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RESEARCH ARTICLE

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Reference values and diagnostic ranges to assess the degree of nutritional balance for cacao plants

Bismark L. Bahia[1], Jose O. Souza-Júnior[1], Loane V. Fernandes[2] and Julio C. L. Neves[2]

[1] *Universidade Estadual de Santa Cruz, Dept. Agricultural and Environmental Sciences. Ilhéus, Bahia, Brazil.* [2] *Universidade Federal de Viçosa, Dept. Soil. Viçosa, Minas Gerais, Brazil.*

Abstract

Aim of study: The interpretation of results of leaf analysis can be performed by nutritional balance methods, such as Kenworthy method (KW) and diagnostic levels of contents, whose achievements for cacao constitute the main objective of this work.

Area of study: Bahia, Brazil.

Material and methods: The database covered cacao trees in two cultivation systems: agroforestry systems and full sun. The reference populations were composed of plots with relative yield higher than the average plus half a standard deviation of each of these cultivation systems, in addition to a combined population of both systems.

Main results: The norms of the KW method were compared by the t test, for mean, with 72% concordance; and F, for variance, 82% concordant. The diagnoses made based on specific norms per cultivation system and the general norm agreed on average of 91%. Potential response curves were obtained as a function of the Balanced Indices of Kenworthy (BIK) for each nutrient, by the boundary-line method, in addition to sufficiency ranges for BIK and for leaf contents for cacao.

Research highlights: It is concluded that the general KW norms associated with the original Kenworthy ranges or the specific ranges for cacao are efficient in the nutritional diagnosis of cacao.

Additional key words: nutritional diagnosis, BIK, boundary-line, *Theobroma cacao*

Abbreviations used: AGF (agroforestry systems); BIK (Balanced Indices of Kenworthy); CV (coefficient of variation); eRY (estimated relative productivity); KW (Kenworthy method); LCI (luxury consumption index); RP (reference population);

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Correspondence should be addressed to Bismark Lopes Bahia: bixmark_bahia@hotmail.com

Introduction

Cacao bean is an important agricultural commodity, being the third most traded worldwide in terms of values (Snoeck *et al.*, 2016), having great importance on the world scenario, especially in countries with a tropical climate (Vriesmann *et al.*, 2011). The world's largest cacao producers are Ivory Coast, Ghana, Indonesia, Ecuador, Cameroon, Nigeria, and Brazil (Leite, 2018). In Brazil, the states with the highest production are Pará, Bahia, and Espirito Santo.

In Brazil, cacao (*Theobroma cacao* L.) is traditionally cultivated in different systems, the main ones are: (i) the Cabruca-type agroforestry system (AGF) (implantation over thinned forest), with a varied number of forest species and a tendency to high diversity (Lobão *et al.*, 2011); (ii) other AGFs, *e.g.* cacao × erythrine, cacao × rubber, cacao × coconut (Piasentin & Saito, 2014); and (iii) monoculture in full sun. In addition to these, in recent years, cultivation has been growing in irrigated and fertigated areas, mainly with clonal plants, with little or no shading. In all the cultivation systems, adequate nutrition is necessary to obtain good yield, profitability, and long-term sustainability (Prado & Rozane, 2020).

The evaluation of the nutritional status of plants using leaf analysis is an efficient and inexpensive practice (Gott *et al.*, 2014). Its use has increased, as the nutritional composition of the plant reflects in an integrated manner the effects of edaphoclimatic conditions (Souza Júnior *et al.*, 2018). It is a good tool for decision making regarding the necessary adjustments in fertilization, and it can be evaluated by several methods (Rozane *et al.*, 2016). The most used method for cacao is the sufficiency range (Souza Júnior *et al.*, 2018). An improvement of this method is the Kenworthy method (KW), which incorporates the variability of nutrient contents in the reference population (RP) (Souza Júnior *et al.*, 2018) and improves the nutritional diagnosis of plants (Gott *et al.*, 2014).

Another relevant aspect in the diagnosis, as pointed out by Rocha (2008), is the need to review the original interpretation ranges proposed by Kenworthy (1961), which should be crop specific, which can be obtained with the boundary-line method. This method considers one variable as a dependent factor (productivity) and another as an independent one (Balanced Indices of Kenworthy – BIK – of nutrients), extracting from a cloud of points those located on the upper border, with which regression equations are generated (Ali, 2018). In these conditions, the study factor is the limiting factor and the other factors are not limiting in natural conditions (Walworth *et al.*, 1986). This method can be used for data obtained from commercial crops, as in the works of Mendonça (2016) for coffee, Ali (2018) for mango, and Maia & Morais (2016) for melon.

The objective of this work was to obtain norms for the use of the Kenworthy method and diagnostic ranges for the interpretation of BIK and for the leaf contents for cacao, considering shaded crops and in full sun.

