

Division - Soil Use and Management | Commission - Soil Fertility and Plant Nutrition

# Critical levels and sufficiency ranges for leaf nutrient diagnosis by two methods in soybean grown in the Northeast of Brazil

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**ABSTRACT:** Establishing sufficiency ranges and critical levels of nutrients are important for a correct evaluation of plant nutrition through leaf diagnosis. This study aimed to propose critical levels and sufficiency ranges of macro and micronutrients based on leaf diagnosis of soybean plants. The database used was generated from 86 samples of the third trifoliate leaf without petiole, collected during the flowering stage from soybean plants of the main cultivars used in the states of Piauí and Maranhão, Northeast region of Brazil. The results of macro and micronutrients and grain yield were used to calculate the critical level by the reduced normal distribution and boundary line methods, the latter was also used to generate the sufficiency ranges. Nutrient levels for 90 % maximum grain yield were considered for the critical level by the reduced normal distribution, and nutrient levels at the upper line of a dispersion diagram were considered for the boundary line method, using the relation between grain yield and nutrient concentration to generate sufficiency ranges for 95 and 99 % maximum grain yields. The critical levels generated by the boundary line method presented a larger number of deficient samples than the reduced normal distribution method, except for boron. The sufficiency ranges generated by the boundary line with 95 % of the maximum grain yield could not diagnose nutrient deficiency, except for copper. The critical levels by the reduced normal distribution and boundary line methods for leaf diagnosis of soybean were 40.2 and 42.1 g kg<sup>-1</sup>, 3.2 and 3.4 g kg<sup>-1</sup>, 17.6 and 19.5 g kg<sup>-1</sup>, 8.7 and 10.3 g kg<sup>-1</sup>, 4.7 and 4.9 g kg<sup>-1</sup>, 2.1 and 2.4 g kg<sup>-1</sup>, 44 and 44 mg kg<sup>-1</sup>, 5 and 12 mg kg<sup>-1</sup>, 125 and 145 mg kg<sup>-1</sup>, 33 and 34 mg kg<sup>-1</sup>, and 48 and 63 mg kg<sup>-1</sup> for N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn, respectively. The critical levels by boundary line showed better distribution for leaf diagnosis for excess, deficiency, and adequate nutrient levels. The sufficiency ranges by the boundary line method for N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn were 38.6-45.7 g kg<sup>-1</sup>, 3.1-3.7 g kg<sup>-1</sup>, 18.3-20.7 g kg<sup>-1</sup>, 9.4-11.3 g kg<sup>-1</sup>, 4.4-5.3 g kg<sup>-1</sup>, 2.1-2.7 g kg<sup>-1</sup>, 35-53 mg kg<sup>-1</sup>, 10-14 mg kg<sup>-1</sup>, 131-159 mg kg<sup>-1</sup>, 23-46 mg kg<sup>-1</sup>, and 58-68 mg kg<sup>-1</sup>, respectively. The reduced normal distribution and boundary line methods allowed the generation of critical levels and sufficiency ranges for leaf diagnosis of soybean. The sufficiency range generated by the boundary line with 95 % maximum grain yield showed no prevalence of diagnosis of nutrient deficiency, except for copper.

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**Keywords:** *Glycine max*, nutritional status, plant nutrition.

## INTRODUCTION

Soybean crops have significant participation in Brazilian farming, with potential for further expansion in agricultural frontier areas such as those in the Cerrado biome, especially in the states of Piauí and Maranhão, Northeast region of Brazil (Hirakuri et al., 2018).

Agricultural frontier areas are usually subjected to intensive application of fertilizers to correct the chemical limitations of the soil and replace nutrients to maintain acceptable productivity levels (Horvat et al., 2015). Therefore, monitoring plant nutrition is essential for proper fertilization management (Withers et al., 2018).

Soybean farmers in the Northeast region of Brazil use different crop nutrition techniques, such as traditional soil fertilizers, leaf nutrients, and slow-release fertilizer formulation applications, with monitoring of nutritional status by tissue analysis or leaf diagnosis. However, in some situations, the critical levels or sufficiency ranges of nutrients used were determined for other regions with different edaphoclimatic conditions and soybean varieties (Embrapa Soja, 2013; Kurihara et al., 2013).

Some tools to assist the generation of critical levels and sufficiency ranges of nutrients based on databases compiled from crop grain yields and experiments are available. However, the generation of classes for interpretation of regional nutrient sufficiency is more reliable, with less variability due to soil and climate conditions and plant productive potential, as long as this is supported by a sufficiently large volume of data (Camacho et al., 2012).

One of the criteria used is the reduced normal distribution, in which the critical level is obtained for each nutrient, considering 90 % maximum grain yield (Maia et al., 2001; Maia and Moraes, 2015). Another used method is the boundary line, which involves plotting the production as a function of leaf nutrient levels, removing some points, leaving only the boundary line of the data, and fitting them to polynomial models to obtain an optimum value or sufficiency range (Webb, 1972). Sufficiency ranges for melon (Maia and Moraes, 2016), mango (Ali, 2018), and dragon fruit (Almeida et al., 2016) crops have been obtained by using the boundary line method.

