



## CASE STUDY

### Soil fertility in agricultural production units of tropical areas

S. Rodelo-Torrente<sup>1</sup>, A.C. Torregroza-Espinosa<sup>2,\*</sup>, M. Moreno Pallares<sup>3</sup>, D. Pinto Osorio<sup>1</sup>, A. Corrales Paternina<sup>2</sup>, A. Echeverría-González<sup>4</sup>

<sup>1</sup>Departamento de Civil y Ambiental, Universidad de la Costa, 080002 Barranquilla, Colombia

<sup>2</sup>Departamento de Productividad e Innovación, Universidad de la Costa, 080002 Barranquilla, Colombia

<sup>3</sup>Departamento de Biología, Universidad del Atlántico, 081001 Puerto Colombia, Colombia

<sup>4</sup>Departamento de Ciencias Empresariales, Universidad de la Costa, 080002 Barranquilla, Colombia

#### ARTICLE INFO

##### Article History:

Received 03 August 2021

Revised 13 November 2021

Accepted 20 December 2021

##### Keywords:

Soil nutrients

Soil physicochemical properties

Soil quality

Soil texture

Tropical soils

#### 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 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.

DOI: [10.22034/gjesm.2022.03.08](https://doi.org/10.22034/gjesm.2022.03.08)



NUMBER OF REFERENCES

46



NUMBER OF FIGURES

4



NUMBER OF TABLES

7

\*Corresponding Author:

Email: [atorreg4@cuc.edu.co](mailto:atorreg4@cuc.edu.co)

Phone: +30176 62812

ORCID: [0000-0001-8077-8880](https://orcid.org/0000-0001-8077-8880)

Note: Discussion period for this manuscript open until October 1, 2022 on GJESM website at the "Show Article".

## 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  $\text{NO}_3\text{-N}$  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<sup>2</sup>, 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	<a href="#">Delsouz Khaki et al. (2017)</a>
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	<a href="#">Nguemezi et al. (2020)</a>
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	<a href="#">Huang et al. (2021)</a>
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%)	<a href="#">Bünemann et al. (2021)</a>

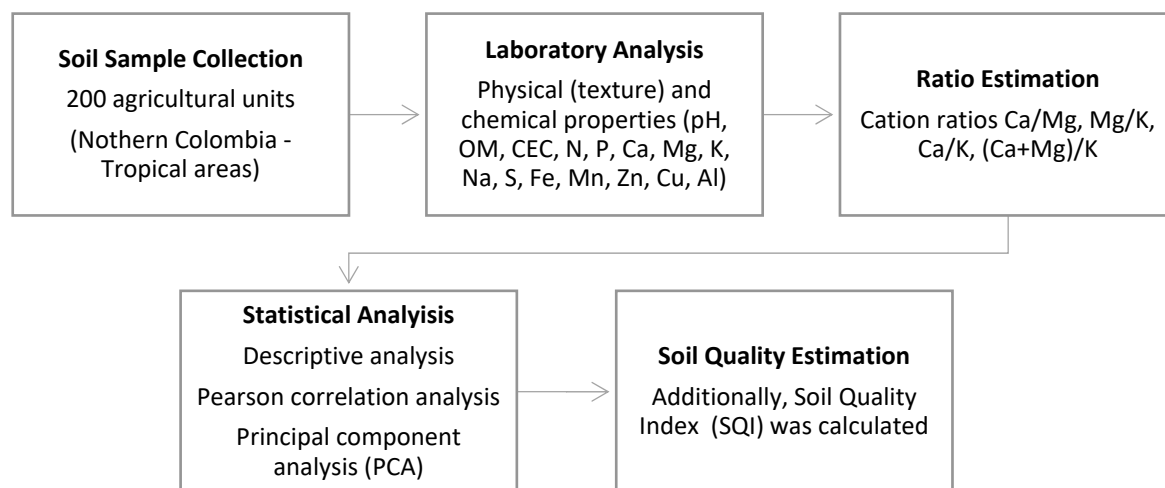


Fig. 1: Scheme of the methodology used in this study.

