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CASE STUDY

Soil fertility in agricultural production units of tropical areas

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ABSTRACT

BACKGROUND AND OBJECTIVES: Soil is the most important basic natural resource for the support of agricultural production systems. Productivity maintenance in these ecosystems depends on their physicochemical. However, there are no significant studies on the current status of soil fertility and quality in tropical areas vulnerable to climate change and lacking management practices. The purpose of this study was to assess the physical and chemical properties of the soil to propose guidelines on soil handling and management in tropical areas.
METHODS: Data on texture, macronutrients, micronutrients, and cation ratios were collected at 200 farms in the Sucre Department of Northern Colombia. Correlation analysis and principal component analysis were performed on the resulting data set, and a soil quality index was calculated.
FINDINGS: Macronutrients N, P, K, S, Ca, Mg, and Na displayed average values of 21.65 ± 10.65 part per million, 40.35 ± 67.21 part per million, 0.46 ± 0.43 meq/100g, 7.94 ± 28.35 part per million, 15.63 ± 17.30 meq/100 g, 5.63 ± 3.58 meq/100g, 0.19 ± 0.20 meq/100g, respectively. Micronutrients Cu, Fe, Zn, and Mn displayed average values of 2.20 ± 1.66 part per million, 48.05 ± 37.87 part per million, 1.16 ± 1.26 part per million, 14.22 ± 12.24 part per million, respectively. The predominant texture among assessed soils was sandy clay loam. A significant correlation was found between (Ca/Mg) K-Ca/K, (Ca/Mg) K-Mg/K, Fe-Cu, and Ca-cation exchange capacity. The soil quality index of the soils assessed in the Department of Sucre indicates a high level of quality, which is strongly influenced by the indicators S, P, Mn (≥ 0.90) Fe, Zn, Cu, K, Na (≥ 0.80).
CONCLUSION: The macronutrients displayed a deficiency of potassium. It is therefore recommended to monitor these soils and apply fertilization plans according to the needs of each assessed soil. Lastly, this study provides relevant information for proposing guidelines for crop improvement.

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INTRODUCTION

The contribution of soils is essential for agricultural productivity, water regulation, climate regulation, and the environmental cycling of energy, carbon and nutrients, as well as the sustainment of biodiversity (van Leeuwen *et al*., 2019). The importance of soil quality is associated with its functional capacity within ecological and land-use limits, while maintaining productivity and plant health (Martínez-Mera et al., 2017). Soil quality is a complex functional concept that cannot be measured directly in the field or laboratory but can only be inferred through a combination of physical, chemical, and biological indicators providing key information on the soil's composition, structure, and function (Paz-Ferreiro and Fu, 2016). The most noteworthy of these indicators is soil fertility, which refers to the soil's capacity to sustain plant growth by producing the required nutrients (León-Moreno, 2019). Soil fertility decrease is a major problem in many regions of the planet and a persistent limitation for agricultural production, particularly in low-potential areas. Therefore, declining soil fertility represents a major threat to food safety and development of small farmer communities (Vanlauwe *et al.,* 2017). Soil degradation implies a decline in soil quality, together with an associated reduction in ecosystem functions and services. One of the main types of soil degradation is chemical degradation (Lal, 2015). Soil chemical degradation includes processes such as acidification, salinization, nutrient depletion, reduced cation exchange capacity (CEC), increased Al or Mn toxicities, Ca, or Mg deficiencies, leaching of NO_3-N or other essential plant nutrients, or contamination by industrial wastes or by-products (Lal, 2015). At the same time, different human activities are producing physical changes, increased concentrations of chemical residues, and accumulation of materials (Muñoz-Rojas, 2018). Due to the above, it is important to assess the physicochemical quality of the soil as an indicator of its fertility and therefore of its environmental condition. Thus, a mathematical or statistical framework was put forward in the early 1990s to estimate soil quality index (SQI) (Mukherjee and Lal, 2014). It is also necessary to assess soil fertility, in order to develop suitable fertilization strategies. Soil management is one of the main factors influencing the improvement or degradation of soil quality (Lal, 2015). Soil health is a key component for addressing the global challenges of food safety, simultaneously ensuring environmental sustainability in view of a growing human population (Kurgat *et al*., 2018). Several studies have been carried out on the evaluation of physicochemical characteristics in soils (Martínez-Mera et al., 2019). Table 1. provides examples of recent research on soil quality around the globe. In Colombia, studies have been mainly developed in the Atlántico (Martínez-Mera *et al*., 2019) and Córdoba departments (Marrugo-Negrete *et al.,* 2017). Some of the most important physicochemical characteristics for the assessment of soil fertility and health include its texture (Bünemann *et al.,* 2018), organic carbon (OC/OM), total N, total P, macronutrients, micronutrients, CEC, potential of hydrogen (pH), exchangeable ions, cation ratios, and mineralization rate (Obriot *et al.,* 2016; Karbassi and Heidari, 2015; Karbassi and Pazoki, 2015). Sustainable soil management is an urgent matter worldwide: 25% of the world's population depends directly on degraded soils (Zhang *et al.,* 2011), mainly in tropical and subtropical areas of developing countries. However, there are no significant studies on the current status of soil fertility and quality in tropical areas vulnerable to climate change and lacking management activities, as is the case in northern Colombia. This study aims to determine soil quality in agricultural units through the analysis of its physical and chemical properties. Research was carried out in 200 properties, owned by small farmers, in five prioritized municipalities (San Onofre, San Marcos, Morroa, Corozal, and Majagual) of the Sucre Department, northern Colombia. Field measurements and laboratory analysis for this study were carried out in 2020.

MATERIALS AND METHODS

The methods employed in this research is summarized in Fig. 1. Soil samples were collected and sent to the laboratory to determine their physical and chemical properties. Relationships between cations were estimated, and statistical analyzes were carried out in order to assess soil. This methodology used allowed to determine which physical and chemical properties are the most significant for soil quality in the region.

