Soil Quality Index in Cocoa Crops

Alberto Ducuara Manrique [1], Alfonso Manrique Medina [1], Luz Elena Vargas Ortiz [2]

[1] *Universidad Surcolombiana, Neiva, Colombia*
[2] *Universidad de Cartagena, Cartagena, Colombia*

***Abstract* – The main objective of this research is to develop a methodology to calculate a soil quality index in cocoa crops (Theobroma cacao L.), based on chemical properties such as pH, cation exchange capacity, organic matter, and percentage of base saturation, essential for the availability of nutrients in each cocoa tree. The problematic situation that causes this research is related to low yields per hectare, in small and medium-sized cocoa farms in the department of Huila – Colombia. A chemical quality index is proposed, which facilitates the analysis of the health behavior of the cultivated soil and nutrition of the cocoa plants, as a result of its interrelation with the physical and biological aspects. The proposed methodology is based on principal components analysis, to obtain weights and variable standardization equations, which evaluate 248 soil samples. The data indicate that in the cocoa producing land lots there are high pH values, cation exchange capacity and base saturation, but low levels of organic matter. It is concluded that in general the soils used showed moderate or low quality (52.42% and 11.29%, respectively), the rest showed high quality (36.29%). A soil intervention can improve its quality, however, the characteristic of the crop and the low levels of organic matter, requires recovering the properties and improving the health of the soil, if possible, through the implementation of regenerative agriculture, the object of future studies and research.**

***Keywords* – Agriculture, principal component analysis, soil quality, cocoa.**

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Corresponding Author: Alberto Ducuara Manrique, *Universidad Surcolombiana, Neiva, Colombia*
Email: alduma@usco.edu.co

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1. Introduction

Cocoa, in addition to being used in food production, has beneficial attributes that include the treatment and prevention of various cardiovascular diseases, cognitive impairment, resistance to wrinkles and protection of the skin against UV rays, among others. The industry has commercially leveraged these attributes through a wide variety of products and brands.

The consumption of cocoa, especially in the form of chocolate, not only satisfies gustatory pleasures, but also generates benefits related to mood, memory impairment and aesthetic factors. These aspects have contributed significantly to the increase in demand for cocoa, which is presented as an essential raw material in both the chocolate and pharmaceutical industries. The intersection of health benefits and sensory experience has positioned cocoa as a valuable resource, not only for food, but also for general well-being and for industry [1].

Worldwide, an approximate volume of 5 million metric tons of dry grains is traded annually. This production is predominantly led by the West African region, representing 76% of the total supply. As to Latin America, it ranks second, contributing 18%, while Asia ranks third with the remaining 6% [2]. Colombia is a self-sufficient country in cocoa, for the cocoa year 2020, approx. 176,050 ha were cultivated with a production of 63,416 metric tons of dry cocoa beans, which represent approximately 1.3% of world production. In this same year, the department of Huila contributed approximately 4,800 metric tons of dry grain [3].

The main cocoa consumer markets are located in countries such as the United States, France, Switzerland, Spain, Holland and Brazil, which recognize and distinguish Colombian cocoa as a high-quality product, classifying it as fine aroma [4]. Despite this recognition in international markets, at the marketing level on the producers' farms, most of the cocoa produced is sold under the category of ordinary cocoa [5].

In a context of global growth in chocolate consumption, there is a risk of a cocoa deficit if production does not increase at the same rate [6].

This imbalance between growing demand and limited supply could have significant implications on the supply chain and economic stability of cocoa farmers. Therefore, it is crucial to explore strategies to increase production and improve the quality of cocoa, to meet the growing expectations of the international market and ensure the long-term sustainability of this industry.

Guaranteeing production and quality are the challenges of the future for the cocoa-chocolate agri-food chain. A special condition for the development of the cocoa tree and its productivity is associated with the installation of the crop under an agroforestry system (AGF), which offers favorable aspects to the chemical quality conditions of the soil, particularly due to the contribution of organic matter and the recycling of nutrients [7].