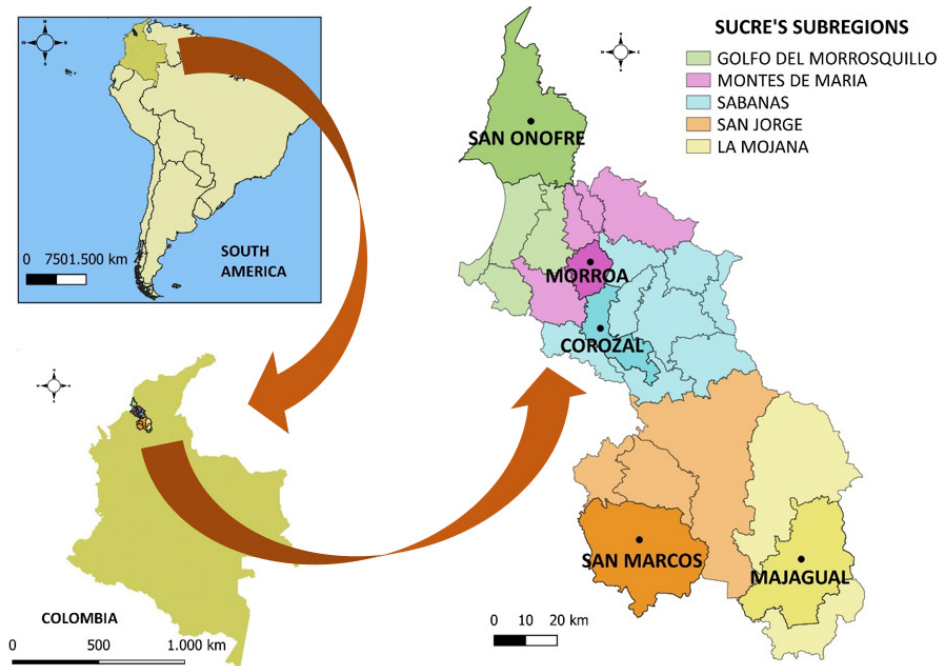


Fig. 2: Geographic location of the study area in the Department of Sucre in northern Colombia

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 Agustín 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 <sup>2</sup> )	Morroa	26.8°C	1000-	9° 20' 42" N	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
		160 masl	1200 mm	75° 18' 21" W				
Sabana (2101 km <sup>2</sup> )	Corozal	27°C	990-	9° 19' 3" N	Tropical dry forest, hills landscape, extensive grassland area	Sand, Sandy loam, Clay loam	Mollisols	Cassava, tropical yam, corn, beans, plantain, watermelon
		143 masl	1275 mm	75° 17' 29" W				
Golfo de Morrosquillo (1886 km <sup>2</sup> )	San Onofre	27.4°C	900-	9° 43' 59" N	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.
		17 masl	1300 mm	75° 31' 59" W				
San Jorge (2934 km <sup>2</sup> )	San Marcos	28°C	1300-	8° 40' 1" N	Tropical humid forest, tropical dry forest, natural grassland	Sand, Clay	Mollisols, Vertisols	Corn, rice, cassava, tropical yam, watermelon.
		25 masl	2300 mm	75° 7' 59" W				
Mojana (2337 km <sup>2</sup> )	Majagual	28°C	2320-	8° 32' 9" N	Tropical humid forest, wetland area	Clay loam	Mollisols, Histosols	Rice, corn, cassava, plantain, pumpkin, sugarcane, watermelon.
		28 masl	3000 mm	74° 39' 23" W				

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  $N_v$  was calculated using Eq. 1.

$$N_v = 1 - \left( \frac{I_m - I_{min}}{I_{max} - I_{min}} \right) \quad (1)$$

Where  $N_v$  = is the normalized value,  $I_m$  = indicator mean,  $I_{max}$  = indicator maximum value,  $I_{min}$  =

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  $1.05 \pm 0.51\%$  (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  $21.65 \pm 10.65$  parts per million (ppm),  $40.35 \pm 67.21$  ppm,  $0.46 \pm 0.43$  meq/100g,  $7.94 \pm 28.35$  ppm,  $15.63 \pm 17.30$  meq/100g,  $5.63 \pm 3.58$  meq/100g, and  $0.19 \pm 0.20$  meq/100g, respectively. For the case of the micronutrients Cu, Fe, Zn, and Mn, average values of  $2.20 \pm 1.66$  ppm,  $48.05 \pm 37.87$  ppm,  $1.16 \pm 1.26$  ppm, and  $14.22 \pm 12.24$  ppm, respectively. Average soil pH was  $6.05 \pm 0.80$ , 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  $22.84 \pm 10.23$

