the ecosystem's health, so the soil quality (SQ) in a forest is considered a critical parameter for determining the system sustainability (Schoenholtz et al. 2000). SQ has been defined as "the ability of a soil to function within an ecosystem and the limits of land use to sustain biological productivity, maintain environmental quality and promote plant and animal health" (Doran & Jones 1996). SQ is a tool for assessing the impact of land use and management practices on the soil (Karlen et al. 1997). The use of indicators has been proposed to estimate the SQ, describing specific soil properties related to its processes or functions. The soil quality index (SQI) arises from the need for a scientific tool to measure and evaluate the SQ (Armenise et al. 2013). Some approaches have been adopted for the soil quality index evaluation. SQI has been used in agricultural and forestry areas, where crop yields and silvicultural production are crucial soil quality indicators; but less frequently in urban soils (Zor-

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noza et al. 2015; Bünemann et al. 2018). Studies on the SQ have focused on selecting the most relevant indicators and interpreting them, given the soil's incredible complexity and specificity (Bünemann et al. 2018). These indicators can be physical, chemical, or biological parameters (Muñoz-Rojas 2018). The most frequently used chemical properties are the soil organic carbon, nitrogen, and pH. The particle size distribution, bulk density, available water, soil structure, and aggregate stability among the physical parameters are possibly the most used parameters for assessing the SQ (Bünemann et al. 2018; Pereira et al. 2018). The use of biological properties such as the microbial biomass or enzymatic activities are less frequent because they require more complicated and expensive methods (Pulido et al. 2017).

The Soil Management Assessment Function (SMAF) developed by the Soil Quality Institute (St. Paul, MN, USA) provides a framework for assessing indicators by combining the scores into an overall assessment based on the definition of ecosystem services or management objectives. The interpretation is based on scoring curves and creating an additive quality index (Andrews et al. 2004). The SMAF has influenced the emergence of several studies that apply multivariate statistical methods to select the most appropriate indicators, which then perform scoring functions to generate an SQI (Zornoza et al. 2015; Biswas et al. 2017; Guo et al. 2017; Raiesi 2017; Bünemann et al. 2018; Yu et al. 2018a, b; Juhos et al. 2019).

The main concern about SQI is the correct selection of the indicators, which must reflect the main processes and functions occurring in the soil, known as the minimum data set (MDS). However, there is no established methodology for selecting soil quality indicators or indices (Rangel-Peraza et al. 2017). The most significant challenges during the selection of indicators may be the lack of data, the uncertainty on multiple scales, the spatial heterogeneity of the soil, the data quality, the sample size, the sample design and the very limitation of the model's (incorrect algorithms) assumptions (de Paul Obade & Lal 2016). As soil is a dispersed system of great complexity, no homogeneous or pre-established evaluation methods can be applied to assess its quality; that is, the same indicators are not used for all soil types. Therefore, the selection of indicators will depend on the type of soil and its intended use.

Andisols are very particular soils and not very abundant globally; their development and formation depend on specific conditions such as a temperate climate with marked seasonality. The parent material from which they derive is pyroclastic volcanic, such as lapilli and ash, which are easily weathered materials (Shoji & Takahashi 2002). Los Volcanes Biosphere Reserve is part of UNESCO's world network of biosphere reserves and is one of the first natural areas protected by the Mexican government (DOF 1935; UNESCO 2010). It is characterised by being in a volcanic activity site where the soils have developed over pyroclastic materials in a pine forest, oyamels, and a high mountain pasture. However, it has been and continues to be threatened by illegal human activities such as illegal logging, species extraction, pollution, and fires, which have contributed to its deterioration. The Los Volcanes Biosphere Reserve has been established as a management programme to protect the ecosystems and regulate activities (SEMARNAT-CONANP 2013); however, it is unknown how these activities have affected the region's volcanic soils.

This work aimed at comparing two methods to obtain an MDS and develop different SQIs in soils of volcanic origin. The initial group of indicators is based on the soil's inherent properties found in the study area, the Andisols. However, some of the indicators are scarcely considered during soil quality evaluations. So, it was essential to include them in the study. One of the MDSs was proposed by expert opinion (EO), in which additive soil quality indices (SQI_A) were calculated using a linear and nonlinear scoring function. On the other hand, a principal component analysis (PCA) was applied to produce the other MDS, and then the linear and nonlinear scoring function was used again in the additive and weighted index. Our research provides an easy calculation reducing the number of indicators and is less time consuming. This SQI integrates information on the most critical soil variables, providing knowledge and direction to contribute to stakeholder management and decision-making for the soil's management and forest land conservation in protected areas.