Material and methods

Data sampling

The data used were obtained from cacao fields in the southern region of Bahia, Brazil, covering commercial crops, under different management systems: 192 cacao fields cultivated in full sun (166 fertigated and 26 non-fertigated), 51 plots in agroforestry systems (AGFs - 50 in consortium with rubber and one in Cabruca system), plus 66 plots (52 in AGFs and 14 in full sun and fertigated) from the works of Cabala-Rosand *et al.* (1982), Malavolta *et al.* (1984), Souza Júnior (1997), and Marrocos *et al.* (2012). In this work, AGFs are systems of intercropping of cacao and forest species, varying the number and species of trees. The genetic materials of cacao were: mixture of hybrids, common, Catongo, and the clones (CCN51, CCN10, CEPEC2002, CEPEC2005, CEPEC2007, PH16, PS1319, TSH516) and plots with mixture of clones.

All crops came from homogeneous plots and the nutrient contents were obtained from diagnostic leaves (third leaf, halfway up the canopy of the plant, with a recently matured branch), which were analyzed according to EMBRAPA (2009).

Obtaining norms

Initially, consistency analysis was performed, aiming at the detection and exclusion of clearly anomalous data. After that, yield was converted to relative yield, considering 100% the value of the highest yield of each system and data source. The RP in each system was composed of plots with relative yield greater than the average plus a half standard deviation.

Three RP clusters were formed for the preparation and comparison of norms: the first consisted of plots in full sun (with and without fertigation), the second by shaded plots in AGFs (cacao planted with rubber, Cabruca and other AGFs) and the third one encompassing both systems and called general.

The norms for the use of KW were constituted by the averages of the nutrient contents (N, P, K, Ca, Mg, S, Cu, Fe, Zn, Mn and B) and by their variability, expressed by the coefficient of variation (CV) of each RP cluster.

Comparison of norms

The specific norms for cacao by cultivation system (AGFs and full sun) were compared with the general norms (both systems together) and with each other by the bilateral t test ($p < 0.05$), for the means, and by the F test unilateral ($p < 0.05$), for the variance, by the quotient between the highest and the lowest variance.

Comparison of diagnoses

The low-yield population (plots that do not make up the norms) was subjected to diagnosis by the KW by general and specific norms (full sun and shade). The BIKs were calculated according to the methodology adapted from the KW methodology, described by Kurihana (2004), which consists of calculating the Pr, I and BIK indices according to Eqs. [1], [2] and [3]:

$$Pr = (Yi / Ym) \times 100 \quad [1]$$

$$I = ([Yi - Ym] \times CV) / Ym \quad [2]$$

$$BIK = Pr - I \quad [3]$$

where Pr = proportion between the nutrient in the sample under diagnosis (Yi) and the average content of the reference population (Ym), in %; I = influence of variability, in %; CV = coefficient of variation of nutrient content in the reference population, in %; and BIK = balanced indices of Kenworthy, in %.

The diagnosis of the indexes was carried out using the nutritional ranges proposed by Kenworthy (1961), in 5 classes: deficient (BIK < 50%); below normal (50 ≤ BIK < 83%); normal (83 ≤ BIK < 117%); above normal (117 ≤ BIK< 150%) and excessive (BIK ≥ 150%).

The diagnosis of each nutrient in each plot using the specific norms by cultivation system was compared to the diagnosis with the general norms, with the frequency of relative agreement between them being calculated.

Validation of norms

The validation of the norms was performed as described by Wadt *et al.* (1998), using the chi-square test (χ^2) (p < 0.05) applied to the frequency of diagnoses obtained with the general norms in the Kenworthy ranges, by diagnostic range, with the null hypothesis being that the frequency of diagnoses in each diagnostic class occurred due to chance. Considering the nutrients as repetition and the expected frequency of plots in each 20% range.

Determination of diagnostic ranges for BIK specific for cacao

Based on the BIK obtained with the general norms of all fields that make up the database, the specific diagnostic ranges for BIK were determined by the boundary-line method, as described by Ali (2018), which uses the relative yield as the dependent variable and the BIK of each nutrient as an independent variable. For this, scatter plots were drawn up and points that aligned with the upper border were selected using the software R CRAN (R Development Core Team, 2019), with the packages 'ggplot2' (Wickham, 2016), 'ggrepel' (Slowikowski, 2019), and 'dplyr' (Wickham *et al.*, 2019), with the points, thus, selected subjected to regression analysis. The equations were selected based on their biological significance, the significance of their coefficients and the determination coefficient (R^2).

From these equations, the estimated relative yield (eRY) was obtained, simulating BIK values within the data range (minimum and maximum observed) for each nutrient; the highest estimated value was considered to be 100%, adjusting the others according to this. After that, the diagnostic ranges were obtained considering the following percentages in relation to the highest eRY value: deficient (eRY < 70%), tendency to deficient (70 ≤ eRY < 90%), sufficient (90 ≤ eRY ≤ 100%), high (100> eRY ≤ 90%, to the right of the maximum), tendency to excess (90 < eRY < 70%, to the right of the maximum), excess (eRY ≤ 70%, to the right of the maximum).

The BIK values obtained for low yield plots were interpreted based on the specific diagnostic ranges for cacao trees. In addition, the luxury consumption index (LCI) was calculated, following Mendonça (2016), according to Eq. [4]:

$$\mathrm{LCI} = \frac{\mathrm{High}}{\mathrm{Sufficient} + \mathrm{High}} \times 100 \qquad [4]$$

where ´Sufficient´ and ´High´ are the relative frequencies of fields with the nutrient in the sufficient and high ranges.

