South African Journal of Plant and Soil

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/tjps20

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To cite this article: Oyédékpo F Chabi, Gustave D Dagbénonbakin, Emile C Agbangba, Brice Oussou, Guillaume L Amadji, Léonard E Ahoton & Saïdou Aliou (14 Nov 2023): Soil nutrient deficiency assessment under soybean cropping systems using the DRIS system in northern and central Benin, South African Journal of Plant and Soil, DOI: 10.1080/02571862.2023.2243274

To link to this article: https://doi.org/10.1080/02571862.2023.2243274

South African Journal of Plant and Soil 2023, 40(3): 1–10
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SOUTH AFRICAN JOURNAL OF PLANT AND SOIL
ISSN 0257-1862 EISSN 2167-034X
https://doi.org/10.1080/02571862.2023.2243274

Soil nutrient deficiency assessment under soybean cropping systems using the DRIS system in northern and central Benin

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Soybean is one of the promising crops in the Benin agro-industrial sector, but its production is carried out at the expense of the inherent soil fertility. The present study aims to apply the DRIS (Diagnosis and Recommendation Integrated System) for nutrient status assessment in farmers' soybean fields in northern and central Benin. Sixty-two plant leaf samples were collected during a survey carried out in 2019 in farmers' fields. Nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and zinc (Zn) concentrations in the leaf samples were analysed. DRIS norms were used to calculate the various paired nutrient ratios in the high-yielding population. Nutrient balance indices (NBI) were also determined. Nutrient requirements based on NBI were ranked according Zn > N > P > Ca > K > Mg, highlighting the importance of Zn and N in soybean nutrition. Paired nutrient ratios (N/P, N/K, Mg/N, N/Ca, Ca/P, K/Ca, Mg/Ca, Zn/Mg) were either significantly ($p = 0.0001$) higher or lower than those in the literature, excluding Mg/P, Mg/K, P/Zn, Ca/Zn, N/Zn K/Zn and P/K paired ratios. This observation indicates the necessity of calibrating DRIS norms taking into account local conditions and cropping systems. The DRIS model could be an important tool for refining soybean nutrient needs in a cropping system. Zinc and N levels limited soybean cultivation in farmers' fields and must be included in the soybean fertiliser formulations to ensure optimal yield of soybean in Benin.

Keywords: DRIS norms, micronutrient, nutrient deficiency, plant nutrition, soil fertility management

Introduction

Worldwide, soybean is one of the most cultivated crops due to its demand in several industries (Khojely et al. 2018). In Sub-Saharan Africa (SSA), soybean is a non-native and non-staple crop with the potential to be a cash crop due to its wide range of uses as food, feed, and an industrial raw material (Khojely et al. 2018). South Africa, Nigeria, Zambia, and Uganda are the leading soybean producers in SSA (FAOSTAT 2018) and soybean production in Africa is expected to increase in the coming decades (Foyer et al. 2019). In Benin, soybean is a new promising sub-sector for the country's economy and also an important crop for food security maintenance (Kpènavou et al. 2018). National production was estimated at 221 997 metric tonnes (t) in 2018 (FAOSTAT 2018). The average soybean yield in Benin was estimated at 1 t ha^{-1}, far below the estimated potential yield of 3 t ha^{-1}. The specific problems encountered by African farmers in grain legume production include yield instability, drought susceptibility, and low soil fertility (Bationo et al. 2011). Although soybean is a nitrogen-fixing plant, this process can be limited by the low availability of other nutrients in the soil, and the water and mineral nutrient supply (Kamanga et al. 2010; Ronner et al. 2016; Ohyama et al. 2017). The majority of soybean farmers in Benin do not apply mineral fertilisers, while the minority apply only fertilisers not tailored for soybean (Chabi et al. 2019). Furthermore, there are no available data on soil fertility status in the soybean cropping system to enable the establishment of appropriate fertiliser requirements. Assessment of soybean nutritional status will contribute to the development of suitable soil fertility management practices to improve crop yield (Llanderal et al. 2018). In general, it is well known that in most of the soybean traditional cropping systems, farmers do not apply mineral fertiliser to improve yield as they believe that leguminous crops do not need fertiliser supplementation (Chabi et al. 2019).

Nutritional diagnosis is an effective way of increasing the yield and quality of agricultural products with effective fertiliser management (Mourão 2004; Carneiro et al. 2015). Traditionally, fertiliser recommendations in agriculture are based on soil and plant analyses (McCray et al. 2013). However, procedures based on soil analysis have some constraints as the soil samples may not be representative of the portion of soil actively utilised by plants, and the assessment of nutrients that are truly available to the plants may be inaccurate (Coleman et al. 2003; Horneck et al. 2011). Critical leaf nutrient concentrations have often been used to diagnose the nutritional causes of crop underperformance (Ramakrishna et al. 2009). However, this approach is sometimes erroneous because the critical nutrient level is not independent and may vary with the increase or decrease in other nutrients in the plant tissues (Bailey et al. 1997).

