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RESEARCH

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

Edilaine I.F. Traspadini[1*], Paulo G.S. Wadt[2], Renato de Mello-Prado[1], Cassiano Garcia-Roque[3], Carlos Roberto-Wassolowski[3], and Daniel Vidal-Perez[4]

[1]Universidade Estadual Paulista, Faculdade de Ciências Agrárias e Veterinárias, Campus Jaboticabal, Vila Industrial, 14884-900, Jaboticabal, São Paulo, Brasil. [*]Corresponding author (edilainetraspadini@gmail.com).
[2]Empresa Brasileira de Pesquisa Agropecuária, Embrapa-Rondônia, Rodovia BR-364, km 5,5, 76815-800, Porto Velho, Rondônia, Brasil.
[3]Universidade Federal de Mato Grosso do Sul, Campus de Chapadão do Sul, Rodovia MS-306, km 105, Zona Rural, 79560-000, Chapadão do Sul, Mato Grosso do Sul, Brasil.
[4]Empresa Brasileira de Pesquisa Agropecuária, Embrapa-Solos, Rua Jardim Botânico, 1024 - Jardim Botânico, 22460-000, Rio de Janeiro, Brasil.

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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).

Table 1. Attributes of soil fertility analysis in 0-20 cm layers in the experimental area of Fundação Chapadão, Chapadão do Sul, Mato Grosso do Sul, Brazil, in 2015.

pH	5.30
Ca, $cmol_c$ dm^{-3}	2.80
Mg, $cmol_c$ dm^{-3}	1.10
Al, $cmol_c$ dm^{-3}	0.05
H+Al, $cmol_c$ 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 m^2 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 CO_2 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 ºC, 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 ºC 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 (CL_{CAL}) 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 CL_{CAL}.

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 (CL_{RND}) 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):

$$NI = (va - VA)/sA \quad (1)$$

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.

$$\text{NBIa: } [NI_N] + [NI_K] + [NI_P] + [NI_{Ca}] + [NI_{Mg}] + [NI_S] + [NI_B] + [NI_{Fe}] + [NI_{Mn}] + [NI_{Zn}] + [NI_{Cu}]/n \quad (2)$$

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.

$$\text{Insufficient: NI} < 0 \text{ and } [NI] > \text{NBIa} \quad (3)$$

The nutritional status was interpreted by the critical level (CL) method as recommended for soybean in the Cerrado (CL_{REF}) (Sousa and Lobato, 2004) or according to the CL method by field calibration established in the present work (CL_{CAL} and CL_{RND}). 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).

$$\text{Deficient: nutrient contents} < \text{CL value} \quad (4)$$

$$\text{Sufficient: nutrient contents} > \text{CL value} \quad (5)$$

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 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, $\sum$DEF is the sum of deficiency, and $\sum$SUF is the sum of sufficiency.

$$\text{AccT} = 100\ (T_{DEF}/n + T_{SUF}/n) \quad (6)$$

$$\text{AccDef} = 100 \times T_{DEF}/\sum \text{DEF} \quad (7)$$

$$\text{AccSuf} = 100 \times T_{SUF}/\sum \text{SUF} \quad (8)$$

$$\text{ER} = T_{DEF}/\sum \text{DEF} \quad (9)$$

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.

$$\text{Net d(Y)} = |P\_T_{DEF}| + |P\_T_{SUF}| - |P\_F_{DEF}| - |P\_F_{SUF}| \quad (10)$$

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

Number of cycles		
	True physiological nutritional status	
Interpretation of 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 ($\sum_{DEF}$)	Sufficiency sum ($\sum_{SUF}$)

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.