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

Variable	Method	Reference values		
		% Sand	% Silt	% Clay
PHYSICAL				
Texture	Bouyoucos NTC ISO 11464 (1975-11-24)	Under	Medium	High
CHEMICAL		<1.49	1.5-3	>3.01
OM (%)	OM = Organic carbon x 1.724 (1.724 constans)	0.09	0.1-0.199	>0.2
N (ppm)	NOM-021-SEMARAT-2000, 7.1.8 As-08 – Volumetry	<9.99	10-20	>20.01
P (ppm)	Bray II extraction – Spectrophotometry	<2.99	3-6	>6
Ca (meq/100 g)	Extraction ammonium acetate 1 M, pH 7.0 – A.A spectrometry	<1.5	1.5-3	>3
Mg (meq/100 g)	Extraction ammonium acetate 1 M, pH 7.0 – A.A spectrometry	<0.15	0.15-0.3	>0.301
K (meq/100 g)	Extraction ammonium acetate 1 M, pH 7.0 – A.A spectrometry	< 1 Normal	>1 Problem	
Na (meq/100 g)	Extraction with calcium monophosphate 0.008 M - Turbidimetry	<10	10-20	>20
S (ppm)	NTC-5526 Method A. DTPA/ A.A spectrometry	<20	20-50	>50
Fe (ppm)	NTC-5526 Method A. DTPA/ A.A spectrometry	<10	10-30	>30
Mn (ppm)	NTC-5526 Method A. DTPA/ A.A spectrometry	<1	1-2	>2
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 Acid	>3 Problem	
Al (meq/100 g)	IN-EE-081: NTC ISO 11464:1995, Extraction KCl 1 M - Volumetry	<5.5 Acid	5.5-6.5 neutral	> 6.5 alkaline
pH <sub>1:1, soil:water</sub>	EPA SW-846 9045 D /Electrometric	< 10	10-20	>20
CEC (mEq/100 g)	Extraction with ammonium acetate 1 M, pH 7.0 – Volumetry	<0.8	0.8-1.6	>1.6
EC <sub>1:5, soil:water</sub>	NTC 5596:2008 / Electrometric			
CATION RATIOS				
Ca/Mg	Estimate	<1	Calcium deficiency	
		1-2	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	

### Soil quality in agricultural production

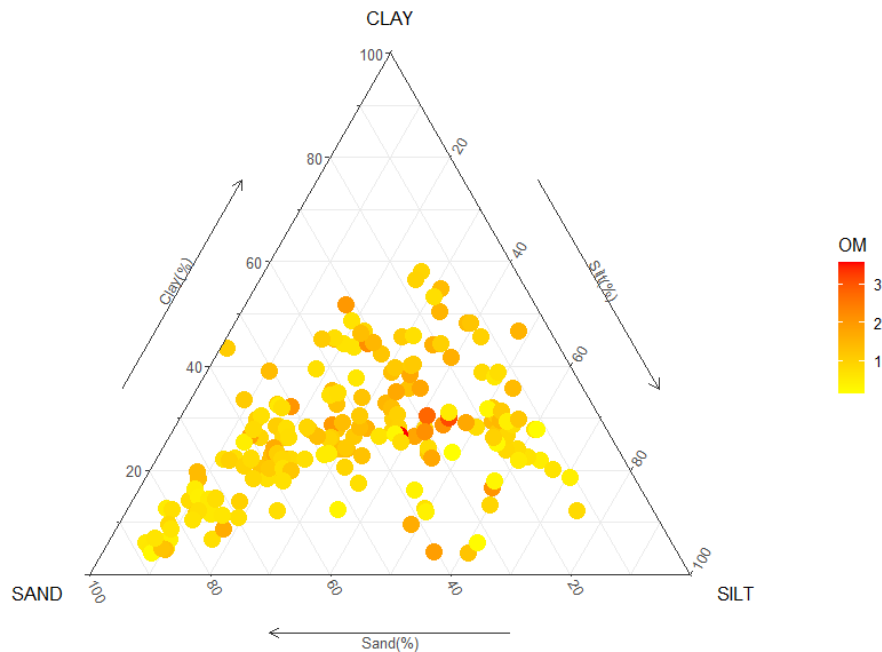


Fig. 3: Texture and OM of the studied soils.

