Efficiency of critical level and compositional nutrient diagnosis methods to evaluate boron nutritional status in soybean

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ABSTRACT

The efficiency of the boron (B) nutritional status in soybean (Glycine max (L.) Merr.) was evaluated by degree of agreement (DA) indicators using different diagnostic methods and by prescient diagnostic analysis (PDA). The objective of this study was to evaluate the efficiency of two interpretation methods of B nutritional status in soybean, that is, compositional nutrient diagnosis (CND) and critical level (CL). An experimental trial was conducted using a randomized block design with five replicates, which evaluated foliar B application rates of 0, 300, 600, 1200, and 1800 g ha⁻¹. Another study consisted of monitoring 140 commercial farms. We sampled leaves to determine nutrient contents and estimate yield in both studies. All samples were diagnosed by CND and CL methods. A reference value in the literature was obtained by the reduced normal distribution and CL methods by field calibration in the experimental trial. All the methods showed a high DA between diagnoses; the efficiency ratio and accuracy for true deficiency were both low, except for the CL method by field calibration, which exhibited an increase in positive net yield. The DA was ineffective to validate the efficiency of nutritional diagnoses; methods with a higher DA showed negative values for the net increase in production (-46 to -53 kg ha⁻¹). The CL method by field calibration showed greater efficiency in assessing the nutritional status of B in foliar fertilized soybean because the net increase in production was 197 kg ha⁻¹.

Key words: Boron fertilization, foliar fertilizer, Glycine max, leaf diagnosis, plant nutrition.

INTRODUCTION

Crop yield has evolved due to improved plant genetics, greater fertilizer supply, and technologies associated with irrigation and pest and disease control, especially for soybean crops (Glycine max (L.) Merr.) (Balbinot Junior et al., 2017). In Brazil, soybean crop yields averaged 1315 kg ha⁻¹ in the 1960s and 1970s and reached 3185 kg ha⁻¹ in the 2010s and 2020s (IBGE, 1970; IBGE, 2021). In addition to yield gains, cropped areas have expanded toward a greater diversity of climatic conditions and equatorial latitudes (Balbinot Junior et al., 2017).

In terms of mineral nutrition, part of the yield gains in soybean crops is associated with a greater supply of primary macronutrients via fertilization and biological N fixation. Therefore, the appropriate management of micronutrients is a decisive factor to ensure yield gains in soybean crops. Boron (B) is the most limiting micronutrient in soybean yield under...
the soil conditions in Brazil (Tomicioli et al., 2021) because B deficiency can reduce soybean yield by up to 40% (Silva et al., 2017).

However, in the Brazilian Cerrado, the reference values to assess soybean nutritional status by the critical level (CL) and sufficiency range (SR) methods still reproduce technological and yield conditions that were established several decades ago (Sousa and Lobato, 2004). However, new reference values require calibration tests that are costly, time-consuming, and are not representative of all soybean growing conditions in the country.

An alternative is to use data from farm commercial crops to estimate the reference values by the reduced normal distribution (DNR) (Maia et al., 2001) or the mathematical double probability method (MDP) (Wadt et al., 2013). Methods based on the nutrient balance, such as the diagnosis and recommendation integrated system (DRIS) (Kurihara et al., 2013) and compositional nutrient diagnosis (CND) (Urano et al., 2007) can also be used.

Studies on the efficiency of nutritional diagnosis methods in soybean have only been indirectly conducted by comparing diagnoses produced by different methods (Urano et al., 2007; Kurihara et al., 2013) and without evaluating plant response to the nutritional assessment prognosis. Some authors have evaluated the performance of nutritional diagnosis for most crops based on plant response to correct the nutritional status (Beverly and Hallmark, 1992; Beverly, 1993; Morais et al., 2019; Silva et al., 2020).

The objective of this study was to evaluate the efficiency of two methods to interpret the nutritional status (CND and critical level) of B in soybean based on field calibration and standards adopted at the site where the crops were planted.

**MATERIALS AND METHODS**

We conducted a field calibration test on foliar B fertilization and nutritional monitoring of commercial soybean crops (*Glycine max* (L.) Merr.) in the municipality of Chapadão do Sul, Mato Grosso do Sul, Brazil. A dystrophic Red Latosol (IBGE, 2001) predominates in the region under tropical wet climate conditions (Aw) (Köppen) with a 2-mo dry season and 1550 mm mean annual rainfall (IBGE, 2002).

