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Accuracy of DRIS and CND methods and nutrient sufficiency ranges for soybean crops in the Northeast of Brazil

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ABSTRACT. This study aimed to evaluate the nutrition of commercial soybean crops in an agricultural frontier region using the diagnosis and recommendation integrated system (DRIS) and compositional nutrient diagnosis (CND) methods, as well as identify sufficiency ranges. The study was performed by collecting leaf samples (third trifoliate leaf without petiole) at flowering from commercial soybean crops in the states of Piauí and Maranhão, Brazil, and evaluating the crop yield by analyzing macro- and micronutrients in the plant tissue of 98 samples. The DRIS and CND methods were applied based on the cataloged data, followed by the generation of norms, analysis of relationships between yield and nutrients (selecting high-yield crops by the cumulative function of the data), generation of sufficiency ranges, and comparison of methods. The relationships obtained by the DRIS and CND indices with the yield and nutrients were significant, indicating that both methods can be employed for the evaluation of leaf nutrients in soybean. The sufficiency ranges from the DRIS and CND methods presented superior nutrient ranges in relation to the values proposed in the literature for macronutrients, except for nitrogen, and greater range amplitudes for micronutrients.

Keywords: *Glycine max*; nutritional status; macronutrients; micronutrients.

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Introduction

Soybean crops account for a significant part of the economy of several producing states in Brazil, especially in the Northeast and North region, among which the states of Piauí, Maranhão, Tocantins, and Bahia form the Matopiba region. This region is recognized as an agricultural frontier, with expressive participation in grain production (Hirakuri, Conte, Prando, Castro, & Balbinot Júnior, 2018) and mean yields close to those of the west-central and southern traditional producing regions, such as the states of Mato Grosso and Paraná.

The Matopiba region, although relatively new to grain production, contains areas previously occupied by degraded pastures and presents a favorable topography for grain production using high technology (Donagemma et al., 2016; Hirakuri et al., 2018), as well as presenting acidic soils with textures ranging from medium to sandy, with low values of organic matter, phosphorus, and exchangeable cations (Donagemma et al., 2016). In a Brazilian phosphorus use scenario, the Matopiba region has a strong demand for this nutrient, with perspectives of future increase in its use, due to the incorporation of new areas for grain cultivation (Withers et al., 2018).

Adequate soybean nutrition is essential to obtain productive levels that provide satisfactory economic returns with a moderate employment of fertilizers. Leaf diagnosis is an important tool for the evaluation of nutritional status and indication of nutrient balance. The most commonly utilized methods for evaluating nutrient balance are the diagnosis and recommendation integrated system (DRIS) (Beaufils, 1973) and compositional nutrient diagnosis (CND) (Parent & Dafir, 1992). Both of these methods have been successful in evaluating soybean nutritional status and have produced promising results, including those for nutrient calibration (Kurihara, Alvarez V., Neves, Novais, & Staut, 2013). However, to present an adequate calibration, data must be obtained in the region of the object of study using management practices similar to the current production systems, to avoid the universality of norms (Rozane, Parent, & Natale, 2016a).

This study aimed to compare the diagnosis generated by the DRIS to that of the CND, and generate sufficiency ranges for soybean commercial crops in the states of Piauí and Maranhão in the Northeast of Brazil.

Material and methods

The leaf macronutrient (nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur) and micronutrient contents (boron, copper, iron, manganese, and zinc) were obtained from the collection of diagnostic leaves in 98 commercial plots in the municipalities in the South of Piauí State (Uruçuí, Bom Jesus, and Regeneração) and in the East and South of Maranhão State (Brejo, Caxias, and São Raimundo das Mangabeiras), in two cropping years.

The diagnostic leaf was sampled when the newly expanded third trifoliate leaf was visible from the apical bud to the plant base at the R2 stage, and the sample consisted of 20 trifoliate leaves without petioles per plot (Oliveira Júnior, Castro, Oliveira, & Klepker, 2020). After collection, the leaves were transported to the laboratory for washing, dried in a forced-air oven at 65°C until constant weight, and ground in a Wiley mill for chemical analysis, as indicated by Miyazawa, Pavan, Muraoka, Carmo, and Melo (2009). Samples were subjected to sulfuric and nitroperchloric digestion, for the determination of total N contents using a semi-micro Kjeldahl distillation apparatus; P and S using a UV-visible spectrophotometer; K, Ca, Mg, Cu, Zn, Fe, and Mn by atomic absorption spectrophotometry (ICE 3500 Thermo Scientific); and B using a muffle furnace at 600°C for 3h. The yields of each crop were measured at soybean harvest, and the data are presented in kg ha^{-1}. Sampling was performed during the 2016/2017 and 2017/2018 cropping years.

The theory of the DRIS and CND calculations followed the methodologies of Beaufils (1973), Jones (1981), Parent, and Dafir (1992), and Parent, Khiari, and Pettigrew (2005). In addition to the DRIS and CND statistical methods, the Mahalanobis distance (D^2) (Parent, Natale, & Ziadi, 2009) was used prior to the normal distribution analysis for the verification and elimination of outliers (p > 0.01) in the evaluation of the leaf samples.