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

Parameter	Maximum	Minimum	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 <sub>1:1, soil:water</sub>	7.68	4.19	6.05	0.80
CEC (meq/100g)	50.84	4.61	22.84	10.23
EC <sub>1:5, soil:water</sub> (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  $0.05 \pm 0.03$  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	Municipality				
	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<sub>3</sub> 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<sup>2+</sup> and Mg<sup>2+</sup> concentrations decrease

K<sup>+</sup> absorption, and high K<sup>+</sup> levels may aggravate Mg<sup>2+</sup> 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<sup>2</sup>=0.93, *p-value* ≤ 0.05), (Ca/Mg)K-Mg/K (R<sup>2</sup>=0.61, *p-value* ≤ 0.05), Fe-Cu (R<sup>2</sup>=0.53, *p-value* ≤ 0.05) and Ca-CEC (R<sup>2</sup>=0.64, *p-value* ≤ 0.05). A high negative correlation was also found between soil textures Silt-Sand (R<sup>2</sup>=0.52, *p-value* ≤ 0.05) and Sand-Clay (R<sup>2</sup>=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<sub>1</sub>). For the case of PC<sub>2</sub>, 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	p - value																						
	Silt	Sand	Clay	OM	N	P	Ca	Mg	K	Na	S	Fe	Mn	Zn	Cu	pH <sub>1:1</sub>	CEC	EC <sub>1:5</sub>	Ca/Mg	Mg/K	Ca/K	(Ca/Mg)/K	
Silt		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	0.00	0.05	0.01
Sand	<b>-0.72</b>		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	0.10
Clay	0.01	<b>-0.70</b>		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	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	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	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	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	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	0.19
K	0.48	-0.45	0.15	<b>0.60</b>	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	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	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	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	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	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	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	<b>0.73</b>	0.06	0.28		0.87	0.15	0.13	0.20	0.68	0.53	0.72	0.72
pH <sub>1:1</sub>	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	0.28
CEC	0.42	-0.59	0.42	0.42	0.07	-0.05	<b>0.80</b>	<b>0.63</b>	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	0.60
EC <sub>1:5</sub>	0.48	-0.30	-0.06	0.45	0.19	-0.04	0.47	0.10	<b>0.61</b>	0.18	0.11	-0.20	-0.09	0.04	-0.14	0.37	0.37		0.00	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	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	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	0.00
(Ca/Mg)/K	-0.24	0.15	0.03	-0.28	0.05	-0.13	0.05	0.12	<b>-0.62</b>	-0.11	-0.05	0.03	0.11	-0.19	-0.03	-0.10	-0.05	-0.36	-0.04	<b>0.78</b>	<b>0.96</b>		

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

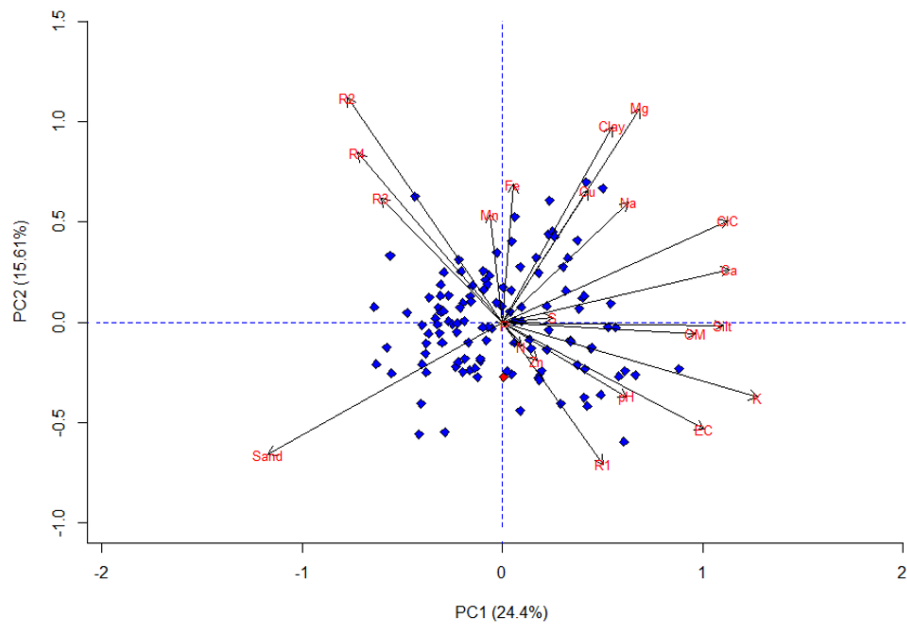


Fig. 4: Principal component analysis. R1= Ca/Mg, R2= Mg/K, R3= Ca/K, R4= (Ca/Mg) K.

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
<b>SQI</b>		<b>0.72</b>

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 and (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 ( $N_v \geq 0.90$ ) and Fe, Zn, Cu, K, Na ( $N_v \geq 0.80$ ), 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.