Crops were evaluated at 140 commercial farms in 2015-2016; these were cultivated under a no-till system using one of the following cultivars with a determinate cycle: P98Y30, M8210 IPRO, M9144 RR, SYN1288 IPRO, BG4184, and 98Y52, indeterminate cycle: DESAFIO, W 791 RR, GMX CANCHEIRO RR, NS7670, and semi-determinate cycle: M7739, TEC7849 IPRO, M 7339 IPRO, AS3797 IPRO. A 1 ha perimeter was established for each crop, leaf samples were taken, and yield (kg ha⁻¹) was adjusted to a 13% moisture content. Soybean producers were divided into two groups for B fertilization: one soil application before sowing or at sowing and two foliar applications at the flowering or production stages. The foliar B fertilization test (field calibration) was designed to determine the response curve of B on yield and on leaf B contents in soybean ‘DESAFIO’ (indeterminate cycle). The soil at the experimental site exhibited 0.32 mg B dm⁻³ extracted with hot water (Table 1); this is considered as a low availability content (Sousa and Lobato, 2004).

| pH       | 5.30 |
| Ca, cmol dm⁻³ | 2.80 |
| Mg, cmol dm⁻³ | 1.10 |
| Al, cmol dm⁻³ | 0.05 |
| H+Al, cmol dm⁻³ | 3.70 |
| K, mg dm⁻³ | 209.70 |
| P(res), mg dm⁻³ | 37.40 |
| S, mg dm⁻³ | 3.30 |
| SOM, g dm⁻³ | 38.80 |
| B, mg dm⁻³ | 0.32 |
| Cu, mg dm⁻³ | 1.50 |
| Fe, mg dm⁻³ | 89.00 |
| Mn, mg dm⁻³ | 21.70 |
| Zn, mg dm⁻³ | 8.30 |
| Clay, % | 48.50 |
| Sand, % | 49.00 |
| Silt, % | 2.50 |

SOM: Soil organic matter.
The experiment consisted of 852.5 m² divided into 25 plots that were 11 m long and 3.1 m wide. Each plot had seven rows and three of the 8 m central rows were used for evaluations. The experiment used a randomized block design with five B rates (0, 300, 600, 1200, and 1800 g ha⁻¹) that corresponded to 0%, 16%, 33%, 67%, and 100% of the recommended rate for soybean in the Cerrado as B amendment (Sousa and Lobato, 2004) applied as boric acid with five replicates per treatment. Using a pre-sowing machine, 100 kg ha⁻¹ KCl was applied to the soil. At sowing on 24 November 2015, 115 kg ha⁻¹ monoammonium phosphate (MAP) were applied in the seed furrow (11-52-00) (Sousa and Lobato, 2004). Soybean seeds were inoculated with *Bradyrhizobium japonicum* using the Simbiosis Nod Soja liquid commercial inoculant (Symbiosis: Biological Agrotechnology, Brazil) containing the SEMIA 5079 and SEMIA 5080 strains (minimum concentration of 72 × 10⁹ viable cells mL⁻¹) at a 150 mL rate for 50 kg of seeds (Zuffo et al., 2019).

Boron was applied on the leaves with a CO₂ pump sprayer that was adjusted to a 150 L ha⁻¹ spray volume. We mixed 0.15% surfactant (Triton X-114) and 1% urea in the molasses mixture to accelerate B absorption. Each dose was divided into three applications, two at the vegetative stage (V2 and V5) and one at the beginning of flowering (R1). Applications were carried out in the morning at approximately 25 °C, 80% relative humidity, and 7 km h⁻¹ wind speed.

We sampled soybean leaves at the experimental site 10 d after the last B application. Sampling at the commercial farms occurred at R1 and the sampling date varied according to the developmental stage of each crop. Each sampling site included the random collection of 25 completely expanded leaves from the third trefoil with petiole counted from the plant apex (Malavolta, 2006).

The leaves that contained the petiole were sampled in the plots for the calibration test and commercial farm plots were rinsed in deionized water and in a detergent solution (0.1%). They were rinsed with a hydrochloric acid solution (0.3%) and deionized water. Afterward, samples were dried in a forced air convection oven at 60 to 70 °C until constant weight and ground in a mill (Prado and Caione, 2012).

The nutrient contents were determined in 1 g subsamples that were subjected to different digestion processes: microwave (K), sulfuric (N), and nitro perchloric (P, S, Ca, Mg, Mn, Fe, Zn, and Cu). After digestion, leaves were analyzed for the concentrations of S, Ca, Mg, Mn, Fe, Zn, Cu (inductively coupled plasma-optical emission spectrometry, ICP-OES), K (flame photometry), and P (molecular spectrophotometry). Total N was determined by distillation according to the Kjeldahl method (Carmo et al., 2000). Two samples from the experimental trial were discarded because they showed a discrepancy in the B contents.

Harvesting at the commercial farms was mechanized and done when plants reached full maturation. It took place on 5 April 2016 at the experimental site, and the productivity (bags ha⁻¹) of the plots was determined. A bag is equivalent to 60 kg grain.

Only in the experimental plots were B contents adjusted in response curves between applied B rates, leaf B contents, and plot yield (25 sample data set of the experimental plots). The calibrated critical level (CLCAL) was obtained as described by Cate and Nelson (1965). The B leaf content corresponding to 90% of the soybean production yield was determined to define CLCAL.

The data set of the soybean yield and B contents in the experimental plots and commercial farms (165 sample data set) was used to obtain the CL value by the reduced normal distribution (CLRND) method with logarithmic transformation (Maia et al., 2001). The data set of the soybean yield and B contents in the experimental plots and commercial farms was used to determine the compositional nutrient diagnosis (CND) standard.

