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Assessment of nutritional status of soybean by the DRIS method in western of Bahia State

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ABSTRACT: Increasing soybean yield in the MATOPIBA region can be attributed to fertility management, which is crucial to achieving maximum agronomic efficiency. Therefore, the proper management begins with the assessment of plant nutrition. This study aimed to evaluate soybean nutritional status in western Bahia using the Diagnosis and Recommendation Integrated System (DRIS). Database comprised 153 samples from commercial fields located in the research area. To carry out the evaluation using the DRIS method, the database contained information on nutritional levels and leaf productivity of the sampled areas. Database was divided into high-productivity populations (reference population) and low-productivity populations, based on the inflection point value of the cumulative cubic function of yield. The DRIS method allowed for evaluating the potential response to fertilization; however, this method was inefficient in recommending fertilizer doses in both subpopulations. For the sufficiency levels proposed by DRIS, the nutrients N, K, Ca, Mg and S had their maximum and minimum limits reduced, while Cu, Fe and Zn had their ranges of sufficiency expanded, when compared with ranges proposed by other authors. In addition, Zn and Mn were more limiting due to lack for the high-yield subpopulation, and P and Mn for the low-yield subpopulation. The most limiting nutrients due to excess were P and Zn for the high-yield, while K and S were limiting for the low yield subpopulation.

Keywords: plant nutrition, *Glycine max* L. Merril, nutritional balance, foliar diagnosis.

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INTRODUCTION

Brazil is responsible for around 40 % of all soybean production in the world, with approximately 154 million tons harvested in the 2022/2023 season (FAO, 2023; Conab, 2023). Among the productive and promising regions for cropping in Brazil there is the MATOPIBA region, composed of the states of Maranhão, Tocantins, Piauí and Bahia, which are part of the Cerrado biome. From this region, the state of Bahia stands out, producing 7.71 million tons and being responsible for 5 % of the national production, raised in 1.9 million hectares (Conab, 2023). Cerrado biome is characterized by a tropical climate, with weathered soils, poor natural fertility, and highly mechanized due to the low slope (Schenfert et al., 2020). Soils in the croplands of Bahia State are classified as poor due to low levels of available nutrients for plants, such as N, P and K; also, the organic matter content is low in this area (Lopes and Guilherme, 2016). Another limiting factor of production in the region is the natural soil pH, which increases the availability of manganese to toxic levels for soybean development (Fageria and Stone, 2008).

Increases in soybean yield in the MATOPIBA region can be attributed to fertility management, which is crucial to achieve maximum agronomic efficiency. Application of fertilizers can reduce the gap between average yield and potential yield (Hochman and Horan, 2018). Therefore, the proper management begins with the assessment of plant nutrition. Among existing methods is tissue analysis, which uses leaf samples to determine nutrient levels. Tissue analysis is an efficient and economical strategy to assist in the management of crops and the assessment of nutritional status (Labaied et al., 2018). The possibility of diagnosing nutritional deficiencies before the appearance of visual symptoms makes leaf analysis a useful tool. Assessment of the plant nutritional concentration can identify deficiencies that can reduce productivity before the appearance of severe symptoms (Rozane et al., 2016).

Among the methods of interpreting nutritional status by analyzing the plant tissue, the Diagnosis and Recommendation Integrated System (DRIS) developed by Beaufils in 1973, can assess the nutritional status of the plant from the binary relationships between the concentration of nutrients. This method is more adequate to diagnose nutritional imbalance than univariate methods because it considers the possible nutritional interactions in the plant tissue (Rozane et al., 2016).

Univariate assessments neglect that biochemical functions in the plant do not occur independently, and it is important to understand these relationships for any diagnosis (Ali et al., 2016). The DRIS method and other bivariate or multivariate methods consider environmental aspects in their assessment. The reference standard will be determined within the database itself, and is subjected to external interferences such as climatic, management and environmental conditions (Urano et al., 2006). Therefore, to be reliable in the diagnosis, the evaluated areas must be under similar edaphoclimatic conditions, generating more regionalized and less universal reference patterns (Rozane et al., 2016). Application of this methodology on a smaller scale increases the level of reliability when compared to general standards, since local characteristics are considered (Gott et al., 2016).

DRIS standards for soybean cultivation have been established over the years considering different cultivars and cultivation locations: Hanson (1981), Vigier et al. (1989); Bell et al. (1995), Urano et al. (2006, 2007), Kurihara et al. (2013), Wenneck et al. (2022), Souza et al. (2023). Despite the vast research on soybean, there are no reports on the nutritional diagnosis of soybean raised in the western state of Bahia. This study aimed to assess the nutritional status and establish DRIS standards for soybean cultivated in the western region of Bahia based on commercial field crop assessments.

