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Determination of the Soil Quality Index by Principal Component Analysis in Cocoa Agroforestry System in the Orinoco Region, Colombia

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Soil quality index can be determined by assessing the physical, chemical and biological properties of the soil. When large datasets are used, redundant information is obtained very often. Therefore, principal component analysis (PCA) is a multivariate method that allows the reduction of datasets, and in this way, it is possible to determine management objectives. This study was carried out in order to obtain a Soil quality index in an agroforestry system of cocoa (*Theobroma cacao* L.) and yopo (*Anadenanthera peregrine* Vell) established in 2012 under Pie de Monte Llanero conditions in the Orinoco Region, Colombia. The properties used to obtain the index were: bulk density, pH in water (1: 1), pH KCl (1: 1), ΔpH, total porosity, drainage porosity, field capacity, available phosphorus, organic matter, clay, silt and sand content, and soil penetration resistance. Using the principal components analysis for this study, the soil quality was: 0.4931, which it can be classified as mean (medium), and this works in function of: BD, O.M, ΔpH, pHh2o and P. Therefore, after

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determination the sensitive elements of this soil and assess its quality regarding to the AFS applied, it was possible to assume that management strategies and decision making would be addressed towards an appropriate litter production, the improvement of organic matter and management of soil structure.

Keywords: Soil quality index; principal component analysis; agroforestry systems; cocoa tree; yopo; Colombia.

1. INTRODUCTION

Soil is a complex terrestrial ecosystem which can be understood as a provision base of different functions and ecosystem services such biomass production, balance, nutrient cycle, water storage and food production, which are essential for development and the maintenance of life [1,2]. Likewise, soil is considered as one of the most important resources that support agriculture and livestock, activities needed in order to satisfy the demand of food security worldwide [3]. However, schemes and approaches of food production have changed on tropical soils, which means that, there has been a transition from traditional and intensive agriculture to agroforestry systems because of the ecosystem services provided by them, due to their dynamics of interaction among different plant species and resources in the same place [4]. Cocoa Tree *Theobroma cacao* L is a specie originally from Neotropical moist forest in South America, likewise there are evidences about its central origin which is attributed to Amazon and Orinoco regions as its ecological niche [5,6]. This plant belongs to the family Malvaceae, it is a tree which can reach a height of 10 meters when cultural practices like pruning are not carried out, it is developed in humid and high temperature conditions, moreover, from harvested cacao pods are obtained its beans, which are taken to make the fermentation and drying processes. Worldwide this product is used to make chocolate, candies, cosmetics among others, which, in turn, great interest has been generated by the volatile substances that can be obtained from the pulp [7], as well as the antioxidant properties of almonds [8], indicating that due to its high demand is an excellent alternative for the farmers in Neotropical zones like the study area of this research. Besides Yopo tree (*Anadenanthera peregrina* Vell) is one of the four species which conform this genus, it is a perennial tree of the family Fabaceae which can reach an height of 20 m, it is endemic from South America and Caribbean zones, and it can be found in the Orinoco River basin (Colombia and Venezuela). Although it is located in savanna or this region also can be found in the north of Brazilian Amazon [9,10]. This tree has high rates of biomass production, and can grows well in conditions of low soil fertility, also it has the capacity of atmospheric nitrogen fixation and phytoremediation capacity [11]. The timber of this tree in the Orinoco Region, Colombia, mainly is used as fuelwood, and also as shade of agroforestry systems, for instance, in silvopastoral systems which nowadays are becoming the most popular ones in those areas. In this sense, soil resource under sustainable production schemes as agroforestry, assume that quality index improving through of its interaction and of course through appropriate practices. Nevertheless, what are the scientific criteria or technic indicators that could measure the factor "soil quality" before, during and after the establishment of agroforestry systems? It must be taken into account that soil is a sensible resource, because any change in the management system influence on their dynamic properties, or can induce directly in the susceptibility to physic and chemic degradation of it [12]. In the beginning, the concept of soil quality evaluation has been suggested as a tool of decision making that look for its adequate management [13]. This instrument is based on a dataset of the physical, chemical and biological properties, because these are useful indicators of functions that this can fulfill from the exosystemic, productive or agronomic point of view [14,15,16]. Several are the methodologies implemented for quality evaluation, among them stand out the use of index and they can classified in three big groups: additive index, weighted additive, and decision support vector [17]. A limitation of the first group (additive index) is that the selection of the properties that represent better some of the functions of the soil are based on the subjective opinion of experts, a situation that makes difficult its use for people with a less experience in this area [18]. However, the quality index obteined by statistical methods like principal component analysis, offers an opportunity to simplify the selection of atributes that represent better the soil functionality, as well as to facilitate the selection of these properties [19]. In this study was obtained an additive index weighted of soil quality using the method of principal component analysis (PCA) from physical chemical properties evalated in a plot with agroforestry system.