For each nutrient, we identified leaf samples with nutrient contents within the ± 95% range of the mean in the data set of sample plots and commercial farms (data set of the soybean yield and B contents in experimental plots and commercial crops was used, 165 sample data set). From this subsample, samples with yield greater than the +0.25 mean standard deviation were considered high-yielding populations. In the high-yielding population, the mean and standard deviation of the multivariate relationships for each nutrient were defined as the reference values and CND standards as described by Parent and Dafir (1992). Afterward, nutrient indices (NI) were obtained using the CND method (Equation 1) as the difference between the multinutrient variables evaluated in the field (va) and the mean of the reference population (VA) divided by the standard deviation of this variable in the reference population (sA) (Urano et al., 2007):

\[
NI = \frac{(va - VA)}{sA}
\]

(1)
The average nutrient balance index (NBIa) was calculated, which corresponds to the arithmetic mean of the sum of the NI in modulus of each nutrient (Equation 2) where n is the number of nutrients.

\[
\text{NBIa: } \frac{[\text{NI } N] + [\text{NI } K] + [\text{NI } P] + [\text{NI } Ca] + [\text{NI } Mg] + [\text{NI } S] + [\text{NI } B] + [\text{NI } Fe] + [\text{NI } Mn] + [\text{NI } Zn] + [\text{NI } Cu]}{\text{n}}
\]  

(2)

The fertilization response potential criterion (Wadt, 2005) was used to interpret the nutrient balance indices by grouping the balance indices for B into two categories of insufficient when the B nutrient balance index was negative and greater than the NBIa when in modulus (Equation 3). The nutrient balance was considered to be equilibrated in all other cases.

\[
\text{Insufficient: } \text{NI } B < 0 \text{ and } [\text{NI } B] > \text{NBIa}
\]  

(3)

The fertilization response potential criterion (Wadt, 2005) was used to interpret the nutrient balance indices by grouping the balance indices for B into two categories of insufficient when the B nutrient balance index was negative and greater than the NBIa when in modulus (Equation 3). The nutrient balance was considered to be equilibrated in all other cases.

The nutritional status was interpreted by the critical level (CL) method as recommended for soybean in the Cerrado (CLREF) (Sousa and Lobato, 2004) or according to the CL method by field calibration established in the present work (CLCAL and CLRND). Leaf B content was considered deficient for each of the limits established whenever the value was below the CL limit (Equation 4). All other values were considered as sufficient (Equation 5).

\[
\text{Deficient: nutrient contents } < \text{CL value}
\]  

(4)

\[
\text{Sufficient: nutrient contents } > \text{CL value}
\]  

(5)

The quality of the prognoses (deficient/insufficient and sufficient/equilibrated status) provided by the different diagnostic methods was evaluated by the prescient diagnostic analysis (PDA) criterion (Beverly, 1993) by comparing the diagnosis of deficient/insufficient or sufficient/equilibrated with the soybean true nutritional status (TNS).

The TNS was obtained from soybean response to B fertilization (B experimental plots) by comparing the yield in a plot with foliar B fertilization with another plot without B fertilization or with lower fertilization rates. Fertilization was considered to be responsive and the nutritional status as true deficiency when there was an increase of at least 10% in soybean yield. In all other cases, the B nutritional status was considered as true sufficiency.

A deficiency or insufficiency diagnosis was considered true when there was an increase in yield with B fertilization (T_DEF) and false when there was no increase in yield (F_DEF). A sufficiency/balance diagnosis was considered true if B application did not increase yield (T_SUF) and false if it increased yield (F_SUF) (Table 2) (Beverly and Hallmark, 1992).

Values obtained from B experimental plots were used to assess diagnostic quality (Beverly and Hallmark, 1992; Beverly, 1993) with total accuracy (AccT), net yield response [Net d(Y)], accuracy of deficient cases (AccDef), accuracy of sufficient cases (AccSuf), and efficiency ratio (ER). All these values were calculated according to the diagnostic quality in relation to TNS (Table 2). The following expressions were used: AccT is the percentage of cases with true diagnoses (Equation 6) where n is the total number of performed comparisons, AccDef is the percentage of cases of true deficiency diagnoses (Equation 7), AccSuf is the percentage of cases with true sufficiency diagnoses (Equation 8), ER is the ratio between true deficiency and false deficiency diagnostic cases (Equation 9) where T_DEF is true deficiency, T_SUF is true sufficiency, Σ_DEF is the sum of deficiency, and Σ_SUF is the sum of sufficiency.

\[
\text{AccT} = 100 \times \frac{T_{\text{DEF}} + T_{\text{SUF}}}{n}
\]  

(6)

\[
\text{AccDef} = 100 \times \frac{T_{\text{DEF}}}{\Sigma_{\text{DEF}}}
\]  

(7)

\[
\text{AccSuf} = 100 \times \frac{T_{\text{SUF}}}{\Sigma_{\text{SUF}}}
\]  

(8)

\[
\text{ER} = \frac{T_{\text{DEF}}}{\Sigma_{\text{DEF}}} / \frac{T_{\text{SUF}}}{\Sigma_{\text{SUF}}}
\]  