MATERIALS AND METHODS

To determine the DRIS standards for soybeans, leaf tissue samples were collected from 153 commercial crops, in the direct planting system (SPD), with soybean - corn - cotton rotation, without irrigation, during the 2017/2018 and 2018/2019 harvests in the municipalities of Barreiras, Formosa do Rio Preto, Luís Eduardo Magalhães and Riachão das Neves, located in the western region of Bahia (Figure 1). The predominant soil in the region is classified as *Latossolo* (Santos et. al., 2018; Soil Survey Staff, 1999), classified into the sandy loam, sandy texture classes (Clemente et al., 2019). Predominant climate in the region is classified as Aw according to the Köppen-Geiger classification system (Alvares et al., 2013), characterized by a defined dry season during winter and abundant rains during summer, with an elevation between 460 and 720 m above sea level.

A composite sample was collected in each evaluated field, consisting of 30 complete leaves (limbus with petiole) chosen randomly. The collected diagnostic leaf was the third or fourth full developed leaf from the apex of the plant, during the initial or full flowering stage “R1” or “R2” (Oliveira Júnior et al., 2020). Collected leaves were washed in the sequence: running water, deionized water with neutral detergent (0.1 %), deionized water with hydrochloric acid (0.3 %) and finally rinsed with deionized water. The drying was carried out in a forced ventilation oven at 65 °C, until the samples reached constant mass. After drying, the samples were ground in a Willey mill with a 20 mesh (0.841 mm) sieve to determine the nutritional concentration of nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), iron (Fe), zinc (Zn) and manganese (Mn).

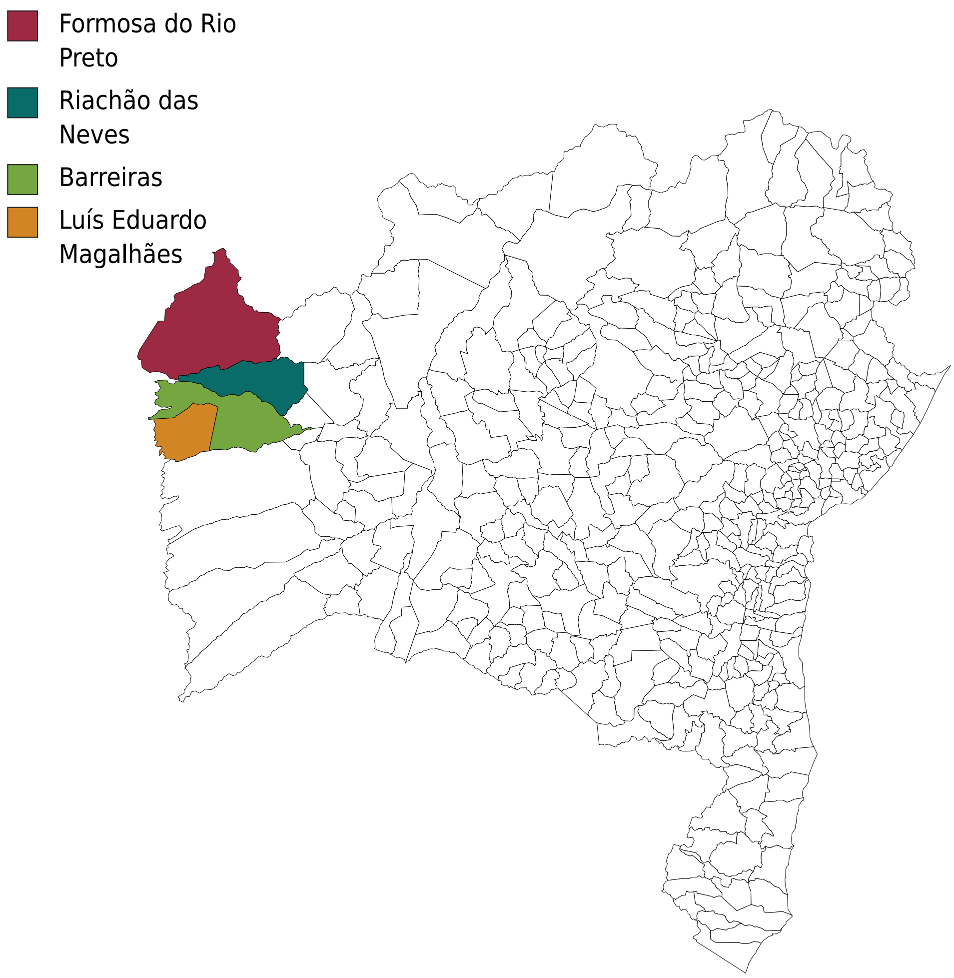

Figure 1. Map of municipalities in the western region of Bahia State.

Nutrient contents were analyzed according to the methodology of Bataglia et al. (1983), with determinations methods: N by micro-Kjeldahl, P and S by colorimetry, B also by colorimetry after calcined for 3 h at 600 °C. The K, Ca, Mg, Cu, Fe, Zn and Mn cations were determined by atomic absorption spectrophotometry, after digestion with a solution of nitric acid and perchloric acid. The yield of each field was determined by dividing the total grain mass produced in the field by its area, at 13 % moisture content in the grains.