Study area

The Sucre Department, located in the Caribbean plains of northern Colombia (Fig. 2), encompasses an area of 10670 km^2, equivalent to 0.9% of the total area

Table 1: Summary of different recent studies about soil quality.

Location	Relevant aspects	References
South-West Cameroon	Assessed two soil fertility approaches in paddy fields for rice cultivation, in order to develop a user-friendly and credible soil fertility index (SFI). According to the two methods used in the study, most of the study area was classified as moderately suitable for rice cultivation. The results of the parametric and fuzzy methods also demonstrated that the most important limiting factors were drainage and the thickness of the plow layer. The other limiting factors were texture, pH, OM, and coarse fragment	Delsouz Khaki *et al.* (2017)
Sub-Saharan Africa	Performed different analyses on various datasets demonstrated the direct impact of physicochemical properties of soil and derived soil fertility parameters on major constraints for plant growth and optimal crop production such as water retention capacity, roots development, soils aeration, nutrients availability, nutrients abundance, and cations balance Based on physicochemical soil properties, fertility parameters and Soil Quality Index (SQI), four soil fertility classes were identified: (*i*) very good fertility soils; (*ii*) good fertility soils; (*iii*) fairly good fertile soils; (*iv*) poorly fertile soils. The principal indicators controlling soil are Ca, Mg, pH water, OM, available P, total Nitrogen, and CEC. Four of the seven indicators (Ca, pH, OM, and P) were also identified as important indicators for assessing the fertility status of the different soil groups	Nguemezi *et al.* (2020)
South-Western China	Calculated a soil quality index found that soil organic carbon, total nitrogen, potassium, and free iron are the most important indicators of soil quality in tropical acidic red soils. Deforestation and corn cultivation related to significant decreases in SQI	Huang *et al.* (2021)
Review paper (around the world)	Revealed how soil quality assessment has changed through time in terms of objectives, tools and methods, and overall approach. Main objectives included: suitability for crop growth, productivity, environment, multi-functionality, ecosystem services, resistance, and resilience. Total organic matter/carbon and pH are the most frequently proposed soil quality indicators, followed by available phosphorus, various indicators of water storage, and bulk density (all mentioned in > 50% of reviewed indicator sets). Texture, available potassium, and total nitrogen are also frequently used (> 40%)	Bünemann *et al.* (2021)

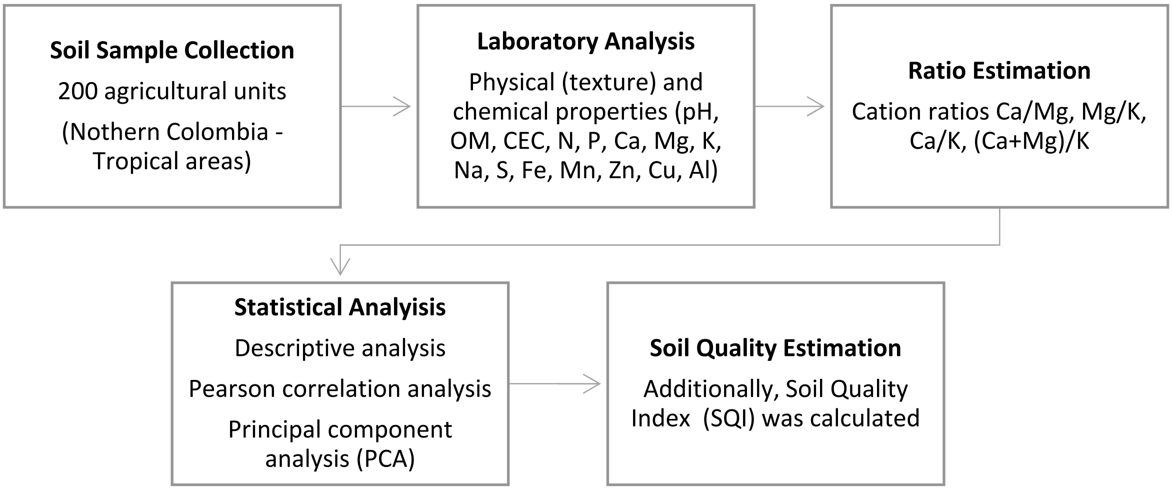

Fig. 1: Scheme of the methodology used in this study.

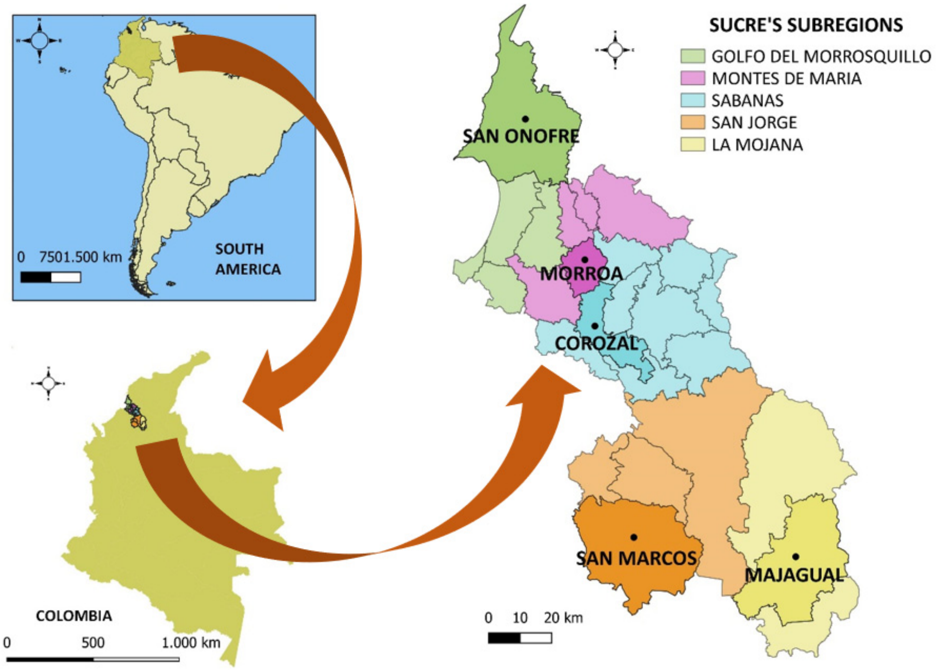

Fig. 2: Geographic location of the study area in the Department of Sucre in northern Colombia

