Production system management

Scientific and technological research article

Liming effect on macronutrient intake for cacao (*Theobroma cacao* L.) in the Colombian Amazon

Efecto del encalado en el uso eficiente de macronutrientes para cacao (*Theobroma cacao* L.) en la Amazonia colombiana

Gelber Rosas-Patiño,[1]* Yina Jazbleidi Puentes-Páramo,[2] Juan Carlos Menjivar-Flores[3]

[1] Associated Professor, Universidad de la Amazonía, Facultad de Ingeniería, Programa Ingeniería Agroecológica. Florencia, Colombia. Email: g.rosas@udla.edu.co. Orcid: https://orcid.org/0000-0002-1044-8103
[2] Consultant. Palmira, Colombia.Email: yjpuentesp@unal.edu.co. Orcid: https://orcid.org/000-0002-3784-9687
[3] Tenured Professor, Universidad Nacional de Colombia, Sede Palmira, Facultad de Ciencias Agropecuarias, Departamento Ciencias Agrícolas. Palmira. Colombia. Email: jcmenjivarf@unal.edu.co. Orcid: https//orcid.org/000-0002-2985-7778

Subject editor: Jairo Rojas Molina (Corporación Colombiana de Investigación Agropecuaria [AGROSAVIA])

Reception date: 18/09/2018
Approval date: 11/12/2018

How to cite this article: Rosas-Patiño, G., Puentes-Páramo, Y. J., & Menjivar-Flores, J. C. (2019). Liming effect on macronutrient intake for cacao (*Theobroma cacao* L.) in the Colombian Amazon. *Ciencia y Tecnología Agropecuaria, 20*(1), 17-28

DOI: https://doi.org/10.21930/rcta.vol20_num1_art:1247

* Corresponding author: Universidad de Sucre, Cra. 14 N.° 16B-32, Barrio La Pajuela – Campus Ciencias de la Salud.

Abstract

In the Colombian Amazon, cacao tree (*Theobroma cacao* L.) plantations have low yield due to soil acidity which limits the efficient use of nutrients. Therefore, the aim of this study was to evaluate the effect of liming and fertilization in an acid soil (*Typic Udorthents*) of the Colombian Amazon on the efficient use of nutrients in terms of nutrient use efficiency (NUE) and fertilizer recovery efficiency (FRE) for N, P and K, in four universal clones of fine cocoa flavor and bouquet. A completely randomized block design was used using a factorial arrangement, being factor A, four clones (a_1: ICS-1, a_2: CCN-51, a_3: ICS-39, and a_4: TSH-565) and factor B, four fertility levels (b_1: absolute control, b_2: soil 90 days after liming (DAL), b_3: absolute control plus N-P-K until reaching the requirements of the crop, and b_4: b_2 plus N-P-K until reaching the requirements of the crop). Results show that liming and fertilization affect NUE and yield, meanwhile, the lowest yield was found in b_1 for all the clones, suggesting that the natural soil fertility is not sufficient for cacao tree development. Clone CCN-51 was more efficient in the use of nutrients than the other clones, in this sense, the four clones responded differentially according to NUE and FRE, evidencing the influence of the genotype, the edaphoclimatic conditions of the area, as well as specific of pH and nutrient preferences for each clone.

Key words: acid soil, crop yield, nitrogen, phosphorus, potassium

Resumen

En la Amazonia colombiana, el cultivo de cacao (*Theobroma cacao* L.) presenta bajo rendimiento debido a que la alta acidez del suelo limita el uso eficiente de nutrientes. Por lo tanto, esta investigación evalúa el efecto del encalado y la fertilización en un suelo ácido (*Typic Udorthents*) de la Amazonia colombiana sobre el uso eficiente de nutrientes (UEN), en términos de la eficiencia agronómica (EA) y la eficiencia de recuperación del fertilizante (ERF) para nitrógeno (N), fósforo (P) y potasio (K), y cuatro clones universales de cacao fino de sabor y aroma. Se utilizó un diseño en bloques completos al azar con arreglo factorial, siendo el factor A cuatro clones (a_1: ICS-1, a_2: CCN-51, a_3: ICS-39, y a_4: TSH-565) y el factor B cuatro niveles de fertilidad (b_1: control absoluto; b_2: suelo 90 días después de encalado (dde); b_3: control absoluto más N-P-K, hasta alcanzar los requerimientos del cultivo; b_4: b_2 más N-P-K, hasta alcanzar los requerimientos del cultivo). Los resultados muestran que el encalado y la fertilización afectaron el UEN y el rendimiento; mientras tanto, el más bajo rendimiento se presentó en b_1 para todos los clones, sugiriendo que la fertilidad del suelo natural no es suficiente para el desarrollo del cultivo de cacao; además, el clon CCN-51 mostró mayor habilidad en el uso de nutrientes que los restantes clones. En este sentido, los cuatro clones respondieron de forma diferencial de acuerdo con la EA y la ERF, evidenciando la influencia del genotipo y de las condiciones edafoclimáticas de la zona, así como las preferencias específicas de pH y nutrientes para cada clon.

Palabras clave: fósforo, nitrógeno, potasio, rendimiento de cultivos, suelo ácido

Introduction

In Colombia, acid soils represent 85 % of all agricultural soils (Casierra & Aguilar, 2007), of which the Amazonian region accounts for 35 % (Quesada et al., 2011). In the department of Caquetá, for example, oxisols, ultisols, and entisoles predominate. The latter consists of very superficial acid soils with high aluminum contents (Instituto Geográfico Agustín Codazzi [IGAC], 2014). However, and despite the fact that cacao *Theobroma cacao* L. (Malvaceae) is native to the Amazon, cacao plantations have a low yield due, in large part, to poor fertility and aluminum toxicity (Shamshuddin, Muhrizal, Fauziah, & Husni, 2004). This circumstance occurs when soil pH is lower than 5.5, which indicates that a high proportion of the exchange sites of clays are occupied by aluminum that generates acidity, and limits nutrient availability for the plants (Dahajipour, Ghanati, & Fujiwara, 2011).

