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PHYSICOCHEMICAL CHARACTERISTICS OF THE SOIL IN SACCHARUM OFFICINARUM L. (SUGAR CANE) CULTIVATION IN THE PROVINCE OF PASTAZA, ECUADORIAN AMAZON

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ABSTRACT

The Ecuadorian Amazon is a mega-diverse ecological niche in flora and fauna. Currently, crop areas that serve as a source of sustenance for rural populations have increased. It was essential to evaluate the physicochemical characteristics of the soil in sugarcane crops (Saccharum officinarum L.) in the Pastaza province of the Ecuadorian Amazon to evaluate its fertility in comparison to a primary forest (PF). The composite soil samples were collected in five agricultural production units (APUs) and PF as a comparison agent at a depth of 0.15 m. The physicochemical variables evaluated were: bulk density, texture, pH, organic matter, macronutrients, micronutrients, and base ratio. High concentrations of organic matter were found (11.99 to 12.78%), as well ashighly acidic soils (pH 3.90 to 4.67) and sandy loam and silty soil textures. Macronutrients were generally medium to low in concentration, and micronutrients medium to high. 64.70% of the variables are concentrated in CP1 and CP2; as factors with the greatest contribution to soil fertility, they are affected by P, NH_4, clay, B, S, Mn, Fe, silt, sand, Mg, Zn, sum of bases, Ca, K, and Cu. The physicochemical results of the soil with S. officinarum and PF cultivation demonstrated a characteristic behavior of Amazonian soils. S. officinarum did not exert any influence on soil fertility, and it adapted fully to the nutritional and highly acidic conditions of the Amazonian soils.

Keywords: Macronutrients, micronutrients, soil texture, principal component.

INTRODUCTION

Although rainforest soils (such as those in the Amazon basin) have high levels of productivity, they are nutrient-poor and depend on soil nutrient cycling. Organic matter maintains fertility, has a high turnover rate, and is sensitive to weathering, which makes soils fragile and susceptible to human disturbance, resulting in loss of soil functions, damage to ecosystems, and a loss of the services they provide (Guimarães et al. 2017).Thus, chemical weathering in the humid tropics degrades soluble soil components, especially plant nutrients of mineral origin (e.g., calcium, potassium, and magnesium), resulting in nutrient deficiencies, low storage capacity over time, and the enrichment of plant-toxic aluminum in soil solutions (Pincus et al. 2017).

This evolutionary condition is particularly true for oxisols, which are typical tropical lateritic soils characterized by high kaolinite content, low cation exchange capacity (<10 cmolc/kg), low alkalinecation availability, high exchangeable aluminum content, and low pH (<5). Meanwhile, CEC, defined as the soil's ability to retain positively charged ions, is an important indicator of soil fertility (Ulusoy et al.2016).

According to Hernandes, Scarpare, and Seabra (2018), bioenergy production from various biomass sources has increased worldwide by converting agricultural raw materials into biomass fuels. Of course, compared to other energy sources, biofuels are only effective if they are environmentally friendly, and their large-scale production is only justified if the social and economic consequences are favorable.

Due to the growing demand for bioenergy, sugarcane cultivation areas in Brazil continue to expand, showing different dynamics in terms of traditional and new cultivation areas, different scales, and alternative land uses. Caldarelli and Gilio (2018) noted that ethanol production in Brazil increased by 170% between 2000 and 2015, reaching 28,488,000 cubic meters. This expansion was made possible by the inclusion of new land: the total area under sugarcane cultivation increased from approximately 4,880,000 hectares in 2000 to 10,870,000 hectares in 2015 (an increase of 123%).

Sugarcane is an important crop grown in tropical and subtropical regions and is now considered a specialty crop for both food production and bioenergy due to its high proportion of solid and liquid biomass. In 2012, an estimated 1.8 billion tons of sugarcane biomass was produced in more than 100 countries worldwide (Silalertruksa&Gheewala 2018). Therefore, agricultural activities of sugarcane cultivation have significant impacts on ecosystems, where deforestation and burning during initial deforestation are the main consequences of biodiversity loss (Semie, Silalertruksa, &Gheewala 2019).

What is most worrying about deforestation is that the cleared land is not being used; in 2008, 15% of Brazil's cleared area (almost 11 million hectares) was underutilized by traditional agriculture (Alkimim& Clarke 2018). This means that the impact of land use changes on dynamic behavior and relevant soil structural properties (i.e., bulk density, soil infiltration resistance, pore size distribution, hydraulic-electrical conductivity, agglomeration stability, and macroaggregation) are indirectly related to soil structure. Soil plays a key role in water, air, and heat transport (Dörner et al. 2010; Cherubin et al. 2017).

