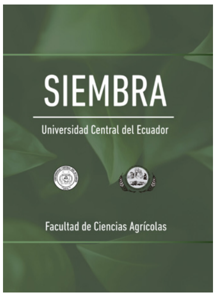
Nutritional quality index in soils cultivated with cocoa in the Colombian Nariño mountain subregion



Índice de calidad nutricional en suelos cacaoteros de la subregión cordillera de Nariño

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Siembra 11 (1) (2024): e6027

Received: 01/15/2024 / Revised: 27/02/2024 / Accepted: 07/03/2024

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Abstract

Soil quality is used to determine whether a production system is sustainable. The objective of this study is to estimate a soil nutrient quality index [NQI] for cocoa by standardizing variables, developing scoring functions, and assigning relative weights. Macronutrients and micronutrients, acidity (pH), organic matter content [%OM] and aluminum saturation [%Al.S] were standardized. The NQI were analyzed according to the soil cartographic units [SCU] and sampling site locations. Computer-assisted machine learning algorithms were used for the calibration of a spatial prediction model of the NQIs. It was found that 70.6 % of the sites were classified with a medium (value of) NQI (0.4-0.7), 23.8 % were low, and 5.6 % were high. The SCU with the highest NQI also had the best water retention, limited effective depth and were located on steep slopes; those with the lower NQI were affected by deficiencies in OM and macronutrient content, but those sites were found in more accessible areas. The spatial distribution map of the NQI was obtained, providing a detailed visual representation of the areas with higher and lower nutritional suitability for cocoa cultivation. The NQI allows to understand the nutritional supply of the soil in the Cordillera subregion of Nariño, but integrating additional factors such as soil depth, relief, and water availability would improve the monitoring and enable a more effective management of cocoa crops in line with environmental sustainability principles.

Keywords: *Theobroma cacao* L., soil quality, soil management, soil sustainability

Resumen

La calidad del suelo sirve para determinar si un sistema productivo es sostenible. El objetivo de este estudio es estimar un índice de calidad de nutrientes del suelo para cacao [ICNs], mediante la estandarización de variables, desarrollo de funciones de puntuación y asignación de pesos relativos. Se estandarizaron los macronutrientes y micronutrientes, acidez (pH), contenido de materia orgánica [%MO] y saturación de aluminio [%S.Al]. Los ICNs se analizaron de acuerdo con las unidades cartográficas del suelo [UCS]. Se utilizaron algoritmos de aprendizaje automático asistido por computadora para la calibración de un modelo de

SIEMBRA
https://revistadigital.uce.edu.ec/index.php/SIEMBRA
ISSN-e: 2477-5788
Frequency: half-yearly
vol. 11, issue 1, 2024
siembra.fag@uce.edu.ec
DOI: https://doi.org/10.29166/siembra.v11i1.6027

predicción espacial del ICNs. Se encontró que el 70,6 % de los sitios se clasificaron con ICNs medio (0,4 -0,7), el 23,8 % fueron bajos y el 5,6 % fueron altos. Las UCS con ICNs más altos también tienen mejor retención de agua, una limitada profundidad efectiva y se encuentran en pendientes pronunciadas; aquellas con ICNs más bajos se vieron afectados por deficiencias de MO y contenido de macronutrientes, pero esos sitios se encontraron en zonas más accesibles. Se obtuvo el mapa de distribución espacial del ICNs que ofrece la representación visual detallada de las áreas con mayor y menor aptitud nutricional para el cultivo de cacao. El ICNs permite entender la oferta nutricional del suelo en la subregión cordillera de Nariño, pero integrar factores adicionales, como la profundidad del suelo, el relieve y la disponibilidad de agua, mejoraría el monitoreo y permitiría un manejo más efectivo de los cultivos de cacao en consonancia con los principios de la sostenibilidad ambiental.

Palabras clave: *Theobroma cacao* L., calidad de suelo, manejo del suelo, sostenibilidad de suelo

1. Introduction

In Colombia, cocoa (*Theobroma cacao* L.) plays a key role in peasant, family and community agriculture [CFCA]. This crop not only provides beans with organoleptic quality in high international demand, but also contributes to environmental sustainability. Its production system favors the capture of atmospheric carbon, low greenhouse gas emissions sequestration, the protection of biodiversity by reducing deforestation and planting native plants as shade forests, as well as soil conservation and the regulation of biogeochemical cycles of nutrients and water, thus offering a sustainable economic development opportunity for rural communities (Rojas-Molina et al., 2021; Trinidad et al., 2016). Although the crop has emerged as an alternative for the Mountain subregion in Nariño, major challenges are faced. Nariño producers encounter major challenges hindering the adoption of the crop. These challenges are linked to the presence of unproductive crops deriving from aging cocoa plantations, lack of technical assistance, genetic incompatibility of clones, and the genetic incompatibility of clones, all to which add to social problems due to the widespread presence of armed groups that control the territory and illicit crops that displace cocoa crops (Ministerio de Agricultura y Desarrollo Rural [MADR], 2020).

The proper implementation of CFCA and the adoption of conservation practices in cocoa production are closely related to soil quality. This quality, originally defined as the suitability of the soil for a specific productive use (Araujo et al., 2018), is being reinterpreted as its capacity to contribute to various ecosystem services, such as: regulating water supply, attenuating environmental pollutants, capturing carbon, maintaining biodiversity or, as in the context of this study, producing healthy and nutritious food (Araujo et al., 2018; Baveye et al., 2016; Bünemann et al., 2018; Castro Méndez et al., 2021; Doran & Parkin, 1994; Kuzyakov et al., 2020; Villareal-Núñez et al., 2013). Assessing soil quality is crucial to determine the long-term sustainability of a productive system (Doran & Parkin, 1994). This involves measuring biological, physical and chemical characteristics (Seybold et al., 1999), and combining them mathematically to understand the effects of soil management and establish monitoring indicators (Castillo-Valdez et al., 2021; Papić, 2016).