MATERIAL AND METHODS

Site description. The study was conducted within the Los Volcanes Biosphere Reserve (UNESCO), located in the Mexican Transversal Neovolcanic Axis. The area is characterised by continuous volcanic activity, which causes ash emissions, so the soils' parent material consists mainly of extrusive igneous pumice rocks. The study sites were in Amecameca,

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Mexico State, Mexico. The area's climate is temperate sub-humid, with more abundant rainfall during the summer months. The average annual temperature is 14 °C, and the average yearly precipitation is 928 mm (SEMARNAT-CONANP 2013). The humidity regime of the soil is udic (Maples-Vermeersch 1992). In the sites selected for the study, the soils have been classified as Typic Melanudands in the grasslands and as Typic Fulvudands in the pine forest, according to the Soil Taxonomy classification (Soil Survey Staff 2014b).

The reserve's management objective is to conserve the ecosystem, so a land management programme has been developed to regulate the reserve activities.

Soil sampling and laboratory analysis. The selection of the sampling sites was based on the land management programme of the Los Volcanes Biosphere Reserve, developed to regulate human activities; thus, it will be possible to determine the effect of the land use on the soil properties and quality. Then we chose four zones to evaluate their soil quality as follows: (1) recovery pine forest (RPF) zone, (2) recovery grassland (RG) zone, (3) pine forest managed by the population (PFM) in the buffer zone and (4) conserved pine forest zone (CPF). Figure 1 shows the study areas location and the type of vegetation present in each sample site. The soil samples were collected in the differently managed areas in the biosphere reserve (Figure 1). In the study area, a grid was drawn using ArcGIS (Ver. 10.5, 2016); each point of the grid was at 250 m. Subsequently, during the field visit, 4 points were selected for each zone. The grid sampling was chosen to allow the uniform distribution of the selection covering homogeneous regions to facilitate the analysis of the properties' distribution, enabling the evaluation of the taxonomic composition of the cartographic units statistically (Jaramillo 2002). The samples were collected in the east face of the mountain, between 3390 and 3741 m a.s.l. with slopes between 10° and 25°. A composite sample was collected at each point sampling, from 0–25 cm depth during 2018. The topsoil layer possesses the main inherent properties of the soils under study (Soil Survey Staff 2014b). These could change rapidly cause of management and land use (FAO 1998). Also, the samples can be obtained faster and cheaper.

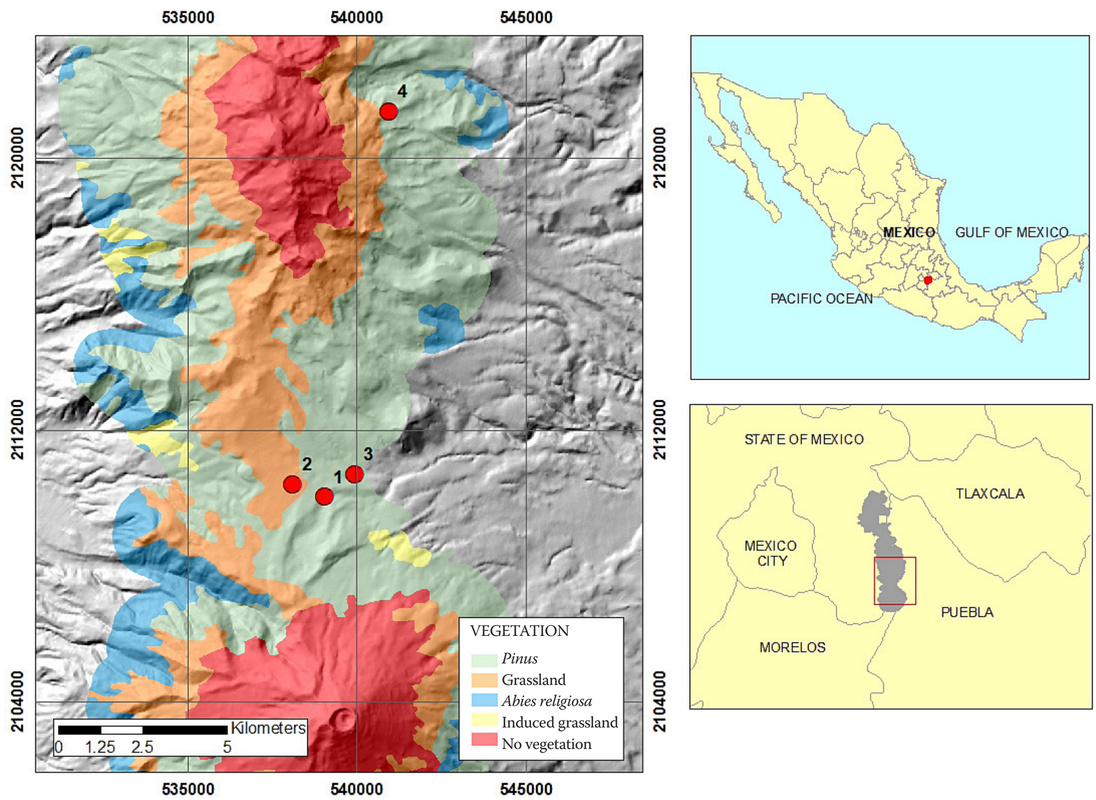

Figure 1. Location map of the study site

1 – recovery pine forest zone; 2 – recovery grassland zone; 3 – pine forest managed by the population in the buffer zone; 4 – conserved pine forest zone