The verification of normal distribution for crop yield was performed using the Shapiro-Wilk test and the correlation between leaf contents and yield was determine with the “R” software.

As indicated by Parent and Dafir (1992), the composition of the plant tissue is a dimensional arrangement of nutrients (*d*), represented by “*d* + 1” nutrient proportions, that is a simplex (set of nutritional contents and the complement at 100%) represented by “S^d,” which includes the nutrients (*d*) and a filling value defined according to Equation 1:

$$S^d = \binom{N>0; P>0; K>0; Ca>0; \dots}{\mathrm{N+P+K+Ca+\cdots+R}d=100} \quad (1)$$

In Equations 1 and 2, the number 100 represents the total value of dry matter (%); N, P, K, [...] (Xi) are the proportions of nutrients (%) and “R_d” is the filling value added to the nutrient proportions to obtain 100% (Khiari, Parent, &Tremblay, 2001a; Parent et al., 2009).

$$R_d = 100 - \sum_{i=1}^{d} Xi \quad (2)$$

The nutrient proportions become scale-invariant after being divided by the geometric mean (*G*) of “*d*+1” components, including “R_d” (Aitchison, 1986; Parent et al., 2009) as shown in Equation 3.

$$G = \left(\prod_{i=1}^{d} Xi\right)^{\frac{1}{(d+1)}} = (N \ x \ P \ x \ K \ x \dots x \ R_d)^{\frac{1}{(d+1)}} \quad (3)$$

The logarithmic equations (*ln*) or centered log-ratios (*clr*) were established according to Equation 4.

$$V_N = ln\frac{N}{G} \ ; \ V_P = ln\frac{P}{G} \ ; \ V_K = ln\frac{K}{G} \ ; \dots ; \ V_{Rd} = ln\frac{Rd}{G} \quad (4)$$

The sum of the “*ln*” values of the nutrients and for the “R*d*,” must satisfy the following equation (Equation 5):

$$V_N + V_P + V_K + V_{Ca} + V_{Mg} + \cdots + V_{Rd} = 0 \quad (5)$$

The multi-nutrient variables (Vnutrient) consisted of the Napierian logarithm (*ln*) of the quotient between the concentration of each nutrient (mg kg^{-1}) and the geometric mean of the concentrations of the dry matter mass constituents (G). By definition, the sum of the tissue components is 100%, and the sum of the logarithm ratio, including the filling value, must be zero (Khiari et al., 2001a). The CND indices were calculated as the difference between the multi-nutrient variables of the evaluated samples ($V_{nutrient}$) and the mean of the reference population ($\overline{V}_{nutrient}$), divided by the standard deviation ($\sigma_{nutrient}$) of this variable in the reference population (Equation 6).

$$I_N = \frac{(VN-\overline{V}N)}{\sigma N}\ ;\ I_P = \frac{(VP-\overline{V}P)}{\sigma P}\ ;\ \ldots ;\ I_{Rd} = \frac{(VRd-\overline{V}Rd)}{\sigma Rd} \quad (6)$$

The values of I_N, I_P, ..., I_{Rd} are the balance indices used to determine the CND. The activity or independence between the composite data is verified using a logarithmic transformation of the computed ratio (Aitchison, 1986). The CND indices are standardized, and the variables are linear as dimensions of a circle (d + 1 = 2), a sphere (d + 1 = 3), or a hypersphere (d + 1 > 3) in three-dimensional space (Aitchison, 1986; Parent et al., 2009). The balance index of the nutrients to determine the general equilibrium index of a diagnosed sample is CND-r^2, which is calculated according to the following equation (Equation 7; Parent & Dafir, 1992):

$$CND - r^2 = I^2{}_N + I^2{}_P + I^2{}_K + I^2{}_{Ca} + \cdots + I^2{}_{Rd} \quad (7)$$

Each sample was characterized by its radius(r), which was calculated based on the CND nutrient indices. The sum of an independent square d + 1 with normal variables produces a new variable with a chi-square distribution (χ^2) with d + 1 degrees of freedom (Ross, 1987). The CND indices are independent, and the value of CND-r^2 must have a chi-square distribution (χ^2).

The Mahalanobis distance (D^2) was calculated using Equation 8, with COV^{-1} as the inverse covariance matrix of the *clr* values for all nutrients, and T as the indicator that the matrix must be transposed; *clr*i* is the arithmetic mean of the *clr* (Parent, 2011). The χ^2 test was calculated based on the D^2 distance, excluding samples whose values were below 1% (p < 0.01).

$$D^2 = \sum (clr\text{i} - clr\text{i}^*)^T COV^{-1} (clr\text{i} - clr\text{i}^*) \quad (8)$$

With a decreasing yield of the sample set, Boltzmann's function (sigmoid) was established by the ratio between the yield (kg ha^{-1}) of the sample set and the cumulative variance (cumulative function) of the values of D^2, whose inflection point is presented by the sigmoid equation of Boltzmann (Caraballo, Rodriguez, & Perez, 2008).