Understanding that soil is an open system, conformed by a complex, discrete and diverse structural network of biotic and abiotic functional components (Obando Moncayo, 2016) is fundamental to adequately select the evaluation variables, as the magnitude of their expression differs between locations and soil formation factors (Arshad & Coen, 1992; Figueroa Jáuregui et al., 2018; Jaramillo, 2002). The identification of variables is done through a descriptive and interpretative process based on the factorial paradigm where soil is a function of climate, organisms, relief, parent material, and time, among others (Cortés Lombana, 2014). The cartographic units [SCUs] delimited within a soil map do not show the internal variability of soil variables. However, these SCUs provide a frame of reference for the spatial analysis of soil variables (Zinck, 2012).

Different authors have investigated soil quality in different regions and time periods (Andrews et al., 2004; Seybold et al., 1999). Soil quality indices [SQI] have been developed in countries such as Panama, Turkey, Mexico, Brazil and Colombia, using a variety of physical, chemical and biological soil properties (Andrews et al., 2004; Araujo et al., 2018; Castillo-Valdez et al., 2021; Şeker et al., 2017; Villareal-Núñez et al., 2013), and applying scoring functions suggested by previous studies (Seybold et al., 2018).

The chemical indicators most commonly used to generate SQI are: soil buffering capacity, nutrients availability, pH, electrical conductivity, organic carbon [SOC], organic matter, cation exchange capacity, nitrogen, phosphate adsorption capacity, and micronutrient availability. The exchangeable organic matter [OM], phosphorus [P], potassium [K], and magnesium [Mg] properties more closely define the current state of soil fertility and evidence its degradation; SOC is very sensitive and presents a high association with tillage systems. Therefore, based on the results of these indicators, macro soil fertility management strategies can be defined for a given area and crop (Bautista-Cruz et al., 2011).

Predicting the current state of soil chemical parameters, in areas without available data, allows obtaining spatial distribution maps and identifying areas with higher and lower nutritional suitability for different crops (Chinea-Horta & Rodríguez-Izquierdo, 2021). Digital soil mapping [DSM] uses environmental covariates associated with soil-forming factors, such as precipitation, temperature, solar radiation, relief, soil cover, among others, to predict the distribution of soil properties (Food and Agriculture Organization [FAO], 2022; Varón-Ramírez et al., 2022). These covariates are associated with soil formation factors and can come from remote sensing, digital terrain analysis, climate or thematic maps (Grunwald et al., 2011). Thus, the DSM has become a valuable tool for improving agricultural planning (Vargas Díaz et al., 2023), contributing to increased productivity and the preservation of natural resources.

In this work, a soil nutrient quality index [NQIs] was adapted for cocoa cultivation in the Mountain subregion of the department of Nariño, Colombia, through the standardization of soil variables and the application of scoring functions. In addition, a digital map showing the spatial distribution of ICNs was constructed. The results obtained offer a valuable tool for local planning of sustainable agricultural activities, contributing significantly to improve productivity and conservation of natural resources in the study region.

2. Materials and Methods

2.1. Description of sampling sites

The present research was carried out in the municipalities of Policarpa, Cumbitara, Los Andes, Leiva and El Rosario, which constitute the Mountain subregion of the department of Nariño in Colombia (Figure 1). Composite soil samples were taken in the first 30 cm of depth from 143 sites with cocoa crops older than 12 years. Sampling was conducted between October 2020 and November 2021.