Many studies have shown that agricultural management practices seen as events manifest themselves in different time periods. In spite of so many studies, little is known about seasonal changes in soil properties and sugarcane crops in subtropical regions under different management systems, as most studies have focused on warm climates (Awe, Reichert,&Fontanela, 2020).

However, the Ecuadorian Amazon is no stranger to the global problem of land expansion for energy extraction through sugarcane cultivation, seen as an income-generating activity for the country's rural population. Ecuador's Amazon region has a tropical and subtropical climate; in this regard, the objective of this study was to evaluate sugarcane as a component of land use change in the Ecuadorian Amazon in order to provide recommendations for the management system of this crop.

MATERIALS AND METHODS

A. Study Area

The research was carried out in the parish of Fátima, located 7 km from the city of Puyo, therefore in the northeast of Pastaza province in Ecuador's Amazon region, with average temperatures of 18–24°C, average rainfall of 3,000–5,000 mm, and relative humidity of above 85%. Soils in this region belong to the inceptisol order. They are young, shallow, generally acidic soils without well-defined horizonsand of low natural fertility (low potassium, calcium, and phosphorus). They have a high iron content (Nieto and Caicedo 2012) and a high susceptibility to erosion (Díaz 2018). Agricultural production of sugarcane (Saccharum officinarum L.), naranjilla (Solanum quitoense), cacao (Theobroma cacao L.), taro (Colocasia esculenta), plantain (Musa × paradisiaca), cassava (Manihot esculenta), and corn (Zea mays) stand out according to the Plan de Ordenamiento Territorial del Cantón Pastaza (Canton Pastaza's Land Management Plan) 2015–2020 (POTCPz, 2015; González et al., 2019).

B. Soil Sample

Soil sample collection is extremely important since the sample must correctly represent the area under study. The arable layer soil is very heterogeneous due to natural phenomena and the incorporation of exogenous materials, such as fertilizers, which modify soil properties (Díaz-Romeu & Hunter 1978). However, soil samples are susceptible to spatial biases in a certain geographical area. For example, soil samples may be taken more in areas that are easier to access (Zhang & Zhu 2019). Before sampling, the boundaries of the horizons above the profile being studied should be marked (Hodgson 1987).

At random, five sugarcane agricultural production units (APUs) in Fátima parish and one primary forest (PF) plot were selected as a standard of comparison, from which the samples were collected. Soil sample collection was performed using the stratified zigzag method with an amplitude of six points to create a composite sample at a depth of 0–15 cm (González et al. 2019; Grahmann et al. 2020). The collected soil samples were placed in 2 kg polyethylene bags and taken to the laboratory, where wood residues, roots, and little stones were removed. The soil was subsequently dried at 45°C under greenhouse conditions for 5 days, then ground and sieved to particles of 2 mm in diameter.

C. Physicochemical Characteristics of the Soil

Physical properties, such as soil texture, were determined using theBouyoucos densimeter method for pre-treated samples after organic matter removal (Porta et al. 2003). pH was determined using a standard pH meter in a soil-water mixture of 1:2.5. (Qiu et al. 2019; Ning et al. 2020). Bulk density (BD) was measured by means of the pycnometer method (González et al. 2019). Organic carbon content was determined using the Walkley-Black wet oxidation method (Nelson and Sommers 1982; Alavaisha et al. 2019), and organic carbon content was multiplied by a factor of 1.72 to determine soil organic matter (SOM) (Bhatti et al. 2016). Nitrogen (N) was determined using the Kjeldahl method (Wang et al. 2016). Total phosphorus (TP) was extracted from the soil composite samples by digestion with H_2SO_4-$HClO_4$. All extracted P was analyzed colorimetrically using the molybdate blue method (Li et al. 2019) by measuring the absorbance of the test mixtures at 880 nm with a UV spectrophotometer (Thermo Fisher Scientific).

Soil samples were digested according to the USEPA method 3050B (United States Environmental Protection Agency 1996). Concentrations of potassium K, calcium Ca, magnesium Mg, zinc Zn, copper Cu, iron Fe, manganese Mn, and boron B, were determined using an atomic absorption spectrometer (Oliveira et al. 2018; Wang et al. 2015; Zhao-Miao et al. 2014).