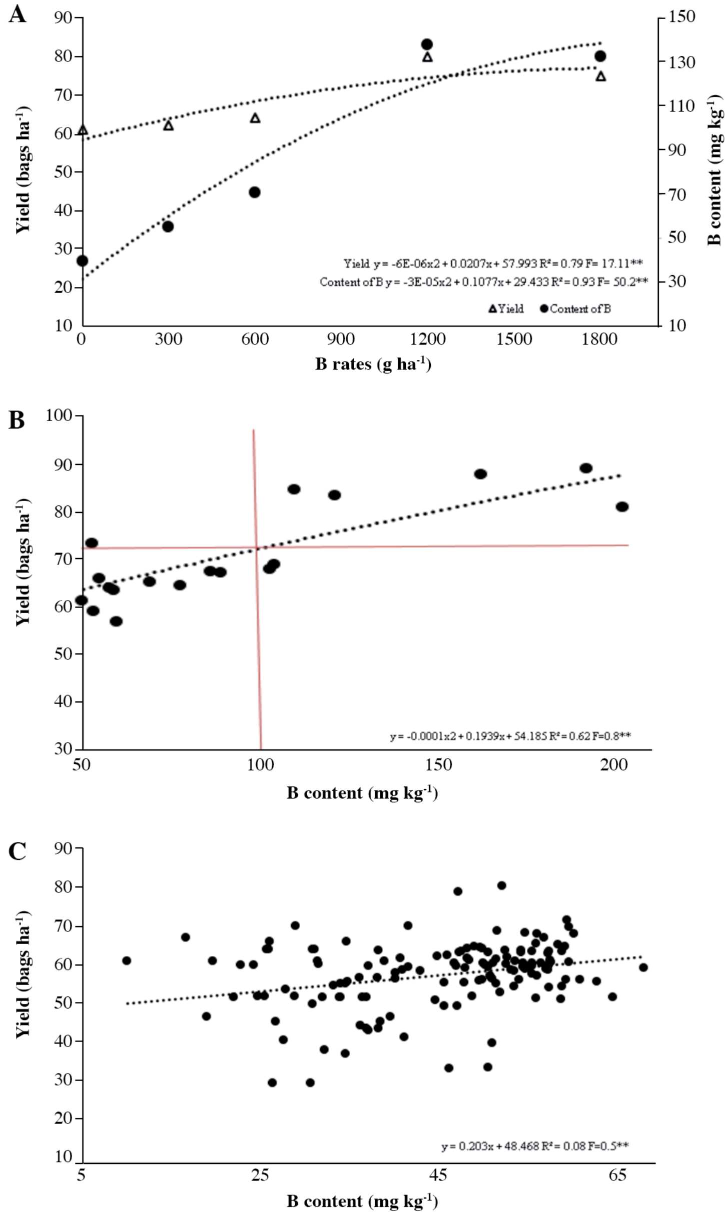
Lacerda et al. (2017) attributed the unresponsiveness of the soybean crop to B fertilization reported by Calonego et al. (2010) to high soil B availability; contents were 0.43 mg dm^{-3} at the study site. Other authors have also associated soybean unresponsiveness with B foliar application to its low 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 (NC_{DNR}), and reference for Cerrado soils (CL_{REF}) (Sousa and Lobato, 2004) of soybean samples cultivated in Chapadão do Sul, Mato Grosso do Sul, Brazil.

	Low-yielding crops		High-yielding crops	
	B content[1]	Soybean grain yield	B content[1]	Soybean grain yield
	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	
Critical levels				
CL_{CAL}[1]	CL_{RND}		CL_{REF}	
100 mg kg^{-1}	37 mg kg^{-1}		21 mg kg^{-1}	

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

Figure 1. Effect of B foliar application on leaf content and yield (A); correlation study between leaf B content and yield of soybean cultivars in 23 experimental plots (B) and commercial farms (C) 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 CL_{RND} 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 (Raij 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_{CAL} estimated by site calibration was 100 mg kg^{-1} (Table 3), which was above the toxicity limit established between 55 and 60 mg kg^{-1} (Raij et al., 1997; Ribeiro et al., 1999; Sousa and Lobato, 2004; Embrapa, 2010); however, it was below the 155 mg kg^{-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_{RND} and CL_{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_{REF} and CL_{RND} with 95% and 75% DA, respectively, with TNS (Table 4). The DA between the CL_{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_{REF} and CL_{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_{RND} and CL_{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_{RND}, and CL_{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_{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_{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^{-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_{CAL} method. A lower criterion to define deficiency leads to a greater number of cases with a true deficiency diagnosis for the CL_{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_{REF}), critical level by field calibration (CL_{CAL}) and reduced normal distribution (CL_{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.

	Degree of agreement (%)			
		Critical level		
Test	CND	CL_{RND}	CL_{REF}	CL_{CAL}
CL_{RND}	95	-	-	-
CL_{REF}	95	100	-	-
CL_{CAL}	15	20	20	-
TNS	75	75	75	35

Table 5. Boron rate (R), mean leaf B content, and yield for each applied rate, true nutritional status (TNS) of the plots and diagnosis of deficient (DF), sufficient (SF), or equilibrated (EQ) obtained by the tested nutritional diagnosis methods of compositional nutrient diagnosis (CND), critical reduced normal distribution level (CL_{RND}), critical reference level (CL_{REF}), and critical level by field calibration (CL_{CAL}).