After the definition of the reference population, considering that the yield presents a normal distribution, and the removal of 12 outlying values by the Mahalanobis distance, the CND index was recalculated (Equations 1 to 6). Subsequently, the DRIS indices were determined according to Jones (1981) using the following equation (Equation 9):

$$f\left(\frac{A}{B}\right) = \left[\left(\frac{A}{Ba}\right) - \left(\frac{A}{Br}\right)\right]\frac{k}{\sigma} \quad (9)$$

where A/B is the ratio of two nutrients; A/Ba is the ratio of two nutrients of the sample to be evaluated, A/Br is the ratio of two nutrients of the reference population, k is the constant of sensibility, and σ is the standard deviation of the reference population. The value of k = 1 was used in the proposed calculation. For the calculation of the DRIS indices, the general formula proposed by Beaufils (1973) was applied, considering the nutrient Y.

$$IY = \frac{\sum f\left(\frac{A}{B}\right) - \sum f\left(\frac{B}{A}\right)}{n} \quad (10)$$

In Equation 10, n is the number of DRIS functions analyzed. The nutritional balance index (NBI) was calculated by summing the absolute values obtained for each nutrient (Equation 11).

$$NBI = |I_N| + |I_P| + |I_K| + \cdots + |I_{Zn}| \quad (11)$$

The mean nutritional balance index (NBI_m) was calculated by summing the absolute values obtained for each nutrient and dividing it by the total number of nutrients (n; Equation 12) (Wadt, Alvarez V., Novais, Fonseca, & Barros, 1998):

$$NBI_m = \frac{|IN| + |IP| + |IK| + \ldots + |IZn|}{n} \quad (12)$$

After the establishment of DRIS (NBI) and CND norms (CND-r^2), it was necessary to validate them using the Cate-Nelson procedure (Cate & Nelson, 1971; Nelson & Anderson, 1997), which involves relating the values of the indices with the yield, and then dividing them into a bidimensional scatter plot (x, y) with four quadrants, maximizing the number of dots in the positive quadrants and minimizing the number in the negative quadrants.

Equation 13 was used to determine the quadrants. This procedure maximizes the sum of squares (SQ) between the upper left and lower right partitions, which represent the positive and negative, respectively.

$$SQ = \left[\left(\frac{(\sum X_i^2)}{k}\right) + \left(\frac{\sum X_j^2}{(n-k)}\right)\right] - \left[\frac{(\sum X_i^2)}{n}\right] \quad (13)$$

In Equation 13, X is the nutritional balance index, i is the set of all indices in the sample set, n is the number of observations (sorted in descending order), k is the elementary counts that start at the first ordered observation, and j is the subsequent number of elementary counts. The highest value presented by the SQ of all observations (n) constituted the critical point, which provides the parameter to determine the distribution of the values in the quadrants. Each quadrant represents a class of responses to the use of the input. The nutritional balance index corresponds to the critical point that establishes the separation of classes in populations with high and low yields. In the high-yield plots, the areas that presented index values lower than that of the critical point were in the false-positive quadrant, and the higher values were assigned to the true-negative quadrant. In the low-yield plots, index values lower than the index at the critical point resided in the true positive quadrant, whereas the higher values were in the false-negative quadrant. These quadrants were defined by Parent, Parent, Rozane, and Natale (2013) as follows:

True Negative (TN): high-yield populations correctly identified as balanced (below predictor critical index), and the nutrient status is adequate; False Positive (FP): high yield populations, incorrectly identified as imbalanced (above the critical value). The FP observations indicate the luxury consumption of nutrients by parts of the plant or exceptionally high nutrient use efficiency; True Positive (TP): low yield populations correctly identified as imbalanced (above the critical value) in which at least one element causes nutritional imbalance; and False Negative (FN): low yield populations incorrectly identified as balanced (below the critical value). The FN observations indicate the impact of other limiting factors on crop performance.

The diagnostic test was interpreted (Parent et al., 2013) as follows: i) Negative Predictive Value (NPV): the probability of a balanced diagnosis returning high performance, calculated as TN / (TN + FN); ii) Positive Predictive Value (PPV): the probability of an imbalanced diagnosis returning a low performance, calculated as TP / (TP + FP); iii) Accuracy: the probability of an observation being correctly identified as balanced or imbalanced, calculated as (TN + TP) / (TN + FN + TP + FP); iv) Specificity: the probability of a high-yield observation being balanced, calculated as TN / (TN + FP); and v) Sensitivity: the probability of a low-performance observation being imbalanced, calculated as TP / (TP + FN).

NPV, accuracy, and sensitivity identify the potentials for nutrient deficiency and indicate that other factors may limit plant development. PPV and specificity detect potential problems related to the luxury consumption of nutrients or contamination.