Calibration curves were prepared in a concentration range from 0.1 to 5.0 mg/l for K, Ca, Mg, Zn, Cu, Fe, Mn, and B, and from 5.0 to 200.0 mg l-1 for Ca, Fe, and Mg. The glassware used in the experiments was previously decontaminated with a nitric acid solution (10% v/v) for 24h then washed with ultrapure water and dried at room temperature, following the methodology of Oliveira-Souza et al. (2014). The base ratio and base sum of exchangeable major cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) were determined according to the methodology of Yu et al. (2020).

D. Statistical Analysis

Principal Component Analysis (PCA) was applied to summarize the values of physicochemical attributes at depths of 0 to 0.15 cm in the soils of the study areas. Errors due to scales and units of variables were reduced, and data were standardized with zero mean and unit variance. Thus, the set of 21 variables was characterized by four new variables (PC1, PC2, PC3, and PC4). The suitability of this analysis was verified by the total information of the original variables retained in the principal components. These data showed higher or lower eigenvalues than the attribute unit; only eigenvalues that explain $\geq 5\%$ of the variation in the data were considered. When more than one parameter was selected in a single PC, correlation analysis was applied to identify their correlations (Guo et al. 2018).Multivariate statistical analysis was analyzed using the software IBM SPSS Statistics version 29.0.1.0 (Statistics, 2023).

RESULTS AND DISCUSSION

A. Physical Properties and pH of the Soil

Table 1 shows the physical characteristics of the soil in the cultivation of S. officinarum L. The bulk density (BD) in this soil fluctuated between 1.98 and 2.21 g/cm^3, values similar to the PF with a BD of 2.15 g/cm3 and to those cited by Mendes-Brito et al. (2018), who indicated that the BD of soils suitable for cultivation is 2.0 g/cm^3, depending mainly on the soil texture, amount of OM, and the crop.

The pH of APUs (3.90 to 4.67) and PFs (4.42), according to the Ecuadorian Environment Ministry’s unified text of secondary legislation(TULAS, 2014), are highly acidic (pH <4.5) and moderately acidic (pH 4.6 to 5.5). The similar pH values for APUs and PFsare a result of the intrinsic edaphoclimatic conditions of the Amazon region; similar values were obtained by Melo et al. (2018) for soils in the Brazilian Amazon region, finding on average pH values of 4.3 and 4.2 at depths of 0–0.05 and 0.05–0.10 m, respectively, and Blum et al. (2012) found soil pH values of 5.1 and 4.9 at depths of 0–0.2 and 0.2–0.4 m, respectively. And for Firman Ghazali et al. (2019), soil pH is important in agricultural activity because it controls the amount and concentration of soil minerals that plants require in order to grow.

The soil textures in the evaluated APUs are sandy loam and silt loam; these results contrast with Fernandes et al. (2018), who indicated that the predominant fraction is sand and silt in Amazonian soil. Furthermore,Meimaroglou&Mouzakis (2019) state that the clay content in soils should be between 5 and 18% to avoid soil compaction.

Table 1. Physical characteristics and pH of soil under cultivation of S. officinarum L. in the study area

Plot	BD	pH	Texture (%)			
	g/cm^3		Sand	Silt	Clay	Denomination
1	2.13	3.90 HA	72	23	5	Sandy loam
2	2.02	4.67 MA	71	22	7	Sandy loam
3	1.98	4.42 HA	48	50	2	Silty loam
4	2.21	4.34 HA	46	51	3	Silty loam
5	2.18	4.58 MA	70	25	5	Sandy loam
0	2.15	4.42 HA	74	15	11	Sandy loam

0=PF: primary forest; interpretation: MA: moderately acidic, HA: highly acidic.

B. Chemical Properties of the Soil (Macronutrients)

The OM values reported in Table 2 of the soils with cultivated S. officinarum L. and PF are similar (11.99 and 12.78%). The OM content in the cultivated areas was mainly due to the tasks that generate agricultural residues in crop management, such as weeding, leaf removal, and finally harvest, which generate a lot of OM that is deposited in the soil, while the PF, due to the Ecuadorian Amazon region's natural dynamics and edaphoclimatic conditions, positively increases the OM content. For Awe et al. (2020), OM is fundamental for the functioning of many physical, chemical, and biological soil processes, such as nutrient storage and exchange capacity, soil structural stability, porosity, water availability, and pollutant degradation.