						Diagnosis			
							Critical level (CL)		
Plot	Comparison	Control yield	Actual yield	Fertilization response	TNS	CND	CL_{RND}	CL_{REF}	CL_{CAL}
		Bags ha^{-1}	Bags ha^{-1}	%					
1	R0-R1	74.6	63.7	-15	EQ	EQ	EQ	EQ	DF
	R1-R2	63.7	67.0	5	EQ	EQ	EQ	EQ	DF
	R2-R3	67.0	87.4	31	DF	EQ	EQ	EQ	DF
	R3-R4	87.4	80.7	-8	EQ	EQ	EQ	EQ	DF
2	R0-R1	63.9	63.2	-1	EQ	EQ	EQ	EQ	DF
	R1-R2	63.2	65.6	4	EQ	EQ	EQ	EQ	DF
	R2-R3	65.6	67.1	2	EQ	EQ	EQ	EQ	DF
	R3-R4	67.1	68.6	2	EQ	EQ	EQ	EQ	DF
3	R0-R1	68.6	73.2	7	EQ	EQ	EQ	EQ	DF
	R1-R2	73.2	65.0	-11	EQ	EQ	EQ	EQ	DF
	R2-R3	65.0	87.9	35	DF	EQ	EQ	EQ	DF
	R3-R4	87.9	83.2	-5	EQ	EQ	EQ	EQ	DF
4	R0-R1	58.0	61.0	5	EQ	EQ	EQ	EQ	DF
	R1-R2	61.0	64.2	5	EQ	EQ	EQ	EQ	DF
	R2-R3	64.2	88.8	38	DF	EQ	EQ	EQ	DF
	R3-R4	88.8	67.7	-24	EQ	EQ	EQ	EQ	EQ
5	R0-R1	54.7	58.7	7	EQ	EQ	EQ	EQ	DF
	R1-R2	58.7	56.5	-4	EQ	EQ	DF	DF	DF
	R2-R3	56.5	84.5	49	DF	EQ	EQ	EQ	EQ
	R3-R4	84.5	51.3	-39	EQ	EQ	EQ	EQ	EQ

Table 6. Percentage of identified cases with true deficiency (T_{DEF}) and sufficiency (T_{SUF}), false deficiency (F_{DEF}) and sufficiency (F_{SUF}), accuracy, deficiency ratio (DR), accuracy for deficiency (AccDef), accuracy for sufficiency (AccSuf), efficiency ratio (ER), and net yield response [Net d(Y)] obtained by the diagnostic methods to diagnose leaf B in a soybean cultivar in Chapadão do Sul, Mato Grosso do Sul, Brazil.

Diagnostic methods	T_{DEF}	F_{DEF}	T_{SUF}	F_{SUF}	Accuracy	AccDef	AccSuf	ER
CND	0	0	79	21	79	0	100	0.0
CL_{RND}	0	0	79	21	79	0	100	0.0
CL_{REF}	0	5	79	21	79	0	94	0.0
CL_{CAL}	16	74	11	5	26	75	13	0.4

Yield net increase							
						Mean	
	T_{DEF}	F_{DEF}	T_{SUF}	F_{SUF}	Total	Bags ha^{-1}	kg ha^{-1}
CND	0	0	81	-96	-15	-0.8	-46
CL_{RND}	0	0	81	-96	-15	-0.8	-46
CL_{REF}	0	-2	81	-96	-18	-0.9	-53
CL_{CAL}	68	-29	54	-28	66	3.3	197

CND: Compositional nutrient diagnosis (Parent and Dafir, 1992); CL_{RND}: critical level values obtained by calculating the reduced normal distribution (Maia et al., 2001); CL_{CAL}: critical level by field calibration (Cate and Nelson, 1965); CL_{REF}: critical reference level for Cerrado soils (Sousa and Lobato, 2004).

These results directly reflect on the overall accuracy of the methods. The CND and CL_{REF} 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 iodentifying T_{SUF}, which does not correspond to the objective of the assessment of the status for purposes of fertilizer management, that is, to identify T_{DEF}.

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.

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