Nutrients such as nitrogen (N), phosphorus (P) and potassium (K) decrease their availability as the soil acidifies (Navarro & Navarro, 2003), as has been corroborated by Quinteiro et al. (2013) in a study conducted under greenhouse conditions, in which an increase in acidity decreased the concentration of N, P and K in most of the cacao plant organs.

Liming is an important agricultural practice in acid soils to neutralize acidity (Castro & Munevar, 2013); in this sense, the addition of lime raises the pH, improves the absorption and redistribution of N in the plant (Lavres et al., 2010), and releases the phosphorus retained in the soil (Fisher, Yarwood, & James, 2017; Zhu, Li & Whelan, 2018). In the same way, Rosas, Puentes and Menjivar (2017) found that the increase in pH improves the availability of P in cacao soils. On the other hand, Baligar and Fageria (2005) showed that liming improves the availability and absorption of nutrients in cacao seedlings, indicating that it not only regulates phytotoxicity but also the efficient use of nutrients (NUE), since acid soils limit the efficiency of fertilizers, as suggested by López, Urbina, Reynoso, and Martínez (2018).

Changes produced by the effect of pH modifications influence soil-plant relationship, the criteria for fertilizing crops (Schlindwein & Gianelo, 2004) and the efficient use of nutrients, either regarding agronomic efficiency (yield increase per unit of applied nutrient) or fertilizer recovery (plant ability to take nutrients applied to the soil) (Baligar, Fageria, & Hi, 2001). However, there is scarce research information for NUE in cacao (Puentes, Menjivar, & Aranzazu, 2014a; Ribeiro, da Silva, Aitken, Machado, & Baligar, 2008), especially under the influence of liming, even understanding that NUE contributes to obtaining higher yields, it would reduce fertilization costs and mitigate environmental pollution (Kurwakumire et al., 2014). According to the above mentioned, the aim of this study was to evaluate the effect of liming and synthesis fertilization in an acidic soil (Typic Udorthents) of the Colombian Amazon, on the efficient use of nutrients in terms of agronomic efficiency (ae) and fertilizer recovery efficiency (FRE) for N, P and K, in four fine flavor and aroma cacao clones (ICS-1, CCN-51, ICS-39 and TSH-565).

Materials and methods

The research was conducted in the municipality of Puerto Rico, Department of Caquetá, Colombia, in the facilities of the Clonal Cacao Garden that belongs to Asociación Departamental de Productores de Cacao y Especies Maderables del Caquetá (Acamafrut), located geographically at 01°52′12" North latitude and 75°12′24" West longitude, at 250 meters above the sea level. The area has an average annual relative humidity of 84 %, an annual average temperature of 25.3 °C, average annual rainfall of 2,960 mm, and solar brightness values of 4.26 hours/day (Instituto de Hidrología y Estudios Ambientales [IDEAM], 2017).

Four universal fine flavor and aroma cacao clones were used, two self-compatible (b_1: ICS-1, b_2: CCN-51) and two self-incompatible (b_3: ICS-39, b_4: TSH-565) with seven years of age; self-compatible materials were established together. Clone ICS-39 was associated with clone IMC-67, and clone

TSH-565 was accompanied by trees of clones IMC-67 and ICS-1. The spatial arrangement consisted of triple rows of each clone, 3 m between plants and 3 m between rows, in an area of 1.5 ha under homogeneous agronomical conditions, and in an agroforestry system with simple furrows every 20 m by 9 m between trees, as in agrosystems associated with Abarco (*Cariniana pyriformis* M.) and Nogal (*Cordia alliodora* R. & P.).

The soil of the study area was characterized physically and chemically in the laboratory of Universidad de la Amazonia (Rosas et al., 2017), classifying this soil as Typic Udorthents (Soil Survey Staff, 2010), with a loam-clay-sandy texture (FArA), and with a predominance of gibbsites ($Al(OH)_3$) (> 50 %), kaolinites ($Al_2Si_2O_5(OH)_4$) (between 15 and 30 %) and traces of micas-goethites (< 5 %); in addition, it has an effective depth greater than 1 m, an apparent density of 1,173 g/cm^3, total porosity of 55.7 %, and resistance to penetration of 1.065 MPa. Nonetheless, all these physical characteristics are not limiting for the development of cacao cropping (Federación Nacional de Cacaoteros de Colombia [Fedecacao], 2013).

Regarding chemical characteristics, this soil has an extremely acid pH (4.36), with high interchangeable aluminum saturation percentage (53.9 %), low cation exchange capacity, as well as N (0.13 %), P (3.89 mg/kg) and K (0.11 Cmol/kg), corresponding to N, P2O5, and K2O, with 11.2, 10 and 60 kg/ha, respectively. This indicates that the chemical conditions of the soil are not ideal for cacao production (Fedecacao, 2013), suggesting specific agronomic management. These physical and chemical characteristics were normal for the area according to Rosas, Rodríguez, and Muñoz (2012).