2. METHODS

The study was carried out in the experimental farm of the University of Los Llanos, located in the Barcelona neighborhood of Apiay municipality (-73° 34'51.51''N, 4° 4'24.21''W; 388 m.a.s.l.). The determination of the soil quality index was done in a 1.10 hectare plot with an agroforestry arrangement of cocoa tree (*Teobroma cacao* L.) and yopo (*Anadenanthera peregrine* Vell.). This system was planted in the year 2012 (plantation 3 m x 3 m in frame, 12 x 12 in frame, respectively); and the soil of this place belongs to a Typic Hapludox taxonomic category [20].

2.1 Experimental Design

In the study area was marked a plot systematically or grid sampling pattern 16 m x 25 m disturbed samples, for a total of 24 samples. These were taken with a soil drill (depth to 20 cm), also was taken a non-disturbed sample with stainless steel rings (depth to 5 cm), and each point had been measured with a digital penetrometer.

2.2 Soil Analysis

Each of twenty four disturbed samples were dried under shade, powdered and also sieved to obtain soil particles of equal diameter or less than 2 mm. In all samples was determinate: pH in water relation (1:1 v/v potentiometric method), pH in potassium chloride (KCL 1/N) relation (1:1 v/v potentiometric method), available phosphorus P (Bray II, spectrometry UV visible), organic matter O.M (Walkley & Black, method), texture (expressed in % Sand, % Silt, % Clay) (Boyocous). The samples non-perturbed were saturated by capillarity until observe that soil surface already contained into the ring looks bright. Immediately the samples were located into the Richard's pressure plate apparatus (0.33 bar) in order to determine the percentage of humidity, which correspond to field capacity (FC), these same were used to determine bulk density (BD) and total porosity (TP). To determine all of these properties is according to the methodology by [21].

With the pH information determined in water and in potassium chloride, the pH delta (equation 1) was calculated:

$$\Delta\mathrm{pH} = \mathrm{pH}_{\mathrm{H20}} - \mathrm{pH}_{\mathrm{KCl}} \quad (1)$$

With the value of the field capacity and the porosity, the drainable porosity was determined [22] (equation 2):

$$\mathrm{DP} = \varepsilon - \mathrm{FC} \quad (2)$$

Where: DP: Drainable porosity (%), ε: Total porosity (%), FC: Field capacity (%)

2.3 Soil Quality Index

Each of the results of the physical and chemical properties evaluated were standardized to values between 0 and 1 (where 1 represents an optimum value for the indicator), standardization was performed using linear equations using the criteria=if it is high is better for: O.M, FC, $\mathrm{pH}_{\mathrm{H2O,}}\mathrm{pH}_{\mathrm{KCl}}$, ΔpH, ε, DP (equation 3), and the criteria= if it is less is better for: BD, IC, (equation 4) or a combination of these P,% Sand,% Silt,% Clay, the lower and upper limits used in standardization are presented in Table 1.

$$\mathrm{Z} = \frac{(\mathrm{X} - \mathrm{Ll})}{(\mathrm{Ul} - \mathrm{Ll})} \quad (3)$$

$$\mathrm{W} = 1 - \frac{(X - Ll)}{(Ul - Ll)} \quad (4)$$

Where: Z and W: standardized value, X: value to be transformed, Ll: lower limit of the property to be transformed Ul: upper limit of the property to be transformed. After standardizing each of the data, we performed a principal components analysis, and selection to examine those with eigenvalues>1 [15,23], assuming that the components with elevated eigenvalues are those which represent better the attributes of the studied system. Furthermore, In each selected principal component were taken those properties of the soil that were in the range corresponding to 10% of the highest eigenvector obtained [14,17]. When more than one property within a principal component fulfilled the selection criteria, it was determined whether there was correlation between them (by calculating Pearson's correlation), then, if there was correlation and significance between properties, that property with less weight was eliminated within the principal component studied, the coefficient of correlation assumed for this was 0.6 (Correlation of 60%) [14].

Once the properties with greater weight were selected within each principal component, the soil quality index (equation 5) was calculated.

$$SQI = \sum\nolimits_{i=1}^{n} = \frac{W_i x S}{\sum W_i} \quad (5)$$

Where: Wi weight factor of each of the principal components in the index, S: standardized value of the selected property. The factor (Wi) of each principal component was calculated by dividing the proportion of each the principal components with eigenvalues > 1, in the cumulative proportion of the components selected for the calculation of the quality index [14]. Statistical analysis was performed with the software R (version 2.15.1). [30].