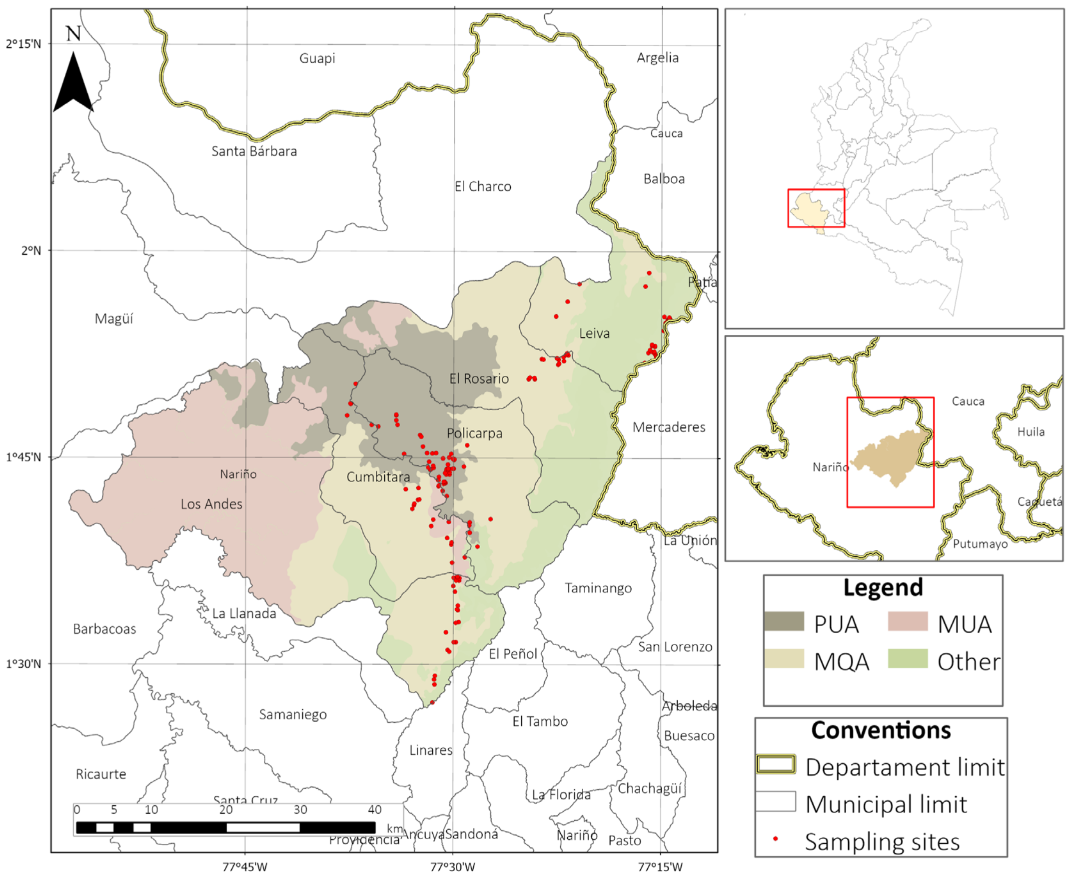

Figure 1. Location of the study area, distribution of sampling sites, and soil cartographic units.

The sampling sites were located in different SCUs, according to the general study of soils and land zoning of the department of Nariño, scale 1:100,000 (Instituto Geográfico Agustín Codazzi [IGAC], 2004). The characteristics of the three SCUs, where the largest number of sites were located (Figure 1, Table 1), are described as follows:

Table 1. Soil cartographic units and taxonomic components where the cocoa plantations of the Mountain subregion of Nariño were located. Taxonomic components correspond to the USDA classification (Soil Survey Staff, 2014).

SCUs	Main taxonomic component (soil modal profile)	Sites sampled
PUA	Oxic Dystrudepts Typic Dystrudepts	56
MQA	Acrudoxic Hapludands	45
MUA	Typic Dystrudepts	12
	Otras	30
	Total	143

We identified that 57 sites were located in the SCUs called MQA and MUA, distributed in 45 and 12, respectively, in the mountain landscape, with steep and moderately steep slopes with an inclination greater than 25 %, humid temperate and humid warm climates (IGAC, 2004). The soil modal profile of the MQA unit corresponds to Acrudoxic Hapludands (Soil Survey Staff, 2014), it is a superficial soil, with moderately coarse textures, excessively drained, very strongly acidic, low fertility, high aluminum saturation and high to low organic matter content. For its part, in the MUA SCU the soil modal profile is Typic Dystrudepts (Soil Survey Staff, 2014), and is characterized by being superficial, of moderately fine textures with gravel and rubble, well drained, very strongly acidic, low natural fertility and with medium to low organic matter (IGAC, 2004).

On the other hand, 56 sites were found in the PUA unit, in the piedmont landscape fans and humid warm climate (IGAC, 2004); the slope inclination ranges between 3 % and 25 %, and there are low areas or sectors of planoconcave relief. The soils of this unit are Oxic Dystrudepts and Typic Dystrudepts (Soil Survey Staff, 2014) are very deep, fine-textured, well-drained, strongly acidic, with low fertility and high and low organic matter content (IGAC, 2004).

2.2. Chemical variables of soil

For the configuration of the NQI, five variables, or groups of variables, associated with soil fertility and considered susceptible to changes as a consequence of agricultural activity were defined, due to a functional part of the soil is to provide mineral nutrition to plants as proposed by Araujo et al. (2018). The variables corresponded to organic matter content (%OM), available macronutrients (P, K, Mg, Ca), available micronutrients (Zn, Fe, Mn, Cu) hydrogen potential in water (pH) and exchangeable acidity saturation (% Sat. Al). The analyses were performed at the Soil Laboratory of the Corporación Colombiana de Investigación Agropecuaria, accredited by ONAC, according to Norma Técnica Colombiana NTC-ISO/IEC 17025:2006. Table 2 shows the methods used to determine the soil chemical parameters mentioned in the previous paragraph.

2.3. Estimation of the nutritional quality index [NQIs].]

The values of each variable were standardized using “more is better”, “optimal ranges” or “less is better” scoring functions (Andrews et al., 2004), according to the nutritional requirements (Table 4) of the cocoa crop (*Theobroma cacao* L.), and were fitted by regression in Microsoft Excel to quadratic models as proposed by Castillo-Valdez et al. (2021) (Figure 2 and Table 3).

Subsequently, the NQIs were determined by the combination or arithmetic sum of the standardized variables, following equation [1]. Each variable (I_i) received a relative weight (W_i) for weighting. The relative weights were assigned according to the importance of each nutrient, or soil attribute in the growth and development of the cocoa crop, based on the following (Araujo et al., 2018) (Table 4).

Table 2. Measured parameters and methods used to determine the concentration of nutrients in soil.

Analytical determination	Unit	Method
pH (1:2,5)	pH units	NTC 5264:2008
Organic matter (OM)	g 100 g^{-1}	NTC 5403 Walkey & Black
Available phosphorus (P) (Bray II)	mg kg^{-1}	NTC 5350
Available sulfur (S)	mg kg^{-1}	Monobasic calcium phosphate
Available boron (B)	mg kg^{-1}	
Acidity ($Al^{+}H$)	cmol(+) kg^{-1}	KCl
Exchangeable aluminum (Al)	cmol(+) kg^{-1}	
Available Calcium (Ca)	cmol(+) kg^{-1}	Soil exchangeable bases NTC 5349: 2008
Available Magnesium (Mg)	cmol(+) kg^{-1}	
Potassium (K) available	cmol(+) kg^{-1}	
Iron (Fe) olsen available	mg kg^{-1}	NTC 5526:2007 Method D
Copper (Cu) olsen available	mg kg^{-1}	
Manganese (Mn) olsen available	mg kg^{-1}	
Zinc (Zn) olsen available	mg kg^{-1}	