To correct the pH, the dose of dolomite lime required to be added to the soil to raise the pH to a value ≥ 5.5 was 7 t/ha [$CaMg(CO_3)_2$], with a total relative neutralization power of 78.4 % (Rosas et al., 2017). The incorporation of lime was carried out at the beginning of the rainy season (May) in the weed-free zone (approximately 4.5 m^2) around the cacao trees in a homogeneous way with a sieve. Subsequently, soil samples were taken 90 days after liming (DAL), each consisting of four equidistant sub-samples in the area of the weed-free zone, one meter away from the tree (Sadeghian, 2011) and 30 cm deep, since most of the roots of the cacao tree that absorb nutrients are found at this depth (Aikpokpodion, 2010). The samples were analyzed in the laboratory of Instituto Geográfico Agustín Codazzi (IGAC) to measure pH in water (1: 2) (potentiometer), N (Kjeldahl), P (colorimetry) and K (atomic absorption). From the availability of N-P-K in the soil with and without liming, four fertility levels were established as follows: b_1: soil with natural fertility without liming; b_2: b_1 limed with nutrient availability 90 DAE; b_3: b_1 fertilized with application of N-P-K until reaching the requirements of the crop proposed by Puentes et al. (2014a); and b_4: b_2 fertilized with application of N-P-K until reaching the requirements of the crop (table 1). The incorporation of N-P-K was divided into two applications per year. The first in March-April, and the second in August, where the trees were in full bloom, using urea $CO(NH_2)_2$ (46-00-00), monopotassium phosphate KH_2PO_4 (00-52-34) and potassium chloride KCl (00-00-60) as fertilization sources.

A completely randomized block design in a factorial arrangement with four repetitions was used. Factor A corresponded to four clones and factor B to fertility levels for a total of 16 experimental units; each experimental unit was comprised of four cacao trees per clone (TSH-565, ICS-39, ICS-1, and CCN-51). To guarantee the response of the clones, fertilization was suppressed one year before the experiment was established, and pruning and manual control of pests and diseases were carried out. Likewise, the existing fruits were eliminated in order to standardize production as suggested by Puentes et al. (2014a).

To establish the content of N-P-K in cacao beans, five mature and healthy pods were collected in each tree per clone. The cacao beans were manually extracted, dried in an oven at 103 °C for 24 hours, milled and subsequently analyzed for N (Kjeldahl method), P (colorimetry) and K (atomic

Table 1. Description of fertility levels

Fertility levels B	Lime	N	P_2O_5	K_2O
	kg/ha			
b_1: Absolute control	0.0	11.2	10.0	60.0
b_2: b_1 + Cal (90 DAL)	7,000.0	15.6	22.6	43.8
b_3: b_1 + Fertilizer	0.0	73.0	35.2	219.7
b_4: b_2 + Fertilizer	7,000.0	73.0	35.2	219.7

DAL: days after liming; N: nitrogen; P_2O_5: phosphorus pentoxide; K_20: potassium oxide.
Source: Elaborated by the authors

absorption) contents. Yield (kg/ha) during 2016 and 2017 was estimated from the ratio between the average number of pods per tree and pod index (PI), i.e. the number of pods to obtain one kilogram of dry cacao beans, multiplied by planting density (1,111 plants/ha).

With yield and N-P-K content data on dry cacao beans, AE and FRE were established for each nutrient by fertility level and by type of clone, following the equations 1 and 2 according to Puentes et al. (2014a):

$$\text{AE (kg/kg)} = \frac{\text{Yield F - Yield C}}{\text{Amount of nutrients applied to the soil}} \quad (1)$$

$$\text{FRE (\%)} = \frac{\text{Nutrient in grain F - Nutrient in grain C x 100}}{\text{Amount of nutrients applied to the soil}} \quad (2)$$

Where F is the variable in a fertility level different from b_1, and C is the variable in the control or b_1.

The statistical analysis comprised an analysis of variance as a result of the type of clone, fertility level, and interaction, and when there were significant differences, averages were compared using the Tukey test ($p \leq 0.05$), in addition to regressions using the SAS software 9.4 (SAS, 2014).

Results and discussion

Experimental soil analysis

The chemical analysis of the experimental soil (Rosas et al., 2017) at 90 DAL showed a moderately acid pH (5.91), N (0.08 %), P (9.53 mg/kg) and K (0.08 Cmol/kg), corresponding to N, P2O5 and K2O, with 15.6, 22.6 and 43.8 kg/ha, respectively, considered values consistent with the increase in pH, as suggested by Kass (1998).

Yield

In the analysis of variance, highly significant differences were found ($p \leq 0.01$) due to the effect of the clone x fertility level interaction, as well as to the clone, and to the novel fertility level (table 2).

Table 2. Analysis of variance for cacao yield variable in a *Typic Udorthents* soil of Caquetá

Source of variation	Yield
Clone	0.000**
Fertility level	0.000**
Clone x Fertility level	0.000**

** Highly significant differences ($p \leq 0.01$)
Source: Elaborated by the authors

The lowest yield was found in b1 for all clones in the following order, from the highest to the lowest: CCN-51 (3,535 kg/ha), ICS-1 (1,667 kg/ha), ICS-39 (1,222 kg/ha) and TSH-565 (1,178 kg/ha). Similar results were obtained by Puentes et al. (2014a), suggesting that the fertility of natural soil is not sufficient for the development of cacao trees; besides, soil acidity is limiting, as argued by López et al. (2018). The highest yield was obtained in CCN-51 with b_2 (4,100 kg/ha), showing superiority compared to the other clones, and evidencing the influence of liming, as suggested by Baligar and Fageria (2005); this clone was followed by clones ICS-1 (3,855 kg/ha) and TSH-565 (2,944 kg/ha) in b_3, indicating the importance of fertilization in acid soils (Koko, 2014); and finally, by ICS-39 in b_4 (2,033 kg/ha), which expresses its greatest potential when the soil was limed and fertilized (figure 1); however, its low yield is associated with the self-incompatible condition according to Mora, Burbano, and Ballesteros (2011), who state that this condition affects pollination and, therefore, fruit set.

In general terms, the clones showed different behaviors due to the effect of various fertility levels; likewise, yields were higher when compared with those reported by Puentes et al. (2014a) and Fedecacao (2013); this is partly due to the higher sowing density used compared to the references mentioned above, as well as to the interaction of the clone type with the contrasting soil and climate conditions of the Amazon region; moreover, also to the fertilization, being evident the influence of the genotype, as suggested by Romero, Puentes and Menjivar (2016).