Graphical representations of the Cate-Nelson procedure were performed by relating the respective nutritional balance indices with the yield of the plots. The values of the classes were organized in the quadrants, presenting the parameters of NPV, PPV, sensitivity, specificity, and accuracy.

To establish the optimal levels (or critical level (NC)) of each nutrient, the relationship of each nutrient with its respective nutritional balance index was traced. Thus, the adequate foliar contents of N, P, K, Ca, Mg, S, B, Cu, Fe, Mn, and Zn for the soybean crop were obtained by equating all indices to zero in the equation (y = ax + b = 0); theoretically, when all of these indices tend to zero, there is an optimal condition for plant nutritional balance. The lower and upper limits of the normal range of nutrient concentrations were determined in a manner similar to the method used by Kurihara et al. (2013) for the soybean crop, which consisted of equating the statistical models of the relationship between nutrient contents and DRIS and CND indices to zero and ± 2/3 of the standard deviation (reference population).

Results and discussion

After verification of the outliers by the Mahalanobis distance, 12 samples were excluded, leaving 86 productive plots. After the exclusion of outliers, the population presented a normal distribution (W = 0.97015 and p = 0.03981) for the yield.

Based on the data, a correlation analysis was performed to verify linear relationships (Table 1). An interpretation classification according to Pearson's correlation coefficients (r) was used, with results considered insignificant (0.0 – 0.3); low (0.31 – 0.50), moderate (0.51 – -0.70), high (0.71 – 0.90), or very high (0.91 – 1.0) (Mukaka, 2012).

Table 1. Matrix of the correlation coefficient (Pearson) between the foliar contents of nutrients and the yield of the soybean crop.

	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
P	0.54**										
K	0.25*	0.43**									
Ca	-0.11	-0.04	-0.22*								
Mg	0.41**	0.36**	-0.22*	0.13							
S	0.22*	0.09	0.21*	0.35*	-0.03						
B	0.39**	0.61**	0.12	0.18	0.36	0.01					
Cu	-0.09	-0.25*	0.05	-0.27*	-0.10	0.02	-0.30*				
Fe	0.07	-0.01	-0.53**	0.04	0.33*	0.09	0.05	-0.12			
Mn	0.29**	0.34*	0.01	0.24*	0.24*	0.02	0.60**	-0.19	-0.05		
Zn	0.31**	0.30*	-0.07	0.22*	0.15	0.09	0.23*	-0.02	0.38*	0.17	
Yield	-0.10	-0.28*	-0.13	-0.08	-0.25*	0.01	-0.41**	0.17	0.09	-0.41**	0.26*

* and ** - Significant at $p \leq 0.05$ and $p \leq 0.01$. N – Nitrogen. P – Phosphorus. K – potassium. Ca – Calcum. Mg – Magnesium. S – Sulfur. B – Boron. Cu – Copper. Mn – Manganese. Fe – Iron. Zn – Zinc.

Of the 32 significant correlations, there were no high or very high correlations between variables, although there were moderate correlations for N–P (0.54), P–B (0.61), K–Fe (-0.53), and B-Mn (0.60).

Subsequently, as indicated by Caraballo et al. (2008), the division of the population into high and low yields indicated an inflection point of 3,420 kg ha^{-1} (Figure 1A), with 38 samples considered of high yield (43%) and 48 samples in the low yield category (57%). Similarly, a correlation analysis between the response variables was performed for the high (Table 2) and low yield populations (Table 3).

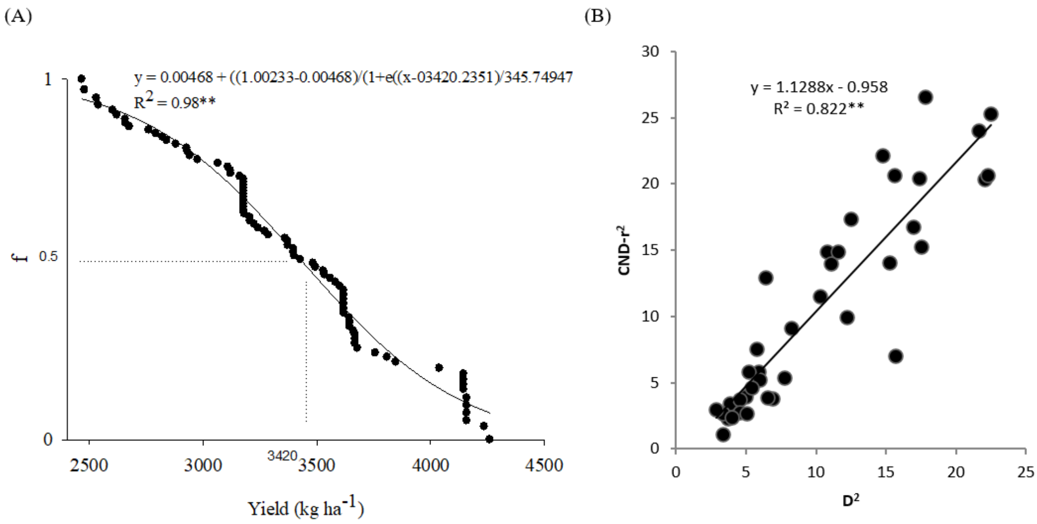

Figure 1. Relationship between the yield (kg ha^{-1}) and cumulative function (f) of the samples of soybean crop (A), and nutritional balance index (CND-r^2) and Mahalanobis distance (D^2) in the high yield population (n = 38) (B). ** - Significant at $p \leq 0.01$.