Using nutrient levels in the leaf tissue and yield (kg ha^{-1}) of the sampled fields, the identification and exclusion of extreme values (outliers) from the database was performed when the value was less than 1 % ($p<0.01$) in the χ^2 test based on the Mahalanobis distance (D^2) as indicated by Parent et al. (2009). Then the DRIS standards for soybean were determined from the bivariate relationships of the transformed logs, as proposed by Beverly (1987).

The database without the outliers was submitted to the Shapiro-Wilk test to assess the normality of yield. For the division of the database, fields with a yield equal to or greater than the inflection point of the cumulative cubic function of yield were classified as "subpopulation of reference" or "high-yield subpopulation", while the other fields, the ones with a yield below the inflection point of the function, were considered "low-yield", as proposed by Khiari et al. (2001).

Reference values of the indices of the high-yield subpopulation were obtained by the arithmetic means and standard deviations between the nutritional dual relationships (Y / X, Y / Z, ..., Y / W) and their inverse relationships (X / Y, Z / Y, ..., W / Y), transformed by the Neperian logarithm. The index for each nutrient was determined using equation 1, proposed by Beverly (1987).

$$I_Y = \left\{ \sum_{i=1}^{d} \left[\frac{\left(\log \frac{Y}{X_n} - Pr_d \right) \cdot k}{\sigma r_d} \right] - \sum_{i=1}^{d} \left[\frac{\left(\log \frac{X_n}{Y} - Pr_i \right) \cdot k}{\sigma r_i} \right] / \left(Nr_d + Nr_i \right) \right\} \quad \text{Eq. 1}$$

in which: I_Y is the index of a given nutrient; Y / X_n is the ratio between two nutrients contained in the plant sample; Y is the evaluated nutrient; and X_n the other evaluated nutrients; Pr_i and Pr_d are the means of the direct Y / X_n and indirect X_n / Y logarithmic ratios, respectively; k is a constant sensitivity value equal to 1; σr_d and σr_i are the respective standard deviation of the reference subpopulation (high-yield) of direct and indirect relationships; and Nr_d and Nr_i are the numbers of direct and indirect relationships.

Nutrient balance index (IBN) was determined by the sum of the indices of each nutrient in module, from each sample (Walworth and Summer, 1987). Average nutritional balance index (IBNm) was calculated by dividing the IBN value by the total number of nutrients, as proposed by Wadt (2005). Nutritional sufficiency ranges were established by the critical level of the nutrient in the leaf ± 2/3 standard deviation to determine the lower and upper limits of the range, as indicated for the soybean culture by Kurihara et al. (2013). Indices obtained by the DRIS methodology were interpreted based on the potential response to fertilization (PRA), divided into five classes of response: positive (p), positive or null (pz), null (n), null or negative (nz) or negative (n), as indicated by Wadt et al. (1998). Chi-square statistical analysis (χ^2), ($p<0.05$), was used to assess whether the observed frequencies (FO) of each nutrient in the response classes satisfied the hypothesis that there were no statistical differences with the expected frequencies (FE). Intervals obtained were later compared with values found in the literature.

RESULTS AND DISCUSSIONS

Database submitted to the verification of outlier data by D^2 was reduced from 153 to 117 samples, so, 36 data points were identified as outliers and removed to avoid distortions. Shapiro-Wilk test (n = 117) indicated the yield data was normal (W = 0.89079; p = 0.09234). The inflection point of the cumulative function of yield (Figure 2) indicated fields with a yield equal to or greater than 3972 kg ha^{-1} comprised the high-yield subpopulation, with 41 samples (35 %), while the low subpopulation was composed of 76 samples (65 %). Table 1 presents the descriptive statistics (mean, standard deviation and coefficient of variation, variance) of the leaf nutrient contents and productivity evaluated in the high and low productivity subpopulations. Sulfur was the macronutrient with the greatest variability in both the high-productivity population (38.75 %) and the low-productivity population (34.79 %). This variation, in part, is attributed to differences in management, including the application of agricultural gypsum. Regarding micronutrients, Cu had the highest coefficient of variation in the high-productivity population (116.34 %) and in the low-productivity population (179.41 %), which may also be related to defensive management. Areas classified as high-productivity subpopulations showed higher productivity than the average for the western region of Bahia, estimated at 4,020 kg ha^{-1} (AIBA, 2023).

Conversion of dual relations by the Neperian logarithm reduces the kurtosis effect in the normal data distribution curve, increasing the method's sensitivity (Beverly, 1987). The greater the kurtosis, the greater the result of infrequent extreme deviations (or outliers), as opposed to frequent deviations from the assessed database. Table 2 shows the averages of the dual ratios and their respective standard deviations of the high-yield subpopulation used to establish the DRIS norms for soybeans. Among the relationships evaluated, those with the highest averages, using their respective absolute values, were those with nutrients S, Fe and P, while the relationships with K, Cu and Mn had the lowest averages, demonstrating the intensity of the nutritional imbalance in the evaluated samples.