(9)

The net productivity gain, Net d(Y) was achieved by hits or misses in nutritional diagnoses (Equation 10) where |P_T_DEF| and |P_T_SUF| are yield increase achieved by true diagnoses for deficiency and sufficiency, respectively, and |P_F_DEF| and |P_F_SUF| are yield loss for false diagnoses of deficiency or sufficiency, respectively.

\[
\text{Net d(Y)} = |P_{T_{\text{DEF}}} - |P_{T_{\text{SUF}}} - |P_{F_{\text{DEF}}} - |P_{F_{\text{SUF}}|
\]  

(10)

### Table 2. Diagnosis of the nutritional status by the interpretation method and the true physiological nutritional status of the crop.

| Number of cycles | Interpretation of nutritional status | True physiological nutritional status | Responsive | Unresponsive |
|------------------|-------------------------------------|---------------------------------------|------------|-------------|
|                  | Deficient                           | True deficiency (T_DEF)                | False deficiency (F_DEF) |
|                  | Sufficient                          | False sufficiency (F_SUF)              | True sufficiency (T_SUF) |
|                  | Subtotals                           | Deficiency sum (Σ_DEF)                 | Sufficiency sum (Σ_SUF) |

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The degree of agreement (DA) was calculated by the frequency of cases with equal diagnoses (agreeing with each other) as related to the total number of diagnoses (165 samples) compared with each other. The DA was used to diagnose B nutritional status provided by each method and between diagnoses with the experimentally determined true nutritional status.

The normal distribution of the soybean yield and B experimental plot data set was tested by the Shapiro-Wilk test. Yield variability related to the B contents was evaluated by regression and correlation analysis. For the B experimental plots, the means of the B contents and yield in the experimental treatments based on applied B rates were evaluated by Tukey’s test at 5% probability. All analyses were performed with the AgroEstat statistical software (Barbosa and Maldonado Júnior, 2014).

RESULTS AND DISCUSSION

The yield of the 163 site samples was 59.3 bags ha⁻¹ with a 9.7 bags ha⁻¹ standard deviation according to the normal distribution according to the Shapiro-Wilk test. There were 36% high-yielding samples (Table 3) in the farm commercial crops and experimental plots.

Leaf B contents had a greater range than the other nutrients. In high-yielding crops, leaf B contents ranged from 16.6 to 202 mg kg⁻¹, while contents ranged from 10.0 to 67.8 mg kg⁻¹ in low-yielding crops. The B content was 30% lower in high-yielding crops, which were on average 25% more productive (Table 3).

In the experimental plots, the response of leaf B content was linear with a maximum of 150 mg kg⁻¹ B (Figure 1A). Soybean yield in this trial also increased linearly with increasing foliar application of B at the rate of 0.01 bag g⁻¹ B to 1800 g B ha⁻¹ (Figure 1A).

The variation in soybean yield in the experimental plots for leaf B contents was fitted to the Cate and Nelson (1965) model (Figure 1B). The CL_CAL for B was estimated at 100 mg kg⁻¹ (Table 3) for a maximum yield of 85 bags ha⁻¹ (Figure 1B). In the farm commercial crops without B application, B contents reached 70 mg kg⁻¹ with a yield of 85 bags ha⁻¹ (Figure 1C). This difference was because the B application in the farm commercial crops was partially applied in the soil at pre-sowing.

Enderson et al. (2015) reported that leaf content ranged from 26 to 65 mg kg⁻¹ B in a study conducted at 42 sites with B foliar fertilization of 180 g ha⁻¹; however, they did not achieve any significant increases in soybean yield. Sutradhar et al. (2017) and Calonego et al. (2010) also reported increased leaf B content of 24% and 39%, respectively, and did not observe any increase in soybean yield.

Lacerda et al. (2017) attributed the unresponsiveness of the soybean crop to B fertilization reported by Calonego et al. (2010) to high soil B availability; contents were 0.43 mg dm⁻³ at the study site. Other authors have also associated soybean unresponsiveness with B foliar application to its low efficiency (Seidel et al., 2015; Bruns, 2017; Nakao et al., 2018; Santos et al., 2019; Ratke et al., 2020).

Table 3. Maximum, minimum, mean, and standard deviation values of yield boron (B) content in low- and high-yielding subpopulations of soybean samples, and calibrated critical level (CL_CAL) (Cate and Nelson, 1965), reduced normal distribution (NCNR), and reference for Cerrado soils (CL_REF) (Sousa and Lobo, 2004) of soybean samples cultivated in Chapadão do Sul, Mato Grosso do Sul, Brazil.

| Soybean grain yield | B content¹ | Soybean grain yield | B content¹ |
|---------------------|------------|---------------------|------------|
|                     | mg kg⁻¹    | Bags ha⁻¹           | mg kg⁻¹    | Bags ha⁻¹ |
| Maximum             | 67.8       | 61.6                | 202.0      | 88.8      |
| Minimum             | 10.0       | 30.0                | 16.6       | 61.9      |
| Mean                | 44.2       | 54.4                | 61.2       | 68.2      |
| Standard deviation  | 11.8       | 7.2                 | 35.7       | 7.0       |
| Coefficient of variation | 26.8    | 13.3              | 58.4       | 10.2      |
| Number of samples   | 105        |                     | 58         |           |

Response curves between applied B rates, leaf B contents, and plot yield.