Agronomic efficiency

The agronomic efficiency for nitrogen (AEN), phosphorus (AEP) and for potassium (AEK) due to the effect of the clone, the fertility level, and their interaction, showed highly significant differences ($p \leq 0.01$). The highest AEN was found in the combination of CCN-51 and b_2 (36.33 kg/kg), that is, its yield increased 36.33 kg for each kilogram of nitrogen applied; followed by clones ICS-1 (29.83 kg/kg) and TSH-565 (24.10 kg/kg) in b_3, and ICS-39 (11.27 kg/kg) in b_4, exceeding the values obtained by Bridges et al. (2014a) in 123 %, 368 % and 103 % for CCN-51, TSH-565 and ICS-39, respectively; this suggests a higher efficiency with lower nitrogen doses for CCN-51 and the influence of soil and climatic conditions

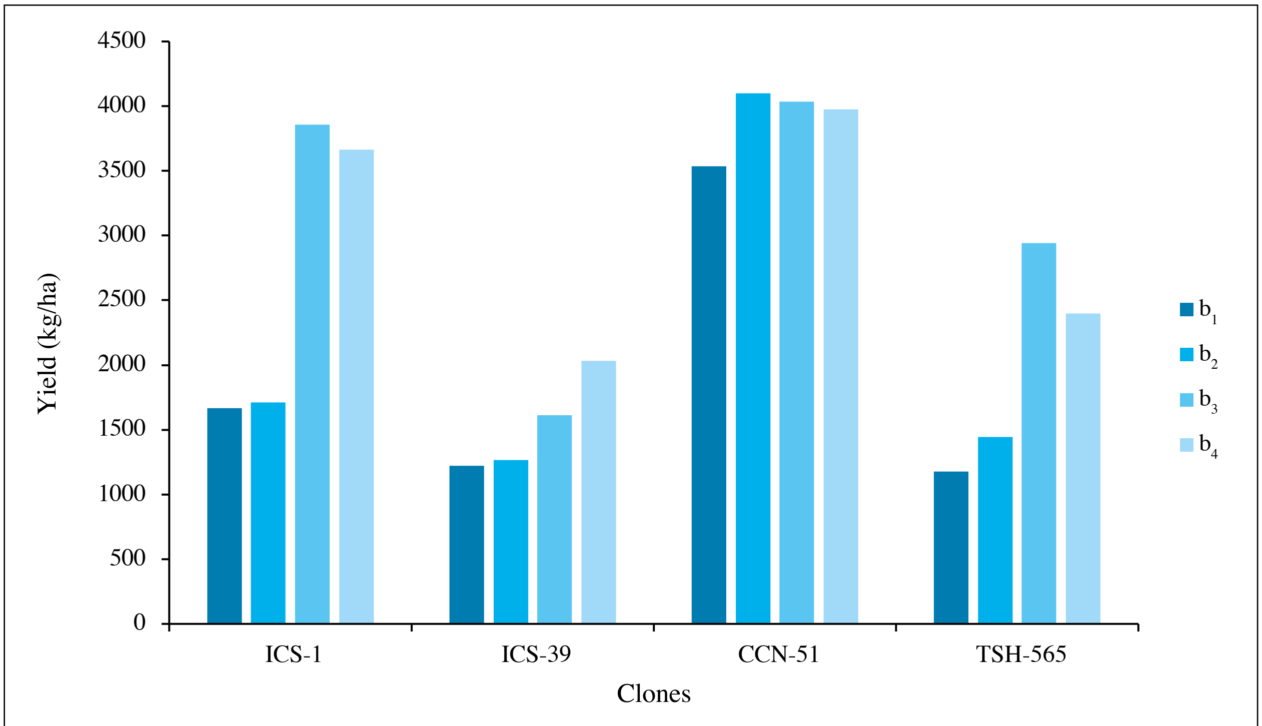

Figure 1. Dry cacao bean yield (kg/ha) for the cacao production during years 2016-2017. Mean values with the same letter per clone do not differ statistically according to the Tukey test ($p \leq 0.05$).
Source: Elaborated by the authors

as well as of the genotype, such as Romero et al. (2016) found. The lowest AEN, in order from the highest to the lowest, was found in clone TSH-565 (16.87 kg/kg) in b_2, followed by CCN-51 (6.87 kg/kg) in b_4, and clones ICS-39 (2.93 kg/kg) and ICS-1 (2.80 kg/kg) in b_2 (figure 2).