#### ACKNOWLEDGMENTS

The author acknowledges funding support from the Government of Sucre (Colombia) through royalty system [Project: “Application of engineering techniques that increase the resilience of agroecosystems to climate variability in the Department of Sucre” [BPIN2017000100029] and executed by the University of the Costa and the University of Sucre (Colombia).

#### 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.

#### OPEN ACCESS

This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution, and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article’s Creative Commons license unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit: <http://creativecommons.org/licenses/by/4.0/>

#### PUBLISHER’S NOTE

GJESM Publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

#### 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 <sub>3</sub>	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

<i>Km<sup>2</sup></i>	Square kilometre
<i>L</i>	Loam
<i>LS</i>	Loamy sand
<i>M</i>	Unit of molar concentration.
<i>masl</i>	Meters Above Sea Level
<i>Mg</i>	Magnesium
<i>mm</i>	Millimetre
<i>Mn</i>	Manganese
<i>meq/100 g</i>	Cation exchange capacity as milli-equivalents per 100 grams
<i>Mun</i>	Municipality
<i>N</i>	Nitrogen
<i>Na</i>	Sodium
<i>NO<sub>3</sub>-N</i>	Nitrate Nitrogen
<i>NOM</i>	Norm
<i>NTC</i>	Colombian Technical Standard
<i>Nv</i>	Normalized value
<i>OM</i>	Organic Matter
<i>p-value</i>	Statistical significance
<i>P</i>	Phosphorus
<i>PCA</i>	Principal component analysis
<i>pH</i>	Potential of hydrogen
<i>ppm</i>	Parts per million
<i>R<sup>2</sup></i>	R-squared
<i>S</i>	Sulfur
<i>SCL</i>	Sandy clay loam
<i>SD</i>	Standard deviation
<i>SEMARNAT</i>	Ministry of Environment and Natural Resources
<i>SFI</i>	Soil fertility index
<i>SL</i>	Silt loam
<i>SQI</i>	Soil quality index
<i>SR</i>	Sub-region
<i>Zn</i>	Zinc

## REFERENCES

- Agronet., (2021). Red de información y comunicación del sector Agropecuario Colombiano. MinAgricultura.
- Amisili, J.P.; van Es, H.M.; Schindelbeck, R.R., (2021). Cropping system and soil texture shape soil health outcomes and scoring functions. *Soil Secur.*, 4: 1000012 (11 pages).
- Bader, B.R.; Taban, S.K.; Fahmi, A.H.; Abood, M.A.; Hamdi, G.J., (2021). Potassium availability in soil amended with organic matter and phosphorous fertiliser under water stress during maize (*Zea mays*) growth. *J. Saudi Soc. Agric. Sci.*, 20(6): 390-394 (5 pages).
- Bonomelli, C.; Mogollon, R.; de Freitas, S.T.; Zoffoli, J.P.; Contreras, C., (2020). Nutritional relationships in bitter pit-affected fruit and the feasibility of vis-NIR models to determine calcium concentration in 'fuji' apples. *Agronomy*, 10: 1474 (13 pages).
- Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; De Deyn, G.; de Goede, R.; Fleskens, L.; Geissen, V.; Kuyper, T.W.; Mäder, P.; Pulleman, M.; Sukkel, W.; van Groenigen, J.W.; Brussaard, L. (2018). Soil quality – A critical review. *Soil Biol. Biochem.*, 120: 105-125 (21 pages).
- Bustamante, N.; Danoucaras, N.; McIntyre, N.; Díaz-Martínez, J.; Restrepo-Baena, O.J., (2016). Review of improving the water management for the informal gold mining in Colombia. *Revista Facultad de Ingeniería Universidad de Antioquia.*, 79: 174-184 (11 pages).
- CCME, (2014). Canadian environmental quality guidelines. Canadian council of ministers of the environment.
- Chabala, L.M.; Chimungu, J.G.; Lark, R.M.; Mtambanengwe, F.; Nalivata, P.C.; Phiri, E.; Sakala, G.M., (2020). Eliciting experts' tacit models for the interpretation of soil information, an example from the evaluation of potential benefits from conservation agriculture. *Geoderma.*, 376: 114545 (11 pages).
- Chang, H.; Wang, Q.; Li, Z.; Wu, J.; Xu, X.; Shi, Z., (2020). The effects of calcium combined with chitosan amendment on the bioavailability of exogenous pb in calcareous soil. *J. Integr. Agric.*, 19(5): 1375-1386 (12 pages).
- Coblinski, J.A.; Inda, A.V.; Demattê, J.A.M.; Dotto, A.C.; Gholizadeh, A.; Giasson, É., (2021). Identification of minerals in subtropical soils with different textural classes by VIS–NIR–SWIR reflectance spectroscopy. *Catena (Giessen).*, 203: 105334 (10 pages).
- Cornell, R.M.; Schwertmann, U., (2006). The iron oxides: structure, properties, reactions, occurrences and uses. 2nd Edition. Wiley.
- De Laurentiis, V.; Secchi, M.; Bos, U.; Horn, R.; Laurent, A.; Sala, S., (2019). Soil quality index: Exploring options for a comprehensive assessment of land use impacts in LCA. *J. Cleaner Prod.*, 215:63-74 (12 pages).
- Delsouz Khaki, B.; Honarjoo, N.; Davatgar, N.; Jalalian, A.; Torabi Golsefidi, H., (2017). Assessment of two soil fertility indexes to evaluate paddy fields for rice cultivation. *Sustainability.*, 9(8): 1299 (13 pages).
- DNP., (2003). Organización de las Naciones Unidas para la Agricultura y la Alimentación (FAO). Programa de desarrollo sostenible de la región de La Mojana, Bogotá. Departamento Nacional de Planeación (567 pages).
- FAO., (2021). Food and Agriculture Organization of the United Nations. Soil portal.
- Huang, W.; Zong, M.; Fan, Z.; Feng, Y.; Li, S.; Duan, C.; Li, H., (2021). Determining the impacts of deforestation and corn cultivation on soil quality in tropical acidic red soils using a