The importance of nutrient balance in determining the yield and quality of crops is well established but there is no means to quantify it other than using the Diagnosis and Recommendation Integrated System (DRIS). In this system, leaf analysis values are interpreted on the basis of inter-relationships among nutrients, rather than the nutrient concentrations themselves (Marschner 1995; Bangroo et al. 2010). The DRIS is based on the comparison of crop nutrient ratios with optimum values from a high yielding group (DRIS norms). The DRIS provides a means of simultaneously identifying imbalances, deficiencies and excesses in crop nutrients and ranks them in order of importance. The major advantage of this approach lies in its ability to minimise the effect of tissue age on diagnosis, thus enabling sampling over a wider range of tissue ages than is permissible under the conventional critical value approach (Ramakrishna et al. 2009; Bangroo et al. 2010). The Diagnosis and Recommendation Integrated System (DRIS) relates the nutrient contents in dual ratios. Because of the relationship between two nutrients, the problem with biomass accumulation and the reduction of the nutrient concentrations in plants with age is solved (Beaufils 1973; Walworth and Sumner 1987; Singh et al. 2000). With the use of a dual relationship in DRIS, the problem with the effect of concentration or dilution on the nutrients in plants is solved. According to Beaufils (1973) and Walworth and Sumner (1987), the concentrations of nitrogen (N), phosphorus (P), potassium (K) and sulphur (S) decrease with leaf ageing, while the concentrations of calcium (Ca) and magnesium (Mg) increase with leaf tissue in older plants. When the DRIS method is used, the values remain constant, minimising the effect of biomass accumulation, which is one of the major problems with the sufficiency range and critical level method.

DRIS is also a model for identifying production-limiting nutrients but uses the determined nutrients in the leaf samples and the estimated yields at the level of the population from which the leaf samples were taken. The DRIS results are often less sensitive than the sufficiency range approach to differences caused by leaf position, tissue age, climate, soil conditions, and cultivar since it is the nutrient ratios that are used (Sanchez et al. 1991). The DRIS approach was designed to provide a valid diagnosis irrespective of plant age, tissue origin (Sumner 1977a, b; Meldal-Johnson and Sumner 1980; Jones 1993; Bailey 1997), cultivar, local conditions (Payne et al. 1990), and changes in the method of tissue sampling or the time of sampling (Moreno et al. 1996). The DRIS was successfully used to interpret the results of foliar analyses for a wide range of crops including annual crops (Meldal-Johnson and Sumner 1980; Elwali and Gascho 1984; Mackay et al. 1987; Szücs et al. 1990; Singh et al. 2000; Ramakrishna et al. 2009; Dagbénonbakin et al. 2010) and perennial crops (Raj and Rao 2006; Carneiro et al. 2015). It has also been applied to soybean in several studies (Beverly et al. 1986; Bell et al. 1995; Castamann et al. 2012).

Once DRIS norms have been established and validated from a large population of randomly distributed observations, they should be universally applicable to that crop (Sumner 1977a, 1979) because for a given species, it appears that specific nutrient ratios for maximum crop performance transcend local conditions such as soil, climate and cultivars (Snyder and Kretschmer 1988). However, Agbangba et al. (2011) found that some DRIS norms developed for the pineapple variety Perola were different for the Smooth Cayenne variety developed by Teixeira et al. (2009). These authors concluded that DRIS norms can vary according to the cultivar, and that for a given crop, it is relevant to evaluate the sensitivity of DRIS to climate and soil conditions. In the present work we hypothesised that DRIS norms developed for soybean in Benin conditions differ significantly from those developed elsewhere.

The aim of the study was to develop the DRIS model parameters for soybean using seed yields and leaf tissue nutrient concentration data from soybean fields in northern and central Benin.

Material and methods

Study area

The database used to calculate DRIS norms for soybean was built up from 62 composite leaf samples collected in farmers' fields in the municipalities of N'Dali and Bembèrèkè (northern Benin) and Ouessè and Glazoué (central Benin). The study areas are shown in Figure 1.

N'Dali and Bembèrèkè are part of the Sudanian zone characterised by a unimodal rainfall pattern with an annual average of 1 000 mm. Ferric and Plinthic Luvisol soils are dominant in the area (FAO 2015). Cotton and soybean are the main cash crops. Ouessè and Glazoué are characterised by a Sudano-Guinean climate with more or less bimodal rainfall patterns. This area is entirely occupied by leached or depleted tropical Ferric and Plinthic Luvisol soils (FAO 2015). Black and hydromorphic soils are also found in the valleys of the rivers that cross the area. Annual