Depending on the method used, the results show positive or negative characteristics for the generation of critical levels or ranges; the easy calculation is an advantage of the reduced normal distribution method (Maia et al., 2001; Maia and Moraes, 2015), despite the relative grain yield proportion (90 %) cannot be changed. The boundary line gives the choice for relative grain yield proportion, but the calculation has some particularities, such as the restriction to only boundary points in the dispersion graph (Vizcayno-Soto and Côté, 2004; Quesnel et al., 2006; Myburgh and Howell, 2014). The choice of points is necessary to create a curve for the model (Webb, 1972; Blanco-Macías et al., 2009).

Both methods are independent, and good options to generate optimal points or ranges for a dataset (nutritional status, soil, and salinity as a function of fruit yield, quality, and other variables), mainly for regional datasets (Camacho et al., 2012); these methods have the advantage of working with datasets (Webb, 1972; Walworth et al., 1986; Maia and Moraes, 2015). Therefore, regional data of leaf nutrient and grain yield levels can be used to estimate critical levels and sufficiency ranges by different methods, and for evaluating the nutritional status of plants, since there are little studies on leaf diagnosis for agricultural frontier areas. The objective of this study was to propose critical levels and sufficiency ranges of macro and micronutrients for soybean plants grown in the Northeast region of Brazil.

## MATERIALS AND METHODS

Data of content for analysis of macronutrients (nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) and micronutrients (boron, copper, iron, manganese, and zinc) were obtained from commercial crops grown in the municipalities of Uruçuí, Bom Jesus,

Nova Santa Rosa, and Regeneração in the state of Piauí (PI), and Brejo, Caxias, and São Raimundo das Mangabeiras in the state of Maranhão (MA), Brazil, in the 2016-2017 and 2017-2018 cropping seasons.

These municipalities are in the microregions Gerais de Balsas, Chapadas das Mangabeiras, Chapadinha, Caxias, Médio Parnaíba Piauiense, and Alto Parnaíba Piauiense. These microregions showed expansion of soybean crops using RR2 Intacta PRO cultivars, which are resistant to glyphosate and the main defoliating caterpillars, and have cycles of 115 to 120 days. However, the microregion Chapadinha has predominance of RR1 cultivars, resistance to glyphosate, with a tendency for adoption of RR2 Intacta PRO cultivars (Hirakuri et al., 2018).

The microregion Alto Parnaíba Piauiense presents predominance of clay soils (0.00-0.20 m layer), which contain clay content of 250 to 350 g kg<sup>-1</sup> in 70 % of the areas; the microregion Gerais de Balsas presents 250 to 350 g kg<sup>-1</sup> of clay in 40 % of the area, 150 to 250 g kg<sup>-1</sup> in 30 %, above 350 g kg<sup>-1</sup> in 25 %, and below 150 g kg<sup>-1</sup> in 5 % of the producing areas (Hirakuri et al., 2018). The most common clay contents found in soils (0.00-0.20 m layer) of the microregions Chapadinha and Caxias are 150 to 250 g kg<sup>-1</sup>; and most soils in the microregions Caxias and Médio Parnaíba Piauiense present clay contents of 250 and 350 g kg<sup>-1</sup> (0.00-0.20 m layer), with 150 to 250 g kg<sup>-1</sup> in 20 %, above 350 g kg<sup>-1</sup> in 25 %, and below 150 g kg<sup>-1</sup> in 10 % of the areas (Hirakuri et al., 2018). Thus, most soils in these regions are Oxisol and Ultisol classes.

Leaf diagnosis was carried out using the third recently expanded trifoliolate leaves from the apex, without petiole, at the flowering stage (R2), with 20 trifoliolate leaves per field. The leaves were collected and taken to the laboratory for washing and drying (Miyazawa et al., 2009).

Crop grain (13 % moisture) yield was measured after harvesting, and the data presented in kg ha<sup>-1</sup>. The samples were from the 2016-2017 (48 samples) and 2017-2018 (38 samples) cropping seasons, totaling 86 samples from eight commercial farms, one of each municipality, except Bom Jesus, which considered two farms. The leaves were collected in different plots of each farm, but not necessarily the same plots were used in both cropping seasons. Macro and micronutrients (P, K, Ca, Mg, S, Cu, Fe, Mn, and Zn) were quantified according to Bataglia et al. (1983), after nitroperchloric digestion; P was determined by colorimetry; K by flame photometry; S by turbidimetry; Ca, Mg, Cu, Fe, Mn, and Zn by atomic absorption spectrophotometry; nitrogen by the Kjeldahl method; and boron by calcination.

Critical level in the leaf analysis interpretation was based on grain yield data and the continuous probability distribution, according to Maia et al. (2001), using grain yield data and the ratio (*Q*) between grain yield (*Y*) and the leaf level of each nutrient for maximum grain yield of 90 % (*ni*), according to equation 1.

$$Q = \frac{Y}{ni} \quad \text{Eq. 1}$$

The reduced normal distribution has mean zero and variance one. When *Y* shows a normal distribution of mean and variance for the variable, it has normal distribution with mean zero and variance one (Maia et al., 2001). The data of a variable is reduced to its mean to transform its mean to zero. Each data of a variable must be divided by the standard deviation to transform its standard deviation into 1. Therefore, equation 2 was used to transform any normal dataset into a reduced normal distribution dataset.

$$Z = \frac{X - \mu}{\sigma} \quad \text{Eq. 2}$$

in which  $Z$  is the value of the variable in the reduced normal distribution,  $\mu$  is the mean of the dataset, and  $\sigma$  is the standard deviation of the dataset (Maia et al., 2001).