3. RESULTS AND DISCUSSION

The results from the lab analysis to the evaluated properties in study area (Table 2) indicates that soil is characterized by: sandy-clay-loam texture, extremely acidic with a low bulk density and medium to high content of organic matter [27,31], content of phosphorus and loam were the most variable properties (Table 2), it is emphasized that the available phosphorus content can be qualified by the canons of interpretation as: medium, high and very high, indicating heterogeneity in the content of this element [31].

Table 1. Upper and lower limits for standardization of evaluated properties

Property	Lower limit (Ll)	Upper limit (Ul)	Source
BD (g cm^{-3})	1.12	1.96	[24,25]
pH water	3.00	6.50	[26,27]
pH KCl	3.00	6.00	[28,27]
Porosity(ε) (%)	20	60	[24,25]
FC (%)	20	70	[24,27]
DP (%)	5	30	[26]
∆pH	0	-2	*
P (mg kg^{-1})	1	30	*
	50	100	
S.O.M. (%)	0	8	[29,23]
Coneindex (Mpa)	0.1	2.0	[26,27]
Sand (%)	45	80	[26]
Clay (%)	20	35	[26]
Silt (%)	0	28	[26]

Table 2. Values of the physical and chemical properties used to estimate the soil quality index

Property	N	Mean	S.D.	S.E.
BD (g cm^{-3})	24	1.29	±0.14	0.04
pH Water	24	4.03	±0.45	0.13
pH KCl	24	3.63	±0.41	0.12
Porosity(ε) (%)	24	51.24	±5.12	1.48
FC (%)	24	30.96	±3.12	0.90
Drainable Porosity (%)	24	20.28	±6.70	1.93
∆pH	24	-0.40	±0.15	0.04
P (mg kg^{-1})	24	46.77	±25.47	7.35
S.O.M. (%)	24	3.34	±0.49	0.14
Coneindex (Mpa)	24	1.40	±0.29	0.08
Sand (%)	24	50.04	±7.54	2.18
Clay (%)	24	24.63	±2.87	0.83
Silt (%)	24	25.32	±9.14	2.64

N = Number of points sampled, S.D. = Standard deviation, S.E. = Standard error

Studies on highly weathered soils with low pH and high carbon content indicates that 53% of total phosphorus from organic sources [32] being this a possible cause to the values reported in this study for this nutrient. In turn the heterogeneity in nutrient contents as phosphorus in the soil (Table 2) can be explained by abiotic factors such as: soil exposure to sunlight, plant growth, fall rate and leaf litter decomposition, conditions which influence heat balances and soil moisture and consequent on the activity of microorganisms [33].

Phosphorus contents as reported in this paper are also consistent in comparison to those obtained by [34], who studied changes in soil chemical properties as a function of the transition to agroforestry systems.

After applying the selected criteria, number of attributes that compose the minimum data set representing the greatest soil variability (initially 13) was reduced to five, the principal components that presented eigenvalues greater than 1 were the first four. Therefore, these explain 91% of the variation in the data set, (PC1= 0.36, PC2= 0.26, PC3= 0.16, PC4= 0.12) (Tables 3 and 4), By subjecting the properties with higher eigenvectors within each major component to the Pearson test (Table 5), a high significant correlation between drainage porosity (DP) and field capacity (FC) were observed (Pearson =0.68; P<.001), a mean correlation between field capacity (FC) and soil organic matter (S.O.M) (Pearson = -0.62; P<.002). Moreover, when the test for bulk density (BD) and total porosity (TP) was performed, a perfect and highly significant correlation was obtained (P=0.99; P<.001).

Therefore, the following properties were removed from the soil quality index model: field capacity (FC), drainable porosity (DP) in the principal component one and total porosity (TP) in the principal component two. However, because no correlation was observed between pHH2O and ΔpH (Table 5) these terms were kept in the equation.