of Colombia and 8.5% of the Colombian Caribbean region (Bustamante *et al.,* 2003). The weather in the region features a marked gradient of heavier rainfall from north to south (IDEAM, 2018). There are five subregions within the Sucre Department, the relevant characteristics of which are described in Table 2. In each subregion, a municipality was prioritized due to differences in precipitation, soil type, vegetation, and crop type. In addition, Sucre has the greatest percentage of area with land use conflicts among Colombian departments. Approximately 78% of the department area is affected by conflict of use, 42% (approximately 446000 Hectares) is affected by overuse, and 36% by underutilization. Proper use of soil, that is, productive systems where natural covers have not been affected, is present in only 22% of the department area. There are two trends of land use in Colombia: one is the use of some soils for agriculture and livestock when they have a different vocation, such as forestry or agroforestry. Another is the underutilization of soils, that is, abandoned or wasted lands that are not used for their true calling (DNP, 2003). Colombia is rich and diverse in soil resources. The Geographical Institute Agustin Codazzi (IGAC, for its initials in Spanish) recognizes 8 types of soils in Colombia, based on their vocation and capacity for use, productivity, and conservation (IGAC, 2021). Class 1, 2, and 3 soils, the most suitable for agricultural developments and controlled livestock, are widely distributed in areas of the Caribbean (northern) region of Colombia. Soils in these classes can support transitory crops and intensive livestock with high-yield pastures, with practices such as fertilization, waxing, watering, and drainage. Class 4, also found in the department of Sucre, includes soils with low fertility and high Al content. This class is suitable for agricultural, and livestock uses, but due to its limitations, it requires agricultural management practices. According to IGAC (2016), soils in the sampled municipalities of Sucre represent the orders Alfisols, Inceptisols, Mollisols, Ultisols, Vertisols, and Histosols.

Sample collection and laboratory analysis

Soil samples were collected at 200 farms in the five prioritized municipalities: 40 samples in Morroa (Montes de María subregion); 40 samples in Corozal (Sabana subregion); 40 samples in San Onofre (Gulf

Table 2: Characteristics of the five subregions and municipalities sampled in the department of Sucre in northern Colombia (Agronet, 2021).

SR/area	Mun	Av T /Av A	AP	Localization	Vegetation	Soil texture	Soil type (Order)	Crops
Montes de María (6466 km^2)	Morroa	26.8ºC 160 masl	1000-1200 mm	9º 20' 42" N 75º 18' 21" W	Tropical dry forest, mountain landscape	Sandy loam, Sand, Clay loam	Alfisols, Inceptisols	Cassava, corn, tropical yam, watermelon, beans, sweet pepper, rice, melon, pumpkin, white cucumber, purple sweet potato, eggplant
Sabana (2101 km^2)	Corozal	27ºC 143 masl	990-1275 mm	9º 19' 3" N 75º 17' 29" W	Tropical dry forest, hills landscape, extensive grassland area	Sand, Sandy loam, Clay loam	Mollisols	Cassava, tropical yam, corn, beans, plantain, watermelon
Golfo de Morrosquillo (1886 km^2)	San Onofre	27.4ºC 17 masl	900-1300 mm	9º 43' 59" N 75º 31' 59" W	Tropical dry forest, anthropic grasslands, hills landscape, mangrove forest	Clay, Clay loam	Mollisols Ultisols	Rice, cassava, tropical yam, corn, plantain, sweet pepper, beans, watermelon, pumpkin, sesame.
San Jorge (2934 km^2)	San Marcos	28ºC 25 masl	1300-2300 mm	8º 40' 1" N 75º 7' 59" W	Tropical humid forest, tropical dry forest, natural grassland	Sand, Clay	Mollisols, Vertisols	Corn, rice, cassava, tropical yam, watermelon.
Mojana (2337 km^2)	Majagual	28ºC 28 masl	2320-3000 mm	8º 32' 9" N 74º 39' 23" W	Tropical humid forest, wetland area	Clay loam	Mollisols, Histosols	Rice, corn, cassava, plantain, pumpkin, sugarcane, watermelon.

SR: Sub-region; Mun: Municipality; Av T: Average Temperature; Av A: Average Altitude; AP: Annual Precipitation.

of Morrosquillo subregion); 40 samples in San Marcos (San Marcos subregion); and 40 samples in Majagual (Mojana subregion) (Fig. 2). Samples were taken in crop fields, on flat terrain, mainly from Mollisols and Alfisols. Average farm area was 3 hectares; within each farm, one hectare was chosen for sampling. 15 subsamples were taken along zigzag transects, making V shaped cuts in the soil at a depth of 30 cm. The external portions of samples were discarded to avoid contamination. Each subsample was placed in a sterile plastic container in order to mix all subsamples and obtain a composite sample weighing 500 g. Sample collection followed the guidelines of Colombian Technical Standard (NTC) 3656 (ICONTEC, 2004). All samples were collected by triplicate to determine the precision of tests. The samples were analyzed at the environmental laboratory Zona Costera S.A.S., which is certified for environmental characterizations by the Institute of Hydrology, Meteorology and Environmental Studies (IDEAM). At the laboratory, physical (e.g., texture) and chemical (e.g., pH, OM, CEC N, P- total phosphorus -, Ca, Mg, K, Na, S, Fe, Mn, Zn, Cu, and Al) characteristics were determined (Table 3).