The shading strategy, an ancestral culture in the territories cultivated with cocoa, is a decisional factor under an arrangement of cultivation in space and time, which provides economic, environmental, and sociocultural benefits [8].

However, this condition is not enough to ensure in the productive system the required quality of soil, despite a continuous deposit of organic material, because the crop generates more output of the nutrients than input [9].

The level of nutrition is determined by the presence of major and minor elements required by the plant at each season and phenology of the tree. Therefore, how farmers manage the fertilization, depends on what they know of the soil quality conditions, which is reflected in the quantity and the quality of fruits produced by each plant per year; a basic aspect to be competitive in the subsector [10].

Knowing the soil's physical, chemical, and biological aspects is very important if one is to define fertilization or the recommendations for conservation based on the phenological development of the plants, Shade and irrigation determine the scope of the density of the crop [11]. This knowledge enables the creation of fertility maps and guides the decisions on technical assistance [12].

The chemical quality of the soil is related to the requirements of organic matter (OM), acidity (pH), cation exchange capacity (CEC), base saturation (%BS) and particularly with the elements: phosphorus (P), potassium (K), nitrogen (N), magnesium (Mg), calcium (Ca), sulfur (S), zinc (Zn), nickel (Ni), boron (B), iron (Fe).

Kongor *et al.* [13] evaluated soil quality in cocoa plantations in Ghana, using a quality index based on 9 physicochemical properties. Principal components analysis, normalization of indicators and aggregation were applied to the estimates to obtain an integrated quality index.

While Mora *et al*. [14] developed a soil quality index for use in cocoa with diffuse logic, following various soil nutrition criteria.

On the other hand, Francisco *et al* [15] developed a methodology to identify the soil and nutritional variables that restrict productivity in cocoa plantations in Chontalpa producing area of Tabasco Mexico. In their conclusions they found that the main edaphic restrictions that affect cocoa cultivation are the rapid loss of organic matter (OM), nitrogen (N), and potassium (K) in the soil.

This paper presents a methodology for calculating soil quality indexes, following the four most influential chemical properties on the fertility of soils cultivated with cocoa, making use of available statistical tools for the analysis of multivariate data with quantitative variables.

2. Materials and Methods

The procedures and the instruments used, as well as the criteria applied for data collection and analysis are detailed below, with the purpose of guaranteeing the objectivity and reliability of the results.

2.1. Location

This study was carried out in the Department of Huila, located in the southwestern part of Colombia between 3º55'12" and 1º30'04" north latitude, 74º25'24" and 76º35'16" longitude west of the Greenwich meridian. Under a bimodal regime, precipitation in the territory varies between 668 and 1500 mm per year, with dry periods in the months of January, February and July, August-September, high monthly solar radiation (1498.2 micromol m^2/s m) and brightness solar (6 hours of sun / day), which requires adaptation under agroforestry systems [16].

The production link is managed under a specific smallholding model with low productivity, low costs and low profitability, where most of the producers define themselves as farmers [17].

The traditional roots in the cultural practices of small and medium cocoa producers, conveyed ancestrally and by the transfer of technology, are object of study, seeking to improve productivity and socioeconomic results. Currently, these cultural practices are developed in systems under shade, with conventional or organic agriculture [18].

2.2. Datasets Used

The data correspond to 248 samples collected by the Colombian Corporation for Agricultural Research (AGROSAVIA) between 2017 and 2019, from 13 municipalities of Huila - Colombia.

The chemical properties of the soil were measured for the various samples: hydrogen potential (pH), organic matter (OM), cation exchange capacity (CEC) and base saturation percentage (%BS); properties that mainly determine the fertility of the soil for cocoa cultivation [19].

Given the particular agroecological characteristics of each territory where cocoa is grown, measurements with soil quality indexes make it easier to evaluate its chemical conditions against minimum existence levels, required to ensure economic sustainability for producers.

For this end, the scale standardized by the Soil Science Society of America, [20] was taken as reference and the principal component analysis (PCA) method was used.

2.3. Statistical Analysis

For the soil properties, descriptive measures were calculated (mean, medium, maximum, and minimum values), the correlation matrix between the properties; as well as the frequency histograms that allowed the observation of their various distributions.