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Each of the composite samples was formed by mixing five random sub-samples in a 50 cm^2 rectangle of the soil surface, and a core was collected at each sampling point to measure the bulk density. The composite samples were dried at room temperature in a dry and ventilated room for the further physical and chemical analyses. Fifteen physical and chemical variables were analysed as possible indicators of the soil quality. The physical and chemical properties of the soils were evaluated in the laboratory using the following methods: The bulk density was measured according to the cylindrical core method (Doran & Jones 1996; USDA 1999), the phosphorous retention by the nitric vanadomolybdate acid reagent technique (Blakemore et al. 1987), the pH(H_2O) and pH(KCl) suspension (SEMARNAT 2002; Soil Survey Staff 2014a) to calculate the ΔpH (Uehara & Gillman 1981), the melanic index by 0.5% of an NaOH solution (Honna et al. 1988), the soil organic carbon by the method of potassium dichromate oxidation, the total nitrogen by Kjeldahl digestion, the C : N ratio; the exchangeable soil basis (Ca^{2+}, K^+, Na^+ and Mg^{2+}) by atomic absorption spectrophotometry, the cation exchange capacity and the base saturation by an ammonium acetate solution (SEMARNAT 2002; Soil Survey Staff 2014a).

Soil quality indexing. The steps to generate the quality indexes were: (1) obtaining the MDS, either by the EO or by the PCA, (2) Scoring (standardisation) of the indicators using a linear and nonlinear function, (3) The SQIs were generated, the additive method was used for the MDS obtained by the EO, and the additive and weighted methods were used for the MDS obtained by the PCA (Andrews et al. 2002).

Minimum data set based on EO. An MDS based on the expert's opinion in the soil type, knowledge about the area studied and the literature review using the conservation approach was chosen. The suggested indicators were the bulk density (BD), phosphate retention (PR), ΔpH, melanic index (MI), soil organic carbon (SOC) and total nitrogen (TN).

Minimum data set based on PCA. After measuring fifteen soil properties, a one-way analysis variance (ANOVA) and Fisher's least significant difference test (with a 95% confidence interval) were applied to evaluate the statistical differences among the indicator's values of the areas. The indicators with a significant difference between the four different areas were analysed by PCA (Andrews et al. 2002). Only the components with eigenvalues ≥ 1 were retained. Highly loaded indicators with a value of 10% of the highest weighted loading were retained in each PC to form the MDS. The PC less weighted indicator was removed from the MDS when two soil variables in the same PC were strongly correlated in the Pearson correlation analysis. All the statistical analyses were carried out using the statistical program Minitab® (Ver.19.1.).

Soil quality index creation. Once the MDS by the EO and by the PCA was chosen, the next step was to interpret MDS indicators and scoring (standardisation).

The standardisation consists of transformed soil indicators on a similar scale for comparison purposes (Mukherjee & Lal 2014). The additive SQI was calculated using linear and nonlinear equations for the data standardisation for the MDS obtained through the expert opinion. The additive and weighted SQI was calculated using linear and nonlinear equations for the data standardisation for the MDS obtained by the PCA method. The standardisation represents the worst and best conditions of the soil quality (Prieto et al. 2012), and for this, the criteria: "more is better", "less is better", and "optimum" are usually used; the "optimum" criterion refers to those properties that have a positive influence up to a certain level, and beyond this level are harmful (Mukherjee & Lal 2014). Each indicator's values were obtained from the maximum and minimum data for each variable studied. The linear functions for obtaining the values of each indicator are shown in Equations (1) and (2):

$$\text{More is better: } S_L = \frac{X}{X_{max}} \tag{1}$$

$$\text{Less is better: } S_L = \frac{X_{min}}{X} \tag{2}$$

where:

S_L – the linear score varying from 0 to 1;

X – soil properties' value;

X_{max}, X_{min} – the maximum and minimum values of each soil indicator, respectively (Yu et al. 2018b).

A sigmoid curve was also used to standardise the MDS indicators:

$$\mathrm{NL}(Y) = \frac{a}{\left\{1 + \left(\frac{X}{X_0}\right)^b\right\}} \tag{3}$$

where:

NL(Y) – the nonlinear score for each indicator ranging from 0 to 1;

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a – the maximum value (defined as $a = 1$ in this study) achieved by the function;
X – the value of the selected indicator;
X_0 – the average value of each indicator corresponding to the soils of the study areas;
b – the slope of the equation, set as –2.5 for the "more is better" functions and +2.5 or "less is better" functions (Yu et al. 2018b).