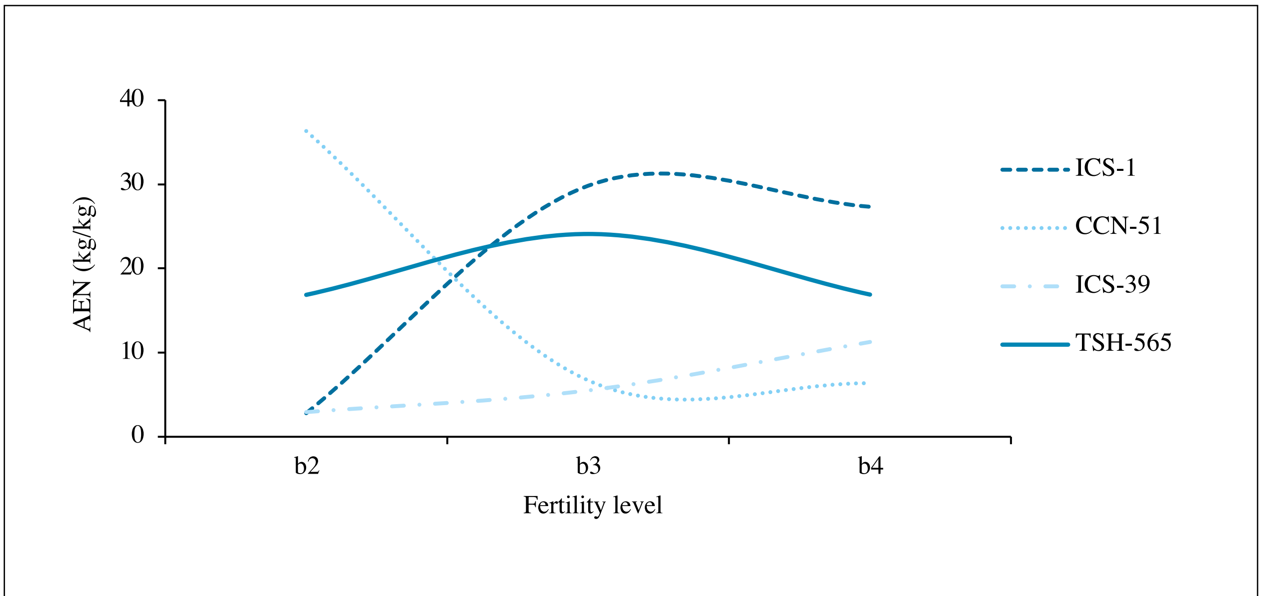

Figure 2. Agronomic efficiency of nitrogen in four cacao clones
Source: Elaborated by the authors

Clone CCN-51 showed both the highest AEN and yield in b_2 and the lowest values in b_4, being consistent with harvest yields. The efficient genotypes in the use of N are more productive (Ribeiro et al., 2008), as well as higher nutrient doses decrease the efficient nutrient use (Puentes, Menjivar, & Ortiz, 2016).

Regarding AEP (figure 3), clones ICS-1 (61.73 kg/kg) and TSH-565 (49.53 kg/kg) showed the highest value in b_3, indicating the effect of fertilization on the AEP as stated by Díaz et al. (2014); these clones were followed by CCN-51 (25.17 kg/kg) in b_2 and ICS-39 (22.80 kg/kg) in b_4. The lowest AEP were obtained in clones ICS-1 (2.00 kg/kg) and ICS-39 (2.03 kg/kg) in b_2, CCN-51 (13.53 kg/kg) in b_4, and TSH-565 (12.03 kg/kg) in b_2, values that were superior to those reported by Puentes et al. (2014a). This evidences among other things, the adaptation of the crop to the cultivation area, as it is originally from the Amazon (Shamshuddin et al., 2004).

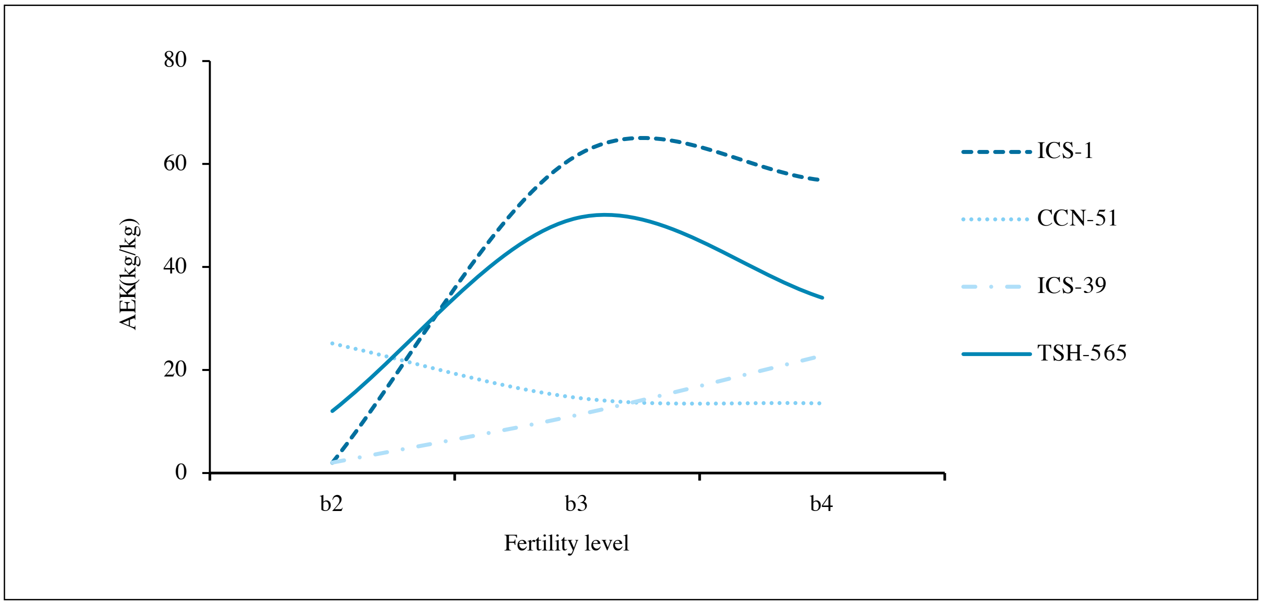

Figure 3. Agronomic efficiency of phosphorus in four cacao clones
Source: Elaborated by the authors

The clones showed a similar response compared to AEN; however, it is important to note that, despite the fact that phosphorus is liberated by liming (Zhu & Whelan, 2018), the dose was not enough to obtain a greater efficiency in most of the clones except for CCN-51; nonetheless, this evidences the effect of the genotype according to Romero et al. (2016).

For the agronomic efficiency of potassium (figure 4), as in the previous AE values, CCN-51 shows the highest value in b2, increasing the yield in 12.57 kg for each kg of applied fertilizer (K); this clone was followed by clones ICS-1 (9.70 kg/kg) and TSH-565 (8.27 kg/kg) in b_3, and ICS-39 (3.77 kg/kg) in b4. The lowest AEK value was found in ICS-39 (1.70 kg/kg) and ICS-1 (2.20 kg/kg) in b_2, followed by CCN-51 (2.53 kg/kg) and TSH-565 (5.53 kg/kg) in b_4.