Thus, considering the value that represents 90 % of the maximum grain yield, the values will be:  $Y_{(90)}$  = critical value of the grain yield above the expected one under the normality hypothesis, in which only 10 % of the grain yields are considered; and  $Q_{(90)}$  = critical value of the quotient  $Q$  above the expected one under normality with only 10 % of the  $Q$  values are considered (Maia et al., 2001). The normal distribution table shows:  $Y_{(90)} (Z \leq 1.281552) = 0.90$ , as found by equation 3.

$$\frac{Pr(90) - \mu}{\sigma} = 1.281552 \rightarrow Y_{(90)} = 1.1281552\sigma + \mu \quad \text{Eq. 3}$$

$Q_{(90)}$  was determined similarly, using equations 4, 5, and 6; equation 4 with  $Y$  and  $Q$  with normal distribution; equation 5 with  $Y$  with normal distribution but  $Q$  transformed into square root; and equation 6 with  $Y$  with normal distribution and  $Q$  transformed into natural logarithm (Maia et al., 2001).

$$CLi = \frac{(1.281552 s_1) + m_1}{(1.281552 s_2) + m_2} \quad \text{Eq. 4}$$

$$CLi = \frac{(1.281552 s_1) + m_1}{[(1.281552 s_2) + m_2]^2} \quad \text{Eq. 5}$$

$$CLi = \frac{(1.281552 s_1) + m_1}{e(1.281552 s_2) + m_2} \quad \text{Eq. 6}$$

In all equations,  $m_1$  and  $s_1$  are the arithmetic mean and standard deviation of  $Y$ , and  $m_2$  and  $s_2$  are the arithmetic mean and standard deviation of  $Q$ , respectively. The tabulated value 1.281552 was used as the standard distribution (Maia et al., 2001).

The basic assumption to find the critical level by the continuous probability function is that the variables  $Y$  and  $Q$  are normally distributed. Thus, the data were tested for normality by the Shapiro-Wilk test ( $p > 0.05$ ), and transformed into square root or natural logarithm when not normally distributed. Data that were not normally distributed after these transformations were subjected to exclusion of discrepant cases from the respective ratio between grain yield and nutrient ( $Q$ ), using the boxplot tool, verifying the posterior normality of grain yield ( $Y$ ), and grain yield to nutrient ratio ( $Q$ ). Therefore, in some cases, the number of individuals may be different from the original ( $n = 86$ ).

Regarding the original dataset, with 86 values for B, Cu, Fe, Mn, and Zn, discrepant (not normally distributed) data after the transformation (logarithm or square root) were also removed, and again tested for normality. Then, the data that were not normally distributed were verified with transformation by square root or natural logarithm of the grain yield to the nutrient ratio ( $Q$ ).

The same data used to calculate the critical level by the reduced normal distribution was used to calculate the boundary line (Quesnel et al., 2006; Blanco-Macías et al., 2009; Lafond, 2013). The data of the nutrient content and the respective grain yield was separated into classes or intervals, after choosing the maximum value within the range (nutrient content). This procedure can be done in spreadsheets or point diagram.

The first step consisted of plotting the data on nutrient content as a function of grain yield. The second step was to select the points at the upper limit of the dispersion diagram, and verify the maximum and minimum contents, and dividing the difference between them by 15 classes, and consequently selecting the highest point (content) within each

interval (Blanco-Macías et al., 2009). Fifteen classes/intervals were used, representing the use of up to 15 data to generate the quadratic model, which is equivalent to less than 25 % of the data.

The use of 15 classes was based on the use of fewer than 25 % of the observations to develop the model, thus limiting the selection of points to those at the upper limit of the dispersion, and maximizing the probability of developing statistically significant models, by increasing the number of observations (Vizcayno-Soto and Côté, 2004). Some studies have indicated that the number of classes should be between 10 and 20 (Blanco-Macías et al., 2009).

Considering that this approach led to the selection of samples at adjacent intervals with large differences in grain yield, indicating that samples with lower grain yield have no optimal conditions for the nutrition level (Vizcayno-Soto and Côté, 2004; Quesnel et al., 2006), the classes representing the production as a concave quadratic model, i.e., the curve that was ascending until the maximum point and descending thereafter, were excluded. The production of the sample selected was divided into the respective class by the mean grain yield to facilitate possible exclusion of classes and identify the highest relative grain yield point, using equation 7 (Lafond, 2009):

$$PR (\%) = \frac{Y_{sample}}{Y_{mean}} \times 100 \quad \text{Eq. 7}$$

in which  $Y$  is the relative grain yield;  $Y_{sample}$  is the highest grain yield in the interval of a determined class; and  $Y_{mean}$  is the mean grain yield.