2.4. Calculation of the Soil Quality Index

According to Kumar *et al.* [21], the soil quality index (QSI) can be calculated by the following expression:

$$SQI = \sum_{i=1}^{p} W_i S_i \quad (1)$$

Where:
p is the minimum number of the soil properties used for the index.
W_i is the weight of the property i
S_i is the standardized i property
To perform the soil quality index calculation, the following stages were followed.

i. Calculation of the weights. A principal components analysis is performed to establish the weights (W_i) of the various soil properties, according to the percentage of participation in the construction of the various factorial axes [13]. The vector of weights is established by the following formula:

$$W_i = A_{ij} B_j \quad (2)$$

Where:
W_i: It is the weight of i property of the soil, within the calculation of the soil quality index.
A_{ij}: It is the contribution of soil property i on the factor axis j.
B_j: It is the vector of percentage to the inertia contributed by the factor axis j.

ii. Standardization of Soil Properties. The standardization of the soil properties is performed with the equations proposed by Calderon et al. [22], as shown in Table 3, a sample of correlations amongst various properties.

a. High Desirable Property Values.

$$Y = 0.1 + \left(\frac{X - b}{a - b}\right) \times 0.9 \quad (2)$$

b. Low Desirable Property Values:

$$Y = 1.1 - \left(0.1 + \left(\frac{X - b}{a - b}\right) \times 0.9\right) \quad (3)$$

iii. Obtaining the Soil Quality Index. Finally, the soil quality index is calculated, through equation (1), which is interpreted considering the scale presented by Klimkowicz, *et al*. [23] and observed in Table 1.

Table 1. Soil quality classification scales

Soil Quality	Scale	Class
Very High	0.80-1.00	1
High	0.60-0.79	2
Moderate	0.40-0.59	3
Low	0.20-0.39	4
Very Low	0.00-0.19	5

The analyzes and graphs were performed with the use of the statistical software R 4.2.0.

3. Results and Discussion

In this section, the results obtained from the exhaustive analysis are presented in detail. The data collected provides deep and nuanced insight by shedding light on significant trends, patterns, and discoveries that emerged during the research.

3.1. Descriptive Statistics

The soils used for cocoa production in the department of Huila tend to be slightly acidic, with low to moderate cation exchange capacity and organic matter content, and high base saturation (Table 2). Due to the characteristics of the crop associated with an understory agroforestry system and protective management conditions, the soils present high variability expressed through the organic matter indices and the cation exchange capacity.

Table 2. Descriptive statistics of soil chemical properties

	pH	OM (%)	CEC (meq/100g)	SB (%)
Mean	6.39	2.39	11.86	96.11
Medium	6.46	2.17	10.9	99.1
Minimum	4.17	0.42	1.99	17.03
Maximums	7.76	8.85	33.63	105.67

Table 3. Matrix of correlations amongst the chemical properties of the soil

	pH	OM	CEC	%SB
pH	1.00	0.02	0.68	0.60
OM	0.02	1.00	0.29	-0.15
CEC	0.68	0.29	1.00	0.33
%SB	0.60	-0.15	0.33	1.00

According to the correlation matrix, it is observed that there are important and positive correlations between the pH with the cation exchange capacity and the percentage of base saturation (0.68 and 0.6, respectively), indicating that alkaline soils tend to have a high nutrient retention ability and base saturates.

3.2. Frequency Histograms

Below are the frequency histograms associated with the 4 soil properties considered in the study.

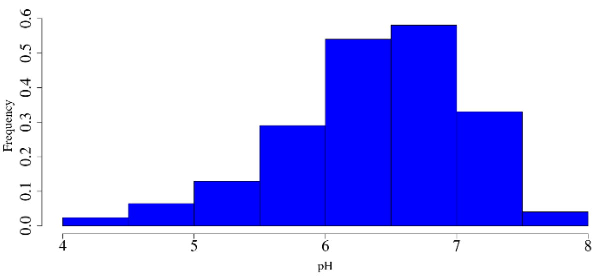

Figure 2. Soil pH

Due to the prevailing characteristics of climate and the formation of the soils dedicated to cocoa farming in the department of Huila, the largest extension of area under cultivation is distributed between neutral to alkaline soils, with a high area density in the pH range, the higher the to 5 and less than or equal to 7, this being the most adequate for a balance of nutrients in the cocoa nutrition process (Figure 2).
The production of abundant leaf litter in areas with cocoa cultivation favors a healthy soil environment for the activity of organisms and the fractioning of organic matter for the benefit of nutrient cycling.