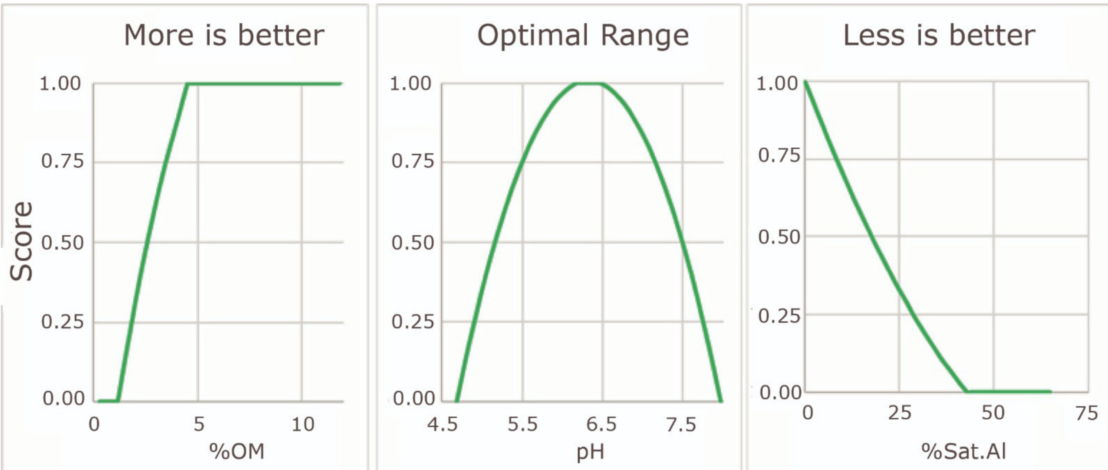

Figure 2. Types of scoring functions used to standardize the NQIs variables in cocoa cultivated sites in the Nariño mountain range.

Table 3. Scoring functions for each soil property, adjusted to quadratic models.

Variable		Adjustment equation	R^2
%OM		$y = -0.032x^2 + 0.4777x - 0.5233$	0.79
Macronutrients	**P**	$y = -0,0007x^2 + 0,0643x - 0,1825$	0.85
	K	$y = -2,2514x^2 + 3,5344x - 0,2813$	0.87
	Ca	$y = -0,0009x^2 + 0,0595x + 0,0152$	0.70
	Mg	$y = -0,0108x^2 + 0,2076x + 0,0595$	0.83
Micronutrients	**Zn**	$y = -0,0189x^2 + 0,2547x + 0,2525$	0.82
	Mn	$y = -0,0101x^2 + 0,1736x + 0,337$	0.75
	Cu	$y = -2,2719x^2 + 5,7558x - 2,546$	0.81
	Fe	$y = -0,0014x^2 + 0,0779x - 0,1365$	0.71
pH		$y = -0.3734x^2 + 4.7263x - 13.949$	0.73
%Sat, Al		$y = 0.0002x^2 - 0.032x + 1.0045$	0.95

[1]

Table 4. Base limit values and standard weights of variables for determining the Nutritional Quality Index in Cocoa Soils (NQIs) of the Nariño Cordillera/mountain range, Colombia.

Primary indicator	Weight (%)	Secundary Indicator	Weight (%)	Base/Limit Values				Unit	Type of Function	Reference
				Low	Medium	Óptimum	High			
OM	20			<2	2.0 - 3.0	-	3	%		Snoeck et al. (2016)
Macronu-trients	40	P	27.5	<6	6 – 15	-	>15	mg kg^{-1}		Dogbatse et al. (2020)
		K	27.5	<0.15	0.15-0.4	-	>0.4	cmol (+) kg^{-1}		Snoeck et al. (2016)
		Ca	22.5	<4	4-18	-	>18	cmol (+) kg^{-1}		Dogbatse et al. (2020)
		Mg	22.5	<0.8	0.8-4.4	-	>4.4	cmol (+) kg^{-1}		Snoeck et al. (2016)
Micronu-trients	25	Zn	50.0	-	<0.5	0.5-2.2	>2.2	mg kg^{-1}		Snoeck et al. (2016)
		Mn	20.0	-	<3	3-12	>12	mg kg^{-1}		Snoeck et al. (2016)
		Cu	20.0	-	<0.4	0.4-1.8	>1.8	mg kg^{-1}		Dogbatse et al. (2020)
		Fe	10.0	-	<19	19-45	>45	mg kg^{-1}		Snoeck et al. (2016)
pH	10			<5.0	5.0 – 5.5	5.5 - 7.0	>7.0	Ad.		Snoeck et al. (2016)
Sat. Al	5			<10	10-30	-	>30	%		Snoeck et al. (2016)

2.4. Analysis of NQIs according to geographic location

To consider soil management constraints and other associated characteristics, the NQIs were grouped according to the distribution of the SCU (IGAC, 2004). Additionally, to identify and validate different conditions, an exploratory analysis of soil water holding capacity, and mechanical resistance to penetration [MRP] was performed. The moisture retention curve was performed on undisturbed samples using the pressure pot method, and plates with permeable membranes. The MRP was measured with an Eijkelkamp penetrologger to a depth of 80 cm.

2.5. Identification of the spatial distribution of NQIs

A prediction model of the NQIs was built to estimate its value in unsampled sites. The model was trained using computer-assisted machine learning algorithms. To build the model, 76 environmental covariates, in raster format, associated with soil formation factors, were used (Table 5). The spatial resolution of the available covariates was adjusted to the same pixel size of 250 m x 250 m (ISRIC — World Soil Information, 2024) to ensure consistency and uniformity of the NQIs predictions. Subsequently, using the recursive feature elimination (RFE) strategy, the set of covariates was reduced to those that showed the greatest predictive capacity of the NQIs (FAO, 2022).