Table 3. Results of eigenvalues of principal component analysis

Principal component	Eigenvalues	Proportion	Accumulated proportion
1	4.64	0.36	0.36
2	3.42	0.26	0.62
3	2.12	0.16	0.78
4	1.59	0.12	0.91
5	0.58	0.04	0.95

Table 4. Results of the eigenvectors for components with eigenvalues >1

Variables	PC1	PC2	PC3	P4
BD	0.27	**0.41**	-0.15	0.09
pH wáter	-0.05	0.28	**0.57**	-0.08
pH KCl	-0.13	0.34	**0.45**	-0.09
Porosity(ε)	0.27	**0.41**	-0.15	0.09
Field Capacity	**-0.39**	0.03	-0.22	0.13
Drainable Porosity	**0.39**	0.29	-0.02	0.01
∆ pH	0.20	-0.09	**0.52**	-0.01
P	-0.04	-0.20	0.19	**0.63**
S.O.M.	**0.41**	0.13	-0.17	0.18
Cone index	0.17	-0.25	0.16	0.48
Sand	-0.30	0.31	-0.09	0.35
Clay	0.36	-0.23	0.02	0.18
Silt	-0.28	0.32	0.00	0.37
pH water	0.27	**0.41**	-0.15	0.09
pH KCl	-0.05	0.28	**0.57**	-0.08
Porosity(ε)	-0.13	0.34	0.45	-0.09

Table 5. Pearson's correlation coefficients for all soil indicators

Property	BD	Porosity	Field capacity	Drainable porosity	S.O.M
BD	**1.0000000**	0.00000	0.35253	0.00008	0.00519
Porosity	0.9997486	**1.00000**	0.35219	0.00008	0.00482
Field Capacity	-0.2946485	-0.29485	**1.00000**	0.01360	0.02977
Drainable porosity	0.8967329	0.89670	-0.68691	**1.00000**	0.00034
S.O.M.	0.7475880	0.75165	-0.62503	0.85969	**1.00000**

Under conditions and the dataset used in this study, it was obtained that quality index model is influenced by: Soil Organic Matter (S.O.M) > bulk density (BD) > (pHH2O) = (ΔpH) > available phosphorus (P) (Equation 6), simplifying equation 6 gives the equation 7 which soil quality index can be calculated.

$$\mathrm{SQI} = \frac{0.39 * (\mathrm{S.O.M.}) + 0.28 * (\mathrm{BD}) + 0.17 * (\Delta\mathrm{pH}) + 0.17(\mathrm{pH_{H2O}}) + 0.13(\mathrm{P})}{1.14} \tag{6}$$

$$\mathrm{SQI} = 0.34 * (\mathrm{S.O.M.}) + 0.25 * (\mathrm{BD}) + 0.15 * (\Delta\mathrm{pH}) + 0.15(\mathrm{pH_{H2O}}) + 0.11(\mathrm{P}) \tag{7}$$

$$\mathrm{SQI} = 0.4931$$

Each of the selected principal components can be interpreted and understood as processes which occurs in the soil and have importance in agroforestry, in this case, it is possible to analyze that the principal component one (PC1) represent the nutrient cycling capacity, meanwhile (PC2) could be interpreted as easiness which the roots of plants already established in the AFS penetrate in to the soil, besides its water and air supply. In the case of principal component three (PC3) corresponds to availability and nutrient mobility, and (PC4) as the capacity to allow the growth and well development of plants with productive aims [13].

By replacing each of the twenty-four standard values of the properties indicated in equation 7 and finding the average, it was obtained that soil quality index in the agroforestry system is 0.4931, if the maximum value that can be reached in the quality index is one (1), the value 0.4931 indicates that this soil has an average level of quality, from this information it can be inferred that management practices which increase the organic matter content and reduce the apparent density, are the ones that will have the highest incidence to improve the functionality of soil evaluated, therefore, this will be reflected in improvements of the soil system.

4. CONCLUSION

The use of the multivariate principal component analysis (PCA) allowed to reduce a set with thirteen soil characteristics to one with five (reduction of redundant information), which allowed to calculate a soil quality index, in which it is inferred that management strategies should be addressed to control of organic matter and physical environment of the soil. Hence, it can be inferred that this agroforestry systems (AFS): Cacao (*Theobroma cacao* L) + yopo (*Anadenanthera peregrina* Vell) through litter production and its interaction with the soil benefit the nutrient cycling, for instance, this is reflected in the high content of P in the studied soil.

In this sense, for the case applied to this study in the AFS (*Theobroma cacao* L. and *Anadenanthera peregrine* Vell) after obtaining the specific elements to focus on the particular soil conditions, possible management strategies and decision making would be adressed towards an appropriate litter production, the improvement of organic matter and management of soil structure [35]. Therefore, although agroforestry systems have been considered for several decades as production schemes that play an important role in reducing nutrient losses unlike traditional agriculture [36], it is important to note that determination of soil quality index by means of multivariate analysis, it will be a crucial, precise and decisive factor for decision making in favor of the improvement for this productive model through the sensitive elements of the soil according to its particular conditions.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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