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

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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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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 Espírito 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 (Plasentin & 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.
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 ($\chi^2$) ($p < 0.05$) 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 ($70 \leq eRY < 90\%$), sufficient ($90 \leq eRY \leq 100\%$), high ($100 > eRY \leq 90\%$), to the right of the maximum), tendency to excess ($90 < eRY < 70\%$, to the right of the maximum), excess ($eRY \leq 70\%$, 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]:

$$\text{LCI} = \frac{\text{High}}{\text{Sufficient} + \text{High}} \times 100 \quad [4]$$

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).
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 deficiency to the deficiency tendency 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 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

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**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 | FS | S |
|-------|---------|----|---|
| N     | 21.98   | 14.7 | 71 |
| P     | 1.88    | 21.1 | 71 |
| K     | 17.72   | 20.3 | 71 |
| Ca    | 10.51   | 34.9 | 71 |
| Mg    | 5.73    | 19.6 | 71 |
| S     | 2.00    | 35.7 | 67 |
| Cu    | 9.04    | 38.1 | 69 |
| Fe    | 51.93   | 38.7 | 71 |
| Zn    | 76.27   | 68.3 | 71 |
| Mn    | 340.73  | 90.2 | 71 |
| B     | 36.80   | 14.7 | 40 |

**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

|       | FS | S |
|-------|----|---|
| N     | 91.4 | 95.5 |
| P     | 96.1 | 94.7 |
| K     | 88.4 | 66.9 |
| Ca    | 100 | 99.6 |
| Mg    | 98.3 | 94.2 |
| S     | 96.5 | 96  |
| Fe    | 93.9 | 89.6 |
| Zn    | 85.3 | 80.8 |
| Mn    | 100 | 61.3 |
| B     | 97.9 | 93.6 |
The degree of nutritional balance for cacao plants

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

| Nutrient | 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.
$> Ca > P > B > Zn > N > Mn$. By the BIK specific ranges method (Table 5) for cacao, the order by limitation for lack was $Mg > K > B > Ca > Zn > Cu > P > N$; 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
The degree of nutritional balance for cacao plants 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 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≤ eRY<90% | Tendency to deficient 90≤ eRY<100% | Normal 100≤ eRY<90% | Tendency to excess 90≤ eRY<70% | Excess ≥70% |
| 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 | <76.7 | 76.7-101.6 | 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

| 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 | 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
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). Mn is a micronutrient with high demand in cocoa, 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

| 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 |
|-----------------|---------------|---------------|---------------|---------------|---------------|
| Nutrient | Deficient <70% | Tendency to deficient 70-90% | Normal | Tendency to deficient 90-100% | Normal | Tendency to excess 90-70% | Excess <70% |
| 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 | - | <1.17 | 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
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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References

Ali AM, 2018. Nutrient sufficiency ranges in mango using boundary-line approach and compositional nutrient diagnosis norms in El-Salhiya, Egypt. Commun Soil Sci Plant Anal 49 (2): 188-201. https://doi.org/10.1080/00103624.2017.1421651

Almeida AAF, Gattward JN, 2018. Resposta do cacau ao colono e a variações de intensidade luminosa. In: Cacao: cultivo, pesquisa e inovação; Souza Júnior JO (Org.). Ilhéus: Editus, pp: 35-58. https://doi.org/10.7476/9786586213188.0002

Araujo Q, Ahnert D, Loureiro G, Faria J, Fernandes C, Baligar V, 2018. Soil quality index for cacao cropping systems. Arch Agron Soil Sci 64: 1892-1909. https://doi.org/10.1080/03650340.2018.1467005

Arévalo-Hernández CO, Pinto FC, Souza Júnior JO, Pavia AQ, Baligar VC, 2019. Variability and correlation of physical attributes of soils cultivated with cacao trees in two climate zones in Southern Bahia, Brazil. Agrofor Syst 93: 793-802. https://doi.org/10.1007/s10457-017-0176-4

Bai SH, Trueman SJ, Nevenimo T, Hannet G, Bapiwai P, Poienou M, Wallace HM, 2017. Effects of shade-tree species and spacing on soil and leaf nutrient concentrations in cocoa plantations at 8 years after establishment. Agr Ecosyst Environ 246: 134-143. https://doi.org/10.1016/j.agee.2017.06.003

Cabala-Rosand P, Santana CJL, Miranda ER, 1982. Respostas de cacauíce "Catongo" a doses de fertilizantes no Sul da Bahia, Brasil. Theobroma 12: 203-216.

Costa LCB, Almeida AAF, Valle RR, 1998. Crescimento, teor de clorofila e estrutura anatômica em plântulas de Theobroma cacao submetidas a diferentes irradianças e doses de nitrogênio. Agrotrópica 10: 21-30.