The NH_4 ammoniacal nitrogen concentrations in the APUs (29 to 35 ppm) and PF (52 ppm) can be categorized as medium and high, respectively (Table 2). These results are similar to those reported by Bravo et al. (2017) who observed NH_4 values from 25 and 98 ppm, categorized as medium to high. The NH_4 concentration in the PF is higher than in the APUs (Table 2) due to the fact that in the PF theforestry, leguminous, and herbaceous species form a heterogeneous ecosystem. For Zhong et al. (2019), the impact of plant species on soil N is caused by different N uptake rates and leaf litter quality; less rich plant communities increase inorganic N accumulation as a result of abundant biomass that is easily decomposed and mineralized. Meanwhile, for Rengel et al. (2011), given that S. officinarum L. is grown as a monoculture, it requires substantial N input for its vegetative development, with vigorous stems and increased leaf area index, growth rate, and stem yield.

Table 2. Chemical characteristics (macronutrients) and OM of the soil under S. officinarum L. cultivation in the study area

Plot	%OM	Macronutrient					
		NH_4 (ppm)	P (ppm)	K (meq/100ml)	Ca (meq/100ml)	Mg (meq/100ml)	S (ppm)
1	11.99	33 M	7.32	0.33 M	2.09 L	0.79 L	19 M

	H		L				
2	12.37 H	35 M	6.55 L	0.35 M	1.97 L	0.74 L	18 M
3	12.56 H	31 M	5.95 L	0.16 L	2.07 L	0.57 L	21 H
4	12.47 H	29 M	6.23 L	0.14 L	2.07 L	0.56 L	23 H
5	12.78 H	34 M	7.93 L	0.38 M	4.93M	1.28 M	15 M
0	12.78 H	52 H	13.96 H	0.18 L	2.11 L	0.59 L	13 M

Interpretation of the concentration: H: high, M: medium, L: low.

The soils of the APUs with S. officinarum L. cover showed low P concentrations (5.95 to 7.93 ppm), while the soil of the PF denoted a high P concentration (13.96 ppm). According to Aleixo et al. (2020), the increase in P concentrations in the PF is attributed to the existence of leguminous trees, while for Rengel et al. (2011) the monoculture of S. officinarum L. needs this macronutrient during almost its entire cycle, accumulating it in stems and leaves. Table 2 outlines how K concentration is low (0.18 meq/100ml) in the PF, as is that in the APUs (0.14 to 0.38 meq/100ml). These results are because of the edaphic characteristics of the Amazon region. For Chorom et al. (2009), S. officinarum L. absorbs K during the tillering and ripening stages, finally accumulating it in the stem during the stages of maximum growth and ripening.

The Ca (1.97 to 4.93 meq/100ml) and Mg (0.56 to 1.28 meq/100ml) concentrations reported in Table 2 were similar for both APUs and the PF. These low concentrations are similar to those reported by Awe et al. (2020) for Ca (1.0 to 1.8 meq/100ml) and Mg (0.3 to 0.5 meq/100ml) for soils with S. officinarum L. Our results contrast withthose reported by Bravo et al. (2017) for Ca (2.84 to 12.28 meq/100ml) and Mg (0.57 to 1.52 meq/100ml), categorized as medium to high, for Amazonian soils with different soil uses. Moreover,the Ecuadorian Amazon's high rainfall (3500 to 5000 mm per year) is responsible for the low concentrations of Ca and Mg.

S concentrations in the soils of the APUS studied ranged from 15 to 23 ppm, classed as medium to high, and the PF presented a value of 13 ppm. S is absorbed by plants in anionic form (SO_4^{2-}), and a deficiency of S causes slow growth and structural weakness in the plants. For Thompson and Troeh (2002), inorganic S compounds are not as resistant to weathering as P minerals; a significant amount of S is removed by washing in the form of SO_4^{2-} ions, although much of this loss is compensated by the contribution of atmospheric S compounds, dissolved in rainwater. S is often applied as a soil amendment; in many fertilizers, itacts as avehicle but is rarely applied as compost because of its sulfur content.

C. Chemical Properties of the Soil (Micronutrients)

Table 3 records the concentrations of micronutrients in soils with S. officinarum L. cultivation. Zn concentrations were low to medium in APUs (1.4 to 7.7 ppm) but were low in the PF (0.7 ppm). This difference in concentrations is due to the edaphic conditions of the region. For Zhang et al. (2014), S. officinarum L. needs this element to strengthen vegetative development, and it is distributed in the lower middle and upper part of the stem during the crop cycle.