Table 2. Matrix of the correlation coefficient (Pearson) between the foliar contents of nutrients and the yield of the soybean crop for the high yield population.

	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
P	0.61**										
K	0.12	0.23									
Ca	-0.51**	-0.08	-0.26								
Mg	0.43**	0.29	-0.51**	-0.01							
S	-0.05	-0.05	0.24	0.31	-0.25						
B	0.16	0.39*	-0.39*	0.27	0.34*	-0.03					
Cu	-0.09	-0.24	0.18	-0.38	-0.25	0.03	-0.52**				
Fe	0.16	0.12	-0.59**	0.11	0.62	0.08	0.44*	-0.23			
Mn	0.14	0.32	-0.46*	0.07	0.40*	-0.20	0.57**	-0.22	0.53**		
Zn	0.41*	0.50*	-0.18	0.18	0.24	0.20	0.25	-0.20	0.49*	0.40*	
Yield	0.03	-0.19	0.31	-0.22	-0.41*	0.06	-0.36*	-0.09	-0.31*	-0.39*	-0.08

* and ** - Significant at $p \leq 0.05$ and $p \leq 0.01$. N – Nitrogen. P – Phosphorus. K – potassium. Ca – Calcum. Mg – Magnesium. S – Sulfur. B – Boron. Cu – Copper. Mn – Manganese. Fe – Iron. Zn – Zinc.

Table 3. Matrix of the correlation coefficient (Pearson) between the foliar contents of nutrients and the yield of the soybean crop for the low yield population.

	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
P	0.53**										
K	0.37**	0.56**									
Ca	0.15	-0.01	-0.18								
Mg	0.41**	0.38**	0.01	0.24							
S	0.37**	0.19	0.20	0.37*	0.11						
B	0.53**	0.66**	0.29*	0.19	0.37*	0.05					
Cu	-0.13	-0.21	-0.06	-0.22	0.16	-0.02	-0.11				
Fe	-0.04	-0.06	-0.40**	-0.08	-0.01	0.13	-0.06	-0.03			
Mn	0.40**	0.30*	0.00	0.35*	0.23	0.07	0.55**	-0.13	-0.14		
Zn	0.27	0.36*	0.12	0.26*	0.17	0.02	0.49**	-0.02	0.13	0.44**	
Yield	-0.35**	-0.15	-0.31*	-0.17	-0.20	-0.12	-0.21	-0.07	0.26	-0.13	0.01

* and ** - Significant at p ≤ 0.05 and p ≤ 0.01. N – Nitrogen. P – Phosphorus. K – potassium. Ca – Calcum. Mg – Magnesium. S – Sulfur. B – Boron. Cu – Copper. Mn – Manganese. Fe – Iron. Zn – Zinc.

For the high yield population, there were no "very high" or "high" correlations; however, there were 22 significant relationships, of which 31.8% were classified as moderate: N-P (0.61); N–Ca (-0.51); K–Mg (-0.51); K–Fe (-0.59); B–Cu (-0.52); B–Mn (0.57); and Fe–Mn (0.53). There were inverse significant relationships with Mg (-0.41); B (-0.36); Fe (-0.31), and Mn (-0.39); however, the correlation values were considered "low."

In the low yield populations, 22 significant relationships were verified between the variables, and there were no "high" or "very high" correlations; however, 22% were moderately correlated: N–P (0.53), N–B (0.53), P–K (0.56), P–B (0.66), and B–Mn (0.55) (Table 3).

When verifying the mean values of the nutrients (Table 4) with those established in the literature for the states of Mato Grosso and Mato Grosso do Sul (Kurihara et al., 2013), P, K, Ca, B, and Zn would have high contents; Mg, Cu, Fe, an excess; S and Mn, sufficient; and N would have a low content categorization.

Table 4. Maximum, minimum, and mean values, and coefficient of variation of the high yield population (n = 38).

	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Yield
	----------------- $g\ kg^{-1}$ ------------------						------------- $mg\ kg^{-1}$ -------------					$kg\ ha^{-1}$
Mean	45.5	3.5	18.7	10.5	5.5	2.6	54.1	32.2	242.4	42.5	63.6	3,821.3
Maximum	57.1	4.5	25.4	17.1	9.5	3.7	106.4	169.3	1,193.4	76.0	97.4	4,440.0
Minimum	26.0	2.3	14.3	7.4	3.7	1.3	31.7	1.8	106.1	9.8	24.5	3,427.0
CV (%)	14.1	14.4	14.8	22.5	19.7	21.2	28.5	148.2	96.5	34.2	24.0	7.7

N – Nitrogen. P – Phosphorus. K – potassium. Ca – Calcium. Mg – Magnesium. S – Sulfur. B – Boron. Cu – Copper. Mn – Manganese. Fe – Iron. Zn – Zinc. CV – Coefficient of variation.