Data analysis

Descriptive statistics (e.g., minimum, maximum, mean, and standard deviation values) were performed on all physicochemical variables, followed by tests of normality and homogeneity of variance. Pearson correlation analyses were performed to test the relationships between physicochemical variables. Lastly, a principal component analysis (PCA) was performed to examine the contribution of each physicochemical variable to the overall variance of the studied soils. All statistical analyses and plots were performed using the R software package (R Core Team, 2020). Additionally, SQI was calculated for each farm production unit, by assigning unique values to each physicochemical variable by means of a weighted average (Nguemezi *et al.,* 2020). The Nv was calculated using Eq. 1.

$$Nv = 1 - \left(\frac{Im - Imin}{Imax - I\,min}\right) \tag{1}$$

Where Nv = is the normalized value, Im = indicator mean, Imax = indicator maximum value, Imin = indicator minimum value. The SQI was calculated using the simple additive method (Mukherjee and Lal, 2014). The SQI was interpreted using a transformation scale of five classes of soil quality (Nguemezi *et al.,* 2020): Very high quality 0.80 – 1.00; High quality 0.60 – 0.79; Average quality 0.40 – 0.59; Low quality 0.20 – 0.39; Very low quality 0.00 – 0.19.

RESULTS AND DISCUSSION

Predominant textures in assessed soils were sandy clay loam (SCL: 26%), clay loam (CL: 13%), clay (C: 12%), loamy sand (LS: 12 %), silt loam (SL: 11%), and loam (L: 10%). Average OM was 1.05 ± 0.51 % (Fig. 3). Loam texture and their products were the most abundant in soil samples. Loam soils generally contain more nutrients, moisture, and humus than sandy soils, have better drainage and infiltration of water and air than silt and clay-rich soils, and are easier to till than clay soils (Moraru *et al.,* 2020). Texture and OM are inherent properties of soil and crops, as well as indicators of soil health; affecting the availability of some macronutrients and micronutrients in the soil (Coblinski *et al.,* 2021). Amsili *et al*. (2021) found that physical and biological indicators were affected both by soil texture and cropping system. According to the classification of Villasanti *et al.* (2013), the content of OM was low in the studied soils. OM content is considered high above 2.8%, medium between 1.2 and 2.8%, and low below 1.2%. Low levels of organic matter are a threat to soil fertility Ndung'u *et al.* (2021). To improve the availability of organic matter, burning of vegetation should be avoided and compost from food waste and animal manure should be added to the soil. OM values in this work are consistent, and sometimes even lower, than those previously reported in other sites of northern Colombia (Martínez-Mera *et al.,* 2019).

Regarding macronutrients average values of N, P, K, S, Ca, Mg, and Na were 21.65 ± 10.65 parts per million (ppm), 40.35 ± 67.21 ppm, 0.46 ± 0.43 meq/100g, 7.94 ± 28.35 ppm, 15.63 ± 17.30 meq/100g, 5.63 ± 3.58 meq/100g, and 0.19 ± 0.20 meq/100g, respectively. For the case of the micronutrients Cu, Fe, Zn, and Mn, average values of 2.20 ± 1.66 ppm, 48.05 ± 37.87 ppm, 1.16 ± 1.26 ppm, and 14.22 ± 12.24 ppm, respectively. Average soil pH was 6.05 ± 0.80, with a maximum of 7.68 and a minimum of 4.19. Acid soils (average pH = 4.68) have been previously reported in Andean soils of Colombia. Average soil CEC was 22.84 ± 10.23

Table 3: Methods used to analyze the physical and chemical properties.

Variable	Method	Reference values		
PHYSICAL				
Texture	Bouyoucos NTC ISO 11464 (1975-11-24)	% Sand	% Silt	% Clay
CHEMICAL				
		Under	Medium	High
OM (%)	OM = Organic carbon x 1,724 (1.724 constans)	<1.49	1.5-3	>3.01
N (ppm)	NOM-021-SEMARNAT-2000, 7.1.8 AS-08 – Volumetry	0.09	0.1-0.199	>0.2
P (ppm)	Bray II extraction – Spectrophotometry	<9.99	10-20	>20.01
Ca (meq/100 g)	Extraction ammonium acetate 1 M, pH 7,0 – A.A spectrometry	<2.99	3-6	>6
Mg(meq/100 g)	Extraction ammonium acetate 1 M, pH 7,0 – A.A spectrometry	<1.5	1.5-3	>3
K (meq/100 g)	Extraction ammonium acetate 1 M, pH 7,0 – A.A spectrometry	<0.15	0.15-0.3	>0.301
Na (meq/100 g)	Extraction ammonium acetate 1 M, pH 7,0 – A.A spectrometry	< 1 Normal	>1 Problem	
S (ppm)	Extraction with calcium monophosphate 0,008 M - Turbidimetry	<10	10-20	>20
Fe (ppm)	NTC-5526 Method A. DTPA/ A.A spectrometry	<20	20-50	>50
Mn (ppm)	NTC-5526 Method A. DTPA/ A.A spectrometry	<10	10-30	>30
Zn (ppm)	NTC-5526 Method A. DTPA/ A.A spectrometry	<1	1-2	>2
Cu (ppm)	NTC-5526 Method A. DTPA/ A.A spectrometry	<1	1-2	>2
Al (meq/100 g)	IN-EE-081: NTC ISO 11464:1995, Extraction KCl 1 M - Volumetry	<= 1 Acid	>3 Problem	
$pH_{1:1,\ soil:water}$	EPA SW-846 9045 D /Electrometric	<5.5 Acid	5.5-6.5 neutral	> 6.5 alkaline
CEC (mEq/100 g)	Extraction with ammonium acetate 1 M, pH 7,0 – Volumetry	< 10	10-20	>20
$EC_{1:5,\ soil:water}$	NTC 5596:2008 / Electrometric	<0.8	0.8-1.6	>1.6
CATION RATIOS				
Ca/Mg	Estimate	<1	Calcium deficiency	
		1-2	Low level of with respect to Mg	
		2-5	Ideal	
		>5	Mg deficiency	
Mg/k	Estimate	<1	Mg deficiency	
		1-3	Acceptable	
		3	Ideal	
		3-18	Acceptable	
		>18	K deficiency	
Ca/k	Estimate	<30	Suitable	
		>30	K deficiency	
(Ca/Mg)k	Estimate	<40	K suitable	
		>40	K deficiency	