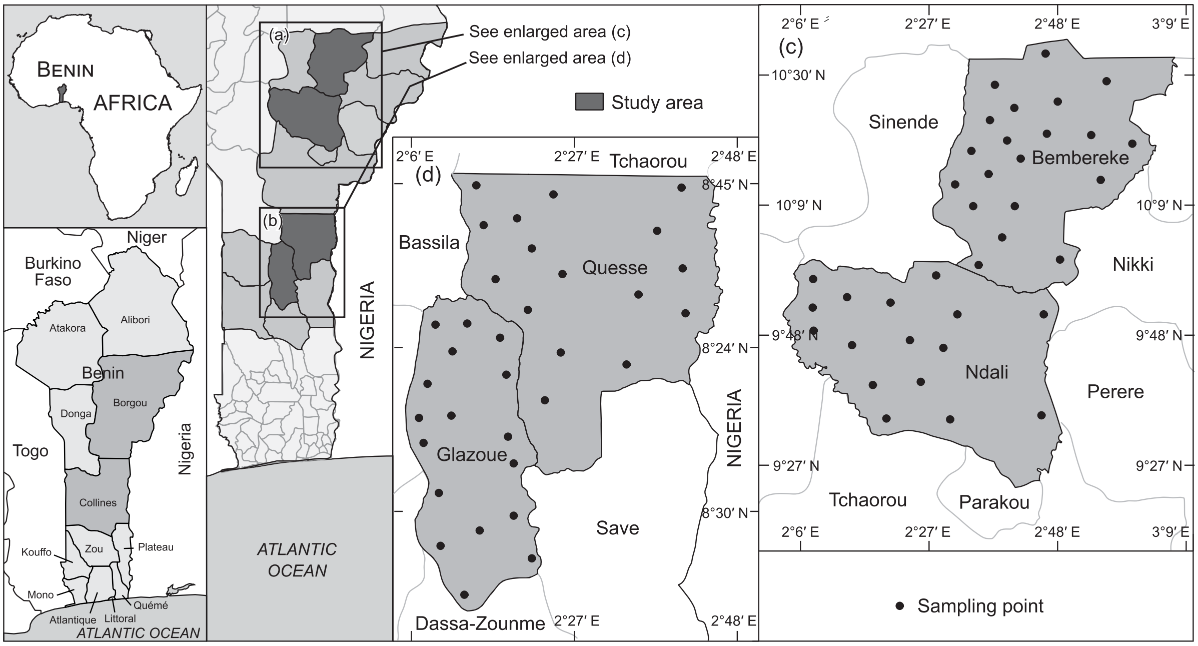

Figure 1: Study areas (a) and (b), and soybean leaf sampling points (c) and (d)

rainfall varies from 600 to 1 400 mm over 80 to 110 days. Cereals and legumes are widely cultivated. Soils in all sites have low fertility levels.

Soils range between sandy to sandy loamy textures. The pH (water) is 6.25 and 6.6 for the central and northern sampled fields, respectively; soil organic C is 6.42 and 5.35 g kg^{-1} for the central and northern sampled fields, respectively; total N is 0.73 and 0.5 g kg^{-1} for the central and northern sampled fields, respectively; the available P is 47.25 and 15.25 mg kg^{-1} for the central and northern sampled fields, respectively and the exchangeable K^+ is 2.8 and 1.5 mmol kg^{-1} for the central and northern sampled fields, respectively. The CEC values of both sample areas were low (61 and 46 mmol kg^{-1} for central and northern sampled fields, respectively). In general, the soils of sampled fields in the study area are slightly acidic with low organic matter content, with C/N ratios varying between 10 and 14.

Leaf sampling and chemical analysis

The leaf samples used were collected from farmers' fields in both zones. The soybean varieties sampled are 'Jupiter' and the improved variety TGX 1910-14 F (a coarse-grained variety). Both had a maturity cycle of 100–120 days. Leaves were sampled along two diagonals in each field while respecting a 20 m distance from the field edges (Gott et al. 2017). A total of 62 soybean fields were surveyed in the four municipalities. Samples were collected from 30 soybean plants in each field, with three fully developed leaves being collected from the top of each plant. Leaves were taken during the full flowering stage (FAO 1998) and were healthy, well developed and without physical injury. Leaves from all plants were mixed together to form composite samples and sent to the laboratory for nutrient analysis. After air drying in the field, materials were further dried at 65 °C to a constant weight in an oven in the laboratory, ground by a Brabender mill and stored in a dry area. The plants on the harvested area of the field (measuring 4 m^2) were pulled out and the pods were manually removed from the plants and weighed. The pods were then sent to the laboratory and dried to a constant weight for dry matter determination. The dried pods were then shelled. The grain yields in each field were assessed according to:

$$Rg = (1000 \times P \times MS \times n)/SI$$

where Rg = pod yield (in kg DM ha^{-1}); P = total weight of pods weighed in the field (in kg); DM = dry matter content of pods; SI = sample harvest area (4 m^2 in this study); and n = ratio of dry pod weight of the sample after ginning to total weight (Dagbénonbakin et al. 2012).

Leaf sample analyses were performed at the reference Laboratory of Soil Science, Water and Environment of the National Agricultural Research of Benin (INRAB). The levels of total N, P, K, Ca, Mg and Zn in the plant tissue were determined. Leaf samples of 1 g were digested with H_2SO_4 and H_2O_2 using a nitrogen catalyser composed of 5 g of K_2SO_4, 5 g of $CuSO_4$ and 0.25 g of selenium. Samples were analysed for N following the Kjeldahl method (Page et al. 1982). The dry samples were ashed in porcelain crucibles at 550 °C in a muffle furnace. The ash was dissolved in concentrated nitric acid to precipitate silicates, then concentrated nitric acid was again added, and the samples were transferred to volumetric flasks. This was followed by several rinses with demineralised water. The Atomic Absorption Spectrophotometer (trademark 'AGILENT') was used to determine Ca, Mg, Zn and K (Page et al. 1982; Kalra 1997). Phosphorus was determined using the molybdo-vanadate blue method (Page et al. 1982). The filtrate was coloured with ammonium molybdate in the presence of ascorbic acid and the intensity of the colour was measured by colourimetry at a wavelength of 600 nm.

Development of DRIS norms

The Walworth and Sumner (1987) procedures for establishing DRIS norms and coefficients of variation were used in this study. The pod grain yields were separated into two yield sub-populations using the average yield plus the confidence interval as a subdivision criterion (Dagbénonbakin 2005; Agbangba et al. 2011). This enabled us to use a sub-population with high yields and another sub-population with low yields for the DRIS procedure.