Then, all the indicator values were integrated into an SQI (Andrews et al. 2004). The standardised values were integrated into two different SQIs using the following equations:

$$\mathrm{SQI}_W = \Sigma_{i_1}^{n} W_i S_i \tag{4}$$

$$\mathrm{SQI}_A = \Sigma_{i_1}^{n} \frac{S_i}{n} \tag{5}$$

where:
SQI_W – weighted-additive SQI;
SQI_A – additive SQI;
$\Sigma_{i_1}^{n}$ – the sum of the data from 1 to n;
n – the total number of indicators;
W_i – the weighting factor for the soil property derived from the factor analysis;
S_i – a linear (L-SQI) or nonlinear (NL-SQI) score.

The equation was normalised to produce a maximum SQI of 1. It was assumed that higher SQI values meant a better soil function (Andrews et al. 2002; Yu et al. 2018b). Finally, the SQIs were compared by an ANOVA to detect the difference between them.

RESULTS AND DISCUSSION

Fifteen soil properties were studied as possible indicators of the SQ. We evaluated how these properties can be affected by different management practices in the soils under the same formative conditions. Table 1 shows the physicochemical analyses of the soil samples obtained in the four study zones in the temperate forest in Mexico's volcanic axis. The soil samples analysed had characteristics of the type of soil that predominates in the area, mainly a low bulk density, $pH(H_2O)$, pH(KCl), variable charge and high phosphate retention.

It was observed that the management had influenced the properties of the soil since a significant difference ($P < 0.05$) was shown between the four areas studied (Table 1).

The bulk density is a property that provides valuable information on the state of the soil in the surface

Table 1. Mean values and standard deviation of the soil quality indicators for each area; one way ANOVA and Fisher's least significant difference test

Indicator	RPF	RG	PFM	CPF	ANOVA	
					F	P
BD (g/cm^3)	$0.71^{c} \pm 0.06$	$0.79^{b} \pm 0.038$	$0.80^{b} \pm 0.00$	$0.90^{a} \pm 0.00$	13.91	< 0.01
$pH(H_2O)$	$5.30^{ab} \pm 0.38$	$5.50^{a} \pm 0.29$	$5.25^{ab} \pm 0.35$	$4.77^{b} \pm 0.55$	2.092	0.147
pH(KCl)	$4.08^{a} \pm 0.33$	$4.37^{a} \pm 0.32$	$4.60^{a} \pm 0.14$	$4.07^{a} \pm 0.40$	1.923	0.172
ΔpH	$-0.96^{b} \pm 0.66$	$-1.12^{ab} \pm 0.09$	$-0.65^{a} \pm 0.49$	$-1.03^{a} \pm 0.41$	0.351	0.789
SOC (%)	$2.19^{b} \pm 0.40$	$2.30^{b} \pm 0.35$	$4.10^{a} \pm 1.27$	$3.73^{a} \pm 0.35$	13.5	< 0.01
TN (%)	$0.14^{c} \pm 0.03$	$0.17^{c} \pm 0.03$	$0.30^{b} \pm 0.07$	$0.40^{a} \pm 0.05$	37.68	< 0.01
C:N ratio	$16.22^{a} \pm 5.59$	$14.00^{a} \pm 3.56$	$13.50^{a} \pm 6.36$	$10.67^{a} \pm 1.15$	1.041	0.40
PR (%)	$70.56^{a} \pm 6.84$	$70.75^{a} \pm 3.20$	$65.00^{a} \pm 11.31$	$42.00^{b} \pm 12.12$	11.26	< 0.01
MI	$1.75^{a} \pm 0.08$	$1.72^{a} \pm 0.05$	$1.21^{b} \pm 0.26$	$0.95^{b} \pm 0.60$	9.89	< 0.01
Ca_{ex} (mg/kg)	$1.48^{b} \pm 0.44$	$2.74^{a} \pm 0.43$	$0.85^{bc} \pm 0.07$	$0.47^{c} \pm 0.06$	22.75	< 0.01
Na_{ex} (mg/kg)	$0.27^{b} \pm 0.08$	$0.28^{b} \pm 0.02$	$0.60^{a} \pm 0.00$	$0.63^{a} \pm 0.15$	20.33	< 0.01
K_{ex} (mg/kg)	$0.19^{b} \pm 0.06$	$0.34^{a} \pm 0.05$	$0.21^{ab} \pm 0.19$	$0.04^{c} \pm 0.01$	10.14	< 0.01
Mg_{ex} (mg/kg)	$0.22^{a} \pm 0.06$	$0.23^{a} \pm 0.10$	$0.32^{a} \pm 0.32$	$0.24^{a} \pm 0.15$	0.446	0.724
CEC (cmol (+)/kg)	$16.02^{b} \pm 5.56$	$26.90^{a} \pm 3.66$	$13.00^{b} \pm 0.99$	$25.67^{a} \pm 3.86$	7.70	< 0.01
BS (%)	$14.31^{a} \pm 4.72$	$12.70^{a} \pm 3.96$	$14.20^{a} \pm 0.70$	$5.27^{b} \pm 1.02$	3.94	< 0.01