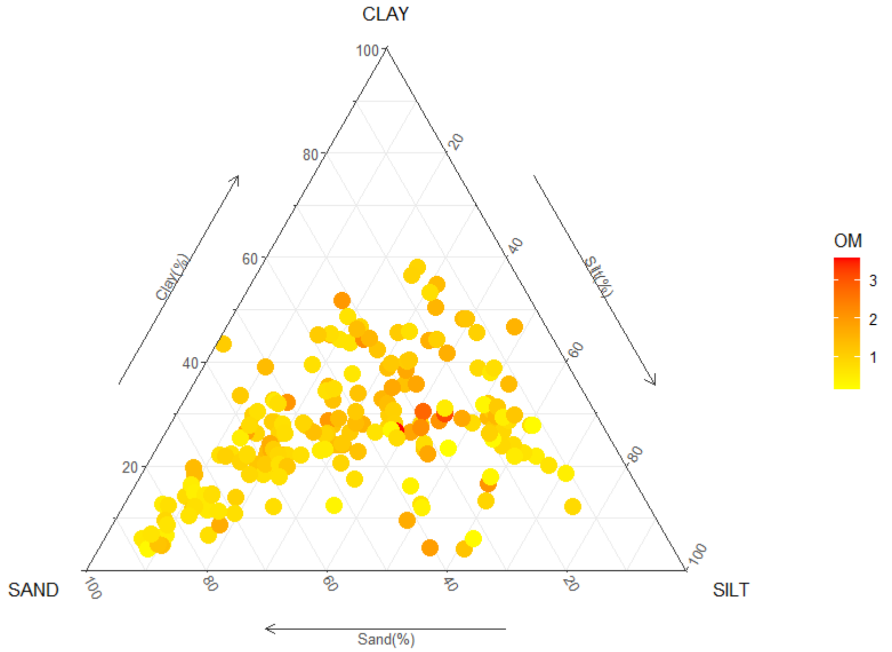

Fig. 3: Texture and OM of the studied soils.

Table 4: Summary for the physicochemical parameters analyzed in agricultural soils of the study area

Parameter	Maximum	Mínimum	Mean	SD
N (ppm)	63.20	5.40	21.65	10.65
P (ppm)	401.49	2.60	40.35	67.21
Ca (meq/100 g)	213.35	0.13	15.63	17.30
Mg(meq/100 g)	18.01	0.07	5.63	3.58
K (meq/100 g)	2.94	0.02	0.46	0.43
Na (meq/100 g)	0.98	0.02	0.19	0.20
S (ppm)	344.00	0.06	7.94	28.35
Fe (ppm)	319.24	2.74	48.05	37.87
Mn (ppm)	131.58	0.50	14.22	12.24
Zn (ppm)	8.35	0.19	1.16	1.26
Cu (ppm)	10.28	0.23	2.20	1.66
Al (meq/100g)	1.97	0.00	0.32	0.48
$pH_{1:1,\ soil:water}$	7.68	4.19	6.05	0.80
CEC (meq/100g)	50.84	4.61	22.84	10.23
$EC_{1:5,\ soil:water}$ (mS/cm)	0.17	0.01	0.05	0.03

P: total phosphorus, CEC: cation exchange capacity, EC: electrical conductivity

meq/100g, and average EC was 0.05 ± 0.03 mS/cm (Table 4). Values of pH and EC found in this study are below the maximum limit established by the Canadian Soil Quality Guidelines for Agriculture (CCME, 2014). Land use significantly influenced the change in CEC values. P content of soil can be altered by crop removal (approximately 80% is absorbed by plants), water erosion, and OM mineralization (Novello and Quintero, 2009). In the studied soils, macronutrients P and Ca displayed high values, whereas S displayed a low value. Phosphorus is essential for plant development and interacts with other nutrients such as C and N (Torri *et al.,* 2017). Continuous application of P from agrochemicals increases the potential risk

Table 5: Summary of the calculated cation ratios by the municipality.

Cation ratios	Municipiality				
	Corozal	Majagual	Morroa	San Marcos	San Onofre
Ca/Mg (Estimate)	2.86±1.48	2.63±5.16	3.94±2.24	2.46±1.40	2.96±0.83
Mg/K (Estimate)	18.53±7.56	36.92±18.37	9.52±5.96	10.31±7.61	14.52±6.41
Ca/K (Estimate)	47.09±19.26	75.68±68.25	29.27±11.09	22.58±16.21	40.83±16.35
(Ca+Mg)/K (Estimate)	65.62±23.65	112.60±73.30	38.79±14.25	32.89±21.94	55.35±21.12

of leaching into surface water through runoff, and underground water contamination via lixiviation (Silva-Leal *et al.,* 2021). In addition, high Ca values in soil are mediated by soil origin materials, as well as by the degree in which weathering and lixiviation have influenced soil formation processes (Chang *et al.,* 2020). In moderate quantities, $CaCO_3$ is beneficial for soil structure, and is often used to neutralize acid pH in soils. However, when high Ca levels are present, this nutrient combines with other components, creating non-soluble compounds that are difficult to absorb by plants. Therefore, an excess of Ca may restrict plant availability of P, B, and Fe (FAO, 2021).