The paired ratio of nutrients was calculated for each sub-population and each element appeared in both the numerator and denominator positions (e.g., Zn/P and P/Zn). For each of these ratios, the variance in the two sub-populations was calculated. This was done by dividing the variance of the ratio for the low-yielding population by the variance of the high-yielding population for the same form of ratio (Elwali et al. 1985; Amundson and Koehler 1987; Payne et al. 1990). For each pair of ratios, the one with the largest variance ratio was selected for the evaluation of DRIS norms. The DRIS indices were then calculated for the nutrients following generalised equations developed by Jones (1981) and Rathfon and Burger (1991):

$$X_{\text{indices}} = [f(X/A) + f(X/B) + \ldots - f(M/X) - f(N/X) - \ldots]$$

where: $f(X/A) = 100 \times [(X/A)\,(x/a) - 1]/CV$ when $(X/A) > (x/a) - SD$; $f(X/A) = 100 \times [1 - (X/A)\,/\,(x/a)]/CV$ when $(X/A) < (x/a) - SD$; X/A is the ratio of concentrations of nutrients X and A in the sample; and x/a, CV, and SD, are the mean, coefficient of variation and standard deviation, respectively for the parameter X/A in the high-yielding population.

To interpret the DRIS indices, the concept of fertilisation response potential (Wadt et al. 1998; Serra et al. 2013) was used. This method compares the nutrient index or its absolute value with the nutritional balance index (NBI). The NBI is the average of the distance to zero of all the nutrient's indices. The index of a nutrient is the arithmetic mean of the ratios obtained after calibration. It is obtained for each individual nutrient in the high-yield sub-population by assigning in the averaging formula the sign (–) to the element whose index is to be determined and which is in the denominator of the ratio and the sign (+) when that element is in the numerator. The average of all individual nutrient indices in the high-yielding sub-population is then the index for that nutrient. According to Wadt et al. (1998):

$$n\,\text{indices} : \text{NBI} = (|\text{Index}\,A| + |\text{Index}\,B| + \ldots + |\text{Index}\,n|)/n)$$

In the case of this study, NBI = (|Index N| + |Index P| + |Index K|+ |Index Ca|+|Index Mg|+|Index Zn|)/6).

According to Wadt et al. (1998) and Serra et al. (2013) for a nutrient *N*, one could make the following conclusion:

deficient and limiting when $IN < 0$ and $|IN| > NBI$ and IN is the lowest DRIS index;
probably deficient when $IN < 0$ and $|IN| > NBI$;
sufficient when $|IN| \leq NBI$;
probably in excess when $IN > 0$ and $|IN| > NBI$;
in excess when $IN > 0$ and $|IN| > NBI$ and IN is the highest value DRIS index
where IN is Nutrient Index.

Statistical analysis

Descriptive statistics were determined for soybean yield, leaf nutrient concentration and nutrient ratio expression data using Microsof Excel 2013. Descriptive statistics included means, minimum and maximum values, variances, CVs and skewness values. Soybean grain yields in the two sub-populations were subjected to one way (sub-population as a factor) analysis of variance. Comparison of the means of the nutrient concentrations and grain yields was performed using Fisher's test (Fisher 1934). Prior to this, the normality of the data was carried out using the Shapiro-Wilk test (Shapiro and Wilk 1965). The comparison of the DRIS norms proposed in this study compared with those found in the literature (Castamann et al. 2012) was done using a *t*-test when the norms followed a normal distribution and the Wilcoxon test when the norms did not follow a normal distribution ($p > 0.05$) (Table 1) (Kim 2015; Ståhle and Wold 1989). This comparison is necessary as it allows to test if the assumption that DRIS norms are universal.

Results

Nutrient concentration in the soybean's leaves

Statistical analyses on soybean grain yield and nutrient concentration in the leaves are presented in Table 1. Grain yield ranged between 312 and 1 750 kg ha^{-1} with a mean of 937 kg ha^{-1} in all of the fields visited. Thirty out of 62 data points were assigned to the high-yielding sub-population (grain yield ≥ 950 kg ha^{-1}), and values less than the normal were used to establish DRIS model parameters regarding the prevalence of low-yielding data points. However, as already noted, a preponderance of high-yielding data is not absolutely essential for the establishment of DRIS norms. The normality test carried out on nutrient contents showed that N, P, K and Mg content were normally distributed ($p > 0.05$). Regarding the leaf nutrient concentration, the Zn content was symmetrical in the low yielding sub-population and in the high yielding sub-population. For N, P, K, Ca and Mg the data sets were relatively symmetric in the two sub-populations except for Ca where the data sets were asymmetric (skewness value > 1) in the high yielding sub-population. Overall, these data sets were deemed suitable for DRIS model development. In addition, grain yields of the two sub-populations were significantly different ($p = 0.0001$), which can be a good precision indicator for established DRIS norms (Table 1).

Binary nutrient ratio statistics and DRIS norms to improve soybean production

Binary nutrient ratio combinations of the six nutrients were calculated, and summary statistics evaluated for each of the resulting 30 nutrient ratios are shown in Table 2. The DRIS norms were selected from the statistical data of the nutrient ratio (Table 2). From the reciprocal expressions

Table 1: Soybean yield and leaf nutrient contents (*n* = 62) classified into low and high yielding sub-populations

Parameters	Low yielding sub-population (*n* = 32)						High yielding sub-population (*n* = 30)						RatioVar
	Mean	CV	Min	Max	Skew	Kurt	Mean	CV	Min	Max	Skew	Kurt	
Grain yield (kg ha^{-1})	675.40	4.68	312.50	924.70	–0.60	–0.73	1216.20	3.31	950.0	1750.0	0.75	0.0	0.66
Nutrients (g kg^{-1})													
N	44.05	1.78	31.36	53.54	–0.40	1.17	44.98	1.60	38.75	51.97	0.00	–1.09	1.27
P	2.64	4.59	1.39	4.36	0.48	0.14	2.73	4.36	1.29	3.96	–0.08	–0.52	1.10
K	19.43	5.61	9.81	32.30	0.29	–0.61	20.09	5.48	10.22	33.77	0.37	–0.72	1.05
Ca	9.06	4.36	5.32	15.88	0.83	1.32	9.04	4.42	6.27	15.48	1.16	1.42	1.04
Mg	3.17	3.34	2.25	4.47	0.71	–0.32	3.23	3.25	2.36	4.63	0.77	0.05	1.08
Zn	0.02	13.28	0.00	0.06	0.04	–1.43	0.03	12.82	0.00	0.06	–0.09	–1.55	0.83