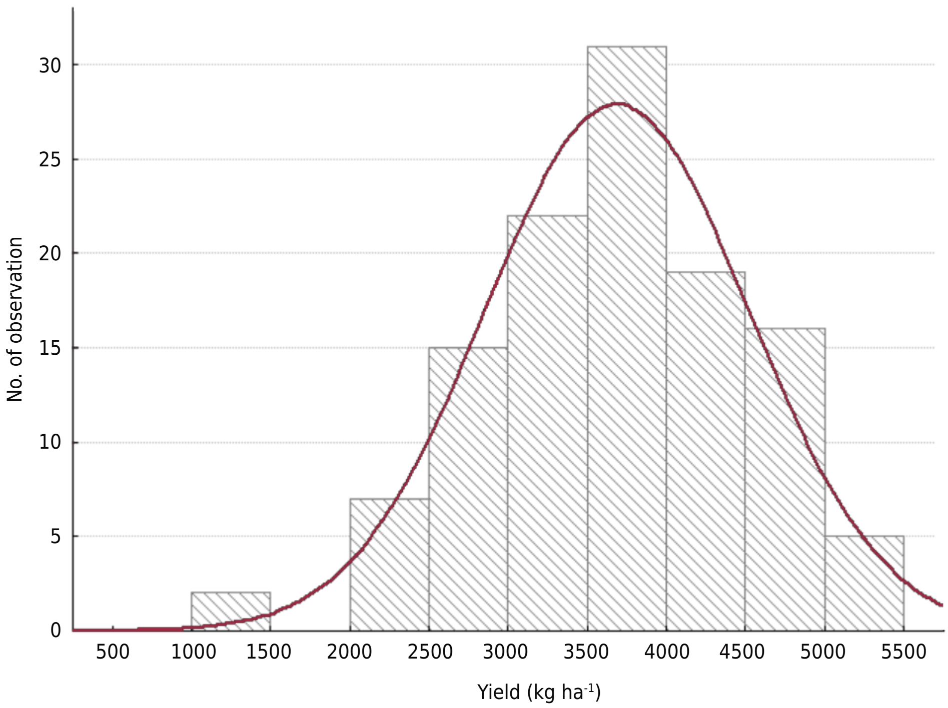

Figure 2. Inflection point of the cumulative yield function.

Table 1. Mean, standard deviation, coefficient of variation (CV) and variance of leaf nutrient contents and productivity of subpopulations of high and low soybean productivity in the western region of the state of Bahia

Variable	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn	Productivity
	g kg^{-1}						mg kg^{-1}					kg ha^{-1}
High productivity subpopulation (n = 41)												
Average	38.76	2.48	15.82	7.53	3.25	1.67	43.77	11.53	96.38	39.06	76.42	4574.47
Standard deviation	5.82	0.86	5.13	2.23	0.80	0.65	9.65	13.41	42.77	26.78	48.64	324.68
C.V (%)	15.02	34.53	32.41	29.61	24.67	38.75	22.05	116.34	44.38	68.55	63.65	7.10
Variance	33.88	0.73	26.29	4.97	0.64	0.42	93.12	179.79	1829.21	717.00	2365.83	-
Low Productivity Subpopulation (n = 76)												
Average	38.36	1.98	18.68	8.15	3.65	1.96	36.11	12.25	90.97	49.71	69.56	3116.98
Standard deviation	5.90	0.64	4.35	2.55	1.26	0.68	9.78	21.97	32.62	42.69	46.43	770.80
C.V (%)	15.39	32.28	23.29	31.25	34.41	34.79	27.08	179.41	35.86	85.88	66.75	24.73
Variance	34.86	0.41	18.92	6.48	1.58	0.47	95.65	482.82	1064.27	1822.33	2155.84	-

The exclusion of outliers by D^2 increased the coefficient of determination (R^2) of the average nutritional balance index (IBNm) with productivity from 0.14 (n = 153) to 0.32 (n = 117) with $p<0.05$, which means the nutritional balance of this database can explain 32 % of the variation in production, the remaining 68 % were influenced by other factors not linked to plant nutrition (Figure 3). Correlating the leaf content of the evaluated nutrients with their respective indexes (Table 3), null indexes of each equation were established to determine the critical values of nutrient content in the tissue analysis, in which the value of the nutritional index equal to zero indicates the nutritional balance. The nutrients P, K, Ca, S, B, Cu, Fe, Mn and Zn had a strong correlation between their content in the leaf and their respective nutritional indices ($R^2 >0.7$), and only the nutrients N and Mg had moderate coefficients ($0.4< R^2 <0.6$), which corroborates the classifications of Dancey and Reidy (2013).