Therefore, classes were excluded using the procedure described by Vizcayno-Soto and Côté (2004) and Quesnel et al. (2006), with adaptations. When the relative outputs prior to the highest relative production among the classes selected did not satisfy the following criterion, they were excluded, considering the point of highest relative production as the cutoff (Equation 8):

$$PR > PR_{-1} \quad \text{Eq. 8}$$

After the point of highest relative production, it was necessary to satisfy the following criterion (Equation 9):

$$PR > PR_{+1} \quad \text{Eq. 9}$$

in which  $PR$ ,  $PR_{-1}$ , and  $PR_{+1}$  are the relative production levels and the adjacent points (lower and upper, respectively).

When these criteria were not satisfied, the sample of the considered class was excluded (Vizcayno-Soto and Côté, 2004; Quesnel et al., 2006). Furthermore, the production of the sample selected from the initial class cannot be higher than the second class, otherwise, the first class is dropped and the selection is begun from the points of the boundary line of the second class, i.e., there must be a rising order until reaching the highest relative production. Similar reasoning applies to the last class selected, with its exclusion when the relative production is higher than that of the previous class, i.e., the order must be decreasing after the point of highest relative production. After the exclusion of the classes with not satisfying values for the assumptions, a second-degree polynomial function was generated.

The optimal content or critical level (CL) was determined by taking the first derivative of the following quadratic equation (Equation 10):

$$NC = \frac{-b}{-2a} \quad \text{Eq. 10}$$

in which  $a$  and  $b$  are the coefficients of the quadratic equation.

Thus, two sufficiency ranges were generated, with values corresponding to 95 and 99 % maximum grain yield by  $0.95$  or  $0.99 \times$  maximum grain yield, and subsequent substitution in equation 11 (Quesnel et al., 2006; Blanco-Macías et al., 2009):

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \text{Eq. 11}$$

in which  $a$ ,  $b$ , and  $c$  are the coefficients of the quadratic equation, and  $x$  is the value corresponding to the level of the nutrient to generate the sufficiency range.

The critical levels obtained by the reduced normal distribution and boundary line methods for each nutrient were used to calculate the frequency that the values of each nutrient could be considered deficient (below critical level). The same procedure was applied to the sufficiency ranges, i.e., verifying the samples where each nutrient was considered excessive, sufficient or deficient, considering the ranges of 95 and 99 % maximum grain yield and in relation to the reference values found in the literature (Kurihara et al., 2013).

## RESULTS

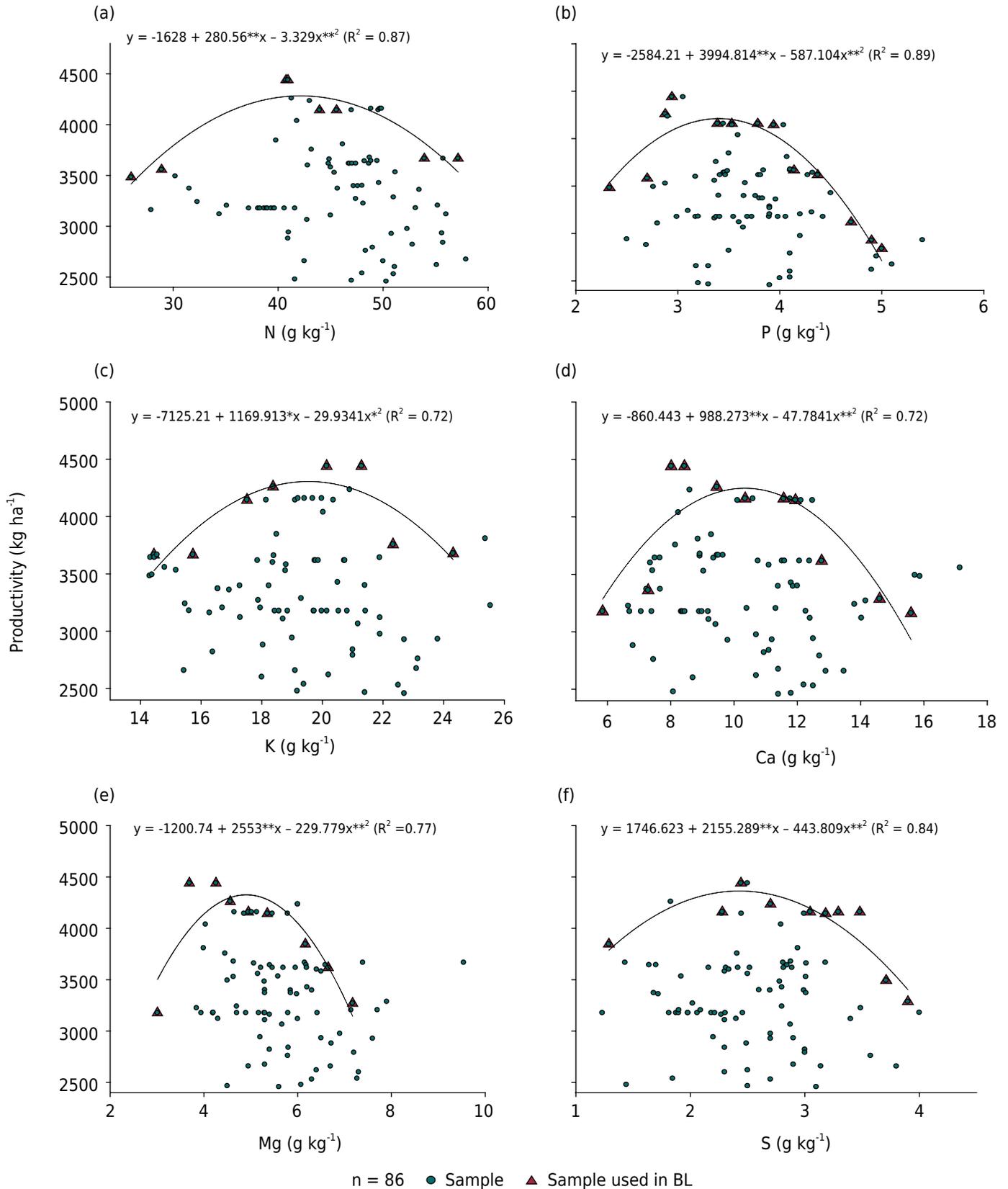
The average grain yield found was  $3,374 \text{ kg ha}^{-1}$ , similar to the Brazilian average in the 2017-2018 cropping season ( $3,394 \text{ kg ha}^{-1}$ ) (Conab, 2019), with maximum and minimum grain yield of  $4,400$  and  $2,457 \text{ kg ha}^{-1}$ , respectively. The parameters evaluated showed the decreasing order of variability of the data, according to the coefficient of variation:  $\text{Cu} > \text{Mn} > \text{B} > \text{Zn} > \text{S} > \text{Fe} > \text{Mg} > \text{Ca} > \text{P} > \text{N} > \text{K}$ . Grain yield and grain yield to nutrient ratio presented normal distribution with and without transformation. Thus the critical levels were calculated by the reduced normal distribution, which were  $40.2$ ,  $3.2$ ,  $17.6$ ,  $8.7$ ,  $4.7$ ,  $2.1$ ,  $44$ ,  $5$ ,  $125$ ,  $33$ , and  $48$  for N, P, K, Ca, Mg, and S ( $\text{g kg}^{-1}$ ), and B, Cu, Fe, Mn, and Zn ( $\text{mg kg}^{-1}$ ), respectively (Table 1), for grain yields of  $4,005 \text{ kg ha}^{-1}$  for macronutrients (N, P, K, Ca, Mg, and S),  $4,052 \text{ kg ha}^{-1}$  for boron,  $3,898 \text{ kg ha}^{-1}$  for copper,  $4,021 \text{ kg ha}^{-1}$  for iron,  $4,067 \text{ kg ha}^{-1}$  for manganese, and  $4,022 \text{ kg ha}^{-1}$  for zinc. The critical level was generated for a grain yield of  $4,020 \text{ kg ha}^{-1}$ , except for Cu ( $3,240 \text{ kg ha}^{-1}$ ). Regarding the boundary line method, the classes 7, 13, 8, 11, 9, and 10 were used for the macronutrients N, P,