Table 3. Maximum, minimum, mean, and standard deviation values of yield boron (B) content in low- and high-yielding subpopulations of soybean samples, and calibrated critical level (CL_CAL) (Cate and Nelson, 1965), reduced normal distribution (NCNR), and reference for Cerrado soils (CL_REF) (Sousa and Lobo, 2004) of soybean samples cultivated in Chapadão do Sul, Mato Grosso do Sul, Brazil.
Urano et al. (2007) reported a 20% difference in yield between low- and high-yielding crops in no-till soybean crops in Mato Grosso do Sul (Brazil). However, the mean leaf B content between the two subpopulations differed by only 1%, and the B content ranged from 23.8 to 59.7 mg kg⁻¹ and 26.9 to 61 mg kg⁻¹ in low- and high-yielding crops, respectively. Campos et al. (2021) reported a 45% increase in leaf B content with a significant effect on soybean yield and a maximum yield of 43 bags ha⁻¹ due to B soil fertilization at 3.27 kg ha⁻¹.

The CLRND estimated by the reduced normal distribution method was 37 mg kg⁻¹ (Table 3). This value was within the CL limits indicated in the literature, which have ranged from 21 mg kg⁻¹ in the Brazilian states of São Paulo (Raj et al., 1997), Paraná (Embrapa, 2010), and the Cerrado region (Sousa and Lobato, 2004) to 40 mg kg⁻¹ in the Minas Gerais State (Brazil) (Ribeiro et al., 1999). Kurihara et al. (2013) indicated a 42 mg kg⁻¹ CL calculated by the lower limit of the sufficiency range for leaf samples with petioles.
The CL\textsubscript{CAL} estimated by site calibration was 100 mg kg\textsuperscript{-1} (Table 3), which was above the toxicity limit established between 55 and 60 mg kg\textsuperscript{-1} (Raij et al., 1997; Ribeiro et al., 1999; Sousa and Lobato, 2004; Embrapa, 2010); however, it was below the 155 mg kg\textsuperscript{-1} limit established by Fageria (2000) and associated with a 10% reduction in maximum yield.

The DA between the diagnoses produced by the limits established by CL\textsubscript{RND} and CL\textsubscript{REF} was 100% and 75%, respectively, with TNS (Table 4). The assessment of the nutritional status of B using CND also showed a high DA with the diagnoses produced by CL\textsubscript{REF} and CL\textsubscript{RND} with 95% and 75% DA, respectively, with TNS (Table 4). The DA between the CL\textsubscript{CAL} diagnoses and the other methods was lower, which ranged from 15% to 20% and reached 35% in relation to TNS (Table 4).

Several authors have used the DA as a criterion to indicate the most appropriate method to assess nutritional status, opting for the methods with high DA between themselves (Politi et al., 2013; Dias et al., 2017). Therefore, the CL\textsubscript{REF} and CL\textsubscript{RND} methods should be the most recommended (100% DA) due to their higher DA followed by the CND method.

Regarding plant response, the highest DA between the diagnostic methods does not necessarily reflect a better performance of the resulting prognosis, given that all diagnoses produced by the CND method were for nutrient balance and the CL\textsubscript{RND} and CL\textsubscript{REF} methods indicated only 1 deficiency case and 19 sufficiency cases (Table 4). This means that high DA was associated with a large number of cases of concurring nutritional sufficiency or balance diagnoses, but notably recognized as nutritional deficiency in such cases (yield gain greater than 10% with fertilizer application). The quality of the prognoses assessed by PDA showed that the CND, CL\textsubscript{RND}, and CL\textsubscript{REF} methods had 0% correct answers in all the deficiency/insufficiency diagnoses. Objectively, these methods were ineffective in identifying cases of nutritional deficiency (Tables 5 and 6). The CL\textsubscript{CAL} was the only method that showed positive accuracy for a situation of true deficiency (Table 6), although with a low DA.

All diagnostic methods showed ER less than 1, which is a situation of low quality because it implies that the number of correct answers was smaller than the number of errors in the nutritional status assessment (Beverly, 1993).

Given that the main objective of nutritional status assessment is to identify cases of true deficiency (Beverly, 1993), CL\textsubscript{CAL} was the only method that obtained valuable nutritional diagnoses. Identifying cases of true deficiency is necessary because there is a greater effect on crop productivity with a deficiency adjustment. On the contrary, little or no effect on crop productivity is achieved with the sufficiency status, even with a great variation in nutrient availability.

However, incorrect diagnoses waste resources and are an environmental hazard. Therefore, the deficiency adjustment must be balanced against the risk of recommending unnecessary fertilization due to false deficiency diagnoses (Beverly and Hallmark, 1992).