Table 5. Environmental covariates by soil formation factor.

No	Covariate	Description	Resolution (m)	Source
1 - 16	Climate	Temperature, precipitation, evapotranspiration, wind speed, number of days with average daily air temperature above 10 °C	1.000	Chelsa Climate (2023)
17 - 24	NDVI vegetation index	Average and standard deviation between the months March to May, June to August, September to November, December to February, from 2000 to 2022.	250	Google for Developers (2023)
25 - 32	Fraction of photosynthetically active radiation (FPAR)		500	
33 - 40	Daytime soil surface temperature		1.000	
41 - 48	Normalized difference of daytime and nighttime ground surface temperature		1.000	
49	Black sky albedo (average June-August 2000 to 2022)		500	
50 - 54	Land Use (NTR)	Estimated average probability of complete cover by: trees, shrubs and bushes, flooded vegetation, grasslands, bare areas.	250	
55 - 67	Terrain attributes	Curvature, elevation, roughness, slope, topographic position index, terrain moisture index.	250	Yamazaki (2023)
68 - 76	Soil texture	Sand, silt and clay fractions. In depths 0-5 cm, 5-15 cm and 15-30 cm.	1.000	Varón-Ramírez et al. (2022)

A predictive model was trained through the Quantile Regression Forests [QRF] algorithm (FAO, 2022; Meinshausen, 2006), using the "caret" package (FAO, 2022; Kuhn, 2008) in R-Studio software. A key advantage of QRF is its ability to store the predictions of each forest built in the algorithm, allowing to obtain a statistical distribution of those predictions. This makes it possible to calculate the averages and standard deviations of the predictions.

For the 65 covariates with the greatest predictive capacity, the root mean squared error [RMSE], the mean absolute error [MAE], and the coefficient of determination (R^2) were determined as trend measures.

Finally, the spatial distribution map of the Nariño mountain range subregion was obtained, and the agricultural areas were delimited using land cover information provided by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM, 2021).

3. Results and Discussion

3.1. Soil chemical variables

The results of our study show that, in the Nariño mountain range subregion, the %OM of soils used for cocoa cultivation ranged between 0.31 % and 20.29 % (Table 6). According to León-Moreno et al. (2019), this percentage (20.29 %) exceeds the national upper limit, set at 13 %; and, 40.19 % of the soils analyzed present an organic matter content lower than 2 %. This, can affect the release of N, P and S, as well as the availability of Fe, Cu, Mn and Zn by chelating action (Julca-Otiniano et al., 2006). Similarly, this can negatively affect the yield of cocoa plantations, producing less than 500 kg per hectare per year (Departamento Nacional de Planeación [DNP], 2022; Unidad de Planificación Rural Agropecuaria [UPRA], 2022). As a result, the incorporation of organic matter into the soil is essential, as the application of organic fertilizers will not only contribute to improve this soil indicator, but will also positively influence other physical, chemical and biological parameters of the soil (Amponsah-Doku et al., 2022).

Additionally, we observed that 30.37 % of the soils analyzed have a %OM greater than 3 %. Within this group, 9.23 % stand out for having a %OM greater than 10 %. Specifically, these soils are located in the MQA SCU, in the municipalities of Policarpa and El Rosario.

Table 6. Summary of the results of the descriptive analysis of soil attributes in cocoa cultivated sites of the Nariño mountain range.

Variable	Mínimum	Average	Maximum	Standard Deviation
SOM (%)	0,31	2,90	20,29	2,33
P mg kg^{-1}	1,29	9,73	81,70	11,74
K cmol (+) kg^{-1}	0,09	0,28	1,07	0,21
Ca cmol (+) kg^{-1}	0,28	9,00	37,15	6,91
Mg cmol (+) kg^{-1}	0,13	3,24	13,31	2,94
Zn mg kg^{-1}	1,00	1,69	17,14	2,00
Mn mg kg^{-1}	1,00	5,54	33,23	4,79
Cu mg kg^{-1}	1,00	3,61	19,16	2,42
Fe mg kg^{-1}	5,00	75,65	249,25	51,43
pH	4,74	6,15	7,97	0,77
Sat, Al (%)	0,00	5,43	65,00	12,86

The pH ranged from "strongly to "extremely acidic" (4.74) to "alkaline" (7.97) (Table 6). This variation according to León-Moreno et al. (2019) is consistent with findings in other cocoa-growing areas of the country. Based on these results, it is crucial to implement liming in soils with a pH below 5.5, given that under these conditions there is evidence of possible aluminum and manganese toxicity. This situation compromises the availability of essential nutrients for cocoa cultivation, generating a direct negative impact on cocoa yield (Jaimes Suárez et al., 2021).

P ranged between 1.29 mg kg^{-1} and 81.7 mg kg^{-1}. In other cocoa-growing areas of the country, León-Moreno et al. (2019) found that this nutrient ranged from 0.1 to 334.9 mg kg^{-1}. However, it is important to note that the mere presence of high P concentrations does not guarantee its availability to plants. In soils with acid pH, this nutrient can be fixed with aluminum, Fe and Mn, while in alkaline soils, it can be precipitated due to the presence of Ca or Mg (Fernández, 2007). On the other hand, 23.36 % of the soils analyzed have a P content lower than 8 mg kg^{-1}. In similar situations, León-Moreno et al. (2019) recommend raising the levels of this nutrient to more than 12 mg kg^{-1}, by implementing an integrated approach that includes both organic and chemical fertilizers.