**Table 1.** Mean values, standard deviations, maximum, minimum level of nutrients, coefficient of variation (CV), grain yield for 90 % of the maximum (P), the ratio between grain yield and nutrient content (Q), and critical level (CL) by the reduced normal distribution method (RNDM) for leaf samples of soybean plants grown in the Northeast region of Brazil

Parameters (RNDM)	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
	g kg <sup>-1</sup>						mg kg <sup>-1</sup>				
Mean	45.4	3.7	19.2	10.2	5.6	2.5	57	8.4	147	48	57
Standard deviation	6.9	0.6	2.6	2.0	1.1	0.6	16	4.4	33	17	13
Maximum	57.9	5.4	25.5	14.6	9.5	4.0	98	25.6	86	96	82
Minimum	26	2.3	14.3	6.7	3.0	1.2	30	2.2	236	19	30
CV (%)	15.2	16.3	13.5	19.5	19.6	23.3	27.1	51.8	22.4	34.7	23.5
n	86	86	86	86	86	86	77	71	73	70	80
p <sup>(1)</sup>	4005	4005	4005	4005	4005	4005	4052	3898	4021	4067	4022
Q	99.7 <sup>(2)</sup>	1233.0	228.0	460.3	854.7 <sup>(2)</sup>	1938.8 <sup>(2)</sup>	92.9	815.5 <sup>(3)</sup>	32.2	122.6 <sup>(2)</sup>	83.3 <sup>(3)</sup>
CL	40.2	3.2	17.6	8.7	4.7	2.1	44	5	125	33	48