Cation ratios Ca/Mg, Mg/K, Ca/K, and (Ca+Mg)/K, displayed average values of 2.97 ± 2.72, 17.96 ± 14.29, 43.09 ± 38.14, 61.05 ± 46.77, respectively. In all the assessed municipalities, an ideal Ca/Mg cation ratio was found, whereas the Mg/K ratio indicated a deficiency of K. Ca/K and (Ca+Mg)/K ratios displayed suitable values only in the municipalities of San Marcos and Morroa (Table 5). On the other hand, calculated cation ratios Mg/K, Ca/K, and (Ca+Mg)/K indicated a deficiency of K in most assessed samples, with average values > 18 in the ratio Mg/K, > 30 in the ratio Ca/K and > 40 in the ratio (Ca+Mg)/K. K is essential for plant physiological processes and is vital for the receptors of tolerance to hydric stress (Ruan *et al.,* 2014). In addition, hydric stress is a main limiting factor affecting plant growth and production. In arid and semi-arid regions, water scarcity limits crop productivity (Bader *et al.,* 2021). Consequently, it is essential to carry out studies in the area to propose management actions to improve the reported K deficiency. Previous studies of acid, low CEC soils in Colombian localities revealed the difficulty to adjust the relationships between exchangeable cations, due to the relationship between base saturation and soil pH (León, 1994). In general terms, it can be argued that very high Ca^{2+} and Mg^{2+} concentrations decrease K^+ absorption, and high K^+ levels may aggravate Mg^{2+} deficiency. However, it is worth noting that plants have a large capacity for adaptation, and their growth would be affected only under extreme conditions.

Pearson analysis found statistically significant correlations between most variables assessed (*p-value* ≤ 0.05), excepting for P, which did not correlate to other parameters. On the other hand, S was correlated only to Ca (*p-value* ≤ 0.05). High, positive correlations were found for (Ca/Mg)K-Ca/K (R^2=0.93, *p-value* ≤ 0.05), (Ca/Mg)K-Mg/K (R^2=0.61, *p-value* ≤ 0.05), Fe-Cu (R^2=0.53, *p-value* ≤ 0.05) and Ca-CEC (R^2=0.64, *p-value* ≤ 0.05). A high negative correlation was also found between soil textures Silt-Sand (R^2=0.52, *p-value* ≤ 0.05) and Sand-Clay (R^2=0.48, *p-value* ≤ 0.05) (Table 6). Similar correlations between cation ratios and Ca were previously reported by Bonomelli *et al.* (2020). Correlation analyses indicate that Fe is interacting with Cu, as well as Ca is interacting with CEC. Iron oxyhydroxides are natural, mineral constituents that are widely distributed, particularly in very mature soils that have been formed over very long periods (Cornell and Schwertmann, 2006). Cu exerts a strong control on the mobility and bioavailability of OM, Fe oxides, and Mn within the soil. It may also precipitate as hydroxide, carbonate, or phosphate (Yu *et al.,* 2016). Yu *et al.* (2014) found that cation exchanges in the soil can reduce the saturation of Ca hydroxide in the soil**.**

The first two principal components of the PCA accounted for 40% of the variance in the data set. The variables K, Ca, CEC, EC, and silt texture displayed the highest factor loads for the first principal component (PC_1). For the case of PC_2, the variables with the highest factor loads were the cation ratios Mg/K, Ca/K, and (Ca/Mg)K, together with Mg and clay texture (Fig. 4). It was also found that the percentage of sand was not related to any of the assessed variables, whereas the percentage of silt was related to OM, and EC is related

Table 6: Correlation between the physicochemical properties of soil in the department of Sucre, in northern Colombia.

Parameter		Silt	Sand	Clay	OM	N	P	Ca	Mg	K	Na	S	Fe	Mn	Zn	Cu	pH$_{1:1}$	CEC	EC$_{1:5}$	Ca/Mg	Mg/K	Ca/K	(Ca/Mg)K
		p - value																					
Silt	Correlation coefficient		0.00	0.93	0.00	0.41	0.65	0.00	0.03	0.00	0.01	0.66	0.45	0.70	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.05	0.01
Sand		**-0.72**		0.00	0.00	0.69	0.57	0.00	0.00	0.00	0.00	0.32	0.04	0.66	0.42	0.00	0.02	0.00	0.00	0.46	0.21	0.11	0.10
Clay		0.01	**-0.70**		0.41	0.78	0.73	0.00	0.00	0.11	0.00	0.33	0.02	0.30	0.15	0.00	0.38	0.00	0.53	0.03	0.08	0.76	0.73
OM		0.45	-0.37	0.08		0.35	0.93	0.00	0.00	0.00	0.19	0.58	0.63	0.72	0.14	0.09	0.05	0.00	0.00	0.28	0.01	0.01	0.00
N		-0.08	0.04	0.03	0.09		0.20	0.15	0.25	0.82	0.41	0.95	0.01	0.20	0.20	0.00	0.12	0.47	0.04	0.38	0.81	0.52	0.56
P		0.04	-0.05	0.03	0.01	-0.12		0.37	0.97	0.80	0.96	0.63	0.90	0.81	0.69	0.19	0.12	0.56	0.68	0.55	0.49	0.13	0.16
Ca		0.49	-0.58	0.32	0.39	0.13	-0.08		0.00	0.00	0.02	0.04	0.42	0.29	0.31	0.25	0.00	0.00	0.00	0.00	0.02	0.08	0.58
Mg		0.20	-0.52	0.55	0.29	0.11	0.00	0.51		0.00	0.00	0.17	0.06	0.05	0.31	0.01	0.75	0.00	0.27	0.00	0.00	0.99	0.19
K		0.48	-0.45	0.15	**0.60**	0.02	-0.02	0.55	0.29		0.12	0.22	0.51	0.86	0.27	0.18	0.00	0.00	0.00	0.01	0.00	0.00	0.00
Na		0.24	-0.50	0.48	0.12	0.08	-0.01	0.21	0.44	0.14		0.83	0.40	0.30	0.63	0.13	0.66	0.00	0.05	0.24	0.81	0.11	0.25
S		0.04	-0.09	0.09	0.05	0.01	-0.04	0.19	0.13	0.11	-0.02		0.35	0.61	0.96	0.64	0.53	0.10	0.25	0.76	0.50	0.70	0.60
Fe		0.07	-0.19	0.21	0.05	-0.23	-0.01	-0.08	0.17	-0.06	0.08	-0.09		0.03	0.09	0.00	0.10	0.69	0.03	0.01	0.08	0.75	0.74
Mn		-0.04	-0.04	0.10	0.03	-0.12	0.02	-0.10	0.18	-0.02	0.10	0.05	0.20		0.73	0.54	0.63	0.20	0.31	0.00	0.00	0.87	0.23
Zn		0.23	-0.08	-0.13	0.14	-0.12	0.04	-0.09	-0.09	0.10	-0.04	0.00	0.16	-0.03		0.00	0.46	0.49	0.70	0.73	0.05	0.06	0.04
Cu		0.40	-0.48	0.28	0.16	-0.32	0.12	0.11	0.24	0.13	0.14	-0.04	**0.73**	0.06	0.28		0.87	0.15	0.13	0.20	0.68	0.53	0.72
pH$_{1:1}$		0.37	-0.21	-0.08	0.18	0.14	-0.14	0.34	-0.03	0.33	0.04	0.06	-0.15	-0.05	-0.07	0.02		0.03	0.00	0.00	0.00	0.94	0.28
CEC		0.42	-0.59	0.42	0.42	0.07	-0.05	**0.80**	**0.63**	0.56	0.38	0.15	0.04	0.12	-0.06	0.13	0.20		0.00	0.01	0.25	0.85	0.60
EC$_{1:5}$		0.48	-0.30	-0.06	0.45	0.19	-0.04	0.47	0.10	**0.61**	0.18	0.11	-0.20	-0.09	0.04	-0.14	0.37	0.37		0.00	0.00	0.00	0.00
Ca/Mg		0.29	-0.07	-0.20	0.10	0.08	-0.06	0.54	-0.37	0.25	-0.11	0.03	-0.23	-0.27	-0.03	-0.12	0.40	0.24	0.38		0.00	0.04	0.69
Mg/K		-0.32	0.12	0.16	-0.25	0.02	-0.06	-0.22	0.37	-0.59	0.02	-0.06	0.16	0.30	-0.18	0.04	-0.29	-0.11	-0.47	-0.55		0.00	0.00
Ca/K		-0.18	0.15	-0.03	-0.25	0.06	-0.14	0.16	0.00	-0.56	-0.15	-0.04	-0.03	0.02	-0.17	-0.06	-0.01	-0.02	-0.26	0.19	0.59		0.00
(Ca/Mg)K		-0.24	0.15	0.03	-0.28	0.05	-0.13	0.05	0.12	**-0.62**	-0.11	-0.05	0.03	0.11	-0.19	-0.03	-0.10	-0.05	-0.36	-0.04	**0.78**	**0.96**	