The relationship between CND-r^2 and D^2 was significant and directly proportional (Figure 1B), which provided the use of a more accurate population for procedures using the DRIS and CND methods.

The relationship between the DRIS or CND index for a certain nutrient and its content allows for the verification of the optimal or critical level (Table 5). The CND index and the nutrient content of N, P, K, Ca, Mg, Cu, Fe, and Zn presented a higher coefficient of determination (R^2) in relation to the DRIS index and its respective content, except for B and Mn; however, for S, the R^2 value was similar (0.70) for both methods.

The sufficiency ranges derived from the relationships between the nutrient contents and the DRIS and CND indices for the states of Piauí and Maranhão, and those of Kurihara et al. (2013) presented distinct values. For N in the proposed ranges, regardless of the DRIS or CND methods, the values are lower compared to those identified for the states of Mato Grosso and Mato Grosso do Sul. However, the P, K, Ca, and Mg, values are superior, while for S, the values are similar, and for micronutrients, the ranges proposed were more varied (Table 6).

Thus, considering the samples with low yield, and the mean values of the index (DRIS or CND) of each nutrient, there were distinct results for the N index measured by the CND and DRIS methods, with an excess when measured by the CND and a deficiency when applying the DRIS (Figure 2).

Considering the partitioning proposed by Cate-Nelson and the interpretation presented by Parent et al. (2013), the CND, in relation to the DRIS, presented greater accuracy (0.60 × 0.57) and sensitivity (0.51 × 0.38) (Figure 3).

Table 5. Statistical models and relationships between DRIS or CND indices and the nutrient contents in the foliar samples of soybean.

Methods	Nutrient	Equation	R^2	CL
CND	N (g kg^{-1})	N = 45.2503 + 4.33(IN)	0.38**	45.3
DRIS		N = 46.29313 + 0.3697(IN)	0.34**	46.3
CND	P (g kg^{-1})	P = 3.5822 + 0.3539(IP)	0.39**	3.6
DRIS		P = 3.6567 + 0.0322(IP)	0.32**	3.7
CND	K (g kg^{-1})	K = 18.8646 + 1.912(IK)	0.48**	18.9
DRIS		K = 19.1486 + 0.1344(IK)	0.42**	19.2
CND	Ca (g kg^{-1})	Ca = 10.4032 + 2.0983(ICa)	0.71**	10.4
DRIS		Ca = 10.7148 + 0.1403(ICa)	0.66**	10.7
CND	Mg (g kg^{-1})	Mg = 5.4946 + 0.8334(IMg)	0.56**	5.5
DRIS		Mg = 5.6692 + 0.0559(IMg)	0.46**	5.7
CND	S (g kg^{-1})	S = 2.5596 + 0.49(IS)	0.70**	2.6
DRIS		S = 2.6161 + 0.035(IS)	0.70**	2.6
CND	B (mg kg^{-1})	B = 52.9 + 20.8318(IB)	0.79**	53
DRIS		B = 53.7869 + 1.4174(IB)	0.85**	54
CND	Cu (mg kg^{-1})	Cu = 17.7823 + 21.0339(ICu) + 7.9043(ICu)^2	0.96**	18
DRIS		Cu = 18.2733 + 0.6751(ICu)	0.54**	18
CND	Fe (mg kg^{-1})	Fe = 199.3068 + 100.977(IFe)	0.63**	199
DRIS		Fe = 200.2889 + 4.6553(IFe) + 0.0206(IFe)^2	0.54**	200
CND	Mn (mg kg^{-1})	Mn = 40.1123 + 25.1238(IMn)	0.80**	40
DRIS		Mn = 50.0145 + 1.3239(IMn)	0.86**	50
CND	Zn (mg kg^{-1})	Zn = 63.575 + 13.2629(IZn)	0.77**	64
DRIS		Zn = 61.3802 + 0.9444(IZn)	0.69**	61
CND	Yield (kg ha^{-1})	Yield = 3,692.4257 - 21.8852(CND-r^2)	0.42**	-
DRIS		Yield = 3,830.679 – 3.3463(IBN)	0.42**	-

CL = critical level. * and ** - Significant at p ≤ 0.01. N – Nitrogen. P – Phosphorus. K – potassium. Ca – Calcum. Mg – Magnesium. S – Sulfur. B – Boron. Cu – Copper. Mn – Manganese. Fe – Iron. Zn – Zinc.

Table 6. Nutrient sufficiency ranges derived from the relationships between nutrient contents and DRIS and CND indices in soybean leaf samples for the states of Piauí and Maranhão.