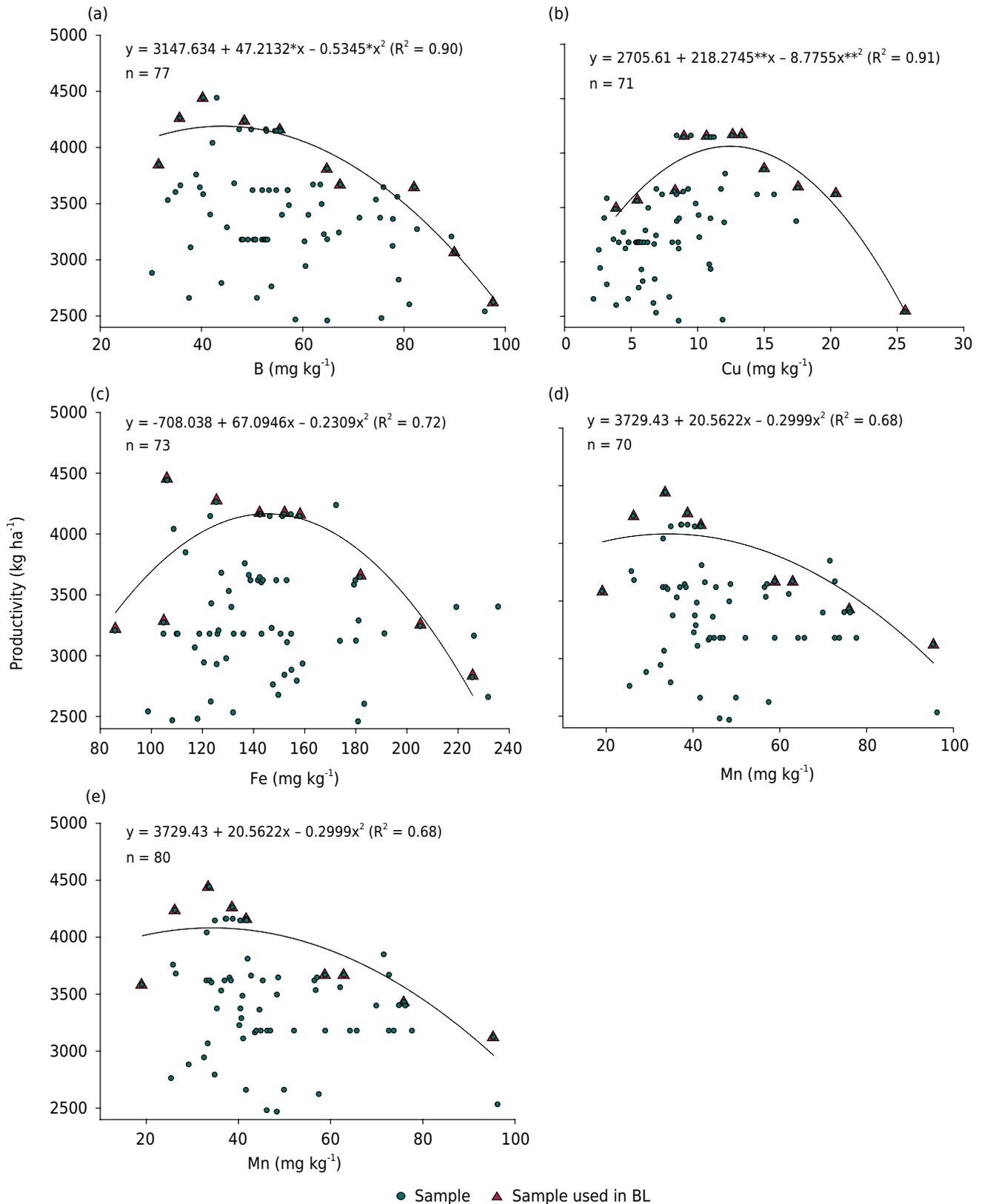
n = number of samples with normal distribution with or without transformation. <sup>(1)</sup> 90 % maximum grain yield, according to the number of samples of each nutrient, in  $\text{kg ha}^{-1}$ . <sup>(2)</sup> Means and standard deviations transformed into square root. <sup>(3)</sup> Means and standard deviations transformed into natural logarithm. The mineral nutrients were analyzed using the methodology described by Bataglia et al. (1983).

K, Ca, Mg, and S, respectively (Figures 1a, 1b, 1c, 1d, 1e, and 1f), and the classes 10, 11, 10, 9, and 10 were used for the micronutrients B, Cu, Fe, Mn, and Zn, respectively (Figures 2a, 2b, 2c, 2d, and 2e).



**Figure 1.** Ratio between macronutrient contents and grain yield plotted by the boundary line method for soybean plants grown in the Northeast region of Brazil.

The quadratic regression model made possible to generate the optimal value for each nutrient and sufficiency ranges at 95 and 99 % maximum grain yield (Table 2). The critical level estimated by the boundary line method was higher than that estimated by the reduced normal distribution criterion (Table 2), except for boron, whose values were similar.



**Figure 2.** Ratio between micronutrient contents and grain yield of soybean plotted by the boundary line method for soybean plants grown in the Northeast region of Brazil.

**Table 2.** Critical levels and sufficiency ranges of nutrients in leaf samples by the reduced normal distribution method (RNDM), boundary line (BL), and literature methods for soybean plants grown in the Northeast region of Brazil

Methods	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
CL <sub>RNDM</sub>	40.2	3.3	17.6	8.7	4.7	2.0	44	5	125	33	48
CL <sub>BL</sub>	42.1	3.4	19.5	10.3	4.9	2.4	44	12	145	34	63
95 % BL Range	34.2-50.2	2.8-4.0	16.9-22.2	8.2-12.5	3.9-5.9	1.7-3.1	24-64	9-17	115-145	8-60	52-73
99 % BL Range	38.6-45.7	3.1-3.7	18.3-20.7	9.4-11.3	4.4-5.3	2.1-2.7	35-53	10-14	131-159	23-46	58-68
Literature <sup>(1)</sup>	50.6-56.5	2.8-3.3	14.4-17.2	6.2-8.9	3.0-3.8	2.4-2.9	37-46	7-9	77-111	38-63	41-56

<sup>(1)</sup> Kurihara et al. (2013). The mineral nutrients were analyzed using the methodology described by Bataglia et al. (1983).