OM: Organic Matter, CEC: cation exchange capacity, EC: electrical conductivity

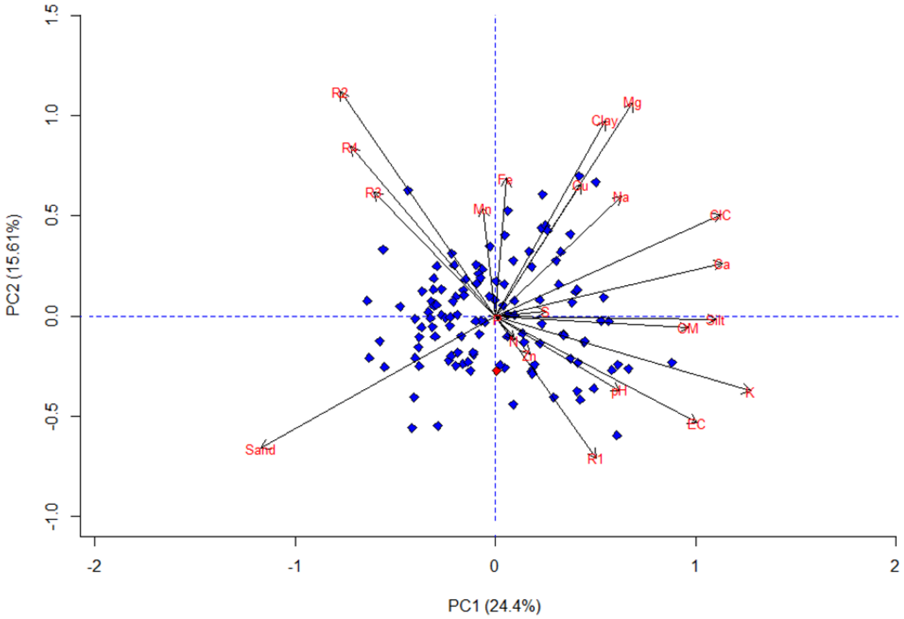

Fig. 4: Principal component analysis. R1= Ca/Mg, R2= Mg/K, R3= Ca/K, R4= (Ca/Mg) K.

Table 7: SQI in the department of Sucre (Northern Colombia).

Physicochemical Characteristics (Indicator)	Im	Nv
Silt	27.07	0.57
Sand	42.83	0.55
Clay	30.10	0.52
OM	1.17	0.74
N	23.26	0.69
P	40.35	0.91
Ca	19.74	0.61
Mg	6.70	0.67
K	0.62	0.82
Na	0.21	0.81
S	7.95	0.98
Fe	37.70	0.89
Mn	14.23	0.90
Zn	1.08	0.89
Cu	1.98	0.84
pH	6.40	0.38
CEC	26.87	0.52
EC	0.05	0.73
SQI		**0.72**

to pH. The percentage of clay is related to Mg and Cu. The PCA indicated that crop physiological processes depend on a balance between the parameters K, Ca, CEC, EC, Mg and the cation ratios Mg/K, Ca/K a,nd (Ca/Mg)K. A PCA analysis by Bonomelli *et al.* (2020) found that the variance was mostly determined by K, Mg, N, and Ca.