These values exceeded those reported by Puentes et al. (2014a) due to the absence of illites (these trap K) in the clays of this soil, as well as the age of the crop, as suggested by Cabala, Miranda, and Prado (1969).

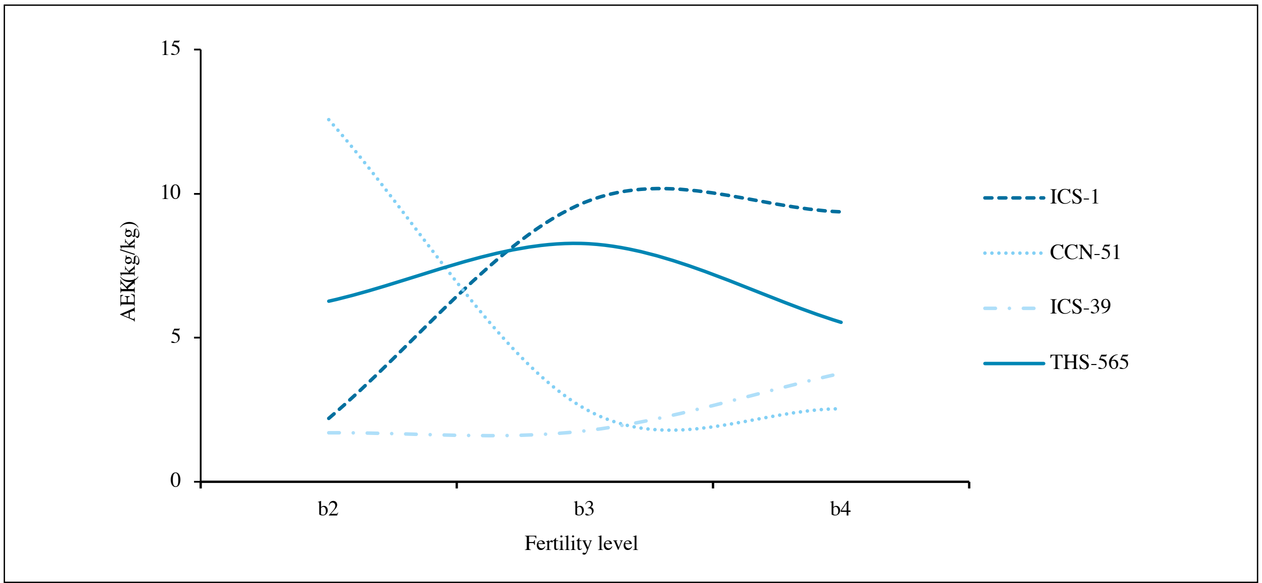

Figure 4. Agronomic efficiency of potassium in four cacao clones.
Source: Elaborated by the authors

The agronomic efficiencies for N-P-K were different, showing clone variability in response to fertility levels as corroborated by Puentes et al. (2014a). In this sense, clone CCN-51 showed a higher ability in the absorption of nutrients than the other clones, with preference for a higher soil pH (moderately acidic), meanwhile ICS-1 and TSH-565 required more nutrients to express their potential without considering the pH (extremely acidic); in turn, clone ICS-39, with the same amount of nutrients as the previous clones, preferred a lower acidity.

On the other hand, the AE, in order of the highest to the lowest contribution to yield per kg of fertilizer in each clone, were the following: P > N > K for clones ICS-1, ICS-39 and TSH-565, and N > P > K for clone CCN-51, coinciding in K as the nutrient that contributed less to yield increase.

Fertilizer recovery efficiency

In the analysis of variance, the efficiency for nitrogen fertilizer recovery (FREN), for phosphorus (FREP) and for potassium (FREK) showed highly significant differences ($p \leq 0.01$), by clone effect, fertility levels, and their interaction.

With respect to the FREN (table 3), most of the clones showed a similar response to fertility levels as well as for AEN, except for clone TSH-565, that achieved the highest FREN value in b_2, and the lowest in b_4. This indicates that, despite having obtained the highest FREN in b_2, this was not reflected in higher yields; however, this was contrary to what occurred with b_4. Similar results were found by Puentes et al. (2014a), although these FREN values were above those reported. The highest FREN was obtained by ICS-1 in b_3 meanwhile the lowest value was obtained by CCN-51 in b_4. The efficiencies with high values for ICS-1 and TSH-565, in contrast to the low ones for CCN-51 and ICS-39 when fertilized (b_3 and b_4), agree with the reports published by Baligar et al. (2001), demonstrating the highest ability in the use of nitrogen by clone CCN-51.

The FREP (table 3) recorded the highest values in clone ICS-1, showing that 100 % of the phosphorus application recovered 30 % and 33 % (for b_4 and b_3, respectively), surpassing the results reported by Baligar et al. (2001). Although TSH-565 and ICS-39 presented their best FREP when the nutrient was incorporated, these were below the ones achieved by ICS-1 and by Puentes et al. (2014a). Clone CCN-51 recorded its largest FREP with the amount of phosphorus released to the solution due to liming. Meanwhile, having higher phosphorus use efficiency is not easy, as it depends

Table 3. Fertilizer recovery efficiency for nitrogen, phosphorus, and potassium in four cacao clones

Clone	FREN (%)			FREP (%)			FREK (%)		
	b_2	b_3	b_4	b_2	b_3	b_4	b_2	b_3	b_4
ICS-1	12.67c	65.60a	61.97b	4.27c	33.37a	30.20b	1.30c	16.63a	10.53b
CCN-51	23.33a	7.97b	5.83c	15.43a	8.87c	9.87b	2.93b	4.53a	1.87c
ICS-39	9.53c	13.87b	26.13a	1.87b	1.60c	12.13a	14.20a	3.97c	5.47b
TSH-565	56.40a	54.90b	45.43c	6.80c	14.03a	12.53b	4.87b	8.10a	2.30c

Note: Mean values with the same letter per clone and FRE do not differ statistically according to the Tukey test ($p \leq 0.05$).
Source: Elaborated by the authors

on soil moisture, since it is a nutrient that moves by pH (> 5.5) diffusion (Malavolta, Vitty, & Oliveira, 1997) as well as the morphology of the root system of the plant (Anghinoni, Volkart, Fattore, & Ernani, 1989).