Determination of the diagnostic ranges for the cacao leaf contents

The diagnostic ranges of the cacao leaf contents were determined in two ways. In the first way the original KW method was used, proceeding to the inverse calculation, that is, from the BIK values recommended in each range (Kenworthy, 1961), then the limits of nutrient contents in each range were obtained. In the second way, the diagnostic ranges were obtained using the KW method with the specific BIK ranges for cacao trees developed by the upper boundary-line method.

Results

The yield of the stands of the reference population varied according to the cultivation system, being in the AGFs from 740 to 2580 kg ha^{-1}, and for cacao trees cultivated in full sun from 2295 to 6357 kg ha^{-1}. In turn, considering the entire database, yield ranged from 93 to 6357 kg ha^{-1}.

Most of the BIK nutritional norms for cacao in the two cultivation systems agreed with the general norms (both systems together, see Table 1); on the other hand, shading caused reduction in the requirement of N, P, and S and an increase in the requirement for K. In general, macronutrients had less variability than micronutrients, with the exception of B. However, Fe, Mn, and Zn had variability greater than 40%.

Allied to the agreement of the norms, there was also high agreement in the nutritional diagnosis by the original KW method, comparing the use of general norms and norms by cultivation system, with the average diagnostic agreement of 94.1% for cacao trees grown in full sun and 87.9% for shaded cacao trees (Table 2). The diagnoses obtained in the Kenworthy diagnostic ranges did not occur due to chance, as indicated by the chi-square test (p < 0.01). From the BIK, nutritional ranges of leaf nutrient contents in cacao plants were obtained using the Kenworthy ranges (Table 3).

Table 1. Norms Kenworthy method (KW) and the agreement of the general norms (G), with cultivation in full sun (FS) and shaded cultivation (S) for cacao, Southern Bahia, Brazil, 2019

	General			Full sun			Shaded			G *vs* FS		G *vs* S		FS *vs* S	
	x̄	CV (%)	n	x̄	CV (%)	n	x̄	CV (%)	n	x̄	s^2	x̄	s^2	x̄	s^2
N	21.98	14.7	71	23.04	13.2	47	19.89	12.9	24	ns	ns	*	ns	**	ns
P	1.88	21.1	71	1.92	22.7	47	1.78	16.0	24	**	ns	**	*	**	*
K	17.72	20.3	71	16.40	21.4	47	20.30	10.1	24	ns	ns	*	**	**	**
Ca	10.51	34.9	71	10.47	34.5	47	10.61	36.3	24	ns	ns	ns	ns	ns	ns
Mg	5.73	19.6	71	5.66	20.4	47	5.87	18.3	24	ns	ns	ns	ns	ns	ns
S	2.00	35.7	67	2.15	37.9	43	1.73	20.7	24	**	ns	**	**	**	**
Cu	9.04	38.1	69	9.62	38.3	45	7.95	34.1	24	ns	ns	ns	ns	ns	ns
Fe	51.93	38.7	71	53.61	32.3	47	48.65	50.9	24	ns	ns	ns	ns	ns	*
Zn	76.27	68.3	71	89.09	66.0	47	51.14	37.0	24	ns	ns	ns	**	ns	**
Mn	340.73	90.2	71	327.11	98.1	47	367.41	77.1	24	ns	ns	ns	ns	ns	ns
B	36.80	14.7	40	36.07	13.0	27	38.32	17.3	13	ns	ns	ns	ns	ns	ns

Contents of N, P, K, Ca, Mg, and S are expressed in g kg^{-1}; and Cu, Fe, Zn, Mn, and B in mg kg^{-1}. x̄ = average, CV = coefficient of variation, n = number of plots that constitute the norm and s^2 = variance. ns, * and **: not significant, significant at $p < 0.05$ and $p < 0.01$, respectively, by t tests for means and F for variance.

To obtain the specific nutritional ranges and to know the response of cacao in productivity to the degree of nutritional balance (BIK), mathematical models were adjusted for all nutrients. For macronutrients, the best-fit models were quadratic (Fig. 1), indicating symmetry between the deficiency and toxicity ranges and region. However, for S, the decrease caused by deficiency is outside the limits of the studied sample space (Fig. 1F).

For micronutrients, the models with the best fit contained an exponential and a linear component, except for Mn that had a quadratic behavior (Fig. 2). Therefore, except for Mn, for the other micronutrients studied there is not symmetry between the regions of deficiency and toxicity, the increase in productivity being more abrupt due to the increase in BIK, from the region of deficiency to the region of sufficiency; in turn, the decrease in yield as a result of the increase in the BIK, from the sufficiency to the toxicity region, is more gradual (Fig. 2). Similar to that observed for S (Fig. 1F), the BIKs for Mn in the deficiency region were outside the sample space (Fig. 2D).