K ranged from 0.09 cmol (+) kg^{-1} to 1.07 cmol (+) kg^{-1}. It was identified that 31.30 % of these soils present levels below 0.15 cmol (+) kg^{-1}. This low concentration may be related to the content of vermiculite, chlorite or montmorillonite clays between 5 % and 15 %, K leaching due to water movement in the soil, intensively cultivated soils, and minerals that retain K in a non-replaceable form (Mengel et al., 2001). According to Hartemink (2005), deficiency of this nutrient can have direct implications on cocoa cob formation.

Ca ranged from 0.28 cmol (+) kg^{-1} to 37.15 cmol (+) kg^{-1}. We found that 24.50 % of these soils had levels below 4 cmol (+) kg^{-1}. This, may be associated with weathering and leaching processes in the formation of these soils (Mengel et al., 2001).

Mg ranged from 0.13 cmol (+) kg^{-1} to 13.31 cmol (+) kg^{-1}; 16.35 % or these soils showed Mg levels higher than 4.4 cmol (+) kg^{-1}. This behavior is probably related to the presence of ferromagnesian minerals, such as biotite, serpentine, olivine, etc. (Mengel et al., 2001).

In relation to Zn, Mn, Cu and Fe, it was observed that the higher concentrations of these micronutrients may be related to the origin of the parent material with which they were formed (Mengel et al., 2001).

3.2. Nutritional quality index

Overall, 70.6 % of the sites were rated with medium NQIs, encompassing values in the range of 0.4 to 0.7, with an average of 0.50, while 23.8 % obtained a low rating, and 5.6 % a high rating (Table 7 and Figure 3). These medium and low ratings of low and medium NQIs correlate, according to their weighted contribution, with OM levels and macronutrient availability, which, on average, are in the medium range for cocoa crop development, as highlighted in Table 7.

Table 7. Summary of total NQIs score and weighted variables in main SCU.

SCU (n)	Descriptive	NQIs	Weighted value of primary indicators on the NQIs				
			%OM	Macronutrients	Micronutrients	pH	% S.Al
	Indicator weight	**100%**	**20%**	**40%**	**25%**	**10%**	**5%**
PUA (56)	Minimum	0,17	0,00	0,04	0,26	0,09	0,00
	Average	0,41	0,41	0,26	0,50	0,71	0,72
	Maximum	0,66	1,00	0,78	0,72	1,00	1,00
MQA (45)	Minimum	0,31	0,00	0,10	0,40	0,06	0,00
	Average	0,55	0,58	0,43	0,53	0,85	0,93
	Maximum	0,82	1,00	0,82	0,78	1,00	1,00
MUA (12)	Minimum	0,39	0,08	0,23	0,41	0,90	1,00
	Average	0,54	0,53	0,39	0,53	0,96	1,00
	Maximum	0,71	0,88	0,55	0,68	1,00	1,00
Total (143)	Minimum	0,17	0,00	0,04	0,26	0,00	0,00
	Average	0,50	0,43	0,41	0,50	0,77	0,87
	Maximum	0,82	1,00	0,96	0,78	1,00	1,00

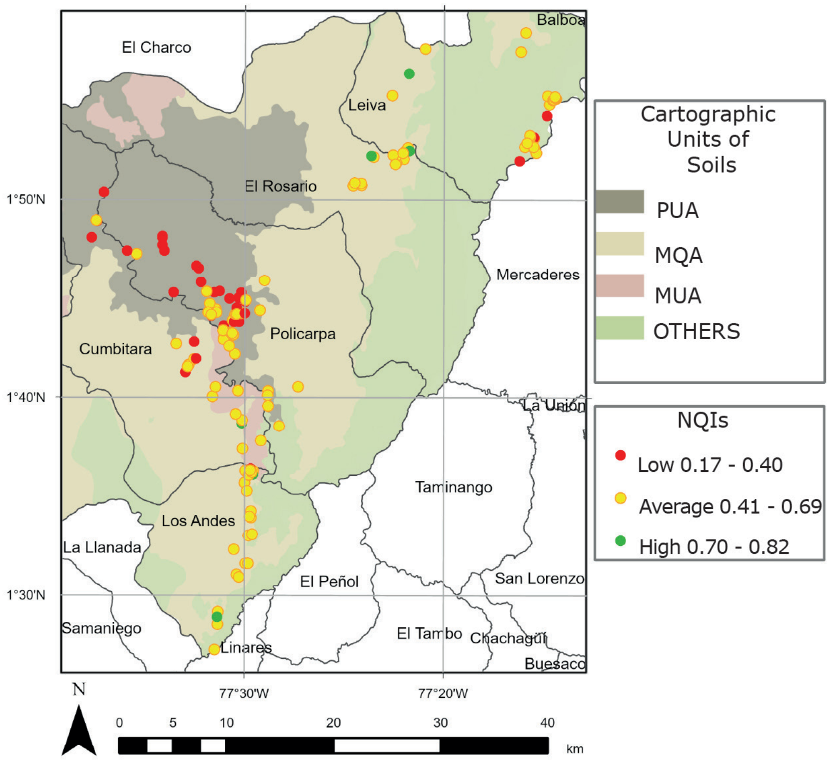

Figure 3. Spatial distribution of classified NQIs (Low 0.17-0.40; Medium 0.41-0.69; High 0.70-0.82).

It is noteworthy that the sites located in the MQA, and MUA SCUs presented, on average, the highest indices, although still within the average rating range with NQIs of 0.55 and 0.54 respectively. Despite these above-average values, these SCUs present significant limitations, such as the presence of abundant rock fragments in the profile and, fundamentally, because they are located on steep slopes, with gradients greater than >25 % (IGAC, 2004). The topographic characteristics of these SCU contribute to erosion in areas devoid of vegetation, resulting in the loss of positive soil properties in terms of quality and nutrient availability.