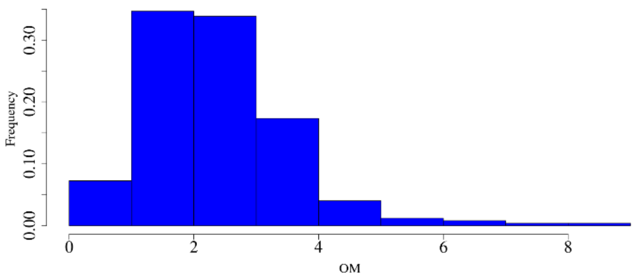

Figure 3. Soil organic matter

Despite the large contribution of litter residues on the surface of the cocoa areas, its incorporation into the soil matrix is not reflected, since the highest frequency of areas presents organic matter values between 1% and 4%, varying from low to moderate (Figure 3), which suggests evidence of soils with a history of other uses.

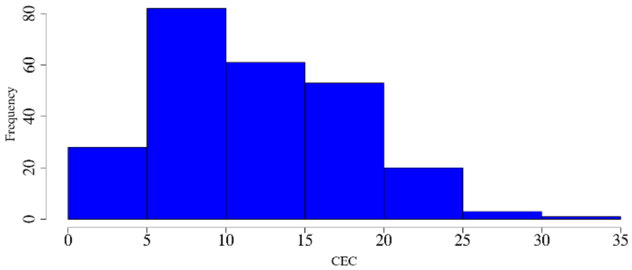

Figure 4. Soil CEC

The CEC as an indicator of soil fertility reflects the highest concentration of soils in the low to medium ranges (Figure 4), which suggests the need to incorporate soil conservation and sustainability practices in the cocoa-growing areas of Huila to increase reserves of water and nutrients for the benefit of plantations.

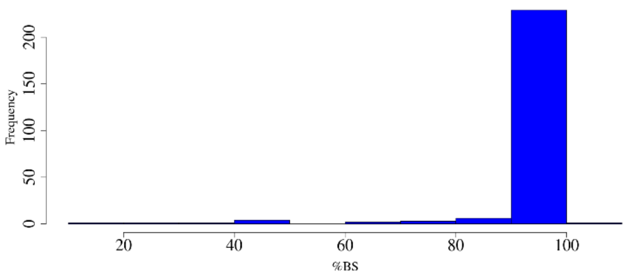

Figure 5. Soil %BS

Soils dedicated to cocoa cultivation tend to have a high reserve of nutrients expressed in the high percentage of base saturation, despite the fertility conditions already noted. It is considered that the areas dedicated to cocoa require the supply of irrigation in the dry seasons for the effective translocation of nutrients in the soil reserve (Figure 4).

3.3. Soil Quality Index Calculation

According to the principal component analysis carried out for the four soil properties, there is the following matrix of contributions for the formation of the factor axes.

Table 4. Contribution of the soil parameters for Cocoa cultivation to the factor axes

	Axis1	Axis2	Axis3	Axis4
pH	0.4	0	0.1	0.6
OM	0	0.7	0.2	0
CIC	0.3	0.1	0.2	0.3
%BS	0.3	0.2	0.5	0.1

It is observed that for the formation of axis 1 and 4, the property that contributes the most is pH, the second axis is mainly explained by organic matter; while the percentage of saturation of bases contributes 50% in the formation of axis 3.