Cu concentration was high for both the APUs and PF (7.8 to 9.1 ppm; see Table 3).Fe behaved similarly with concentrations of 304 to 418 ppm, while Mn concentrations were in the range of

5.2 to 8.8 ppm, categorized as medium, and B presented values of 0.17 to 0.41 ppm, considered as low for both the APUs and PF.These results contrast with those reported by Bravo et al. (2017), who indicated that Cu ranged from 4.99 to 8.20 ppm, Fe from 87.93 to 333.85 ppm, Mn from 3.42 to 23.65 ppm, and B from 0.35 to 0.60 ppm, ranges considered medium to high, in Amazonian soils with different uses in the Napo and Pastaza provinces of Ecuador.

Table 3. Chemical characteristics (micronutrients) of the soil under cultivation of S. officinarum L. in the study area

Plot	Micronutrient				
	Zn (ppm)	Cu (ppm)	Fe (ppm)	Mn (ppm)	B (ppm)
1	2.2 M	8.9 H	305 H	6.8 M	0.27 L
2	2.4 M	8.6 H	307 H	5.2 M	0.17 L
3	1.4 L	8.4 H	305 H	6.2 M	0.21 L
4	1.4 L	8.5 H	310 H	5.3 M	0.18 L
5	7.7 H	9.1 H	304 H	7.7 M	0.21 L
0	0.7 L	7.8 H	318 H	8.8 M	0.41 L

Interpretation of the concentration: H: high, M: medium, L: low.

D. Base-Cation Exchange Ratios in the Soil

Table 4 shows the ratios and sum of cation exchange bases in the soils with S. officinarum L. Ca/Mg content ranged from 2.65 to 3.85 for the APUs and 3.58 for the PF, categorized as ideal (2 to 5); Mg/K from 2.11 to 4.00 for the APUs and 3.28 for the PF, categorized as acceptable from 3 to 18; the Ca/K ratio from 5.63 to 14.79, considered as adequate,given the values are ≤ 30; and the (Ca+Mg)/K ratio ranged from 7.74 to 18.79, categorized as adequate (≤40) depending on the K content. The sum of bases for the APUs was 2.77 to 6.59 meq/100ml and 2.88 meq/100ml for the PF, values categorized as low. In humid tropical regions such as the Ecuadorian Amazon, the climate exerts a primary influence on edaphogenesisthat favors the leaching of bases (Ca^{+2}, Mg^{+2}, Na^{+1}, and K^{+1}), which induces a predominance of poorly alterable minerals and simple clays, such as quartz, kaolinite, halloysite, gypsum, and iron oxides (Gardi et al. 2014).

The sum of bases and cation exchange capacity (CEC) are measures of the total amount of cations, such as Ca, Mg, K, and Na, which are taken up by soil colloids. The value depends on the type of colloids, soil texture, pH, and OM. In general, the CEC is higher for clay soils and lower in an acidic environment. As such, soil CEC plays a key role in describing nutrient retention and supply. It is one of the most commonly examined soil chemical properties in soil science and the key indicator of soil quality and productivity (Wan et al. 2020).

Table 4. Ratio and sum of bases of the cation exchange capacity of soil under cultivation of S. officinarum L. in the study area

Plot	Ca/Mg	Mg/K	Ca/K	(Ca+Mg)/K	$\sum$ Bases meq/100ml

1	2.65	2.39	6.33	8.73	3.21
2	2.66	2.11	5.63	7.74	3.06
3	3.63	3.56	12.94	16.50	2.8
4	3.70	4.00	14.79	18.79	2.77
5	3.85	3.37	12.97	16.34	6.59
0	3.58	3.28	11.72	15.00	2.88

E. Principal Component Analysis (PCA)

In the statistical analysis of the 18 physicochemical variables of the soils (Table 5), significant correlations were found ($P \leq 0.05$). Thus, NH_4 presented a positive correlation with P (r=0.9738), Fe (r=0.8214), and B (r=0.8985) but a negative correlation with S (r=0.8170). P, being a variable that strongly correlates with NH_4, presented similar behavior with the same correlation variables. Ca presented a positive correlation with Mg (r=0, 0.9311), Zn (r=0.9630), and clay (r=0.9919). Mg presented a positive correlation with the same variables as Ca, that is to say, they are mutually dependent. S was inversely correlated with NH_4 (r=0.8170), P (r=0.8447), and Mn (r=0.9334). Zn was positively correlated with clay (r=0.9850), and Cu was inversely correlated with Fe (r=0.8803). Mn was positively correlated with B (r=0.8494), and the physical variable sand was inversely correlated with silt (r=0.9924). The purpose of applying the correlational analysis was to select the soil attributes with R2 values higher than 0.65, which allowed it to be a good tool to evaluate alternative semivariogram models that will perform kriging to predict values in unsampled sites, as well as optimize the sampling grids (Benedito Mendes Brito et al. 2018).