Dias JRM, Tucci CAF, Wadt PGS, Silva AM, Santos JZL, 2010. DRIS norms for cupuacu trees cultivated in monocultures and in agroforestry systems. Pesquisa Agropec Bras 45: 64-71. https://doi.org/10.1590/S0100-204X2010000100009

EMBRAPA, 2009. Manual de análises químicas de solos, plantas e fertilizantes, 2nd ed. Empresa Brasileira de Pesquisa Agropecuária, Informação Tecnológica, Brasília, DF; Embrapa Solos, Rio de Janeiro.

Fernández JC, Bohórquez W, Rodríguez A, 2016. Cocoa nutritional dynamics under different fertilization treatments of N, P and K in nursery. Revista Colombiana de Ciencias Hortícolas 10 (2): 367-380. https://doi.org/10.17584/rchc.2016v10i2.4702

Gott RM, Aquino LA, Carvalho AMX, Santos LPD, Nunes PHMP, Coelho BS, 2014. Indices diagnósticos para interpretação de análise foliar do milho. Rev Bras Engenh Agric Amb 18 (11): 1110-1115. https://doi.org/10.1590/1807-1929/agriambi.v18n11p1110-1115

Hermida JIF, Toro MCH, Guzmán M, Cabrera RI, 2013. Determining nutrient diagnostic norms for greenhouse roses. HortScience 48: 1403-1410. https://doi.org/10.21273/HORTSCI.48.11.1403

Isaac ME, Ulzen-Appiah F, Timmer VR, Quashie-Sam SJ, 2007. Early growth and nutritional response to resource competition in cocoa-shade intercropped systems. Plant Soil 298: 243-254. https://doi.org/10.1007/s11104-007-9362-x

Kenworthy AL, 1961. Interpreting the balance of nutrient-elements in leaves of fruit trees. In: Plant analysis and fertilizers problems; Reuther W (ed). Am Inst of Biol Sci, Washington, pp: 28-43.

Kurihara CH, 2004. Demanda de nutrientes pela soja e diagnose de seu estado nutricional. Tese de Doutorado. Universidade Federal de Viçosa, Viçosa-MG. 101pp.

Leite LRC, 2018. Estudo de competitividade do cacau e chocolate no Brasil: Desafios para aumentar a produção e participação no comércio global. UNESCO.

Lima Neto AJ, Neves JCL, Martínez HEP, Sousa JS, Fernandes LV, 2020. Establishment of critical nutrient levels in soil and plant for eucalyptus. Rev Bras Ciênc Solo 44: e0190150. https://doi.org/10.1590/18069657rbcs20190150

Lobão DE, Setenta WC, Santos ES, Curvelo K, Lobão ESP, Valle RR, 2011. Cacau cabruca system and Atlantic Forest: Arboreal diversity, conservation and potential. Agrotrópica 23: 115-124.

Maia CE, Morais ERC, 2016. Boundary line model to estimate the nutrient sufficiency range in muskmelon leaves. Rev Bras Ciênc Solo 40: e0160033. https://doi.org/10.1590/18069657rbcs20160033

Malavolta E, 2006. Manual de nutrição mineral de plantas. Agronômica Ceres, São Paulo.

Malavolta E, Malavolta ML, Cabral CP, 1984. Nota sobre as exigências minerais do cacauíce. Anais da Escola Superior de Agricultura Luiz de Queiroz 41: 243-255. https://doi.org/10.1590/S0071-12761984000100014
Marrocos PCL, Sodré GA, Costa AN, Valle RRM, 2012. Avaliação do estado nutricional do cacau de morangos PCL, Sodré GA, Costa AN, Valle RRM, 2012. Avaliação do estado nutricional do cacau com o sistema integrado de diagnóstico e recomendação (DRIS). Anais do III Congresso Brasileiro do Cacau, Ilhéus.

Marrocos PCL, Loureiro GAHA, Araujo QR, Sodré GA, Ahnert D, Escalona-Valdez RA, Baligar VC, 2020. Mineral nutrition of cacao (Theobroma cacao L.): relationships between foliar concentrations of mineral nutrients and crop productivity. J Plant Nutr 43 (10): 1498-1509. https://doi.org/10.1080/01904167.2020.1739295

Mendonça LP, 2016. Curvas de respostas potencial e de viabilidade de fertilizantes. EMBRAPA/CEPLAC/UESC, Rio de Janeiro.