Table 5. Percentage of inertia contributed by each factor axis

	Inertia	Cum	%	Cum (%)
Ax1	2.089	2.089	52.23%	52.23
Ax2	1.1792	3.268	29.48%	81.71
Ax3	0.4999	3.768	12.50%	94.2
Ax4	0.2319	4	5.80%	100

According to the principal components analysis, axes 1 and 2 accumulate 81.71% of the total variation of the soils, with pH and organic matter being the properties that mostly contribute to the formation of said axes.

The weights of each variable, according to equation (2), are established by:

Table 6. Vector of Property Weights

	Weights
%BS	0.284
pH	0.256
OM	0.231
CEC	0.229

Observing similar weights of the various parameters, being the percentage of base saturation the one with the highest weight (0.284), followed by pH (0.256); while the cation exchange capacity presents the lowest weight (0.229).

Regarding Formula (1), the following behavior is observed for the soil quality index.

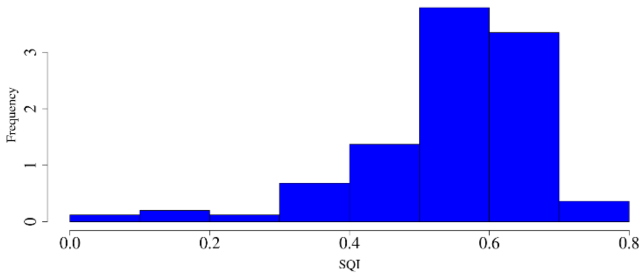

Figure 6. Soil quality index

According to the methodology, the soil quality index for cocoa cultivation in the department of Huila tends towards values higher than 0.5 in soil quality, confirming the benefit in soil sustainability, when compared with soils dedicated to management of crops other than cocoa (Figure 6).

Table 7. Soil quality classification scales

Level	Percentage
High	36.29%
Moderate	52.42%
Low	8.06%
Very Low	3.23%

The soils dedicated to cocoa crops in the department of Huila present a high percentage (59.3%) a moderate quality index, and the low-quality percentage is low (3.6%).

This is largely attributed to the notable advantages of cocoa crops in terms of soil sustainability. This sustainability derives from its condition as a permanent crop, characterized by constant recycling of leaf litter waste. Furthermore, the implementation of agroforestry practices, such as covering the soil with dense mulch, resulting from continuous organic contributions, proves crucial to improving soil quality.

The projected trend for the coming years suggests an increase in soil quality indices, with the possibility of a conversion towards high quality categories, as illustrated in Table 7. This positive evolution is based on the sustainable practices associated with cocoa crops, highlighting their role in the continuous improvement of soil health and productivity in the region.

4. Conclusion

The presented methodology provides a clear and simple way to obtain specific soil quality indices for cocoa crops, based on their key chemical properties.

Although the properties used in the calculation have similar weights, it is important to highlight that the percentage of base saturation and the pH of the soil are the variables that have the greatest weight in determining the quality index.

In this sense, the percentage of base saturation and soil pH emerge as critical factors that significantly influence the global evaluation of soil quality for cocoa cultivation. This differentiated highlighting the importance of monitoring and adjusting these specific aspects to optimize soil conditions and, therefore, improve the production and health of cocoa crops.

The descriptive analysis of the properties indicates that the soils tend to be alkaline, with high base saturation percentages and low to moderate organic matter values.

In general, the soils used showed moderate or low quality (52.42% and 11.29%, respectively), the rest showed high quality (36.29%). A soil intervention can improve its quality; however, the characteristic of the crop and the low levels of organic matter require recovering the properties and improving the health of the soil.

The creation of proprietary technologies in tropical territories such as those of Huila, for regenerative agriculture in the context of climate change and guaranteeing good nutritional status for cocoa trees, are the subject of future studies and research. It is possible today, with the implementation of regenerative agriculture, to foresee a more competitive future for the cocoa subsector.

Topics such as the supply of mycorrhizae or the development of bio-regeneration are sources for new research. A nourished and strong soil has a balance between all its components to continue fulfilling its natural functions, such as producing cocoa with long-term sustainability.

The greatest practical limitation of the implementation of soil quality indices would be the veracity of the official information for its calculation by agricultural exploitation. In this context, it is proposed to require this in the technical assistance report and in access to economic benefits by public or private development entities.

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