The nutritional diagnosis using the specific nutritional ranges for the cacao tree of the KW method allowed the separation of the plots with adequate nutrition and high yield from those with low yield caused by lack or excess of nutrients. In addition, the use of six diagnostic ranges allowed stratification of plots with nutrition in the normal range into two other ranges, sufficient and high (luxury consumption), except for S and Mn, for which it was not possible to obtain this stratification of the normal range (Table 4). The BIK limits for each range varied between nutrients, differing from the one originally proposed by Kenworthy (1961), which establishes fixed values, regardless of crop and nutrient. For the nutrients P, Ca, and Cu, it was not possible to establish the separation limit of the specific BIK between the deficiency endency range and the deficient range; and for S and Mn, it was not possible to determine the lack limitation (deficiency and deficiency tendency), as they were outside the sample space (Figs. 1 and 2).

The order of frequency of plots with nutritional limitation, due to lack or excess, ordered from highest to lowest, was also influenced by the diagnostic range used (Table 5). By the original Kenworthy method, the order by limitation for lack was Ca> S> K> Mg> B> Fe> P> Cu> Zn> N; and by excess limitation, it was Mg > Cu > S > K > Fe

Table 2. Relative frequency (in %) of agreement of diagnoses by the original KW method for the Kenworthy range using the general norms (G) with the norms per cultivation system: full sun (FS) and shading (S), Southern Bahia, Brazil, 2019

	N	P	K	Ca	Mg	S	Fe	Zn	Mn	B
G *vs* FS	91.4	96.1	88.4	100	98.3	96.5	93.9	85.3	100	97.9
G *vs* S	95.5	94.7	66.9	99.6	94.2	96	89.6	80.8	61.3	93.6

Table 3. Interpretation ranges for leaf nutrient content obtained by the original Kenworthy method (1961) for cacao, Southern Bahia, Brazil, 2019

		Deficient	Under normal	Normal	Above normal	Excessive
		<50	50 ≤ BIK < 83	83 ≤ BIK < 117	117 ≤ BIK < 150	≥ 150
N	g kg^{-1}	<9.09	9.09-17.59	17.60-26.35	26.36-34.86	>34.86
P	g kg^{-1}	<0.69	0.69-1.46	1.47-2.27	2.28-3.04	>3.04
K	g kg^{-1}	<6.61	6.61-13.93	13.94-21.49	21.50-28.84	>28.84
Ca	g kg^{-1}	<2.44	2.44-7.76	7.77-13.25	13.26-18.54	>18.54
Mg	g kg^{-1}	<2.17	2.17-4.51	4.52-6.93	6.94-9.29	>9.29
S	g kg^{-1}	<0.45	0.45-1.46	1.47-2.52	2.53-3.56	>3.56
Cu	mg kg^{-1}	<1.7	1.7-6.5	6.6-11.4	11.5-16.3	>16.3
Fe	mg kg^{-1}	<9.5	9.5-37.4	37.5-66.2	66.3-94.3	>94.3
Zn	mg kg^{-1}	-	<35.3	35.3-117.1	117.2-196.6	>196.6
Mn	mg kg^{-1}	-	-	<930.2	930.2-2074.4	>2074.4
B	mg kg^{-1}	<15.2	15.2-29.4	29.5-44.0	44.1-58.4	>58.4