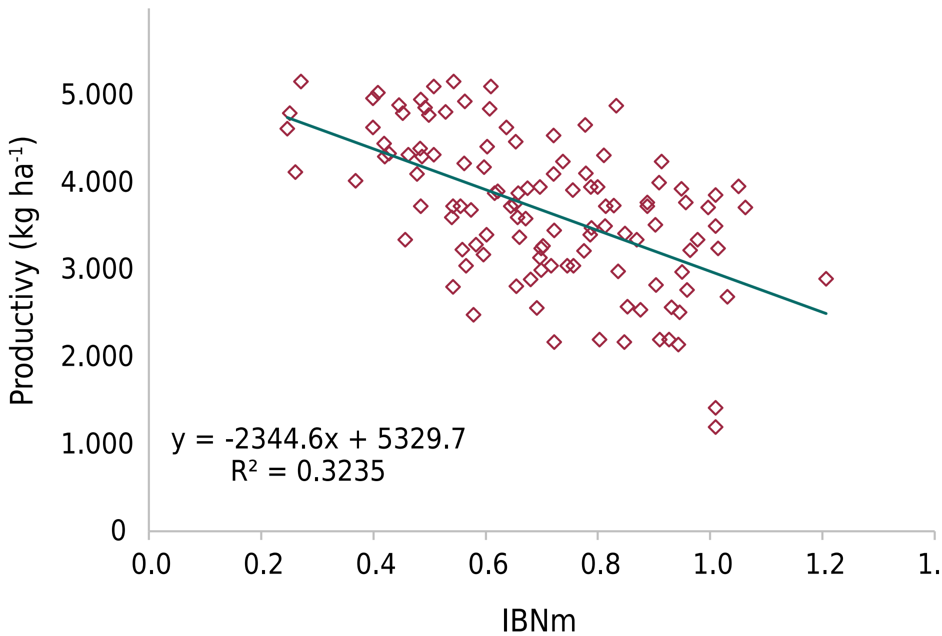

Figure 3. Relationship between productivity and the average nutritional balance index (IBNm) of commercial soybean plots in western Bahia.

Table 2. Means and standard deviations (σ) of the quotients between nutrient content in soybean leaves, in the high yield subpopulation, transformed by Neperian logarithmic function, in samples collected in the western region of the state of Bahia

N/	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
mean	1.17	0.40	0.72	1.07	1.34	-0.06	0.64	-0.42	0.05	-0.27
σ	0.09	0.15	0.11	0.08	0,16	0.09	0.32	0.10	0.19	0.28
P/	N	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
mean	-1.17	-0.76	-0.45	-0.10	0.17	-1.22	-0.52	-1.58	-1.12	-1.44
σ	0.09	0.19	0.16	0.12	0.19	0.11	0.35	0.14	0.22	0.29
K/	N	P	Ca	Mg	S	B	Cu	Fe	Mn	Zn
mean	-0.40	0.76	0.31	0.67	0.94	-0.46	0.24	-0.82	-0.36	-0.67
σ	0.15	0.19	0.14	0.14	0.12	0.19	0.27	0.13	0.20	0.33
Ca/	N	P	K	Mg	S	B	Cu	Fe	Mn	Zn
mean	-0.72	0.45	-0.31	0.35	0.62	-0.77	-0.08	-1.14	-0.67	-0.99
σ	0.11	0.16	0.14	0.08	0.17	0.13	0.31	0.10	0.19	0.29
Mg/	N	P	K	Ca	S	B	Cu	Fe	Mn	Zn
mean	-1.07	0.10	-0.67	-0.35	0.27	-1.13	-0.43	-1.49	-1.02	-1.34
σ	0.08	0.12	0.14	0.08	0.16	0.10	0.31	0.09	0.19	0.29
S/	N	P	K	Ca	Mg	B	Cu	Fe	Mn	Zn
mean	-1.34	-0.17	-0.94	-0.62	-0.27	-1.40	-0.70	-1.76	-1.29	-1.61
σ	0.16	0.19	0.12	0.17	0.16	0.19	0.27	0.15	0.18	0.33
B/	N	P	K	Ca	Mg	S	Cu	Fe	Mn	Zn
mean	0.06	1.22	0.46	0.77	1.13	1.40	0.70	-0.36	0.10	-0.21
σ	0.09	0.11	0.19	0.13	0.10	0.19	0.35	0.14	0.22	0.26
Cu/	N	P	K	Ca	Mg	S	B	Fe	Mn	Zn
mean	-0.64	0.52	-0.24	0.08	0.43	0.70	-0.70	-1.06	-0.60	-0.91
σ	0.32	0.35	0.27	0.31	0.31	0.27	0.35	0.31	0.24	0.47
Fe/	N	P	K	Ca	Mg	S	B	Cu	Mn	Zn
mean	0.42	1.58	0.82	1.14	1.49	1.76	0.36	1.06	0.46	0.15
σ	0.10	0.14	0.13	0.10	0.09	0.15	0.14	0.31	0.17	0.30
Mn/	N	P	K	Ca	Mg	S	B	Cu	Fe	Zn
mean	-0.05	1.12	0.36	0.67	1.02	1.29	-0.10	0.60	-0.46	-0.32
σ	0.19	0.22	0.20	0.19	0.19	0.18	0.22	0.24	0.17	0.34
Zn/	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn
mean	0.27	1.44	0.67	0.99	1.34	1.61	0.21	0.91	-0.15	0.32
σ	0.28	0.29	0.33	0.29	0.29	0.33	0.26	0.47	0.30	0.34