Values with the same lowercase letters within rows (study area) are not significantly different at $P < 0.05$; BD – bulk density; SOC – soil organic carbon; TN – total nitrogen; PR – phosphorus retention; MI – melanic index; CEC – cation exchangeable capacity; BS – base saturation; RPF – recovering pine forest; RG – recovering grassland; PFM – pine forest managed by the population; CPF – conserved pine forest; ex – exchangeable

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layer since a low bulk density is characteristic of the type of soil studied (0.6 to 0.9 g/cm^3). If it increases considerably, it may indicate disturbances in the system. In all the zones studied, the bulk density remained around 0.9 g/cm^3, though it was higher in the conserved pine forest zone, followed by the site under the population management. The recovery zones had the lowest values and improved the soil's condition. The soil's pH(H_2O) and pH(KCl) solution was between strongly acidic and very strongly acidic. A negative ΔpH value indicates particles of variable charge, where negative charges predominate (Jaramillo 2002). The pH(H_2O), pH(KCl) and ΔpH showed no significant difference between the study areas.

The TN and SOC concentrations showed a considerable difference between the four study zones. The highest TN and SOC concentrations were found in the preserved pine area and the population management area. In both under-recovery areas, the concentrations were lower. In both cases, abundance is the desire for the soil and ecosystem. However, the C : N ratio did not vary significantly, indicating that the proportion of organic matter and nitrogen species present are similar between the zones.

The site with the lowest PR was the conserved forest, followed by the managed forest, and finally, the recovery zones had the highest values. The above indicates phosphate anions are released in the areas with the lowest PR values, which is beneficial for plant growth in the ecosystem.

The melanic index contemplates the type of humic acid formed in the most superficial layer of the soil and indicates its management change. According to Honna et al. (1988), in soils with a melanic index less than or equal to 1.7, humic acids type A predominate; these values were found in both recovery zones. In soils with values above 1.7, humic acids type P or B predominate, as was the case in the recovery and preservation zones. The proportion of humic acids found has changed over time since we would expect the pasture areas to have values below 1.7 and the forest areas to have values greater than 1.7. Changes could be due to the species selection in the reforestation plans and forest cover loss, modifying the soil's organic fraction. It is known that vegetation effects on grass and forest ecosystems contribute significantly to melanic and fulvic Andisols (Shoji 1988).

The exchangeable calcium (Ca_{ex}) content varied significantly between the zones; it was highest in the RG zone, followed by the RPF, PFM and CPF zones with the lowest concentration. The Na_{ex} content also varied significantly between zones; it was found in lower concentrations in the PFM and CPF zones; it was higher in both recovering zones. The K_{ex} content was different in all the zones; the lowest concentration was found in the CPF zone, followed by the RPF, PFM and RG zones. No significant difference in the Mg_{ex} concentration was observed among the study zones. The cation exchangeable capacity (CEC) in the volcanic soils depends on the exchange complex of the organo-mineral fraction and is, therefore, considered an intrinsic property in this soil type. According to the literature, the values obtained were medium to high in this work (Abera & Wolde-Meskel 2013). The CEC was higher in the RG and CPF zones and lower in the RPF and PFM zones, and the soils studied showed a low base saturation.

Minimum data set by the PCA. The indicators BD, SOC, TN, PR, MI, Ca_{ex}, Na_{ex}, K_{ex}, CEC and BS, had a significant difference ($P < 0.05$) among the four land uses. Therefore, these indicators were analysed by the PCA to reduce their redundancy in the calculation of the SQI. Then, the soil indicators that showed the highest correlation in the PCA (Table 2) were considered to make up the SQI (Mukherjee & Lal 2014). Of the PCA results, the first three principal components (PCs) had eigenvalues > 1.0 and explained 84.17% of the variance. The first PC (PC1) explained 55.70% of the total variance. The highest value indicators were the total nitrogen, Na, melanic

Table 2. Principal component analysis

Soil indicators	PC1	PC2	PC3
Bulk density	**–0.33**	0.22	0.14
Soil organic carbon	**–0.33**	–0.11	0.44
Total nitrogen	<u>**–0.39**</u>	0.03	0.10
Phosphorus retention	**0.34**	–0.09	–0.01
Melanic index	**0.35**	0.08	–0.15
Ca_{ex}	0.30	0.44	0.29
Na_{ex}	**–0.36**	–0.17	0.28
K_{ex}	0.27	0.18	<u>**0.64**</u>
Cation exchangeable capacity	–0.11	<u>**0.73**</u>	–0.02
Base saturation	0.30	0.30	0.42
Eigenvalue	5.70	1.66	1.18
Variance (%)	55.70	16.63	11.84
Cumulative variance (%)	55.70	72.33	84.17