Nutrients	CND	DRIS	DRIS (Kurihara et al., 2013)
N (g kg^{-1})	40.7 - 49.9	41.7 - 50.9	50.6 - 56.5
P (g kg^{-1})	3.2 - 4.0	3.2 - 4.1	2.8 - 3.3
K (g kg^{-1})	17.1 - 20.6	17.4 - 20.9	14.4 - 17.2
Ca (g kg^{-1})	8.8 - 12.0	9.1 - 12.3	6.2 - 8.9
Mg (g kg^{-1})	4.8 - 6.2	4.9 - 6.4	3.0 - 3.8
S (g kg^{-1})	2.2 - 3.0	2.2 - 3.0	2.4 - 2.9
B (mg kg^{-1})	35 - 71	35 - 72	37 - 46
Cu (mg kg^{-1})	11 - 25	11 - 26	7 - 9
Fe (mg kg^{-1})	133 - 266	134 - 266	77 - 111
Mn (mg kg^{-1})	12 - 68	22 - 78	38 - 63
Zn (mg kg^{-1})	53 - 74	51 - 71	41 - 56

N – Nitrogen. P – Phosphorus. K – potassium. Ca – Calcum. Mg – Magnesium. S – Sulfur. B – Boron. Cu – Copper. Mn – Manganese. Fe – Iron. Zn – Zinc.

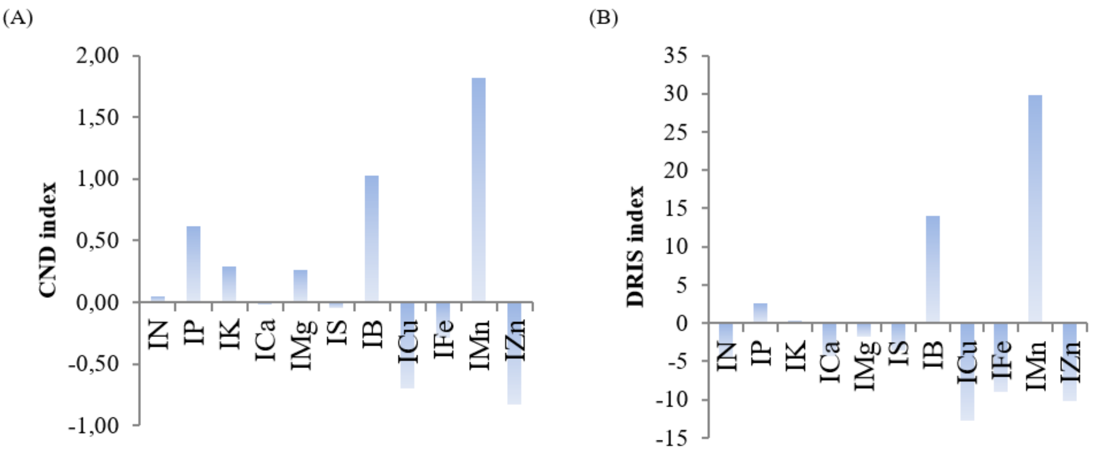

Figure 2. CND indices of the mean contents in the low yield evaluation in soybean leaf samples (A) and DRIS indices of the mean contents in the low yield evaluation in soybean leaf samples (B). N – Nitrogen. P – Phosphorus. K – Potassium. Ca – Calcium. Mg – Magnesium. S – Sulfur. B – Boron. Cu – Copper. Mn – Manganese. Fe – Iron. Zn – Zinc.