- soil quality index. *Ecol. Indic.*, 125: 107580 **(10 pages)**.
- ICONTEC., (2004). NTC 3656, Gestión ambiental suelo, Toma de muestras de suelo para determinar contaminación. Instituto Colombiano de Normas Técnicas y Certificación. Bogotá, Colombia.
- IDEAM, (2018). Atlas climatológico de Colombia. Instituto De Hidrología, Meteorología y Estudios Ambientales.
- IGAC, (2016). Suelos y tierras de Colombia, subdirección de agrología. Instituto Geográfico Agustín Codazzi. Bogotá DC, Tomo 1 **(854 pages)**.
- IGAC, (2021). Colombia, un país con una diversidad de suelos ignorada y desperdiciada. Bogotá, Colombia. Instituto Geográfico Agustín Codazzi.
- Karbassi, A.R.; Pazoki, M., (2015). Environmental qualitative assessment of rivers sediments. *Global J. Environ. Sci. Manage.*, 1(2): 109-116 **(8 Pages)**.
- Karbassi, A.R.; Heidari, M., (2015). An investigation on role of salinity, pH and DO on heavy metals elimination throughout estuarial mixture. *Global J. Environ. Sci. Manage.*, 1(1): 41-46 **(6 pages)**.
- Klimkowicz-Pawlas, A.; Ukalska-Jaruga, A.; Smreczak, B., (2019). Soil quality index for agricultural areas under different levels of anthropopressure. *Int. Agrophys.*, 33: 455-462 **(8 pages)**.
- Kurgat, B.K.; Ngenoh, E.; Bett, H.K.; Stöber, S.; Mwonga, S.; Lotze-Campen, H.; Rosenstock, T.S., (2018). Drivers of sustainable intensification in kenyan rural and peri-urban vegetable production. *Int. J. Agric. Sustainability.*, 16(4-5): 385-398 **(14 pages)**.
- Lal, R., (2015). Restoring soil quality to mitigate soil degradation. *Sustainability.*, 7(5): 5875-5895 **(21 pages)**.
- León-Moreno, C.E.; Rojas-Molina, J.; Castilla-Campos, C.E., (2019). Physicochemical characteristics of cacao (Theobroma cacao L.) soils in Colombia: Are they adequate to improve productivity? *Agronomía Colombiana.*, 37(1): 28-38 **(11 pages)**.
- León, S.L.A., (2001). Evaluación de la fertilidad del suelo. En: Silva F. (ed.). Fertilidad de suelos, diagnóstico y control. 2a edición. Sociedad Colombiana de la Ciencia del Suelo **(15 pages)**.
- Marrugo-Negrete, J.; Pinedo-Hernandez, J.; Díez, S., (2017). Assessment of heavy metal pollution, spatial distribution and origin in agricultural soils along the Sinú River Basin, Colombia. *Environ. Res.*, 154: 380-388 **(9 pages)**.
- Martínez-Mera, E.A.; Torregróza-Espinosa, A.C.; Valencia-García, A.; Rojas Jerónimo, L., (2017). Relationship between soil physicochemical characteristics and nitrogen-fixing bacteria in agricultural soils of the Atlántico department, Colombia. *Soil and Environment.*, 36: 174-181 **(8 pages)**. <https://doi.org/10.1016/j.heliyon.2019.e02217>
- Martínez-Mera, E.A.; Torregróza-Espinosa, A.C.; Crissien-Borrero, T.J.; Marrugo-Negrete, J.L.; González-Márquez, L.C., (2019). Evaluation of contaminants in agricultural soils in an Irrigation District in Colombia. *Heliyon.*, 5(8): e02217 **(9 pages)**.
- Moraru, S.S.; Ene, A.; Badila, A., (2020). Physical and hydro-physical characteristics of soil in the context of climate change. A case study in danube river basin, SE Romania. *Sustainability.*, 12(9174): 9174 **(26 pages)**.
- Mukherjee, A.; Lal, R., (2014). Comparison of soil quality index using three methods. *PLoS One.*, 9(8): e105981 **(15 pages)**.
- Muñoz-Rojas, M., (2018). Soil quality indicators: critical tools in ecosystem restoration. *Curr. Opin. Environ. Sci. Health.*, 5: 47-52 **(6 pages)**.