Table 5. Pearson correlation matrix of soil quality variables with S. officinarum L. cultivation in the study area

	BD	pH	OM	NH_4	P	K	Ca	Mg	S	Zn	Cu	Fe	Mn	B	∑ b	Sand	Silt	Clay
BD (g/cc)	1	-0.2397	0.1594	0.1275	0.319	-0.0095	0.3851	0.2926	-0.2687	0.2792	0.1237	0.3062	0.3364	0.2315	0.3727	0.3963	0.3945	0.3542
pH		1	0.7021	0.1339	0.0296	0.0988	0.3258	0.2112	-0.1589	0.3142	-0.1284	0.0767	-0.0857	-0.2733	0.3874	0.0996	0.1877	0.3007
OM (%)			1	0.4464	0.474	-0.2243	0.4835	0.1962	-0.5281	0.2885	-0.3727	0.3987	0.4917	0.2497	0.8483	0.5785	0.6621	0.3967
NH_4 (ppm)				1	0.9738	-0.1089	-0.0844	-0.131	-0.817	-0.2335	-0.7017	0.8214	0.7735	0.8985	0.0915	-0.1037	-0.069	-0.0979
P (ppm)					1	-0.151	0.0112	-0.07	-0.844	-0.169	-0.651	0.831	0.8525	0.9369	0.2122	0.0402	0.071	-0.015

	4		2	7	5	4							3
K (meq/100 ml)	1	0.541	0.8057	-0.2943	0.7128	0.7245	-0.5339	0.0546	-0.2313	-0.4419	-0.7047	-0.6388	0.6429
Ca (meq/100 ml)		1	0.9311	-0.4680	0.9630	0.5852	-0.3715	0.3874	-0.1451	0.503	0.192	0.2894	0.9919
Mg (meq/100 ml)			1	-0.4384	0.9793	0.7465	-0.5083	0.2956	-0.199	0.1532	-0.16	-0.0682	0.9697
S (ppm)				1	-0.3371	0.2172	-0.4266	-0.9334	-0.7472	-0.2339	0.1043	0.0244	-0.4677
Zn (ppm)					1	0.7499	-0.5467	0.2035	-0.32	0.288	-0.0128	0.0808	0.9842
Cu (ppm)						1	-0.8803	-0.2906	-0.642	-0.1883	-0.2449	-0.2191	0.6468
Fe (ppm)							1	0.4574	0.7496	0.2158	0.2229	0.2091	-0.4222
Mn (ppm)								1	0.8494	0.3493	0.1134	0.1671	0.3612
B (ppm)									1	0.0826	0.0078	0.0094	-0.1666
Sum of bases (meq/100 ml)										1	0.8992	0.9455	0.3898
Sand (%)											1	0.9924	0.0702
Silt												1	0.1

(%)	67 9
Clay (%)	1

Significant at $P \leq 0.05$

The PCA (Figure 1) was used to evaluate the interaction of physicochemical properties in soil in a PF and soil with S. officinarum L. The study showed that the first four principal components (PCs) explained 96.63% of the total cumulative variance, namelyPC1 (35.30%), PC2 (29.39%), PC3 (24.01%), and PC4 (7.91%). These results are similar to those reported by Benedito Mendes Brito et al. (2018) for the explained and cumulative variances. Each of the two principal components was accumulated and explained between 64 and 70% of the total data variance and indicated that PCA is a pattern recognition technique and not a classification technique. It only illustrates the relationship between the variables in the graph; it does not show how to classify them.