Calculated indicators and soil quality index values are shown in Table 7. The calculated SQI was 0.72, indicating that assessed soils in the Department of Sucre are of high quality. SQI value in the study is strongly influenced by the indicators S, P, Mn (Nv ≥ 0.90) and Fe, Zn, Cu, K, Na (Nv ≥ 0.80), whereas the indicator pH exerted very little influence. However, previous research has shown that soil quality should be determined by analyzing both physicochemical and biological soil characteristics. Therefore, contamination levels should be incorporated into the SQI valuation in those agricultural regions exposed to anthropogenic activity (Klimkowicz-Pawlas *et al*., 2019).

Lastly, using the soil quality index enables farmers to assess the current status of soil. This allows in turn to identify critical points for sustainable development, assess the possible impacts before any intervention, and monitor the impact of human interventions, thus helping to determine whether the use of soil is sustainable (De Laurentiis *et al.,* 2019). A proper understanding of the soil fertility conditions and is essential for food safety and sustainable development of agricultural systems. Reliable methods for the assessment of soil fertility are of great assistance for the management and monitoring of this resource. In general terms, assessed soils from the Sucre Department display high quality, indicating that soil fertility is well correlated with potential crop yields (Chabala *et al.,* 2020), as reflected in the variety of crops present in the municipalities. A better understanding of the interactions between crops and soil fertility will help to inform decisions aimed to increase crop productivity.

CONCLUSION

Soil quality is a major proxy for soil functional capacity within the ecological and land-use limits, while maintaining productivity and plant health. Soil degradation leads to a reduction in ecosystem functions and services of interest to humans and conservation of nature. According to the results, the macronutrients P and Ca displayed high values and S content was low. Phosphorus, an essential nutrient for plant development, interacts with other nutrients such as C and N. On the other side, when a high Ca level cannot be absorbed, it combines with other components to create non-soluble compounds that are difficult for plants to absorb. Cation ratios Mg/K, Ca/K and (Ca+Mg)/K indicated a deficiency of potassium. Correlation analyses suggest that Fe is interacting with Cu and that Ca is interacting with CEC. The PCA indicated that crop physiological processes depend on a balance between the parameters K, Ca, CEC, EC, Mg and of the cation ratios Mg/K, Ca/K, and (Ca/Mg)K. On the other hand, the SQI indicates high quality levels in soils assessed at 200 productivity units in selected municipalities of the Sucre Department of Colombia. Indicators S, P, Mn, Fe, Zn, Cu, K, and Na determined the current fertility status of studied soils. Therefore, it is recommended to monitor these soils, implementing fertilization plans according to the needs of each assessed soil. Physicochemical and cation ratio results will inform decision-making in order to define corrective strategies to increase soil fertility increase within the study area, as well as to develop decisions and actions at the national and local levels. A proper understanding of the conditions and dynamics of soil fertility is fundamental for food safety and the sustainable development of the agricultural system. In Latin America, Colombia is the third country with the highest resources, climate diversity, and annual precipitation rates, characteristics that favor its role in food production. Therefore, Colombia is considered by The United Nations Food and Agriculture Organization (FAO) as a country with great potential to be a pantry of the world. In this context, to ensure food security, regulatory measures should be implemented in agricultural activities and soil management. In this sense, the results of this study will serve as a baseline to propose monitoring and follow-up strategies on the agricultural practices in the region. Fertility was assessed using simple procedures and available information, which implies that this methodology can be replicated in other Colombian departments.

AUTHOR CONTRIBUTIONS

S. Rodelo-Torrente performed the literature review, analyzed, and interpreted the data, prepared the original draft. A.C. Torregroza-Espinosa performed

analyzed and interpreted the data, writing - original draft, writing – review and editing. D. Pinto Osorio helped in the contextualization and prepared the original draft. M.I. Moreno Pallares performed the literature review, experimental design, analyzed and interpreted the data, writing – original draft, writing – review, and editing. A. Corrales Paternina helped in the contextualization and prepared the original draft. A. Echeverría-González helped in the contextualization and prepared the original draft.

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CONFLICT OF INTEREST

The authors declare no potential conflict of interest regarding the publication of this work. In addition, ethical issues including plagiarism, informed consent, misconduct, data fabrication and, or falsification, double publication and, or submission, and redundancy have been completely witnessed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS

%	Percentage
>	Greater-than sign
<	Less-than sign
≥	Greater-than or equal to sign
±	Plus or minus sign
A.A.	Atomic absorption
Al	Aluminum
AP	Annual Precipitation
Av A	Average Altitude
Av T	Average Temperature
C	Clay
Ca	Calcium
CEC	Cation exchange capacity
$CaCO_3$	Calcium carbonate
CL	Clay loam
cm	Centimeter
Cu	Copper
DTPA	Diethyle netriamine pentaacetic acid
e.g.	For example
EC	Electrical conductivity
EPA	Environmental Protection Agency
Eq.	Equation
Fe	Iron
Fig.	Figure
g	Gram
h	Hectare
Im	Indicator mean
Imax	Indicator maximum value
Imin	Indicator minimum value
K	Potassium
KCL	Potassium Chloride

Km^2	Square kilometre
L	Loam
LS	Loamy sand
M	Unit of molar concentration.
masl	Meters Above Sea Level
Mg	Magnesium
mm	Millimetre
Mn	Manganese
meq/100 g	Cation exchange capacity as milli-equivalents per 100 grams
Mun	Municipiality
N	Nitrogen
Na	Sodium
NO_3-*N*	Nitrate Nitrogen
NOM	Norm
NTC	Colombian Technical Standard
Nv	Normalized value
OM	Organic Matter
p-value	Statistical significance
P	Phosphorus
PCA	Principal component analysis
pH	Potential of hydrogen
ppm	Parts per million
R^2	R-squared
S	Sulfur
SCL	Sandy clay loam
SD	Standard deviation
SEMARNAT	Ministry of Environment and Natural Resources
SFI	Soil fertility index
SL	Silt loam
SQI	Soil quality index
SR	Sub-region
Zn	Zinc

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