Cases of true deficiency depend on the criterion adopted for yield limit, 10% in this case, as suggested by the literature (Beverly, 1993). In the present study, any yield increase less than 10% led to classifying the experimental plot as unresponsive to fertilization (Table 5). This criterion can be considered as rigorous because plants require smaller quantities of micronutrients with a lower impact on crop yield. Recent studies have shown a maximum increase of 8% in soybean grain yield when 1.5 kg ha\textsuperscript{-1} B was applied to soils with low B availability in India (Longkumer et al., 2017).

Our data showed many cases with a yield increase between 5% and 7%, but which were diagnosed as equilibrated (EQ) for TNS (Table 5). This resulted in false deficiency diagnoses attributed to the CL\textsubscript{CAL} method. A lower criterion to define deficiency leads to a greater number of cases with a true deficiency diagnosis for the CL\textsubscript{CAL} method; however, there was no improvement in diagnoses produced by the other methods (Table 5).

Table 4. Degree of agreement between the diagnoses by the critical reference level (CL\textsubscript{REF}), critical level by field calibration (CL\textsubscript{CAL}) and reduced normal distribution (CL\textsubscript{RND}), B nutritional balance by compositional nutrient diagnosis (CND), and the true nutritional status determined by the plant response to B foliar fertilization (TNS) in soybean ‘DESAFIO’ cultivated in Chapadão do Sul, Mato Grosso do Sul, Brazil.

| Critical level | Test   | CND  | CL\textsubscript{RND} | CL\textsubscript{REF} | CL\textsubscript{CAL} |
|---------------|--------|------|-----------------------|-----------------------|-----------------------|
|               | CL\textsubscript{RND} | 95   | -                     | -                     | -                     |
|               | CL\textsubscript{REF}  | 95   | 100                   | -                     | -                     |
|               | CL\textsubscript{CAL}  | 15   | 20                    | 20                    | -                     |
|               | TNS    | 75   | 75                    | 75                    | 35                    |
These results directly reflect on the overall accuracy of the methods. The CND and CLREF methods showed accuracy greater than 50% as recommended by Beverly (1993). However, as explained above, accuracy of the diagnoses produced by these methods was attributed to identifying TSUF, which does not correspond to the objective of the assessment of the status for purposes of fertilizer management, that is, to identify TDEF.

CND: Compositional nutrient diagnosis (Parent and Dafir, 1992); CLRDND: critical level values obtained by calculating the reduced normal distribution (Maia et al., 2001); CLCAL: critical level by field calibration (Cate and Nelson, 1965); CLREF: critical reference level for Cerrado soils (Sousa and Lobato, 2004).
The CND and CL_{REF} methods had a zero accuracy value for deficiency (AccDef) and high accuracy for sufficiency (AccSuf), while the CL_{CAL} method exhibited higher AccDef and lower AccSuf (Table 6). Beverly (1993) found similar results for soybean and reported high total accuracy for P (75%) associated with cases of high AccSuf and for K diagnoses with low total accuracy (25%) associated with high AccDef (72%).

The CND, CL_{REF}, and CL_{RND} methods had negative values for the net increase in production (Table 6), reflecting the inability to identify true cases of nutritional deficiency for B. Teixeira et al. (2002) found Net d(Y) ranging from 20 to 70 t ha\(^{-1}\) in banana due to the correct diagnoses provided by CL_{REF} for N and K.

Silva et al. (2020) evaluated the quality of the nutritional diagnosis of P by the CND method in sugarcane and reported negative values for Net d(Y). Morais et al. (2019) verified that the CND method was the most suitable when compared with the CL_{CAL} method to diagnose P in eucalyptus seedlings cultivated under a controlled environment using the Dickson quality index as a yield criterion to calculate Net d(Y).

The CL_{CAL} was the only diagnostic method that showed positive Net d(Y) (Table 6). Morais et al. (2019) found similar results and reported that CL_{CAL} was more suitable than the CND method for the nutritional diagnosis of N, K, Ca, B, and Fe using DM as a factor to measure eucalyptus production.

**CONCLUSIONS**

The calibrated critical level (CL_{CAL}) method was better than all other diagnostic methods to assess the nutritional status of B in foliar fertilized soybean.

The interpretation of B nutritional status by the nutritional balance method using the compositional nutrient diagnosis (CND), the critical reference level (CL_{REF}) values, and the critical reduced normal distribution level (CL_{RND}) did not show the minimum efficiency to be recommended for the management of B fertilization in soybean.

The use of the degree of agreement criterion to select the diagnostic method proved to be ineffective in validating the efficiency of nutritional diagnoses.

The better performance of the CL_{CAL} method was associated with greater efficiency in identifying cases of true deficiency, thus meeting the primary objective of nutritional diagnosis.

**REFERENCES**

Balbinot Junior, A.A., Hirakuri, M.H., Franchini, J.C., Debiasi, H., e Ribeiro, R.H. 2017. Análise da área, produção e produtividade da soja no Brasil em duas décadas (1997-2016). Boletim de Pesquisa e Desenvolvimento N°11. Embrapa Soja, Londrina, Paraná, Brasil.