Min = minimum Max = maximum Skew = skewness Kurt = kurtosis

Table 2: Mean values of nutrient paired ratios for high and low-yielding sub-populations together with their respective coefficients of variance (CV) and variances (low and high), skewness values for the high-yielding sub-population, and the variance ratios (V_{low}/V_{high})

Nutrient ratios	Low yielding sub-population (*n* = 32)						High yielding sub-population (*n* = 30)						Ratio Var
	Mean	CV	Min	Max	Skew	Kurt	Mean	CV	Min	Max	Skew	Kurt	
N/P	17.9	5.3	10.2	32.0	1.1	0.8	17.6	5.9	13.1	40.3	2.5	8.1	2.1
N/K	2.5	6.7	1.4	4.8	1.0	0.4	2.4	5.2	1.5	3.8	0.6	–0.8	2.0
N/Mg	5.2	4.9	3.0	9.4	0.9	1.1	5.2	3.8	3.1	7.8	0.1	–0.1	1.7
N/Ca	14.3	3.7	9.7	22.1	0.6	–0.1	14.3	3.0	11.2	20.6	1.0	1.1	1.6
N/Zn	9 745.2	34.0	730.0	7 7081.0	3.0	8.8	9 353.7	58.3	689.0	165 279.0	5.2	28.1	0.7
P/N	0.1	4.8	0.0	0.1	0.3	0.1	0.1	4.0	0.0	0.1	–0.9	0.3	1.5
P/K	0.1	6.1	0.1	0.3	1.0	0.6	0.1	5.7	0.1	0.2	0.6	–0.9	1.3
P/Ca	0.3	4.3	0.2	0.5	0.4	0.5	0.3	4.7	0.1	0.5	0.3	0.0	0.8
P/Mg	0.8	3.6	0.4	1.2	–0.3	0.3	0.9	3.6	0.4	1.2	–0.3	1.0	1.0
P/Zn	620.3	36.1	42.0	5 321.0	3.1	9.7	579.4	61.1	31.0	10 746.0	5.3	28.8	0.9
K/N	0.4	6.0	0.2	0.7	0.3	–0.7	0.4	4.9	0.3	0.7	0.2	–1.1	1.6
K/P	6.9	5.8	3.6	14.3	0.6	0.3	7.1	5.3	4.3	11.8	0.1	–1.1	1.3
K/Ca	2.3	6.4	0.6	4.4	0.2	0.6	2.4	6.6	1.0	4.1	0.0	–0.8	0.9
K/Mg	6.1	4.4	2.6	9.7	0.2	0.0	6.2	4.2	3.6	8.9	0.1	–1.0	1.1
K/Zn	3 813.2	36.6	328.0	34 237.0	3.4	11.2	3 506.6	49.7	307.0	52 328.0	4.9	25.7	1.3
Ca/N	0.1	4.7	0.1	0.3	0.4	–0.2	0.1	4.1	0.1	0.3	0.9	0.4	1.5

Min = minimum Max = maximum Skew = skewness Kurt = kurtosis

Table 3: DRIS norms, CV and skewness values for the high-yielding sub-population, and variance ratios (Vlow/Vhigh) of nutrient paired ratio expressions selected for inclusion in the DRIS model for soybean

	High yielding sub-population (*n* = 30)						
Parameters	Mean	CV	Min	Max	Skew	Kurt	V low/high
N/P	17.6	5.9	13.1	40.3	2.5	8.1	0.9
N/K	2.4	5.2	1.5	3.8	0.6	–0.8	2.0
Mg/N	0.2	2.8	0.0	0.1	–0.2	–0.5	1.8
N/Ca	14.3	3.0	11.2	20.6	1.0	1.1	1.6
N/Zn	9 353.7	58.3	689.0	165 279.0	5.2	28.1	0.7
P/K	0.1	5.7	0.1	0.2	0.6	–0.9	1.3
Ca/P	3.2	5.3	2.0	6.7	1.3	2.3	0.9
Mg/P	1.2	4.7	0.8	2.5	2.2	7.1	1.0
P/Zn	579.4	61.1	31.0	10 746.0	5.3	28.8	0.9
K/Ca	2.4	6.6	1.0	4.1	0.0	–0.8	0.9
Mg/K	0.2	5.5	10.2	33.8	0.4	–0.7	1.3
K/Zn	3 506.6	49.7	307	52 328.0	4.9	25.7	1.3
Mg/Ca	0.4	4.0	0.2	0.5	–0.3	0.2	1.2
Ca/Zn	2 513.6	69.7	131	53 130.0	5.4	29.4	1.2
Zn/Mg	0.009	13.1	0.0	0.0	0.0	–1.6	1.6