- Ndung'u, M.; Ngatia, L.W.; Onwonga, R.N.; Mucheru-Muna, M.W.; Fu, R.; Moriasi, D.N.; Ngetich, K.F., (2021). The influence of organic and inorganic nutrient inputs on soil organic carbon functional groups content and maize yields. *Heliyon.*, 7(8): e07881 **(10 pages)**.
- Nguemezi, C.; Tematio, P.; Yemefack, M.; Tsozue, D.; Silats, T.B.F., (2020). Soil quality and soil fertility status in major soil groups at the Tombel area, South-West Cameroon. *Heliyon.*, 6(2): e03432 **(10 pages)**.
- Novello, O.A.; Quintero, C.E., (2009). Contenidos de fósforo total en suelos distrito Villa Eloisa (Santa Fe). *Inf. Agronómicas.*, 41: 11-15 **(5 pages)**.
- Obriot, F.; Stauffer, M.; Goubard, Y.; Cheviron, N.; Peres, G.; Eden, M.; Revallier, A.; Vieublé-Gonod, L.; Houot, S., (2016). Multi-criteria indices to evaluate the effects of repeated organic amendment applications on soil and crop quality. *Agric. Ecosyst. Environ.*, 232: 165-178 **(14 pages)**.
- Paz-Ferreiro, J.; Fu, S., (2016). Biological indices for soil quality evaluation: Perspectives and limitations. *Land Degrad. Dev.*, 27(1): 14-25 **(12 pages)**.
- R Core Team, (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing.
- Ruan, L.; Zhang, J.; Xin, X., (2014). Effect of poor-quality irrigation water on potassium release from soils under long-term fertilization. *Acta Agric. Scand. Sect. B.*, 64(1): 45-55 **(11 pages)**.
- Silva-Leal, J.A.; Pérez-Vidal, A.; Torres-Lozada, P., (2021). Effect of biosolids on the nitrogen and phosphorus contents of soil used for sugarcane cultivation. *Heliyon.*, 7(3): e06360 **(8 pages)**.
- Torri, S.I.; Correa, R.S.; Renella, G., (2017). Biosolid application to agricultural land a contribution to global phosphorus recycle: a review. *Pedosphere.*, 27(1): 1-16 **(16 pages)**.
- Vanlauwe, B.; AbdelGadir, A.H.; Adewopo, J.; Adjei-Nsiah, S.; Ampadu-Boakye, T.; Asare, R. et al., (2017). Looking back and moving forward: 50 years of soil and soil fertility management research in sub-Saharan Africa. *Int. J. of Agric. Sustainability.*, 15(6): 613-631 **(19 pages)**.
- Van Leeuwen, J. P.; Creamer, R. E.; Cluzeau, D.; Debeljak, M.; Gatti, F.; Henriksen, C. B.; Kuzmanovski, V.; Menta, C.; Pérès, G.; Picaud, C.; Saby, N.P.A.; Trajanov, A.; Trinsoutrot-Gattin, I.; Visioli, G.; Rutgers, M., (2019). Modeling of soil functions for assessing soil quality: soil biodiversity and habitat provisioning. *Front. Environ. Sci.*, 7: 113 **(13 pages)**.
- Villasanti, C.; Román, P.; Pantoja, A., (2013). El manejo del suelo en la producción de hortalizas con buenas prácticas agrícolas. In Food and Agriculture Organization of the United Nations **(31 pages)**.
- Yu, H.; Huang, X.; Ning, J.; Zhu, B.; Cheng, Y., (2014). Effect of cation exchange capacity of soil on stabilized soil strength. *Soils Found.*, 54(6): 1236-1240 **(5 pages)**.
- Yu, H.; Liu, C.; Zhu, J.; Li, F.; Deng, D.; Wang, Q.; Liu, C., (2016). Cadmium availability in rice paddy fields from a mining area: The effects of soil properties highlighting iron fractions and pH value. *Environ. Pollut.*, 209: 38-45 **(8 pages)**.
- Zhang, C.; Xue, S.; Liu, G.; Song, Z., (2011). A comparison of soil qualities of different revegetation types in the loess plateau, china. *Plant Soil.*, 347(1/2): 163-178 **(16 pages)**.