BIK = balanced indices of Kenworthy. -: values not obtained in the data range

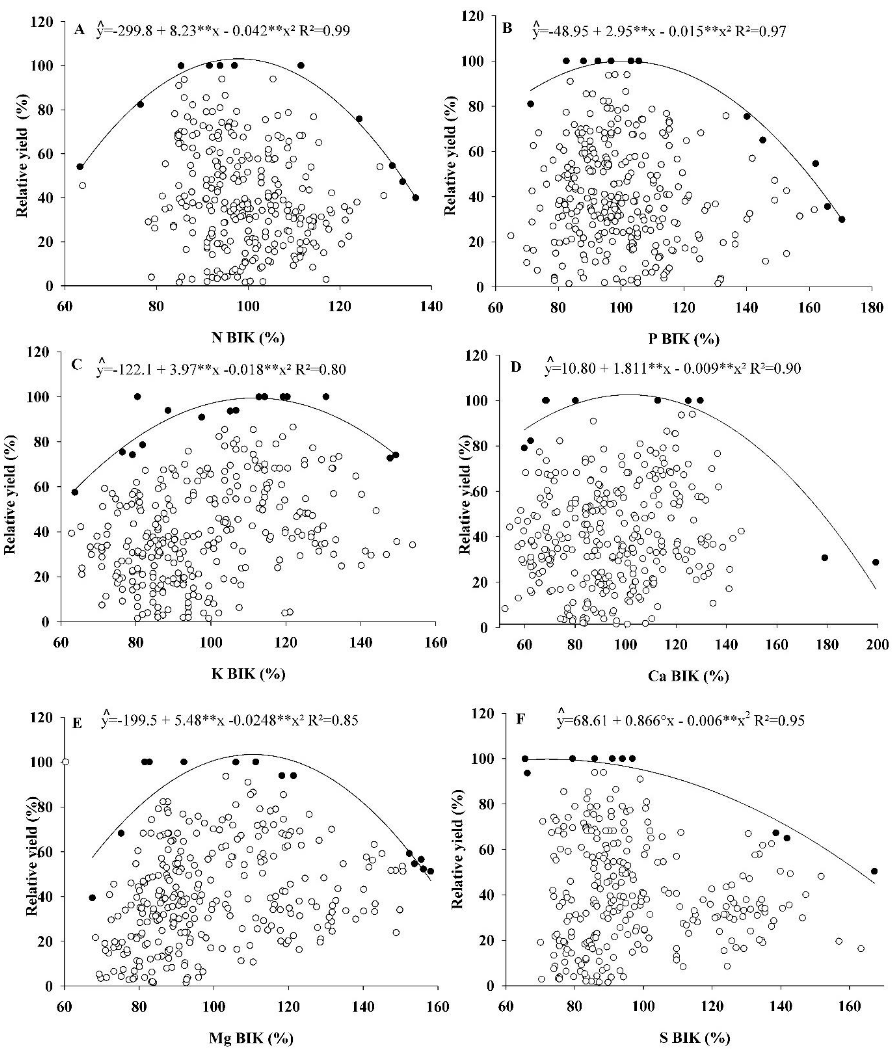

Figure 1. Potential response curve of cacao to balanced indices of Kenworthy (BIK) for nitrogen (A), phosphorus (B), potassium (C), calcium (D), magnesium (E) and sulfur (F), Southern Bahia, Brazil, 2019. ° and **: significant at 10% and 1% by the F test, respectively.

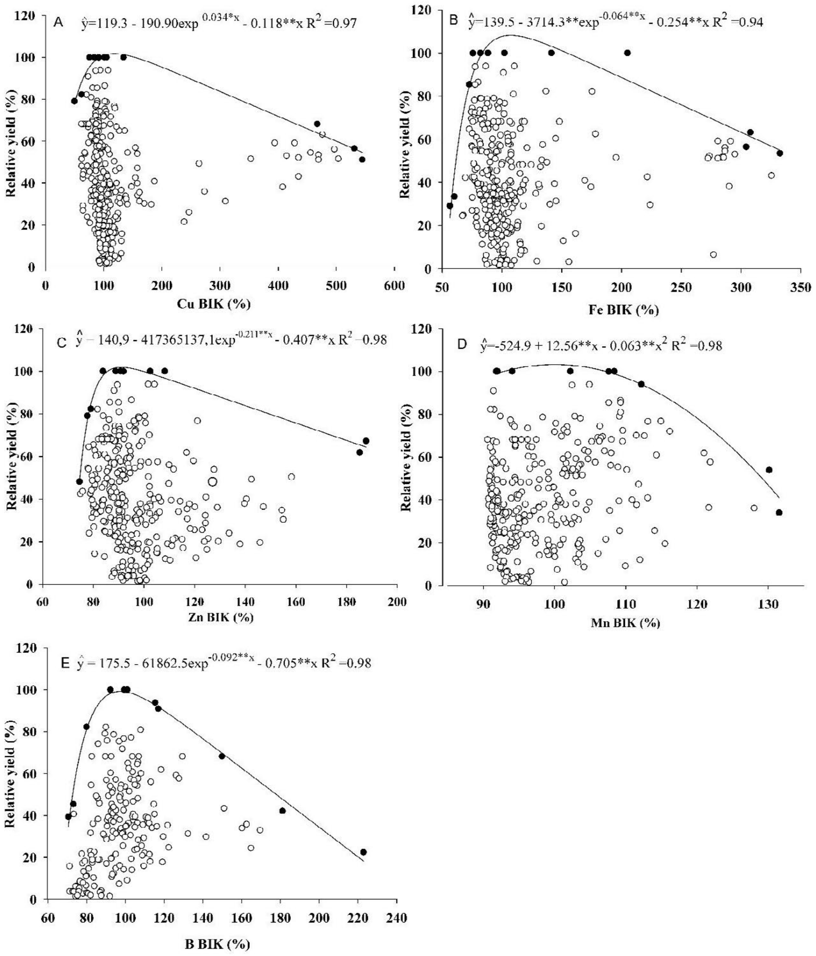

Figure 2. Potential response curve of cacao yield to balanced indices of Kenworthy (BIK) for copper (A), iron (B), zinc (C), manganese (D) and boron (E), Southern Bahia, Brazil, 2019. * and **: significant at 5% and 1% by the F test, respectively.

> Ca > P > B > Zn > N > Mn. By the BIK specific ranges method (Table 5) for cacao, the order by limitation for lack was Mg > K > B > Fe > Ca > Zn > Cu > P > N; and for excess limitation, it was S > Mg > N > Fe > P = B > Cu > Zn > K > Mn > Ca. The order of nutrients with the highest frequency of indicative LCI was: B > Zn > N > Mg > Ca > P > K > Mn > Fe > Cu.

Specific diagnostic ranges for foliar levels of nutrients for cacao were also established (Table 6), based on the specific ranges of the BIK (Table 4). These ranges had the lower limit of the sufficient range lower than that obtained by the original KW method, except for K, Mg, and B (Table 3). The specific sufficiency ranges (Table 6) were more flexible for P, K, Ca, Mg, Cu, and Fe, and more rigid for N and B in relation to the sufficiency ranges obtained by the original KW method (Table 3).