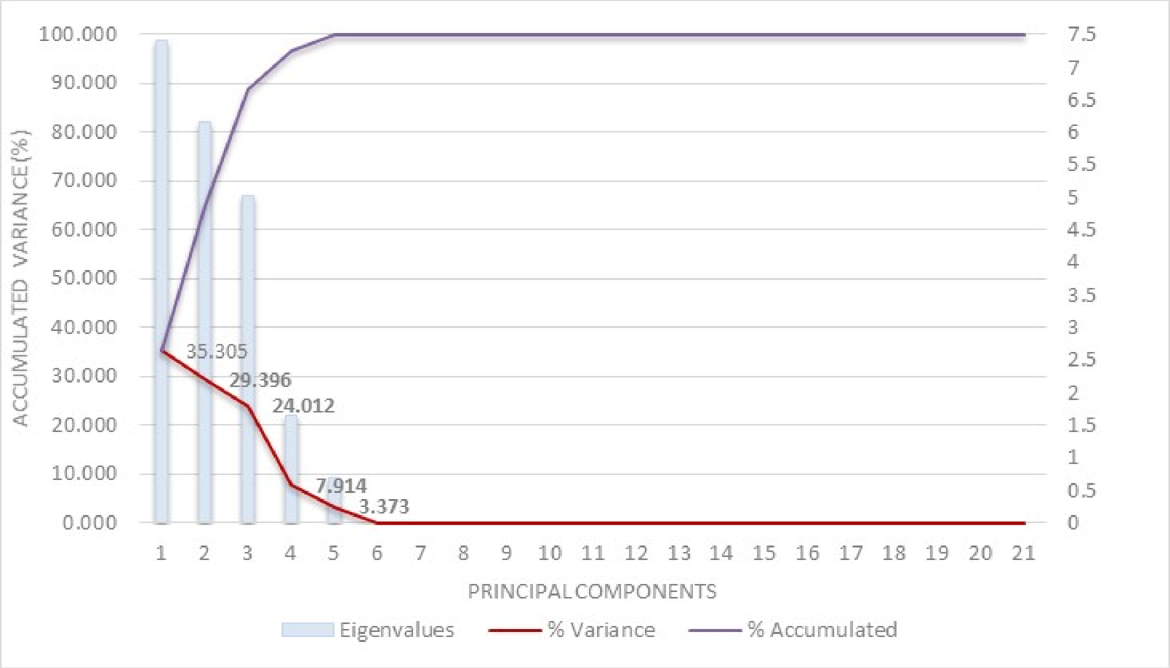

Figure 1. Contribution of the principal components to the different factors of the variables analyzed

For the distribution of the PCs, those variables with charges of ≥ 0.6 were selected to explain fertility in the change of land use from PF to the cultivation of S. officinarum L. (Table 6). The first PC grouped the variables P, NH_4, B, S, Mn, Fe, clay, silt, and sand, the second PC grouped Mg, Zn, sum of bases, Ca, K, and Cu, the third PC grouped OM and the ratios of bases, and the fourth PC comprised pH andBD. In the first component, P, NH4, clay, B, Mn, Fe, and sand presented a positive charge, while S and silt presented a negative charge. This component is defined by structural parameters and chemical parameters that fulfill certain functions, such as aeration capacity and nutrient recycling. These trends are commonly observed in soils under slash-and-burn agriculture, where pH and nutrients increase after burning as a consequence of ash deposition from burned vegetation and increased rates of OM decomposition.Over time, the extra store of nutrients is depleted and these attributes tend to return to their previous state (Moreira et al. 2009).

Table 6. Variable loading coefficient (eigenvectors) of the four principal components for the 21 physicochemical variables of soils under S. officinarum L. cultivation

	Component			
Variable	1	2	3	4
BD	0.288	0.177	0.390	0.644
pH	0.112	0.191	0.354	-0.882
OM	0.473	0.045	0.771	-0.423
NH_4	0.964	-0.231	-0.061	-0.111
P	0.974	-0.201	0.069	0.074
K	0.064	0.888	-0.445	-0.074
Ca	0.150	0.853	0.498	0.025
Mg	0.114	0.981	0.153	0.047
S	-0.926	-0.324	-0.094	-0.003
Zn	0.002	0.952	0.304	-0.025
Cu	-0.510	0.824	-0.093	0.228
Fe	0.718	-0.617	0.117	-0.009
Mn	0.872	0.152	0.219	0.246
B	0.880	-0.311	-0.053	0.278
Ca/Mg	0.148	-0.013	0.987	-0.040
Mg/K	-0.101	-0.305	0.929	0.181
(Ca+Mg)/K	-0.050	-0.220	0.967	0.118
Sum of bases	0.143	0.911	0.386	0.023
Sand	0.707	0.471	-0.526	-0.001
Silt	-0.778	-0.377	0.494	0.033
Clay	0.920	-0.072	-0.277	-0.155