Min = minimum Max = maximum Skew = skewness Kurt = kurtosis e.g., N/P and P/N, the most appropriate nutrient ratio is selected (based on the highest value of V_{low}/V_{high}). Therefore, 15 mean values of nutrient ratio expression in the high-yield sub-population involving all nutrients were selected as the diagnostic norms for soybean (Table 3). The norms of paired ratios selected were N/P, N/K, Mg/N, N/Ca, N/Zn, P/K, Ca/P, Mg/P, P/Zn, K/Ca, Mg/K, K/Zn, Mg/Ca, Ca/Zn and Zn/Mg. Magnesium, N, K and Zn were often present in the binary ratios found for suitable soybean nutritional balance. The scatter plot (Figure 2) then allowed us to select 11 ratios that have a Gaussian distribution as DRIS norms. These were Ca/P, K/Ca, Mg/Ca, Mg/K, Mg/N, Mg/P, N/Ca, N/K, N/P, P/K and Zn/Mg. The comparison of the norms to the published norms (Table 4) showed that the norms of N/P, N/K, Mg/N, N/Ca, Ca/P, K/Ca, K/Zn, Mg/Ca and Zn/Mg were significantly different, whereas the

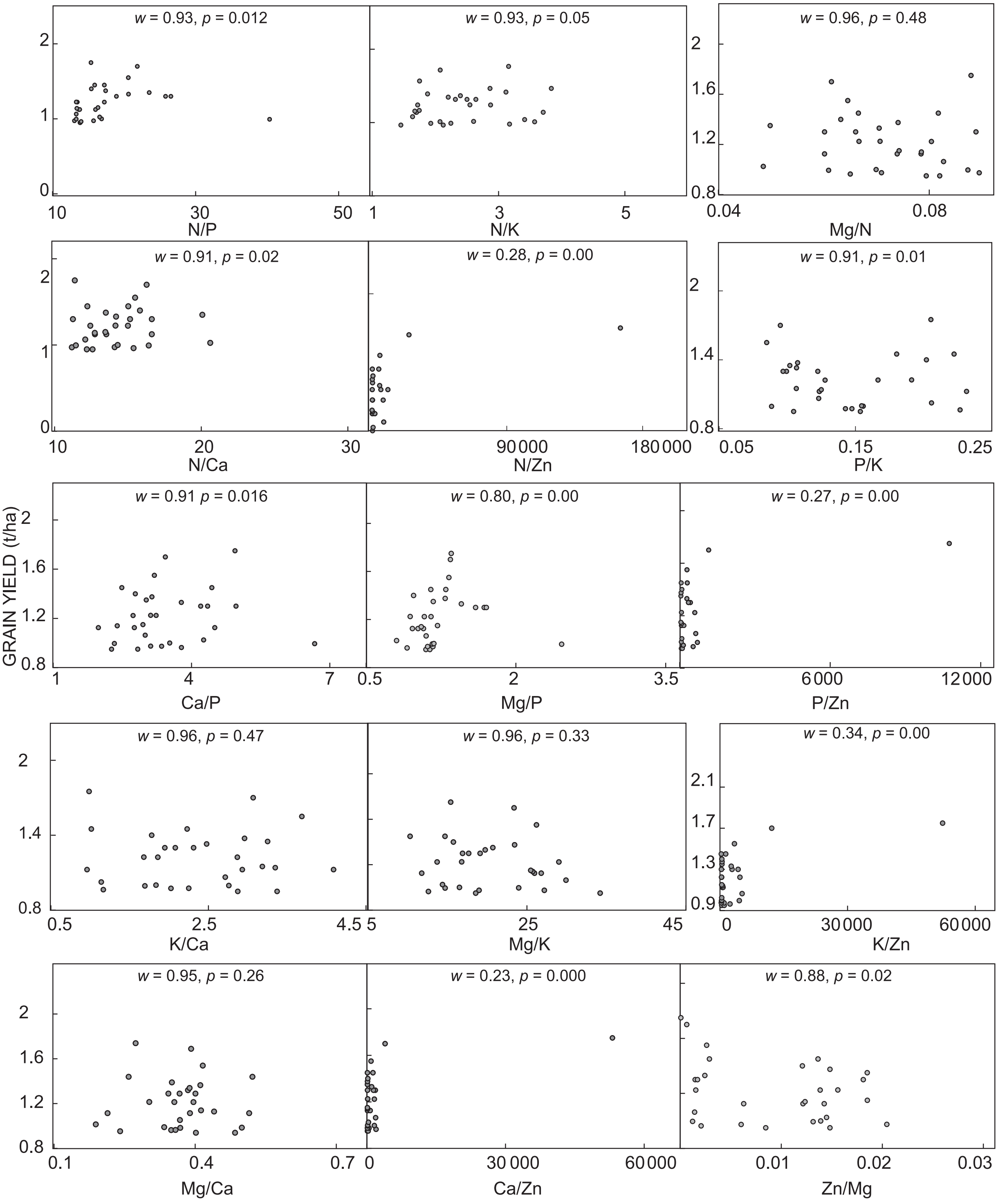

Figure 2: Plots of grain yield versus nutrient ratios showing the Gaussian distribution for the 15 selected DRIS norms

Table 4: Selected DRIS norms compared with the norms proposed by Castamann et al. (2012)

Proposed DRIS norms		DRIS norms proposed by Castamann et al. (2012)	
Parameter	Mean	Parameter	Mean
N/P*	17.6	N/P	15.06
N/K**	2.4	N/K	2.00
Mg/N***	0.2	Mg/N	0.083
N/Ca***	14.3	N/Ca (i)	5.88
N/Zn ns	9 353.7	N/Zn	0.128
P/K ns	0.1	P/K (i)	0.135
Ca/P***	3.2	Ca/P	2.498
Mg/P ns	1.2	Mg/P	1.252
P/Zn ns	579.4	P/Zn(i)	100.0
K/Ca***	2.4	K/Ca(i)	2.958
Mg/K ns	0.2	Mg/K	0.166
K/Znns	3 506.6	K/Zn	0.064
Mg/Ca***	0.4	Mg/Ca	0.498
Ca/Zn ns	2 513.6	Ca/Zn	0.021
Zn/Mg***	0.009	Zn/Mg(i)	90.909

Inverse relation in the original norm:
*$p < 0.05$; **$p < 0.01$; ***$p < 0.0001$

paired ratios Mg/P, Mg/K, P/Zn, Ca/Zn, N/Zn and P/K were similar to the norms.