#### AUTHOR (S) BIOSKETCHES

**Rodelo-Torrente, S.**, M.Sc. Student, Departamento de Civil y Ambiental. Universidad de la Costa, Barranquilla Atlántico, Colombia.

- Email: [srodela2@cuc.edu.co](mailto:srodela2@cuc.edu.co)
- ORCID: 0000-0002-5820-6701
- Web of Science ResearcherID: NA
- Scopus Author ID: NA
- Academic Homepage: <https://www.researchgate.net/profile/Sara-Rodelo-Torrente>

**Torregroza-Espinosa, A.C.**, Ph.D., Associate Professor, Departamento de Productividad e Innovación. Universidad de la Costa, Barranquilla Atlántico, Colombia.

- Email: [atorregr4@cuc.edu.co](mailto:atorregr4@cuc.edu.co)
- ORCID: 0000-0001-8077-8880
- Web of Science ResearcherID: ABB-5481-2021
- Scopus Author ID: 57189332407
- Academic Homepage: <https://www.researchgate.net/profile/Ana-Torregroza>

**Moreno Pallares, M.**, Ph.D. Candidate, Departamento de Biología. Universidad del Atlántico, Barranquilla Atlántico, Colombia.

- Email: [odonata12@gmail.com](mailto:odonata12@gmail.com)
- ORCID: 0000-0002-4136-0104
- Web of Science ResearcherID: ABE-3273-2021
- Scopus Author ID: NA
- Academic Homepage: <https://www.researchgate.net/profile/Maria-Moreno-110>

**Pinto Osorio, D.**, Ph.D., Professor, Departamento de Civil y Ambiental. Universidad de la Costa, Barranquilla Atlántico, Colombia.

- Email: [dpinto3@cuc.edu.co](mailto:dpinto3@cuc.edu.co)
- ORCID: 0000-0002-1496-5722
- Web of Science ResearcherID: AAV-5458-2021
- Scopus Author ID: 57195677095
- Academic Homepage: <https://www.researchgate.net/profile/Diana-Pinto-Osorio>

**Corrales Paternina, A.**, M.Sc., Professor, Departamento de Productividad e Innovación. Universidad de la Costa, Barranquilla Atlántico, Colombia.

- Email: [acorrales@cuc.edu.co](mailto:acorrales@cuc.edu.co)
- ORCID: 0000-0003-1046-467X
- Web of Science ResearcherID: NA
- Scopus Author ID: 57209807305
- Academic Homepage: <https://www.researchgate.net/profile/Amaira-Corrales>

**Echeverría González, A.**, M.Sc., Professor, Departamento de Civil y Ambiental. Universidad de la Costa, Barranquilla Atlántico, Colombia.

- Email: [aecheverria@cuc.edu.co](mailto:aecheverria@cuc.edu.co)
- ORCID: 0000-0002-0256-1130
- Web of Science ResearcherID: NA
- Scopus Author ID: 57218249185
- Academic Homepage: <https://www.researchgate.net/profile/Ana-Echeverria-Gonzalez>

#### HOW TO CITE THIS ARTICLE

Rodelo-Torrente, S.; Torregroza-Espinosa, A.C.; Moreno Pallares, M.; Pinto Osorio, D.; Corrales Paternina, A.; Echeverría-González, A., (2022). Soil fertility in agricultural production units of tropical areas. *Global J. Environ. Sci. Manage.*, 8(3): 403-418.

DOI: [10.22034/gjesm.2022.03.08](https://doi.org/10.22034/gjesm.2022.03.08)

url: [https://www.gjesm.net/article\\_248238.html](https://www.gjesm.net/article_248238.html)