Discussion

The RPs have different yield depending on the cultivation system, due to the different conditions encountered by the cacao tree. The yield of the shaded cacao tree was lower than in full sun, due to the smaller number of plants per area and the light restriction (Almeida & Gattward, 2018). In addition, the trees that make up the shading can compete for resources (Isaac *et al.*, 2007), such as water and nutrients. Plants grown in full sun show greater gas exchange, transpiration, and photosynthesis, and consequently they produce more carbohydrates and need to extract more nutrients from the soil (Almeida & Gattward, 2018). In turn, plants grown in full sun and fertigated have the additional advantage of not only being limited in terms of light availability, but also having a better and better distributed supply of water and nutrients throughout the year. Shading affected the nutrition of plants on N, P, S, and K, which corroborates with what is described by Costa *et al.* (1998), Isaac *et al.* (2007), Bai *et al.* (2017), and Van Vliet & Giller (2017).

High yield cacao trees grown in full sun had a lower average leaf content (KW norm) than those under AGFs (Table 1), possibly because K is the most exported nutrient for the fruit (Souza Júnior *et al.*, 2018), and since in the areas under full sun the yield was higher, this nutrient

Table 4. Specific ranges for interpreting balanced indices of Kenworthy (BIK, in %), as a function of estimated relative productivity (eRY) for cacao, Southern Bahia, Brazil, 2019

	Deficient <70%	Tendency to deficient 70≤ eRY< 90%	Normal		Tendency to excess 90≤ eRY< 70%	Excess ≥70%
			Sufficient 90≤ eRY< 100%	High 100≤ eRY< 90%		
N	<70.7	70.7-82.1	82.2-97.7	97.8-113.4	113.5-124.8	>124.8
P	-	<74.8	74.8-100.8	100.9-126.9	127.0-146.2	>146.2
K	<70.6	70.6-87.8	87.9-111.4	111.5-135.1	135.2-152.5	>152.5
Ca	-	<67.6	67.7-101.6	101.7-135.8	135.9-160.7	>160.7
Mg	<75.1	75.1-90.0	90.1-110.4	110.5-130.9	131.0-146.0	>146.0
S	-	-	<72.1	72.1-112.8	112.9-142.8	>142.8
Cu	-	<67.3	67.3-118.4	118.5-233.4	233.5-405.8	>405.8
Fe	<68.9	68.9-80.8	80.9-107.4	107.5-165.3	165.4-250.9	>250.9
Zn	<76.8	76.8-80.8	80.9-91.0	91.1-120.7	120.8-170.8	>170.8
Mn	-	-	<100	100.0-112.8	112.9-122.2	>122.2
B	<76.5	76.5-83.4	83.5-97.2	97.3-120.9	121.0-150.3	>150.3

-: values not obtained in the data range

is more translocated from the leaf to the fruit. In turn, cacao trees grown in full sun had higher average levels of N, P, and S (Table 1), probably as a result of needing a greater protective apparatus against excess radiation and its consequences, such as photoinhibition, which reduces photosynthesis. The excess of radiation makes it necessary to synthesize regulatory, protective, and/or energy storage molecules such as proteins, alkaloids, carotenoids, glutathione, ATP, NADP etc., increasing the demand for structural function nutrients, such as N, P, and S (Taiz *et al.*, 2017).

Despite the differences pointed out between cacao trees nutrition with and without shading, for K, N, P, and S, there was a high agreement of the KW norms (mean and variance) for most nutrients between the two cultivation systems (Table 1) and of nutritional diagnoses (Table 2), when general norms are compared with specific ones according to the cultivation system. This corroborates with Dias *et al.* (2010), who recommend the use of general norms for cupuaçu. This is reinforced by the diagnosis not being attributed to chance, since according to Wadt *et al.* (1998), when the frequencies of nutrients diagnosed in a class are not attributed to chance, these norms can be used for nutritional diagnosis.

On the other hand, the feasibility of using general norms is pointed out by Reis Júnior (2002) when reporting

Table 5. Relative frequency (in %) of cacao plots in the Kenworthy diagnostic ranges and specific for cacao in the BIK indexes, and luxury consumption index (LCI), Southern Bahia, Brazil, 2019

	N	P	K	Ca	Mg	S	Cu	Fe	Zn	Mn	B
	Kenworthy ranges										
Limiting for lack [1]	4.0	13.9	25.3	30.0	22.8	23.4	12.3	16.0	11.0	0.0	19.6
Normal	90.1	71.8	54.9	55.3	53.6	56.5	67.4	65.4	80.2	98.7	70.3
Excessive limiting	5.9	14.3	19.8	14.7	23.6	20.1	20.3	18.6	8.8	1.3	10.1
	Specific ranges										
Limiting for lack	3.6	3.8	40.1	12.3	43.9	0.0	4.2	12.6	8.0	0.0	21.6
Enough	45.5	54.4	35.0	52.7	25.8	1.9	75.9	57.8	38.0	66.2	30.4
High	40.5	33.0	20.3	32.5	18.1	75.7	11.4	20.7	47.7	30.8	39.2
Excessive limiting	10.4	8.8	4.6	2.5	12.2	22.4	8.5	8.9	6.3	3.0	8.8
LCI	47.1	37.8	36.7	38.1	41.3	-	13.1	26.4	55.6	35.4	56.3

[1] Limiting for lack (deficient + tendency for deficient) and limiting for excess (tendency for excess + excessive). -: values not obtained in the data range

that the norms can be extrapolated when the contents of the high-yield populations in the locality to be extrapolated are similar to the contents of the norms. This can be verified with the fact that the average levels of nutrients in the RP (KW norms) are within the general sufficiency ranges proposed by Souza Júnior *et al.* (2018), with the exception of K, which was slightly below. In addition, general norms have better results when extrapolated (Wadt & Dias, 2012).