Nutritional status of soybean plants in farmers' fields

Using the mean values of nutrient ratio expressions taken as the reference values (Table 3), the DRIS indices were calculated for each nutrient and are presented in Figure 3. These indices range from negative to positive values depending on the nutrient levels (relatively deficient or excessive). The nutrient requirements for soybean production were ranked as Zn > N > P > Ca > K > Mg. Our results showed that Zn was the most limiting nutrient, while N and P could limit soybean production in the study area. The NBI obtained was 30.34. This means that Zn is deficient in the soil and limits soybean yield. Furthermore, N was also probably deficient. Figure 3 shows that K, P and Ca were sufficient and Mg was probably in excess.

Discussion

The DRIS model established in this study for soybean production could be used to predict deficiencies or imbalances in N, P, K, Mg, Ca and Zn in the soil. The tool has been tested by several authors, including Ramakrishna et al. (2009); Agbangba et al. (2011); and Dagbénonbakin et al. (2013). From our results, 15 standards were selected and included the six nutrients measured in the leaf samples. The leaf nutrient concentration in the high-yielding sub-population (reference population) had a relatively symmetric distribution except for Ca, so they provided realistic approximations of the probable range of interactive influences of different nutrients on crop productivity (Ramakrishna et al. 2009). Although the database used for model development was relatively small, most of the DRIS norms selected in our study had relatively small CVs (≤ 15) in keeping with their diagnostic importance (Walworth et Sumner 1986), thus giving credibility both to the database and to the DRIS model. Fertiliser recommendations should take these standards into account to avoid nutrient excess or deficiency and also to prevent nutrient antagonism in the plant (Ujwala 2001; Yan et al. 2015).

Most of the selected ratios as DRIS norms for soybean are significantly different from the norms provided for soybean by Castamann et al. (2012). This is in contrast with one of the common advantages of the DRIS approach, which is less sensitive to the difference caused by the cultivar effect due to the nutrient ratios calculated (Sanchez et al. 1991) as shown by Agbangba et al. (2011) for pineapple cultivars. The

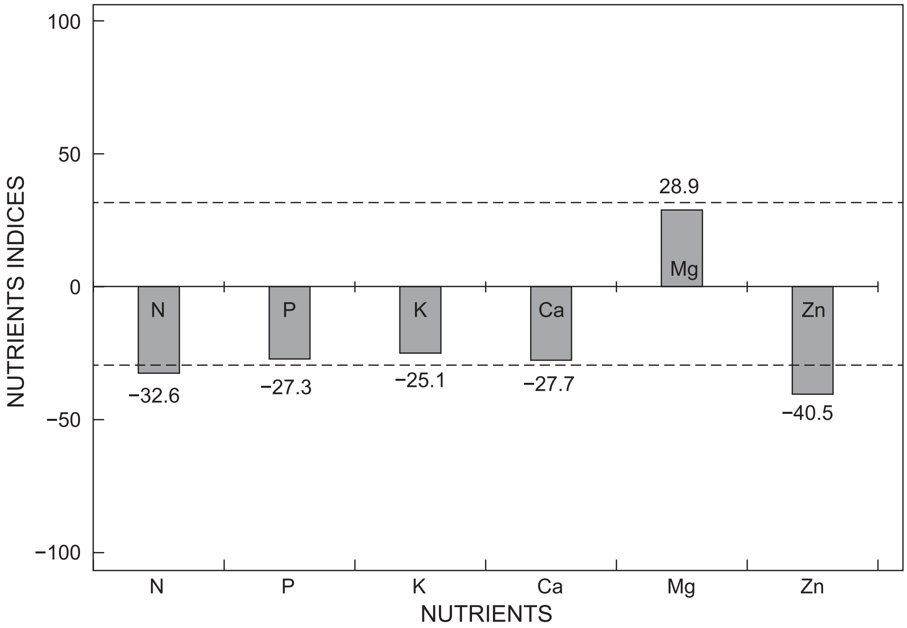

Figure 3: Nutrient indices for soybean leaves. The two horizontal lines (above and below the *x* axis) represent the NBI values

difference between the norms found in the present study and those reported in the literature could be explained by the climatic conditions of the study area and the soybean variety used. The nutrients taken up in the soil by soybean plants may vary according to the variety since nutrient requirements are not necessarily the same. The fact that some norms are significantly different from those established elsewhere supports the demand for calibration of the DRIS norms taking into account the local conditions and cropping system.

In general, Mg, N, K and Zn were often present in the paired ratios found for suitable soybean nutritional balance. This shows the importance of these nutrients for adequate soybean production. However, Mg activates many enzymes, mainly phosphorylation enzymes, which are essential for photosynthesis, respiration, and organic compound synthesis reactions (Nachtigall and Dechen 2007). Soybean oil content is also strongly influenced by Mg (Castamann et al. 2012), and Mg plays a critical role in the translocation of starch from leaves to pods and grains in soybean. This nutrient also appears in all energy-consumption processes, including protein and oil synthesis and symbiotic nitrogen fixation by leguminous crops such as soybean.