Clone ICS-1 showed the highest FREK value (table 3) in b_4 and b_3, respectively, as well as in FREN and FREP, which shows that this clone responds positively to fertilization with potassium. This clone was followed by ICS-39 that reached the highest levels of recovery in b_2. On the other hand, TSH-565 and CCN-51 showed the lowest potassium recovery levels. These values are considered low compared to the results reported by Baligar et al. (2001), and high compared with Puentes et al. (2014a) that argued the absence of illites in clays of the experimental soil.

In general, the FRE, in order of the highest to the lowest fertilizer (N-P-K) recovery value for each of the clones, were the following: N > P > K for ICS-1, CCN-51, and TSH-565, coinciding with the results obtained by Bridges, Menjivar, Gómez and Aranzazu (2014b), and N > K > P for ICS-39, being consistent with the low yields showed by this clone, given that phosphorus is a nutrient that accumulates especially in the seed (Marshner, 1995).

Conclusions

Soil acidity in the Colombian Amazon is an unfavorable condition for the yield of the cacao clones ICS-1, CCN-51, ICS-39 and TSH-565, so it is necessary to carry out liming or fertilize considering the edaphic preferences for each clone, whether of pH or nutrients. Of these genotypes, clone CCN-51 shows a higher skill in the use of nutrients compared to the other clones, reflected also in obtaining high yield with fewer nutrients. In this sense, the four clones assessed respond differentially according to the agronomic efficiency and fertilizer recovery efficiency, evidencing the influence of the genotype and the edaphoclimatic conditions of the area.

Acknowledgments

The authors express their gratitude to Asociación Departamental de Productores de Cacao y Especies Maderables del Caquetá (Acamafrut) and to Universidad de la Amazonia for their support to carry out this research.

Disclaimers

The authors agree with the publication of this article and declare that there are no conflicts of interest that affect the results.

References

Aikpokpodion, P. E. (2010). Nutrients Dynamics in Cocoa Soils, Leaf and Beans in Ondo State, Nigeria. *Journal of Agricultural Sciences, 1*(1), 1-9. doi:10.1080/09766898.2010.11884647.

Anghinoni, I., Volkart, C. R., Fattore, N., & Ernani, P. R. (1989). Morfología de raizes e cinética da absorçao de nutrientes em diversas especies e genotipos de plantas. *Revista Brasileira de Ciência do Solo, 13*, 355-361.

Baligar, V. C., Fageria, N. K., & He, Z. L. (2001). Nutrient use efficiency in plants. *Communications in Soil Science and Plant Analysis, 32*(7), 921-950. doi:10.1081/CSS-100104098.

Baligar, V. C., & Fageria, N. K. (2005). Aluminum influence on growth and uptake of micronutrients by cacao. *Journal of Food Agriculture and Environment, 3*(3-4), 173-177.

Cabala, R. P., Miranda, E. D., & Prado, E. P. (1969). *Efeito da remoção de sombra e da aplicação de fertilizantes sobre a produção do cacaueiro na Bahia*. Paper presented at the 3rd International Cocoa Research Conference. Tafo, Ghana.

Casierra, P. F., & Aguilar, A. O. (2007). Stress for aluminum in plants: reactions in the soil, symptoms in plants and amelioration possibilities. A review. *Colombian Journal of Horticultural Science, 1*(2), 246-257.

Castro, H., & Munevar, O. (2013). Mejoramiento químico de suelos ácidos mediante el uso combinado de materiales encalantes. *Revista UDCA. Actualidad & Divulgación Científica, 16*(2), 409-416.

Dahajipour, M., Ghanati, F., & Fujiwara, T. (2011). Interaction between boron and aluminum and their effects on phenolic metabolism of *Linum usitatissimum* L. roots. *Plant Physiology and Biochemistry, 49*, 1377-1383. doi:10.1016/j.plaphy.2011.09.008.

Díaz, L. E., Loeza, C. J. M., Brena, H. I., Campos, P. J. M., Orlando, G., I. J., & Salgado, B. G. (2014). Eficiencia agronómica del fósforo, biomasa y rendimiento de dos variedades nativas de maíz y un híbrido en el centro de México. *Fyton, 83*, 171-178.

Federación Nacional de Cacaoteros de Colombia (Fedecacao). (2013). *Guía ambiental para el cultivo del cacao* (2ª ed.). Bogotá, Colombia: author.

Fisher, K. A., Yarwood, S. A, & James B. R. (2017). Soil urease activity and bacterial ureC gene copy numbers: Effect of pH. *Geoderma, 285*, 1-8. doi:10.1016/j.geoderma.2016.09.012.

Instituto de Hidrología y Estudios Ambientales (IDEAM). (2017). *Indicadores climáticos*. Retrieved from http://institucional.ideam.gov.co/jsp/1772.

Instituto Geográfico Agustín Codazzi (IGAC). (2014). *Estudio general de suelos y zonificación de tierras: departamento de Caquetá. Escala 1:100.000.* Bogotá, Colombia: autor.

Kass, D. C. L. (1998). *Fertilidad de suelos*. San José, Costa Rica: Editorial de la Universidad Estatal a Distancia (EUNED).

Koko, L. (2014). Teractiv Cacao as a new fertilizer based Reactive Phosphate Rock for cocoa productivity in Côte d'Ivoire: A participatory approach to update fertilization recommendation. *Procedia Engineering, 83*, 348-353. doi:10.1016/j.proeng.2014.09.027.