PC – principal component; the factor values in bold are considered highly weighted; the bolded and underlined values correspond to the soil indicators included in the minimum data set (MDS)

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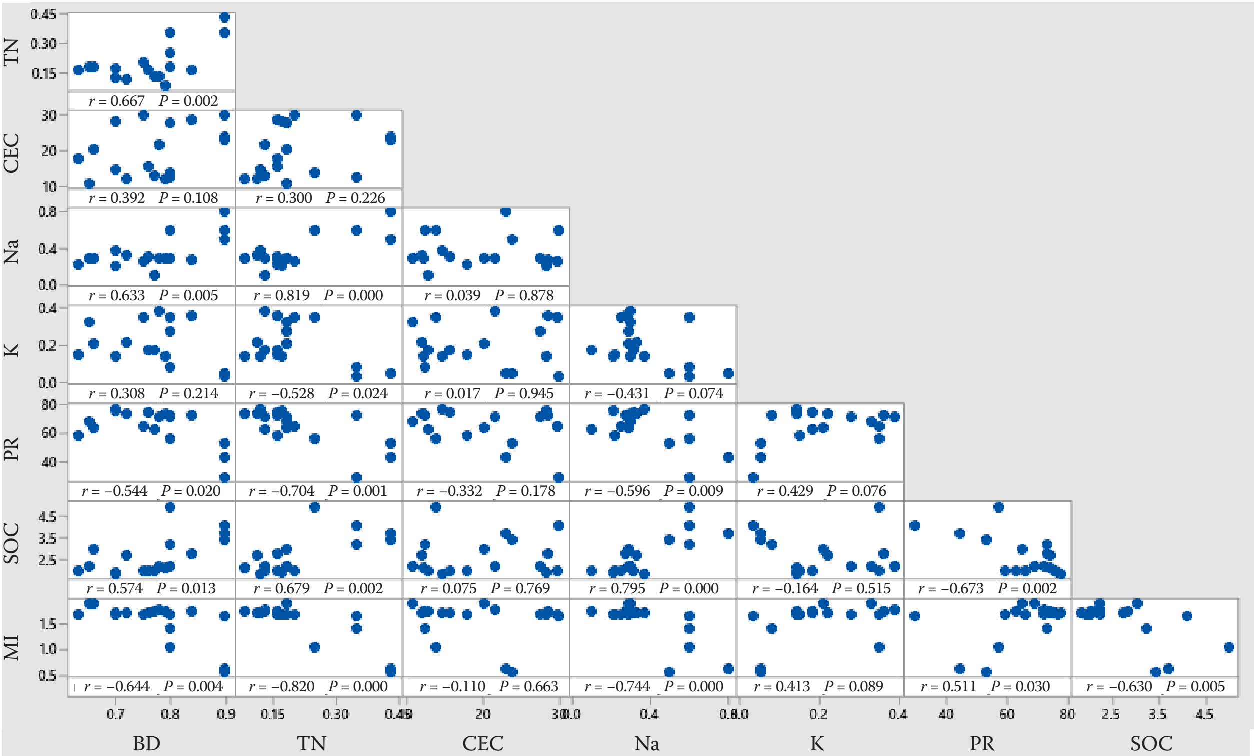

Figure 2. Matrix correlation of the high loaded indicators in the principal component analysis (PCA)
See Table 1 for the abbreviations

index, soil organic carbon, phosphate retention, and bulk density. From the PC1 indicators, only the TN was selected for inclusion in the SQI due to its high correlation according to the Pearson correlation ($P < 0.05$) between the other indicators in PC1 (Figure 2). The second PC (PC2) explained 16.33% of the variance and had one indicator with a high value, the CEC. The third PC (PC3) explained 11.84% of the variance and the indicator with the highest value was K_{ex}. Thus, the indicators to make up the MDS and calculate the SQI were TN, CEC and K_{ex}.

Integration of the indicators in the soil quality index. All the MDS indicators obtained by EO and PCA were transformed using linear and nonlinear functions. Table 3 describes the criteria used in the equations to standardise the SQ indicator values into scores to integrate them with the SQI. The variation in each PC assigned the weights for calculating the SQI by the PCA.