The equations of the statistical models were chosen according to their significance and the highest R^2. Equating the indexes of each equation to zero, the critical level of the evaluated nutrient was obtained. Sufficiency ranges were determined by adding or subtracting 2/3 of the standard deviation of the respective indices. Comparing the nutritional ranges determined by DRIS with the ranges proposed by the literature (Table 4), it is evident that the levels of N, K, Ca, Mg, S and Mn had their lower and upper limits reduced, indicating the need to work with narrower ranges for high yield populations. The ranges of the micronutrients Cu, Fe, and Zn have been expanded, indicating greater variability in the levels than those presented in the literature.

To avoid inconsistencies in the chi-square test (χ^2), the fertilizer response classes were grouped into limitation due to lack (p + pz) and limitation due to excess (n + nz). When grouping the classes, in both subpopulations, it was observed (Table 5) that for the subpopulation of high-yield, the order of limiting excess nutrients was P > Zn > K = Ca = Mn > N = B = Fe > Cu = S > Mg; limiting due to lack the order was Zn = Mn > K > Cu

Table 3. Statistical models, determination coefficient (R^2) and critical level of nutrients determined by the DRIS standard for soybean in western Bahia (n = 117)

Nutrient	Statistical model	R^2	Critical level
N	$IN = -0.0015(N)^2 + 0.1978(N) - 5.1292$	0.60	35.5 g kg^{-1}
P	$IP = -0.3146(P)^2 + 2.7357(P) -4.893$	0.90	2.5 g kg^{-1}
K	$IK = -0.0026(K)^2 + 0.2495(K) - 3.092$	0.85	14.6 g kg^{-1}
Ca	$ICa = -0.0393(Ca)^2 + 1.021(Ca) - 5.204$	0.80	7.0 g kg^{-1}
Mg	$IMg = -0.2804(Mg)^2 + 2.94(Mg) - 6.4398$	0.64	3.1 g kg^{-1}
S	$IS = -0.3201(S)^2 + 2.5776(S) - 3.459$	0.90	1.7 g kg^{-1}
B	$IB = -0.0003(B)^2 + 0.0977(B) - 3.5869$	0.85	42.2 mg kg^{-1}
Cu	$ICu = -0.0025(Cu)^2 + 0.2078(Cu) - 1.7431$	0.91	9.5 mg kg^{-1}
Fe	$IFe = -0.00009(Fe)^2 + 0.0467(Fe) - 3.727$	0.85	98.5 mg kg^{-1}
Mn	$IMn = -0.0005(Mn)^2 + 0.1119(Mn) - 3.3424$	0.94	35.5 mg kg^{-1}
Zn	$IZn = -0.00008(Zn)^2 + 0.033(Zn) - 1.9523$	0.96	71.6 mg kg^{-1}

> P > Ca > S > B > N = Fe > Mg. For the low-yield subpopulation, the excess limiting order was K > S = Mn > Ca > Zn > Mg > N > Cu > B > Fe > P; limiting due to lack of the order was P > Mn = B > Cu > Fe > Zn > S > Ca > Mg > N > K.

By classifying the samples according to the PRA, it was possible to reject the hypothesis that the observed frequencies are statistically similar to the expected frequencies for all classes because the calculated χ^2 value was higher than the tabulated (Table 6), therefore, the PRA was considered inefficient for the recommendation of fertilizers.

The most limiting nutrients for excess in the high-yield subpopulation were P, Zn and K. The samples categorized with an excess of P had their average levels (3.3 g kg^{-1}) close to the upper limit of 2.9 g kg^{-1} determined by the DRIS method for soybeans in the region of the research. Average levels of K and Mn were also observed in samples classified as LE, with values above the upper limit of the appropriate range. Nutrients classified as lacking for the high-yield subpopulation were Zn, Mn and K. Both Zn and K were classified as limiting due to lack and excess; this indicates heterogeneity in the management of the areas, or that environmental factors in addition to the availability of the nutrient in the soil may be affecting their availability to the plants.