Kurwakumire, N., Chikowo, R., Mtambanengwe, F., Mapfumo, P., Snapp, S., ... Zingore, S. (2014). Maize productivity and nutrient and water use efficiencies across soil fertility domains on smallholder farms in Zimbabwe. *Field Crops Research, 164*, 136-147. doi:10.1016/j.fcr.2014.05.013.

Lavres, J. J., Reis, A. R., Rossi, M. L., Cabral, C. P., Nogueira, N. L., & Malavolta, E. (2010). Changes in the ultrastructure of soybean cultivars in response to manganese supply in solution culture. *Scientia Agricola, 67*, 287-294. doi:10.1590/S0103-90162010000300006.

López, B. W., Urbina, H. L.H., Reynoso, S. R., & Martínez, S. J. (2018). Efectos del encalado en suelo ácido cultivado con café (*Coffea arabica* L.) en la reserva de la biósfera el triunfo, Chiapas, México. *Agroproductividad, 11*(4), 55-60.

Malavolta, E., Vitty, G. C., & de Oliveira, S. A. (1997). *Availação do estado nutricional das plantas. Principios e aplicações* (2ª ed.). Piracicaba, Brazil: Associação Brasileira para Pesquisa da Potassa e do Fosfato.

Marschner, H. (1995). *Mineral nutrition of higher plants* (2ª ed.). New York, U.S.A.: Academic Press.

Mora, R. J., Burbano, O. H, & Ballesteros, P. W. (2011). Efecto de la fertilización con diversas fuentes sobre el rendimiento de cacao. *Revista de Ciencias Agrícolas, 28*(2), 81-94.

Navarro, B. S., & Navarro, G. G. (2003). *Química agrícola: El suelo y los elementos químicos esenciales para la vida vegetal* (2ª ed.). Madrid, Spain: Ediciones Mundi-Prensa.

Puentes, P. Y. J., Menjivar, F. J. C., & Ortíz, C. A. M. (2016). Eficiencia fisiológica de uso de NPK en clones autoincompatible y autocompatible de cacao (*Theobroma cacao* L.) en Colombia. *Revista de Investigación Agraria y Ambiental, 7*(1), 17-24.

Puentes, P. Y. J., Menjivar, F. J. C., & Aranzazu, F. (2014a). Eficiencia en el uso de nitrógeno, fósforo y potasio en clones de cacao (*Theobroma cacao* L.). *Bioagro, 26*(2), 99-106.

Puentes, P. Y. J., Menjivar, F. J. C., Gómez, A., & Aranzazu F. (2014b). Absorción y distribución de nutrientes en clones de cacao y sus efectos en el rendimiento. *Acta Agronómica, 63*(2), 145-152. doi:10.15446/acag.v63n2.40041.

Quesada, C. A., Lloyd, J., Anderson, L. O., Fyllas, N. M., Schwarz, M., & Czimczik, C. I. (2011). Soils of amazonia with particular reference to the RAINFOR sites. *Biogeosciences, 8*, 1415-1440. Retrieved from https://www.biogeosciences.net/8/1415/2011/bg-8-1415-2011.pdf.

Quinteiro, M., Furtado, A., Schramm, M., Pinto, F., Viana, M., & Baligar V. C. (2013). Aluminum effects on growth photosynthesis and mineral nutrition of cacao genotypes. *Journal of Plant Nutrition, 36*(8), 1161-1179. doi:10.1080/01904167.2013.766889.

Ribeiro, M. A., da Silva, J. O., Aitken, W. M., Machado, R. C. R., & Baligar, V. C. (2008). Nitrogen use efficiency in cocoa genotypes. *Journal of Plant Nutrition, 31*, 239-249. doi:10.1080/01904160701853720.

Romero, L. M. P., Puentes, P. Y. J., & Menjivar, F. J. C. (2016). Eficiencia de uso de nutrientes en ají tabasco (*Capsicum frutescens* L.) y habanero (*Capsicum chinense* Jacq). *Revista de Investigación Agraria y Ambiental, 7*(2), 121-127. doi:10.22490/21456453.1562.

Rosas P. G., Puentes, P. Y. J., & Menjivar, F. J. C. (2017). Relación entre el pH y la disponibilidad de nutrientes para cacao en un entisol de la Amazonia colombiana. *Corpoica Ciencia y Tecnología Agropecuaria, 18*(3), 529-541. doi:10.21930/rcta.vol18_num3_art:742.

Rosas, P. G., Rodríguez, P. W., & Muñoz, R. J. (2012). Caracterización edafológica de lomeríos bajo sistema agroforestal y rastrojo en el Centro de Investigaciones Amazónicas Macagual, Caquetá-Colombia. *Momentos de Ciencia, 9*(2), 153-161.

Sadeghian, S. (2011). Respuesta de cafetales al sol y bajo semisombra a nitrógeno y su relación con la materia orgánica del suelo. *Revista Facultad Nacional de Agronomía-Medellín, 64*(1), 5781-5791.

SAS. (2014). *User's guide: Statistics*, Release 9.4. Cary, U.S.A.: Statistical Analysis System STAT Software.

Schlindwein, J. A., & Gianello, C. (2004). Necessidades de novos estudos de calibração e recomendação de fertilizantes para as culturas cultivadas sob plantio direto. *Revista Plantio Direto, 79*, 12-15.

Shamshuddin, J., Muhrizal, S., Fauziah, I., & Husni A. (2004). Effects of adding organic materials to an acid sulfate soil on the growth of cocoa (*Theobroma cacao* L.) seedlings. *Science of the Total Environment, 323*, 33-45. doi:10.1016/j.scitotenv.2003.10.003.

Soil Survey Staff. (2010). *Keys to Soil Taxonomy* (11ª ed.). Washington, U.S.A.: United States Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS).

Zhu, J., Li, M., & Whelan, M. (2018). Phosphorus activators contribute to legacy phosphorus availability in agricultural soils: A review. *Science of the Total Environment, 612*, 522-537. doi:10.1016/j.scitotenv.2017.08.095.