Regardless of the norm, general or by cultivation system, the lowest CVs were observed for N, P, K, Mg, and B (Table 1), indicating greater sensitivity in the diagnosis for these nutrients (Hermida *et al.*, 2013). In turn, the highest CVs were observed for metallic micronutrients: Mn, Zn, Fe, and Cu (Table 1).

Rocha (2008) considers that variability is the main limitation to the use of the KW method, due to the sensitivity of the method to diagnose nutritional deficiencies or excesses decreasing with increasing variability. Kurihara (2004) suggests the CV limit of the KW norm of 40%, for a good sensitivity of the diagnosis. According to this limit, the norms for Zn and Mn should cause less precision in the diagnosis, except for the Zn norm in shaded cacao trees (Table 1).

The high variability of leaf nutrient content in cacao confirms that observed by Marrocos *et al.* (2012), which may be a consequence of the diversity of edaphoclimatic conditions of its cultivation in the south of Bahia, with soils with wide variability of mineralogical, chemical, and physical attributes (Santana *et al.*, 2002; Araujo *et al.*, 2018; Arévalo-Hernández *et al.*, 2019).

Accuracy in diagnosing the nutritional status of plants is a key element for decision making in the competitive market (Rozane *et al.*, 2016). There was an improvement in the efficiency of the nutritional diagnosis of cacao by the BIK interpretation ranges obtained by the upper boundary-line method (Table 4). They add biological significance and model the response in relative yield according to the BIK, being specific for each nutrient (Figs. 1 and 2), unlike the original range by Kenworthy (1961), which is based only on statistical criteria, considering a fixed CV of 20%, where high variability limits the use of this method (Mendonça, 2016). In addition, Kenworthy considered the existence of symmetry in the diagnostic ranges for the different nutrients, in addition to the similarity in the response of the different nutrients to the variation in the degree of nutritional balance and especially the deficiency and excess zone. Fact not observed for the curves (Figs. 1 and 2) and diagnostic ranges (Table 4) for cacao, which corroborates with Fernández *et al.* (2016), who observed different responses for the relationship between the biomass production of cacao seedlings and the leaf contents of N, P, and K.

In addition, the border population is made up of plots of higher yield within each cultivation system, but also plots of lower yield due to deficiencies or excess of nutrients; resulting in specific models of the relationship between RY as a function of the BIK for each nutrient (Figs. 1 and 2), which reinforces the improvement in the quality of the diagnosis, as it allows the establishment of specific BIK ranges for the cacao tree (Table 4).

For macronutrients, the best fit model was the quadratic model (Fig. 1), indicating symmetry between the regions of deficiency and toxicity. In turn, for micronutrients, the predominant models express an abrupt increase in eRY between the deficiency and sufficiency ranges and, after this, the decrease in eRY due to the increase in BIK is more gradual, with no symmetry, except for Mn which presented a behavior similar to that observed for macronutrients. The fact that Mn behaves differently from other micronutrients possibly occurs because the cacao tree tolerates high concentrations of this nutrient, including leaf contents in order of magnitude from those observed for some macronutrients (Souza Júnior *et al.*, 2012).

In the productive phase of cacao, and independent of the cultivation system, it is also possible to establish diagnostic ranges for leaf nutrient levels based on two distinct criteria: original KW method (Table 3) and specific boundary-line method for the cacao tree (Table 6). It should be noted that for cacao there are few studies that establish sufficiency ranges. Oliveira *et al.* (2019) obtained sufficiency ranges for the leaf contents of cacao clones CCN51 and PS1319, using 20 commercial plots; these authors indicate these ranges only for the south of Bahia and the north of Espirito Santo and for these clones. Souza Júnior *et al.* (2018) in a broad review of this theme in the international literature, identified 14 sufficiency ranges proposed by different authors, for cacao, in different countries. Souza Júnior *et al.* (2018) also point out that there is a great divergence between these ranges of sufficiency for various nutrients and that there is often a lack of information on the methodology used to obtain them, being commonly based on the authors' experience with the crop and / or a small number of crops; indicating that they need to be improved and redefined. In the present work, the ranges were obtained from a database with 309 plots and statistical methods used for other crops.