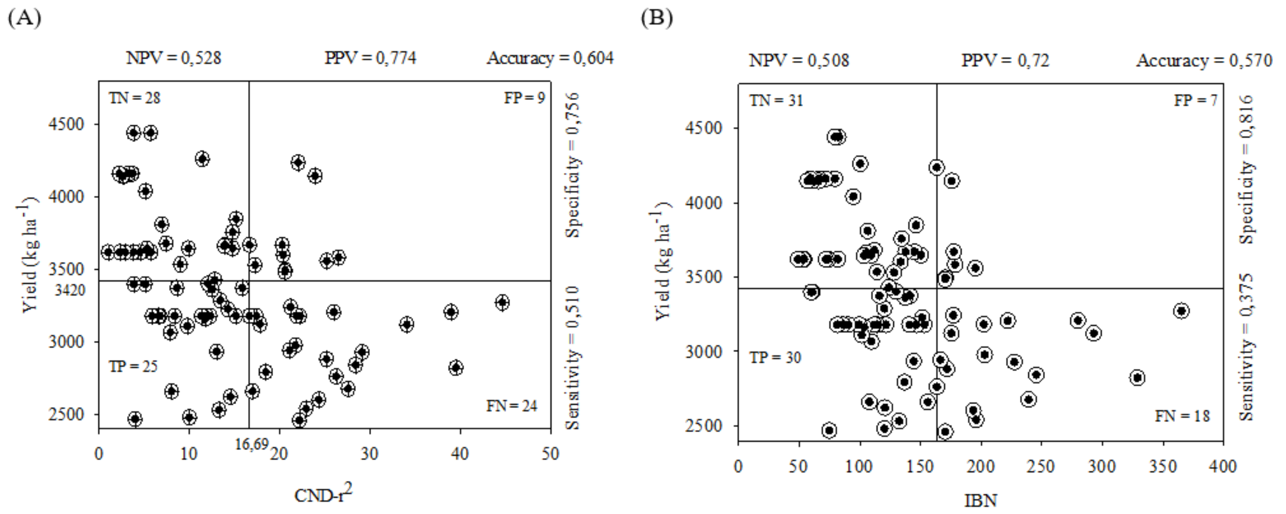

Figure 3. Cate-Nelson partitioning for the relationship between the CND-r^2 indices and the yield (A) and for the relationship between the NBI indices and the yield (B), for the soybean crop. NPV = Negative Predictive Value; PPV = Positive Predictive Value; TN = True Negative; TP = True Positive; FP = False Positive; FN = False Negative.

There was an inverse correlation between the content of nitrogen and the yield, with r = -0.35 for the low yield population, suggesting that an excessive nitrogen application may occur which causes a decreased yield, although this correlation value can be considered "low." In some cases, producers use monoammonium phosphate (MAP) because it presents a high concentration of P_2O_5, although N is present in its constitution, which would justify this result (Table 3).

The Mahalanobis distance (D^2) was used in the analysis of the data to calculate the CND index to exclude imbalanced data. This is one of the advantages of multivariate analysis in relation to bivariate methods, such as DRIS (Rozane et al., 2016a). Parent et al. (2009) showed that the CND provides a plant nutrient imbalance index (CND-r^2), assuming a χ^2 distribution. The Mahalanobis distance (D^2), which detects anomalous cases in sets of compositional data, also has a χ^2 distribution, whereby the F-test is employed (Rozane et al., 2016a).

For the data of the present study, the relationship between CND-r^2 and D^2 was equivalent to 0.82 (Figure 1), which surpassed the relationships found for potato (Khiari, Parent, & Tremblay, 2001b), grapevine (Rozane et al., 2016b), and pear (Rozane et al., 2017), of 0.32, 0.42, and 0.73, respectively. Thus, for the soybean crop, the importance of nutritional status is highlighted by obtaining satisfactory production levels, since the relationship between the CND index and the Mahalanobis distance (D^2) of the reference population indicates that greater distances relate to increased nutritional imbalance (Rozane et al., 2017).

The equations presented in relation to the DRIS and CND indices and the yield revealed a statistical significance ($p > 0.01$), along with a coefficient of determination of 0.42 for both relationships (Table 5). Annual crops, such as cotton (0.50 to 0.84) (Serra, Marchetti, Vitorino, Novelino, & Camacho, 2010) and rice (0.66 to 0.73) (Guindani, Anghinoni, & Nachtigall, 2009) present significant relationships between yield and NBI, which indicates the influence of nutrition on grain yield.

The difference in the sufficiency ranges presented in this study compared to what was observed in other producing regions can be justified by the fact that these were open-field areas that have been recently incorporated into productive systems. The soils presented low natural fertility, even with the use of high doses of fertilizers and correctives (Donagemma et al., 2016; Hirakuri et al., 2018).

Soil management and agronomic practices must be adequate to ensure nutrient availability through early and late season growth stages to meet soybean needs (Barth, Francisco, Suyama, & Garcia, 2018).

A similar trend was observed for Mg with P, K, Ca, and S, whereby the indices presented the same results for both methods (excess for P and K, and deficiency for Ca and S) (Figure 2). However, the micronutrients presented the same diagnosis with both methods, with B and Mn showing positive indices (excess) and Fe and Mn having negative indices (deficiency) (Figure 2).

These results are important, because some nutrients show high values of harvest index (HI). In this situation, more attention is required to perform the extraction; six nutrients presented HI values greater than 50%: P (84%), N (77%), S (65%), K (63%), Cu (63%), and Zn (61%) (Barth et al., 2018).

The order of limitation by deficiency using the CND method, for the mean values of the low-yield population, was Zn > Cu > Fe > S, and for the limitation by excess, the order was Mn > B > P > K > Mg > N. For the DRIS method, the decreasing order of limitation by deficiency was Cu > Zn > Fe > Ca > N > S, and the decreasing order of limitation by excess was Mn > B > P > K.

These results were similar between DRIS and CND, showing that both methods could be used to aid in the management of fertilization, as proposed by other authors (Castamann, Escostegy, Berres, & Zanella, 2012).

The DRIS and CND methods have been evaluated by partitioning in other crops, such as mango, with results similar to those observed in this study (Parent et al., 2013). However, such a comparison has not yet been performed with annual grain crops, such as soybean.

Conclusion

The relationships obtained by the DRIS and CND indices with the yield and nutrients were significant, indicating that both methods could be employed for the evaluation of foliar diagnosis in soybean. However, the CND method presented greater accuracy and sensitivity compared to the DRIS. The sufficiency ranges originating from the DRIS and CND methods presented values greater than those proposed in the literature for macronutrients, except for nitrogen, and greater amplitude ranges for micronutrients.

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