On the other hand, the sites in the PUA unit, which presents better relief and accessibility conditions, obtained an average NQI of 0.41, with a very low content of OM and macronutrients (P, K, Ca and Mg).

Figure 4 shows in an exploratory manner the behavior of the MRP evaluated in the SCU with the largest number of sampled sites. In the PUA SCU there are no physical limitations to the effective depth of the soils up to 80 cm. On the other hand, in the MQA and MUA SCUs the test was interrupted between 20 and 35 cm, highlighting limitations to the effective depth of the soils due to abundant rock fragments, corroborating what was described by IGAC (2004).

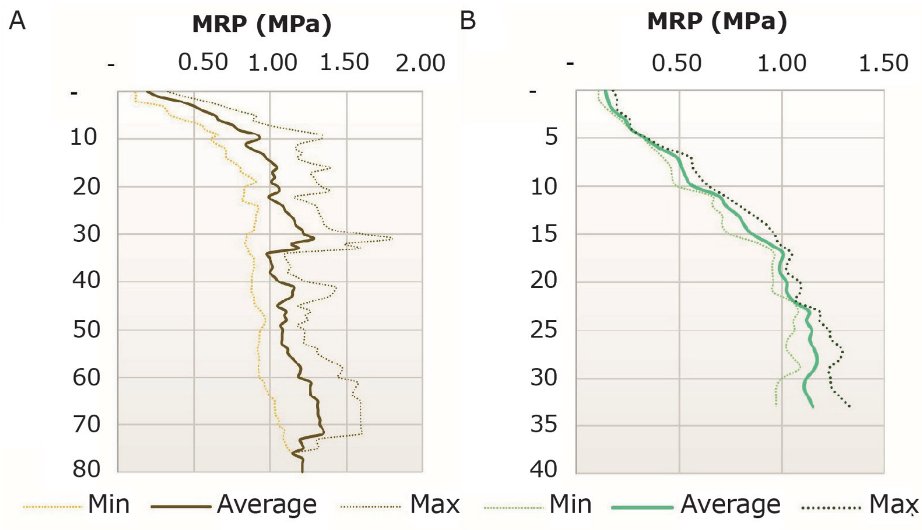

Figure 4. Mechanical Resistance to Penetration in the main SCU. A PUA SCU; B MQA and MUA SCUs.

On the other hand, the moisture retention capacity was higher in the MQA and MUA SCUs compared to the PUA SCU (Figure 5). This indicates that the crop has a higher water availability in the surface horizon of the soil profile in the units where the highest NQIs were found. This is associated with the %OM, higher in these SCU, which contributes to better soil structure and porosity, and also favors better availability and absorption of nutrients for crop development.

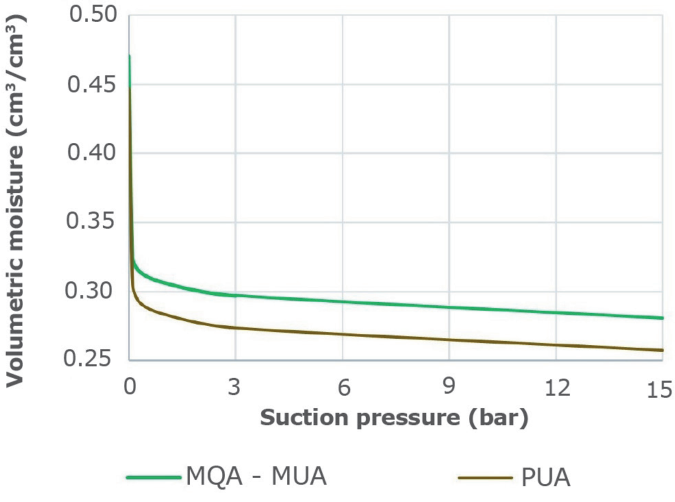

Figure 5. Moisture retention curves (RFE) in the main SCU.

3.3 Spatial distribution of NQIs

The RFE strategy reduced the set of 76 covariates to 65, which showed greater predictive capacity of the NQIs with a lower RMSE of 0.098, an MAE of 0.078 and an R^2 of 0.424. Within this subset, the covariates associated with the fraction of photosynthetically active radiation [FPAR], the normalized difference in surface temperature [NDLST], and the normalized difference vegetation index [NDVI] stood out. These variables, related to solar absorption for photosynthesis, heat distribution affecting evapotranspiration and water availability, as well as vegetation cover affecting nutrient retention, showed the greatest capacity for spatial prediction of NQIs.

The predictive model was built through 500 random forests in which, according to our results, the lowest error is obtained when each tree is built with 17 covariates randomly selected within the subset of 65 covariates. In terms of model performance, we obtained an MAE of 0.09, a RMSE of 0.11 and a correlation coefficient (r) of observed vs. predicted of 0.55 (Figure 6).

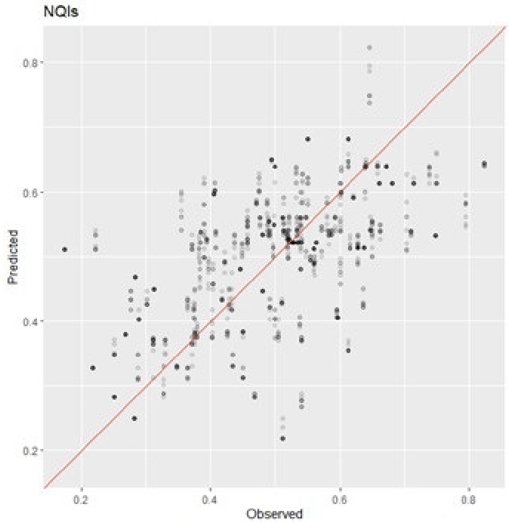

Figure 6. Observed vs. Predicted NQIs by the model. The red line represents the perfect model.