Analyzing the normal range, its lower limit, which generally equals the critical level (Souza Júnior *et al.*, 2018), was higher by the original KW methodology (Table 3) than by the boundary-line methodology (Table 6), except for K and Mg, which had the opposite behavior, and for B, which presented similar values. The original KW method was more rigid in establishing the limits of the normal ranges (narrower ranges) than the frontier method, which was more flexible (wider range), except for N (Tables 3 and 6), a fact also reported for various nutrients for coffee (Mendonça, 2016) and eucalyptus (Lima Neto *et al.*, 2020). The absence of symmetry in the response between the deficiency and toxicity ranges for Cu, Fe, Zn, and B

Table 6. Interpretation ranges for leaf nutrient levels, obtained by specific ranges for balanced indices of Kenworthy, as a function of estimated relative productivity (eRY) for cacao, Southern Bahia, Brazil, 2019

		Deficient <70%	Tendency to deficient 70-90%	Normal		Tendency to excess 90-70%	Excess <70%
				Sufficient 90-100%	High 100-90%		
N	g kg-1	<14.43	14.43-17.38	17.39-21.40	21.41-25.45	25.46-28.37	>28.37
P	g kg-1	-	<1.27	1.28-1.89	1.90-2.51	2.52-2.98	>2.98
K	g kg-1	<11.17	11.17-15.01	15.02-20.26	20.27-25.52	25.53-29.38	>29.38
Ca	g kg-1	-	<5.28	5.29-10.77	10.78-16.30	16.31-20.31	>20.31
Mg	g kg-1	<3.96	3.96-5.01	5.02-6.47	6.48-7.93	7.94-9.01	>9.01
S	g kg-1	-	-	<1.12	1.12-2.39	2.40-3.33	>3.33
Cu	mg kg-1	-	<4.2	4.3-11.6	11.7-28.4	28.5-53.7	>53.7
Fe	mg kg-1	<25.6	25.6-35.6	35.7-58.2	58.3-107.3	107.4-179.9	>179.9
Zn	mg kg-1	<20.4	20.4-30.3	30.3-54.3	54.4-126.1	126.2-246.7	>246.7
Mn	mg kg-1	-	-	<340.7	340.7-787.9	788.0-1110.5	>1110.5
B	mg kg-1	<26.7	26.7-29.6	29.7-35.5	35.6-45.8	45.9-58.5	>58.5

-: values not obtained in the data range

(Fig. 2) helps to understand the enlargement of the upper limit of the normal range by the boundary-line method (Table 6).

Most of the low yield plots (plots that did not make up the RP), regardless of the diagnostic ranges used for the interpretation of the KW method, had adequate nutrition (Table 5), indicating that other non-nutritional factors, together, influenced yield, among which: water relations (deficit or excess of water), excess of shading, low genetic potential and attack of diseases and pests.

From a nutritional point of view, the most limiting macronutrients were K, Mg, and Ca (Table 5), possibly because cacao has a high demand for these nutrients (Souza Júnior *et al.*, 2018), in addition to the many plots in this study that are found in Oxisols with low availability of exchangeable cations. It is important to highlight that the K^+, Ca^{2+}, Mg^{2+} ions present competitive inhibition in the absorption process, that is, they compete for the same root absorption site, consequently the greater presence of one inhibits the absorption of the other (Malavolta, 2006), which justifies the fact that K, Mg, and Ca deficiencies occur in plots where it was diagnosed that one of these nutrients was in excess or luxury consumption. Focusing on Mg and Ca, in addition to this competitive inhibition, the fact that cacao requires a close Ca / Mg ratio (Souza Júnior *et al.*, 2018). These interactions highlight the need to also study the balance of nutrients and be careful in fertilizing these interactions.

Deficiencies of all micronutrients were found, except for Mn (Table 5). B and Zn deficiencies in cocoa trees are the most reported in the literature (Souza Júnior *et al.*, 2018). Zn deficiency occurred in plots with excess of K and or P, corroborating with Malavolta (2006) who reports a negative correlation between leaf K contents with B, Mn, and Zn, as well as that the high availability of P can induce deficiency of Cu, Fe, and Zn.

Considering both KW methods, the nutrients that had higher and lower frequencies due to excess were S and Mn, respectively (Table 6). This, in a way, corroborates the observations made by Souza Júnior *et al.* (2018), for the cultivation of cacao trees in the region covered by this study; these authors state that deficiencies by S have little occurrence and that very high Mn leaf levels are frequently found, without these causing toxicity to the cacao tree. In addition, Mn is a micronutrient with high demand in areas of high yield, mainly in the productive phase (Marrocos *et al.*, 2020).

For making decisions about the nutritional management of crops, the use of tools that assess the nutritional balance is very important, especially for the diagnosis of deficiencies or excesses, which would indicate the need for adjustments in nutrient doses; this can be achieved using five (original Kenworthy tracks) or six ranges. However, the high range (luxury consumption) should deserve greater attention by technicians, aiming at the rational use of nutrients and reduction of fertilization costs, since this can only be done with the subdivision of the original normal KW range. There was a high frequency of plots in "luxury consumption", with only Cu and Fe the nutrients that had low LCI (Table 5). This demonstrates that there is a need to improve the process of fertilization and nutritional management of cacao, considering not only soil analysis, but also leaf analysis and diagnosis with appropriate tools.

In conclusion, full sun cacao plants have higher requirements for N, P, and S compared to shaded plants. Norms of contents and sufficiency ranges were obtained for balanced indices of Kenworthy and for leaf nutrient contents for cacao, regardless of the cultivation system, which maximize the assessment of nutrition as a production factor. In general, the boundary-line method provides sufficiency ranges for broader leaf contents of nutrients with a lower limit than those of the original Kenworthy method.

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