Table 3. Indicators selected to create the soil quality index (SQI), scoring functions curve and parameters of nonlinear and linear weights for the indicators in the minimum data set (MDS)

Indicators	Scoring curve	Linear		Nonlinear mean (X_m)	Slope[a]	Weight
		X_{max}	X_{min}			
Bulk density	less is better		0.63	0.77	2.50	–
Phosphorus retention	less is better		29.0	65.22	2.50	–
Soil organic carbon	more is better	5.0		2.68	–2.50	–
ΔpH	less is better		0.57	1.05	2.5	–
Melanic index	optimum	1.9	0.57	1.55	–2.50 and 2.50	–
Total nitrogen	more is better	0.43		0.22	–2.5	0.66
Cation exchangeable	more is better	30.1		19.71	–2.5	0.20
K_{ex}	less is better		0.03	0.20	2.5	0.14

[a]Indicates the slope in Equation (3)

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The following equations gave the final expression of the SQI:

$$\text{L-SQI}_A \text{ or NL-SQI}_A = (S_{\text{BD}} + S_{\text{SOC}} + S_{\text{TN}} + S_{\text{PR}} + S_{\text{MI}} + S_{\Delta\text{pH}})/6 \quad (6)$$

$$\text{L-SQI}_W \text{ or NL-SQI}_W = (0.66 \times S_{\text{TN}}) + (0.20 \times S_{\text{CEC}}) + (0.14 \times S_{\text{K}}) \quad (7)$$

$$\text{L-SQI}_A \text{ or NL-SQI}_A = (S_{\text{TN}} + S_{\text{CEC}} + S_{\text{K}})/3 \quad (8)$$

L-SQI and NL-SQI indicate the linear (L) or nonlinear (NL) SQI. *A* shows the weighted additive SQI, *W* shows the weighted SQI, and *S* shows the standardised value of each indicator.

The values in Table 4 show the SQI obtained by the MDS selection method from the expert opinion and calculated with the additive (*A*) equation using the linear and nonlinear scoring functions. Additionally, the SQI results calculated from the MDS obtained by the PCA are shown, using the additive equations (*A*) and the linear and nonlinear scoring function; and the weighted (*W*) equations both for the linear and nonlinear scoring function.

Table 4 shows that all the SQIs were significantly different between the study regions ($P < 0.05$). The values of the SQIs were considerably higher in the CPF zone, which is due to the greater degree of protection in the area. The area of PFM had values very close to the preservation area, which can be attributed to the fact that it is an area managed by the population who have actively participated in reforestation programmes and the recovery of their environment. The lowest SQI values were observed in both recovering zones. In the past, these areas have suffered from activities that contributed to its degradation, such as illegal logging, soil and plants extraction for sale, cattle grazing, among others. The above indicates that the CPF zone, having the highest SQI values, has a better function and soil process. The higher *F* values (ANOVA) indicate the better ability to differentiate the calculated SQI values. The results showed that the additive and weighted linear score indices obtained by the PCA method presented the soil function better than the nonlinear score indices obtained by PCA and those obtained by the expert opinion. In the cases where the nonlinear scoring function was used, lower values were observed than those evaluated by the linear scoring function.

Figure 3 shows the correlation matrix between the different quality indices calculated. Some of the indexes were positively correlated ($P < 0.05$), indicating that they can be used to evaluate the soil function and quantify the effects of the land-use change on the SQ.

This work shows a comparison between two different methods of selecting the MDS. One of the methods appeals to the expert opinion given their experience in the study site, knowledge of the type of management being carried out, and relationship to the decision-makers. The other method consists of a statistical way that is very useful when there is not enough experience and knowledge. It also helps identify subtleties among the data and considerably reduces the number of variables. The sampling sites were relatively homogeneous and selected based on their similarities to understand the effect of the land use on the soil. For this work, the most appropri-

Table 4. Soil quality index calculated for the different management areas

	EO		PCA			
	L-SQI$_A$	NL-SQI$_A$	L-SQI$_W$	L-SQI$_A$	NL-SQI$_W$	NL-SQI$_A$
RPF	0.53^b	0.41^a	0.35^c	0.35^c	0.19^b	0.40^b
RG	0.47^b	0.40^a	0.45^{bc}	0.46^b	0.24^b	0.42^b
PFM	0.67^a	0.53^b	0.58^b	0.45^{bc}	0.46^a	0.50^b
CPF	0.68^a	0.56^b	0.89^a	0.84^a	0.57^a	0.82^a
F value	10.72	19.33	39.26	27.57	25.33	13.53
P	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

EO – expert opinion; PCA – principal component analysis; L-SQI$_A$ – linear soil quality index by additive method; NL-SQI$_A$ – linear soil quality index by additive method; L-SQI$_W$ – linear soil quality index by weighted method; NL-SQI$_W$ – linear soil quality index by weighted method; RPF – recovering pine forest; RG – recovering grassland; PFM – pine forest managed by the population; CPF – conserved pine forest; lowercase letters – Fisher's least significant difference test