Based on the PCA of soil fertility in the presence of S. officinarum L., it was found that the concentrations of P, NH_4, clay, and Mn are not a limiting nutritional factor nor are the concentrations of Mg, Ca, sum of bases, or K.Rather, S, silt, and Fe are the parameters that limit plant nutrition in Amazonian soils that have been evaluated. Moreira et al. (2009) reported the results of 3,340 soil samples analyzed (at depths of 0–20 cm) from the 62 municipalities located in the state of Amazonas, Brazil. The soils had the following characteristics: pH <5.4 (96%); P <5.4 mg/dm3 (82%); V% <40% (99%); K <40 mg/dm^3 (75%); Ca + Mg <1.6 cmolc/dm^3 (90%); effective CEC (ECEC) <4.6 cmolc/dm^3 (89%); m%> 50% (76%); SB <1.8 cmolc/dm^3 (84%). The results all soils in the municipality of Benjamin Constant were within the same ranges with respect to pH and P, limitations that are generally reported for Amazonian soils.

The behavior of the chemical properties of the soils in the Ecuadorian Amazon is marked by the formation processes and the climate that together play an important role in the ferralitization process. The latter process is helped by the climatic conditions of the area (high rainfall) and tends toward a total hydrolysis of the alterable primary materials and of the complex clays of the rocks by the leaching of bases (Ca^{+2}, Mg^{+2}, Na^{+1}, and K^{+1}) and silica. This induces a predominance of poorly alterable minerals and simple clays, such as quartz, kaolinite, halloysite, gypsum, and iron oxides, conferring them certain morphological characteristics and causing a decrease in chemical parameters, mainly pH (Bravo et al. 2017).

Studying the physical, chemical, and biological attributes of soil in different applications and comparing these attributes with those in areas without anthropogenic action makes it possible to quantify the magnitude of changes that have occurred due to different exploitation models.Based on the sensitivity of these attributes, it is possible to establish the occurrence of degradation or improvement of soil quality compared to soil in a non-anthropized environment (De Carvalho et al. 2018). Good levels of these attributes provide ideal conditions for plant growth and development and help maintain the diversity of organisms that exist in the soil.

Generally, the climate of the Amazon region of Ecuador is humid and favors forest development. The forest, in turn, influences soil type, such as the flushing effect that is typical of humid climates. According to Thompson and Troeh (2002), most of the organic matter contributed by trees is deposited on the soil in the form of leaf litter, branches, and tree trunks that have completed their life cycle. When they decompose, they produce organic acids, increasing the effects on the minerals in the water that leach through the soil, favoring weathering and flushing. As forest vegetation usually has lower needs for bases such as Ca and Mg, they return lower quantities of these elements to the soil than any crop.

Moreover, De Carvalho et al. (2018) demonstrated the potential of S. officinarum L. for the phytostabilization of soils with high concentrations of heavy metals, which are mostly concentrated in the root and to a lesser degree in the stem, ensuring a source of quality raw material for safe energy production. For this reason and in this study, it was demonstrated that the cultivation of S. officinarum L. is a crop that is fully adapted to the nutritional conditions of the soils of the Ecuadorian Amazon region.

CONCLUSION

The concentrations of$NH_4$and P in the primary forest soil are slightly higher than those in the sugarcane cultivation, and they presented similar behavior in their soil chemical composition when compared to the other physicochemical parameters.

The high concentrations of OM (11.99 to 12.78%), S (13 to 23 ppm), Fe (304 to 318 ppm), and Cu (7.8 to 9.1 ppm) have a direct effect on the other chemical properties of the soil. Thus, with the correlation analysis, the dependence of the variables was demonstrated at $P \leq 0.05$ and coefficients of determination of $R2 \geq 65\%$. Certain pairs of variables were found to be strongly correlated: NH_4 presented a positive correlation with P (r=0.9738), Fe (r=0.8214), and B (r=0.8985) and a negative correlation with S (r=0.8170). The high concentrations of S, Fe, and OM negatively affected the fertility of the soils, turning them into highly acidic soils with pH values of 3.90 to 4.67.

The four principal components typically explained 96.63% of the total variation of the fertility variables of the soils evaluated, which were P, NH_4, B, S, Mn, Fe, clay, silt, sand, Mg, Zn, sum of bases, Ca, K, Cu, organic matter, pH, and bulk density. With the PCA, the influence of the variables silt, S, and pH on soil fertility was verified. Crop fertilization plansand the adoption of good agricultural practices to contribute to the equilibrium of the Amazonian production systems are both necessary.

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