Mourão Filho FAA, 2004. DRIS: Concepts and applications on nutritional diagnosis in fruit crops. Scientia Agricola 61: 550-560. https://doi.org/10.1590/S0103-90162004000500015

Oliveira MG, Partelli FL, Cavalcanti AC, Gontijo I, Vieira HD, 2019. Soil patterns and foliar standards for two cocoa clones in the States of Espirito Santo and Bahia, Brazil. Ciência Rural 49 (10): e20180686. https://doi.org/10.1590/0103-8478cr20180686

Piasentin FB, Saito CH, 2014. The different methods of soil chemical analysis and perceptions. Bol Museu Para Emílio Goeldi Ciênc Hum 9: 61-78. https://doi.org/10.1590/S0100-204X2012-0001-00005

Prado RM, Rozane DE, 2020. Leaf analysis as diagnostic tool for balanced fertilization in tropical fruits. In: Fruit crops: Diagnosis and management of nutrient constraints; Srivastava AK, Hu C (Eds). Elsevier. pp: 131-143. https://doi.org/10.1016/B978-0-12-818732-6.00011-3

R Development Core Team, 2019. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Viena, Austria. http://www.r-project.org [30 Mar, 2020].

Reis Jr RA, 2002. DRIS norms universality in the corn crop. Commun Soil Sci Plant Anal 33: 711-735. https://doi.org/10.1080/001035300500050011

Rocha JBO, 2008. Diagnose nutricional de plantios jovens de eucalipto na região litorânea do Espirito Santo e Sul da Bahia. Tese de mestrado, Universidade Federal de Viçosa, Viçosa-MG. 66 pp.

Rozane DE, Parent LE, Natale W, 2016. Evolution of the predictive criteria for the tropical fruit tree nutritional status. Científica 44: 102-112. https://doi.org/10.1536/1984-5529.2016v44n1p102-112

Santana SO, Santos RD, Gomes IA, Jesus RM, Araujo QR, Mendonça JR, Calderano SB, Faria Filho AF, 2002. Solos da região sudeste da Bahia: atualização da legenda de acordo com o sistema brasileiro de classificação de solos. EMBRAPA/CEPLAC/UESC, Rio de Janeiro.

Silva GGC, Neves JCL, Alvarez V, VH, Leite FP, 2005. Avaliação da universalidade das normas DRIS, M-DRIS e CND. Rev Bras Ciênc Solo 29: 755-761. https://doi.org/10.1590/S0100-06832005000500011

Slowickowski K, 2019. ggplot2: automatically position non-overlapping text labels with ‘ggplot2’. R package version 0.8.1. 2019. https://CRAN.R-project.org/package=ggplot2 [30 Mar, 2020].

Souza Júnior JO, 1997. Fatores edaf-climáticos que influenciam a produtividade do cacau cultivado no sul da Bahia, Brasil. Tese de Mestrado, Universidade Federal de Viçosa, Viçosa-MG. 146 pp.

Souza Júnior JO, Meneses AA, Sodré GA, Gattward JN, Dantas PA, Cruz Neto RO, 2012. Diagnose foliar na cultura do cacau. In: Nutrição de plantas: diagnóstico foliar em frutíferas; Prado RM (ed). FCAV/FAPESP, Jaboticabal; pp: 443-476.

Souza Júnior JO, Marrocos PCL, Neves JCL, 2018. Diagnose nutricional para o cacau de morangos. In: Ca- cai: cultivo, pesquisa e inovação; Souza Jr, JO (Org.). 1 Editus, Ilhéus, pp: 305-332. https://doi.org/10.7476/9786586213188.0010

Taiz L, Zeiger E, Moller IM, Murphy A, 2017. Fisiologia e desenvolvimento vegetal, 6th ed., Artmed, Porto Alegre.

Van Vliet Já, Giller KE, 2017. Mineral nutrition of cacao: a review. Adv Agron 141: 185-270. https://doi.org/10.1016/basin.2016.10.017

Wadt PG, Dias JRM, 2012. Normas DRIS regionais e inter-regionais na avaliação nutricional de cafeteiro Conilon. Pesq Agropec Bras 47 (6): 822-830. https://doi.org/10.1590/S0100-06832012000600013

Wadt PGS, Novais RF, Alvarez VVH, Fonseca S, Barros NF, 1998. Valores de referência para macronutrientes em eucalipto em eucalipto obtidos pelos métodos DRIS e chance matemática. Rev Bras Ciênc Solo 22: 685-686. https://doi.org/10.1590/S0100-06831998000400014

Walworth JL, Letzsch WS, Summer ME, 1986. Use of boundary lines in establishing diagnostic norms. Soil Sci Soc Am J 50 (1): 123-128. https://doi.org/10.2136/sssaj1986.03615995005000010024x

Wickham H, 2016. ggplot2: elegant graphics for data analysis. Springer-Verlag, NY. https://doi.org/10.1007/978-3-319-24277-4

Wickham H, François R, Henry L, Müller K, 2019. dplyr: a grammar of data manipulation. R package version 0.8.1. 2019. https://CRAN.R