Figure 7 shows the spatial distribution of the NQIs in the agricultural areas of the Nariño mountain range. This map corroborates what Näsi et al. (2023) reported, finding similar patterns of NQIs variability in agricultural areas. Moreover, the results are in line with the findings of Cherubin et al. (2019), who evaluated the spatial variability of soil chemical attributes in six typical land uses (forest, pasture and four agroforestry systems) using the Visual Evaluation of Soil Structure [VESS] method in the northwestern Colombian Amazon, thus demonstrating that these tools can be a valuable strategy to recover soil quality and reincorporate degraded lands into productive and sustainable production systems in Amazonian regions by monitoring physical soil changes.

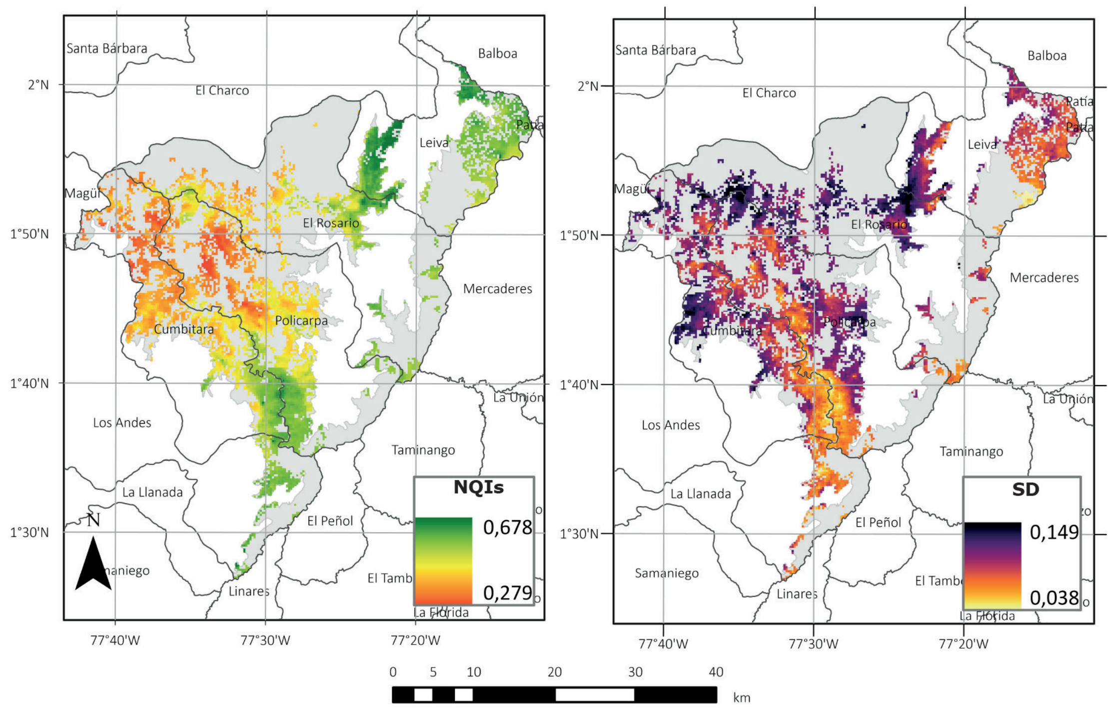

Figure 7. Left. Spatial distribution of NQIs of the agricultural areas of the Nariño mountain range, Colombia. Right. Spatial distribution of prediction standard deviation.

These similarities suggest a generalized trend in the distribution of soil quality in various regions of Latin America. This study complements these findings by providing a detailed visual representation of areas with higher and lower suitability for cocoa cultivation, considering the influence of environmental conditions on soil nutritional quality.

4. Conclusions

The NQIs of the Nariño mountain range can be considered as a tool to evaluate the nutritional supply of soils for cocoa cultivation. However, it is important to complement it with other soil attributes and environmental factors for comprehensive monitoring, as well as to apply management strategies that promote both environmental sustainability and the objectives of the production system.

The nutritional quality of soils in the Nariño mountain range is heterogeneous in the territory and is influenced by variations in relief, topography, and climatic conditions. Therefore, it is necessary to define specific fertilization management strategies, adapted to production niches, to optimize the linkage of technologies with local producers.

The variability of NQIs in the region does not always correlate with uniformity in soil-forming factors. This can be attributed to the fact that the NQIs, calculated according to the proposed methodology, derives mainly from chemical properties influenced by fertilization and crop management practices.

This study can be the basis for defining optimal niches for cocoa production in the Mountain subregion of the Nariño region, providing specific recommendations for sustainable agronomic management adapted to the particular conditions of peasant family agriculture in this territory.

Acknowledgments

We thank the Corporación Colombiana de Investigación Agropecuaria - AGROSAVIA and Fundación Ayuda en Acción for the development of the project "Development of a low cadmium cocoa production model for the Nariño mountain range sub-region".

Authors' contributions

- Diego Leonardo Cortes-Delgadillo: conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, writing – original draft, writing – review & editing.
- Jose Libardo Lerma-Lasso: data curation, investigation, visualization, writing – original draft, writing – review & editing.
- Juan Fernando López: data curation, investigation, writing – original draft, writing – review & editing.
- Diego Hernán Meneses: data curation, writing – original draft, writing – review & editing.
- Eliana Martínez Pachón: conceptualization, methodology, project administration, writing – review & editing.

Ethical implications

Ethics approval not applicable.

Conflict of interest

The authors declare that they have no affiliation with any organization with a direct or indirect financial interest that could have appeared to influence the work reported.

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