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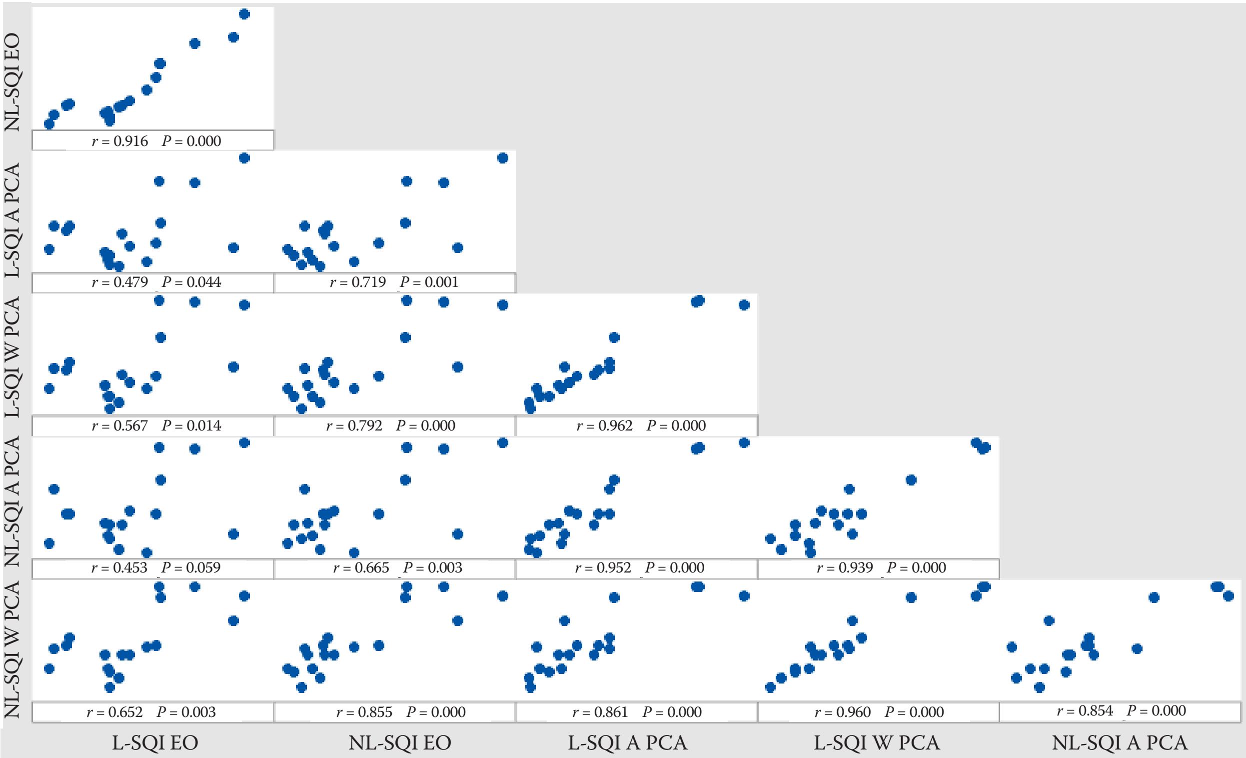

Figure 3. Correlation matrix for the different calculated soil quality indexes (SQIs)
See Table 4 for the abbreviations

ate indices to determine the study areas differences were L-SQI-A and L-SQI-W, both obtained by the PCA method.

It was detected that the most critical indicator was the TN, which is closely related to SOC, so the areas with higher SQI were those with higher TN and SOC values. The soil quality among the four zones studied was different and depended on other indicators and relies on the degree of protection and limitation of public activities within the biosphere reserve. The zone with the preserved pine forest showed higher soil quality since it obtained the highest value in all the calculated indices due to its high degree of protection and, therefore, the restriction of anthropogenic activities. The pine forest zone managed by the population had low quality; however, in the quality indexes calculated by the expert opinion, its values were very close to those of the conserved forest zone. The recovery zones showed the lowest soil quality due to the level of degradation that occurred years before implementing the recovery programme.

In the Los Volcanes Biosphere Reserve, it appears that conservation practices have improved or maintained the soil properties and, therefore, its functions, unlike other studies where this did not occur (Cotler et al. 2013). It is necessary to continue evaluating different sites within the biosphere reserve, showing a more significant heterogeneity of the slopes, relief, climates, vegetation types, and biological indicators to adequately characterise all the zones and, thus, make it possible to compare the quality concerning their management.

CONCLUSIONS

The use of indicators to integrate into the SQI can provide soil quality information to compare areas with different types of management and the same soil formation factors. The evidence suggests that soil management practices could significantly modify the soil properties. The zone with the highest SQI values was the zone with the preserved pine forest, followed by the zone with the pine forest managed by the population, and the zones with the pine forest and grassland in recovery showed the lowest SQI. The linear score indices obtained by the PCA indicated the better ability to differentiate the calculated SQI values, which would provide information to contribute to the stakeholder management and decision making in the protection, conservation and management

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of the ecosystems present in the biosphere reserve. Complementary studies are needed in broad areas and different land uses and soil types to validate the set of indicators. The PCA obtained the most appropriate index since it better reflected the study zones' differences.

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