Table 4. Adequate range of nutrients in soybean leaf obtained by DRIS for western Bahia in relation to the findings of other authors for the Cerrado region

References	N	P	K	Ca	Mg	S
	g kg^{-1}					
DRIS	32.0 – 38.9	2.1 – 2.9	11.6 – 17.6	5.9 – 8.1	2.8 – 3.4	1.3 – 2.1
Souza et al. (2023) – CND	41.7 – 50.9	3.2 – 4.1	17.4 – 20.9	9.1 – 12.3	4.9 – 6.4	2.2 – 3.0
Souza et al. (2023) – DRIS	40.7 – 49.9	3.2 – 4.0	17.1 – 20.6	8.8 – 12.0	4.8 – 6.2	2.2 – 3.0
Kurihara et al. (2013)	36.8 – 41.8	2.3 – 2.8	17.3 – 21.2	6.8 – 9.3	2.9 – 3.7	2.1 – 2.6
Urano et al. (2007) – DRIS	37.0 – 44.2	2.8 – 3.2	21.1 – 25.2	10.1 – 13.2	2.6 – 3.8	2.0 – 2.7
Urano et al. (2007) – CND	37.0 – 44.2	2.8 – 3.2	21.1 – 25.2	10.1 – 13.1	2.6 – 3.8	2.0 – 2.7

References	B	Cu	Fe	Mn	Zn
	mg kg^{-1}				
DRIS	36.1 – 48.4	2.1 – 17.0	81.3 – 115.7	16.5 – 54.5	40.1 – 103.0
Souza et al. (2023) – CND	35.0 – 72.0	11.0 – 26.0	134.0 – 266.0	22.0 – 78.0	51.0 – 71.0
Souza et al. (2023) – DRIS	35.0 – 71.0	11.0 – 25.0	133.0 – 266.0	12.0 – 68.0	53.0 – 74.0
Kurihara et al. (2013)	33.0 – 41.0	6.0 – 8.0	59.0 – 86.0	28.0 – 48.0	31.0 – 42.0
Urano et al. (2007) – DRIS	38.0 – 47.4	7.4 – 11.4	75.6 – 104.5	44.7 – 69.6	43.6 – 69.9

Table 5. Observed frequency (%) of samples classified according to the potential for response to fertilization (PRA) in the high and low-yield subpopulations proposed by the DRIS method for soybean

PRA	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Zn
High-yield subpopulation (n = 41)											
n	2.4	4.9	7.3	7.3	4.9	4.9	9.8	12.2	9.8	7.3	29.3
nz	14.6	34.1	14.6	14.6	7.3	9.8	7.3	2.4	7.3	14.6	4.9
z	70.7	36.6	48.8	58.5	78.0	68.3	68.3	58.5	70.7	46.3	34.1
pz	7.3	14.6	14.6	7.3	7.3	4.9	9.8	22.0	7.3	17.1	17.1
p	4.9	9.8	14.6	12.2	2.4	12.2	4.9	4.9	4.9	14.6	14.6
LF	12.2	24.4	29.3	19.5	9.8	17.1	14.6	26.8	12.2	31.7	31.7
NL	70.7	36.6	48.8	58.5	78.0	68.3	68.3	58.5	70.7	46.3	34.1
LE	17.1	39.0	22.0	22.0	12.2	14.6	17.1	14.6	17.1	22.0	34.1
Low-yield subpopulation (n = 76)											
n	1.3	0.0	27.6	11.8	2.6	11.8	2.6	9.2	3.9	25.0	3.9
nz	14.5	0.0	26.3	19.7	15.8	26.3	3.9	3.9	1.3	13.2	15.8
z	81.6	60.5	44.7	61.8	76.3	50.0	60.5	55.3	71.1	28.9	64.5
pz	1.3	19.7	1.3	5.3	5.3	9.2	15.8	14.5	18.4	2.6	10.5
z	1.3	19.7	0.0	1.3	0.0	2.6	17.1	17.1	5.3	30.3	5.3
LF	2.6	39.5	1.3	6.6	5.3	11.8	32.9	31.6	23.7	32.9	15.8
NL	81.6	60.5	44.7	61.8	76.3	50.0	60.5	55.3	71.1	28.9	64.5
LE	15.8	0.0	53.9	31.6	18.4	38.2	6.6	13.2	5.3	38.2	19.7

*PRA: potential response to fertilization; n: negative, with high probability; nz: negative, with low probability; z: null; pz: positive, with low probability; p: positive, with high probability; LF: limit for lacking; NL: non-limiting; LE: limiting for excess.

For the low-yield subpopulation, the nutrients K, S and Mn were the most limiting due to excess, result different from that obtained by Serra et al. (2010), that the evaluation by the DRIS method for cotton cultivated in the same region indicated K and Mn as the most limiting due to lack.

Potassium limitation in the soil of the region has already been evidenced by Lopes and Guilherme (2016), demonstrating grain production is highly dependent on the addition of K through fertilization. The areas evaluated by the DRIS method have shown fertilization is being applied excessively, increasing costs and reducing efficiency. This indicates fertilization imbalance is occurring, and the management needs to be changed to increase the efficiency of the use of inputs on the farm. It is also important to consider in the management of K fertilization that light soils have a low capacity to retain this nutrient (Sharma and Sharma, 2013). Manganese has its availability for plants affected by soil pH, and unlike K, its natural availability is high, which can be toxic to soybeans, so the proper management of soil pH can control this excess (Fernández and Brown, 2013; Mayanna et al., 2015). Sulfur is present in several fertilizers, such as single superphosphate (8 % S) and ammonium sulfate (24 % S), thus, the addition of S occurs indirectly when other nutrients are being applied, resulting in an over S application in the field.