Barbosa, J.C., e Maldonado Júnior, W. 2014. AgroEstat - Sistema para análises estatísticas de ensaios agronômicos - versão 1.1.0.71. Faculdade de Ciências Agrárias e Veterinárias, Universidade Estadual Paulista, Jaboticabal, São Paulo, Brasil.

Beverly, R.B. 1993. DRIS diagnoses of soybean nitrogen, phosphorus, and potassium status are unsatisfactory. Journal of Plant Nutrition 16(8):1431-1447. doi:10.1080/01904169309364625.

Beverly, R.B., and Hallmark, W.B. 1992. Prescient diagnostic analysis: a proposed new approach to evaluating plant nutrient diagnostic methods. Communications in Soil Science and Plant Analysis 23(17/20):2633-2640. doi:10.1080/00103629209364625.

Bruns, H. 2017. Effects of boron foliar-fertilization on irrigated soybean (*Glycine max* L. Merr.) in the Mississippi River Valley Delta of the midsouth, USA. Archives of Agriculture and Environmental Science 2(3):167-169.

Calonego, J.C., Ocani, K., Ocani, M., e Santos, C.H. 2010. Adubação boratada foliar na cultura da soja. Colloquium Agrariae 6(2):20-26. doi:10.5747/ca.2010.v06.n2.a054.

Campos, T.S., Sousa, S.W., Rossetti, C., Souza, A.G.V., Faria, L.O., Cintra, P.H.N., et al. 2021. Productivity, quality and composition of soybean seeds in storage as a function of boron doses at different phenological stages. Revista Brasileira de Ciências Agrárias 44(1):68-81. doi:10.2134/agronj2005-0131.

Carmo, C.D.S, Araujo, W.S., Bernardi, A.D.C., e Saldanha, M.F.C. 2000. Métodos de análise de tecidos vegetais utilizados na Embrapa Solos. Circular Técnica N°6. 41 p. Embrapa Solos, Rio de Janeiro, Rio de Janeiro, Brasil.

Cate, R.B., and Nelson, L.A. 1965. A rapid method for correlation of soil test analyses with plant response data. Technical Bulletin N°1. 13 p. International Soil Testing Series. Agricultural Experiment Station, North Carolina State University, Raleigh, North Carolina, USA.
Dias, J.R.M., Wadt, P.G.S., Partelli, F.L., Espindula, M.C., Perez, D.V., Souza, F.R., et al. 2017. A normal nutrient ranges and nutritional monitoring of ‘Pêra’ orange trees based on the CND method in different fruiting stages. Pesquisa Agropecuária Brasileira 52(9):776-785. doi:10.1590/S0100-204X2017000900010.

Embrapa. 2010. Tecnologias de Produção de Soja - Região Central do Brasil 2011. Sistemas de Produção Nº14. 247 p. Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Embrapa Soja, Londrina, Paraná, Brasil.

Enderson, J.T., Mallarino, A.P., and Haq, M.U. 2015. Soybean yield response to foliar-applied micronutrients and relationships among soil and tissue tests. Agronomy Journal 107(6):2143-2161. doi:10.2134/ajronj14.0536.

Fageria, N.K. 2000. Nutrient diagnosis for optimal nutrient management in soybean (Glycine max L.) Grown in an acid soil. Communications in Soil Science and Plant Analysis 31(5):235-238. doi:10.1080/00103624.20010003000015.

Fageria, N.K., Venegas, V.H., Neves, J.C.L., Novais, R.F., and Staut, L.A. 2013. Fertilizer recommendations for soybean (Glycine max L.) Grown in acid soil. Communications in Soil Science and Plant Analysis 31(5):235-238. doi:10.1080/00103624.2013.67157.

Lacerda, J.J., Lopes, L.O., Rambo, T.P., Marafon, G., Silva, A.O., Lira, D.N.S., et al. 2017. Soybean yield responses to foliar-applied micronutrients and relationships among soil and tissue tests. Agronomy Journal 107(6):2143-2161. doi:10.2134/ajronj14.0536.

IBGE. 2021. Anuário Estatístico do Brasil. Vol. 80. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, Brasil.

IBGE. 2002. Mapa de clima do Brasil. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, Brasil.

IBGE. 2001. Mapa de Solos do Brasil. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, Brasil.

IBGE. 1970. Anuário Estatístico do Brasil 31:1-772. Instituto Brasileiro de Geografia e Estatística (IBGE), Rio de Janeiro, Brasil.

Kurihara, C.H., Venegas, V.H., Neves, J.C.L., Novais, R.F., and Staut, L.A. 2013. Faixas de suficiência para teores de nutrientes em gramíneas em solos de Cerrado. Revista Brasileira de Engenharia Agrícola e Ambiental 17(3):312-327.

Maia, C.E., Morais, E.R., and Oliveira, M.D. 2001. Nível crítico pelo critério da distribuição normal reduzida: uma nova proposta para interpretação de análise foliar. Revista Brasileira de Engenharia Agrícola e Ambiental 5:235-238. doi:10.1590/S1415-43662001001000010.