**Table 3.** Frequency of nutrient contents of leaf samples below the critical level by the CLRNDM and CLBL methods for soybean plants grown in the Northeast region of Brazil

Methods	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
CLNCRIz	20.5	20.5	23.9	30.4	21.6	22.7	20.8	21.1	26.0	10.0	28.8
CLBL	31.4	30.2	52.3	49.4	25.6	40.7	20.8	84.5	54.8	19.6	60.0

The sufficiency ranges generated for the 95 % maximum grain yield had higher amplitude than that generated with 99 % maximum grain yield (Table 2).

The critical level values calculated by the two methods (reduced normal distribution and boundary line) showed that the percentage of data was deficient, or below the optimal point. According to the boundary line, the critical level had higher percentages in the deficient classification for all the nutrients, except for boron, for which the frequency was the same by both methods, 20.8 % (Table 3).

Based on the sufficiency ranges by the boundary line method, the samples were classified as limited by deficiency (LD), not limited (NL), and limited by excess (LE) of nutrients, and the nutrient levels were compared to reference values in the literature (Kurihara et al., 2013). Kurihara et al. (2013) used similar leaf diagnosis, with samples of the third trifoliate leaf collected during flowering without petiole (Table 4).

The classification percentage for each nutrient followed a decreasing order, considering the sufficiency ranges with 95 and 99 % maximum grain yield for the boundary line (BL 95 % and BL 99 %) and the data reported by Kurihara et al. (2013): BL 95 % for N, not limited (NL)>limited by excess (LE)>limited by deficiency (LD); BL 99 % for N, LE>NL>LD; and Kurihara et al. (2013) for N, LD>NL>LE. This order indicates the proportion of population in each classification in different interpretations (deficiency, excess, and inadequate). In other words, each sufficiency range for nitrogen had distinct classifications for the population studied due to the different sufficiency classes generated by the boundary line and the literature used for comparison. The same reasoning was used for the other nutrients, whose orders were: for phosphorous, boundary line with 95 % maximum grain yield (BL 95 %), NL>LE>LD; boundary line with 99 % maximum grain yield (BL 99 %), LE>NL>LD; and Kurihara et al. (2013), LD>NL>LE; for potassium, BL 95 %, NL>LE>LD, LD 99 %, NL>LD>LE, and Kurihara et al. (2013), LE>NL>LD; for calcium, BL 95 %, NL>LD>LE, BL 99 %, LD>LE>NL, and Kurihara et al. (2013), LE>NL>LD (LD = 0); for magnesium, BL 95 %, NL>LE>LD, BL 99 %, LE>NL>LD, and Kurihara et al. (2013), LE>NL>LD (LD = 0); for sulfur, BL 95 %, NL>LE>LD, BL 99 %, LE>NL>LD, and Kurihara et al. (2013), LD>NL>LE; for boron, BL 95 %, NL>LE>LD (LD = 0), BL 99 %, LE>NL>LD, and Kurihara et al. (2013), LE>NL>LD; for copper BL 95 %, LD>NL>LE, BL 99 %, LD>NL>LE, and Kurihara et al. (2013), LD>LE>NL; for iron, BL 95 %, LE>NL>LD, BL 99 %, NL>LD>LE, and Kurihara et al. (2013), LE>NL>LD

**Table 4.** Frequency of nutrient contents of leaf samples limited by deficiency (LD), not limited (NL) and limited by excess (LE), according to the sufficiency ranges proposed by the boundary line method at 95 and 99 % of maximum grain yield, and the literature for soybean plants grown in the Northeast region of Brazil

Nutritional status	N			P		
	95 % BL Range	99 % BL Range	Literature <sup>(1)</sup>	95 % BL Range	99 % BL Range	Literature
LD (%)	7.0	12.8	81.4	7.0	15.1	7.0
NL (%)	74.4	33.7	16.3	65.1	37.2	16.3
LE (%)	18.6	53.5	2.3	27.9	47.7	76.7
	K			Ca		
	95 % BL Range	99 % BL Range	Literature	95 % BL Range	99 % BL Range	Literature
LD (%)	19.8	32.6	3.5	17.7	40.5	0.0
NL (%)	68.6	39.5	17.4	72.2	21.5	30.4
LE (%)	11.6	27.9	79.1	10.1	38.0	69.6
	Mg			S		
	95 % BL Range	99 % BL Range	Literature	95 % BL Range	99 % BL Range	Literature
LD (%)	3.5	12.8	0.0	8.1	23.3	40.7
NL (%)	59.3	30.2	2.3	77.9	37.2	33.7
LE (%)	37.2	57.0	97.7	14.0	39.5	25.6
	B			Cu		
	95 % BL Range	99 % BL Range	Literature	95 % BL Range	99 % BL Range	Literature
LD (%)	0.0	6.5	7.8	66.2	70.4	47.9
NL (%)	71.4	41.6	16.9	28.2	19.7	18.3
LE (%)	28.6	51.9	75.3	5.6	9.9	33.8
	Fe			Mn		
	95 % BL Range	99 % BL Range	Literature	95 % BL Range	99 % BL Range	Literature
LD (%)	15.1	35.6	0.0	0.0	1.4	30.0
NL (%)	39.7	41.1	13.7	78.6	57.1	51.4
LE (%)	45.2	23.3	86.3	21.4	41.4	18.6
	Zn					
	95 % BL Range	99 % BL Range	Literature			
LD (%)	38.8	46.3	15.0			
NL (%)	48.8	33.8	26.3			
LE (%)	12.5	20.0	58.8			

<sup>(1)</sup> Kurihara et al. (2013).