Phosphorus was considered the most limiting nutrient due to lack in the low yield subpopulation, and no samples indicated limitation by excess. In tropical soils, P has low natural availability because the rocks that originated the soils of the region have a low content of this nutrient. Therefore, P is the main limiting nutrient for agricultural production in the region (Silva et al., 2019). The study by Hanson (1981) showed soybean yield had a direct relationship with the P index and the most productive samples were those in which the P index was close to the neutral balance (equal to zero). Important functions are performed in the plant by P, such as a constituent of cell membranes and

Table 6. Frequencies of nutrients limiting by excess (n and nz), by lack (p and pz) and non-limiting (z), categorized by PRA and chi-square (χ^2) for the high and low yield soybean subpopulations

Nutrient	High-yield subpopulation						Low-yield subpopulation					
	(Fe-Fo)²/Fe						(Fe-Fo)²/Fe					
	n	*Nz*	*z*	*pz*	*p*	χ^2 (4 DF)	*n*	*nz*	*z*	*pz*	*p*	χ^2 (4 DF)
N	2.00	2.40	28.39	5.99	0.80	39.58*	5.05	4.56	82.18	18.78	5.05	115.63*
P	0.80	0.71	1.30	2.40	0.02	5.24^{ns}	6.91	20.73	30.81	1.58	9.47	69.51*
K	0.14	2.40	6.95	2.40	1.39	13.28*	28.74	0.03	8.50	18.78	6.91	62.95*
Ca	0.14	2.40	14.69	5.99	0.43	23.66*	0.63	1.58	33.30	13.50	5.05	54.07*
Mg	0.80	5.99	38.76	5.99	2.00	53.53*	3.49	3.67	67.03	13.50	6.91	94.60*
S	0.80	4.61	25.30	7.54	0.43	38.68*	0.63	0.03	14.39	9.09	3.49	27.63*
B	0.02	5.99	25.30	4.61	0.80	36.72*	3.49	15.16	30.81	3.67	5.37	58.51*
Cu	0.43	9.27	14.69	0.43	0.80	25.63*	0.00	15.16	21.83	4.56	5.37	46.93*
Fe	0.02	5.99	28.39	5.99	0.80	41.19*	2.21	18.78	53.41	2.18	1.22	77.81*
Mn	0.14	2.40	5.47	1.56	1.39	10.96*	21.16	5.55	0.08	16.92	37.47	81.18*
Zn	18.36	7.54	0.71	1.56	1.39	29.56*	2.21	3.67	38.56	7.81	1.22	53.49*
χ^2 (10 DF)	23.66*	49.70*	189.9*6	44.46*	10.24*	-	74.53*	88.93*	380.92*	110.38*	87.55*	-

*: Significant at 5 %; ^{ns}: not significant; n: negative, with high probability; nz: negative, with low probability; z: null; pz: positive, with low probability; p: positive, with high probability; DF: degree of freedom.

energy storage in the form of ATP (Dechen and Nachtigall, 2007). Phosphorus limitation for plant may reflect a reduction in the viable number of pods, which, according to Alcântara Neto et al. (2011), is the main component of soybean yield.

An experiment conducted by Nowaki et al. (2017) showed the yield response with fertilization can vary depending on the water availability for the crop; therefore, in soils with low water retention capacity, periods of drought can cause or increase nutritional deficiency in the crop, even with adequate nutrient levels in the soil.

Urano et al. (2006), studying soybean crops in the Midwest of Brazil, using the same methodology, found Zn, P and Fe as the most limiting nutrients due to their lack, and Mg and Mn the most limiting by excess. In this case, the relationships were very similar to those found for soybeans in Bahia, meaning the crop showed similar responses to the management system even in another region. More than assessing which elements are in excess or missing, the DRIS method aims to relate the physiological responses of plants and the imbalance between the elements, whether derived from antagonistic or synergistic relationships.

CONCLUSIONS

Sufficiency ranges proposed by the DRIS method for soybeans in western Bahia, for nutrients N, K, Ca, Mg, S and Mn have reduced upper and lower limits, while the micronutrients Cu, Fe and Zn have greater amplitudes in sufficiency ranges when compared to the ranges proposed by other authors. The PRA method is inefficient in recommending fertilization in both subpopulations. In the high-yield subpopulation, Zn and Mn are the most limiting nutrients due to deficiency, while P and Mn are the most limiting nutrients in the low-yield subpopulation. Manganese and Cu, in both subpopulations, are among the most limiting nutrients due to lack. Nutritional ranges obtained in the present study can be used by soybean producers in western Bahia, allowing greater precision in the nutritional diagnosis of the crop in current production bases.

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