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

Moraes, T.C.B.D., Prado, R.D.M., Traspadini, E.I.F., Wadt, P.G.S., Paula, R.C.D., and Rocha, A.M.S. 2019. Efficiency of the CL, DRIS and CND methods in assessing the nutritional status of Eucalyptus spp. rooted cuttings. Forests 10(9):786.

Nakao, A.H., Costa, N.R., Andreottti, M., Souza, M.F.P., Dickmann, L., Centeno, D.C., et al. 2018. Características agronômicas e qualidade fisiológica de sementes de soja em função da adubação foliar com boro e zinco. Revista Cultura Agronômica 27(3):312-327.

Parent, L.E., and Dafir, M.A. 1992. Theoretical concept of compositional nutrient diagnosis. Journal of the American Society for Horticultural Science 117:239-242. doi:10.21273/JASHS.117.2.239.

Polití, L.S., Flores, R.A., Silva, J.A., Wadt, P.G., Pinto, P.A.D.C., and Prado, R.D.M. 2013. Estado nutricional de mangueiras determinado pelos métodos DRIS e CND. Revista Brasileira de Engenharia Agrícola e Ambiental 17:11-18. doi:10.1590/S1415-43662013000100002.

Prado, R.M., and Caione, G. 2012. Plant analysis. Soil fertility 115-134. doi:10.5772/53388.

Raij, B.V., Cantarella, H., Quaggio, J.A., and Furlani, A.M.C (eds.) 1997. Recomendações de adubação e calagem para o Estado de Minas Gerais. 5ª Aproximação, Comissão de fertilidade do solo do Estado de Minas Gerais, Viçosa, Minas Gerais, Brasil.

Seidel, E.P., Egwarth, W.A., Piano, J.T., and Egwarth, J. 2015. Effect of foliar application rates of calcium and boron on yield and yield attributes of soybean (Glycine max). African Journal of Agricultural Research 10(4):170-173. doi:10.5897/AJAR2014.9046.

Silva, G.P., Prado, R.M., Wadt, P.G.S., Moda, L.R., and Caione, G. 2020. Accuracy of nutritional diagnostics for phosphorus considering five standards by the method of diagnosing nutritional composition in sugarcane. Journal of Plant Nutrition 1:1-14.

Silva, R.C.D., Silva Junior, G.S., Silva, C.D.S., Santos, C.T., and Pelá, A. 2017. Nutrição com boro na soja em função da disponibilidade de água no solo. Scientia Agraria 18(4):155-165. doi:10.5380/rsa.v18i4.52762.

Sousa, D.M.G., and Lobato, E. (eds.) 2004. Cerrado: correção do solo e adubação. 2ª ed. Embrapa, Brasília, Brasil.

Sutradhar, A.K., Kaiser, D.E., and Behnken, L.M. 2017. Soybean response to broadcast application of boron, chlorine, manganese, and zinc. Agronomy Journal 109(3):1048-1059. doi:10.2134/agronj2016.07.0389.
Teixeira, L.A.J., Santos, W.D., e Bataglia, O.C. 2002. Diagnose nutricional para nitrogênio e potássio em bananeira por meio do Sistema Integrado de Diagnose e Recomendação (DRIS) e de Níveis Críticos. Revista Brasileira de Fruticultura 24:530-535. doi:10.1590/S0100-29452002000200050.

Tomicioli, R.M., Leal, F.T., e Coelho, A.P. 2021. Limitação da produtividade pela deficiência de boro nas culturas da soja, milho, feijão e café. South American Sciences 2(1):e21100. doi:10.17648/sas.v2i1.

Urano, E.O.M., Kurihara, C.H., Maeda, S., Vitorino, A.C.T., Gonçalves, M.C., e Marchetti, M.E. 2007. Determinação de teores ótimos de nutrientes em soja pelos métodos Chance Matemática, Sistema Integrado de Diagnose e Recomendação e Diagnose da Composição Nutricional. Revista Brasileira de Ciência do Solo 31:63-72. doi:10.1590/S0100-068320070000100007.

Wadt, P.G.S. 2005. Relationships between soil class and nutritional status of coffee plantations. Revista Brasileira de Fruticultura 29:227-234. doi:10.1590/S0100-06832005000200008.

Wadt, P.G.S., Anghinoni, I., Guindani, R.H.P., Lima, A.S.T., Puga, A.P., Silva, G.S., et al. 2013. Padrões nutricionais para lavouras arrozeiras irrigadas por inundação pelos métodos da CND e Chance Matemática. Revista Brasileira de Ciência do Solo 37:145-156.

Zuffo, A.M., Aguilera, J.G., Yokota, L.A., Morais, D.B., Santos Filho, F.N., e Fonseca, W.L. 2019. Características agronômicas da soja em função da adubação nitrogenada associada à inoculação de Bradyrhizobium japonicum. p. 6-13. In Zuffo, A.M., Aguilera, J.G., e Oliveira B.R. (eds.) Ciência em Foco. Pantanal Editora, Nova Xavantina, Mato Grosso, Brasil.