(LD = 0); for manganese, BL 95 %, NL>LE>LD (LD = 0), BL 99 %, NL>LE>LD, and Kurihara et al. (2013), NL>LD>LE; and for zinc, BL 95 %, NL>LD>LE, BL 99 %, LD>NL>LE, and Kurihara et al. (2013), LE>NL>LD (Table 4).

The interpretations carried out with the sufficiency ranges indicated different proportions of the categories not limited, limited by excess, and limited by deficiency for the 11 nutrients evaluated. However, when the range proposed was calculated by the boundary line with 95 % maximum grain yield, the limited by deficiency was not predominant for most nutrients, except for copper.

## DISCUSSION

The establishment of critical levels of nutrients for soybean crops grown in the Northeast region of Brazil is possible through the reduced normal distribution. Critical levels with this method have also been proposed for sugarcane (Santos et al., 2013) and orange (Camacho et al., 2012) crops.

The correction of the number of classes to apply the boundary line method allows the generation of quadratic regression models with high coefficient of determination (Vizcayno-Soto and Côté, 2004). The  $R^2$  values ranged from 0.72 to 0.89 for macronutrients, and from 0.68 to 0.91 for micronutrients. The use of the boundary line method has shown high coefficients of variation for other crops, such as *Opuntia ficus-indica*, as reported by Blanco-Macías et al. (2009). They used 18, 17, 11, 14, and 11 intervals, from the 20 classes initially proposed, for N, P, K, Ca, and Mg, respectively, for the boundary line. However, Iheshiulo et al. (2019) evaluated *Lonicera caerulea* with 5 to 7 intervals for the macronutrients N, P, K, Ca, and Mg, with  $R^2$  values of 0.67 to 0.89.

Quadratic equations generated by the boundary line for data of mango crops presented models with coefficients of determination ( $R^2$ ) of 0.50 to 0.85 (Ali, 2018); and *Opuntia ficus-indica* crops showed  $R^2$  values between 0.48 and 0.90 for macronutrients (Blanco-Macías et al., 2009).

The range proposed by the boundary line with 99 % maximum grain yield showed no predominance of any limitation category (NL, LD, or LE). However, Kurihara et al. (2013) found no limitation by deficiency (LD) for the nutrients Ca, Mg, and Fe. The interval reported by Kurihara et al. (2013) was developed with samples of soybean crops grown in the states of Mato Grosso, and Mato Grosso do Sul, which are older soybeans producing regions been grown than the states of Piauí and Maranhão, with a perspective of increasing use of fertilizers to restore soil fertility to assure high levels of compensatory yield (Donagemma et al., 2016; Withers et al., 2018).

The sufficiency range generated with 99 % maximum grain yield was related to its smaller amplitude and the diagnoses distributed to the classes not limited, limited by deficiency, and limited by excess; thus, these ranges were more sensitive. Therefore, the use of this sufficiency interval is indicated for the Northeast region of Brazil. Embrapa Soja (2013) presented also another study for the Central-West region of Brazil comparing the sufficiency range, but the intervals for P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn showed greater amplitude than those in the present study, except for N, where the sufficiency range was lower than that found by Embrapa Soja (2013).

These results are important for nutrient management; for example, N, P, and K uptake of current soybean varieties are higher than those in the 1970s, 1980s, 1990s, and 2000s due to genetic modifications of cultivars to meet the demands of the production systems (Bortolon et al., 2018).

Other techniques are used to generate sufficiency ranges or optimal points, such as mathematical chance or evaluation of nutrient balance by the correlation between nutrient concentrations and Diagnosis and Recommendation Integrated System (DRIS) or Composition Nutritional Diagnosis (CND) indices (Camacho et al., 2012; Matos et al., 2016; Ali, 2018).

Studies using diagnoses generated by the nutrient balance methods (DRIS × CND) have shown that CND is more accurate than DRIS (Parent et al., 2013); and sufficiency ranges by the boundary line method are closer to those by the CND methods (Vizcayno-Soto and Côté, 2004; Blanco-Macías et al., 2010). Studies have reported that the boundary line is a promising tool to understand soil properties and evaluate the nutritional status of agricultural crops (Guedes Filho et al., 2019; Iheshiulo et al., 2019).

## CONCLUSION

The reduced normal distribution and boundary line methods allowed the generation of critical levels and sufficiency ranges for leaf diagnosis of soybean.

The critical level generated by the boundary line indicated a larger number of deficient samples than the reduced normal distribution method, except for boron.

The sufficiency range generated by the boundary line with 95 % maximum grain yield showed no prevalence of diagnosis of nutrient deficiency, except for copper.

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