The DRIS norms for the paired K/N ratio (0.41) found in this study were not within the expected range for higher plants (0.6 to 0.9) (Marschner 1995). This shows that the current fertilisation practices for soybean plants, which are characterised by either no or low application of mineral fertilisers (Chabi et al. 2019) are not suitable for balanced potassium and N nutrition for soybean. The importance of N for good soybean development has been widely reported. Nitrogen is an important constituent of amino acids and is necessary in small quantities for leguminous crops (Marschner 1995). In addition, K plays a key role in N uptake and translocation (Blevins et al. 1978), while basic P fertiliser application is often necessary for efficient symbiotic fixation of atmospheric N_2 and for good plant growth, according to Giller and Dashiell (2007), Kindomihou et al. (2014) and Bado (2018). However, due to the potential of soybean to fix atmospheric N_2, most of the farmers did not apply nitrogen fertiliser to the crop in either study area. Compounding this, P input is also not common practice even though these areas are reportedly deficient in P (Saïdou et al. 2018). According to Chabi et al. (2019), P determines soybean yield in these two agro-ecological zones. It is essential for seed development and early maturation and is part of several compounds, including oils and amino acids in soybeans (Uchida 2000). For balanced soybean mineral nutrition, it will therefore be necessary to focus on P at fertiliser blenders so that this nutrient is included in fertiliser formulations.

Nutrient indices calculated from the DRIS standards established in this study showed the order of importance to be Zn > N > P > Ca > K > Mg. The NBI showed that N and Zn were the most deficient nutrients in both study areas. Zinc is deemed to be deficient at levels below the critical value of 15 mg kg^{-1} (Melsted et al. 1969). Nitrogen is deemed to be deficient at levels below 2.5% in plant tissue (Hornek et al. 2011). For balanced plant nutrition, it is necessary to also supply P, K and Mg to improve the efficiency of N and Zn (Fageria and Baligar 2005). Currently, Zn is considered to be one of the most limiting micronutrients in cropping systems in many parts of the world (Fageria and Baligar 2005; Kihara et al. 2020). Zinc deficiency is also found to occur in Benin's soils, as shown by the results of this study. In the current farmers' practices, few if any of the micronutrients are of concern during fertiliser formulation development. Crops tend to utilise the nutrients which are naturally present in the soil, leading to mining of the existing elements. Another factor contributing to Zn deficiency is the low level of organic matter in Benin's soils (Hafeez et al. 2013). Consequently, the yield of leguminous crops could be affected in the long term. Our study indicates that Zn and Mg should be considered in further fertiliser-formulating recommendations for soybean.

From this preliminary study on nutrient requirements for soybean, the DRIS model was shown to be effective for highlighting nutrients that are deficient in the soybean cropping systems in central and Northern Benin. This tool could be used in the process of fertiliser recommendations for soybean to substantially improve yield and promote sustainable production that minimises soil nutrient mining.

Conclusions

The statistical values determined provided acceptable DRIS standards for proper nutritional diagnosis for soybean plants. The DRIS norms proposed in our work were different from those established elsewhere which indicates that they are dependent on local conditions and the crop cultivars used. The DRIS indices determined from the diagnostic norms indicated that the order of the nutrient requirements for soybean was Zn > N > P > Ca > K > Mg. Our study also indicated N and Zn as potentially limiting nutrients in achieving optimal yields in the farmers' fields of the study area. It is suggested that these nutrients together with Mg be included in the fertiliser recommendation for sustainable and environmentally-friendly soybean cultivation.

Acknowledgements — The authors thank the Improvement of Smallholder Agricultural Productivity (PAPAPE/SAPEP-Benin) Project implemented by the Benin National Agricultural Research Institute (INRAB), funded by the Islamic Development Bank (IDB) and Benin Government, for the financial support of the present research.

Disclosure statement

The authors declare no conflict of interest.

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References

Agbangba CE, Sossa EL, Dagbénonbakin DG, Diatta S, Akpo LE. 2011. DRIS model parameterization to access pineapple variety

'Smooth Cayenne' nutrient status in Benin (West Africa). *Journal of Asian Scientific Research* 1: 254–264.

Amundson RL, Koehler FE. 1987. Utilization of DRIS for Diagnosis of Nutrient Deficiencies in Winter Wheat. *Agronomy Journal* 79 :472–476.

Bado BV. 2018. Rôle des légumineuses sur la fertilité des sols ferrugineux tropicaux des zones guinéenne et soudanienne du Burkina Faso. PhD thesis. Quebec City: Université de Laval.

Bailey JS, Cushnahan A, Beattie JAM. 1997. The diagnosis and recommendation integrated system (DRIS) for diagnosing the nutrient status of grassland swards: II. Model calibration and validation. *Plant and Soil* 197: 137–147.

Bangroo SA, Bhat MI, Ali T, Aziz MA, Bhat MA, Wani MA. 2010. Diagnosis and recommendation Integrated System (DRIS) – A review. *International Journal of Current Research* 10: 84–97.

Bationo A, Kimetu J, Vanlauwe B, Bagayoko M, Koala S, Mokwunye AU. 2011. Comparative analysis of the current and potential role of legumes in integrated soil fertility management in West and Central Africa. In: Bationo A, Waswa B, Okeyo JM, Maina F, Kihara J, Mokwunye U (eds), *Fighting poverty in sub-Saharan Africa: the multiple roles of legumes in integrated soil fertility management*. Dordrecht: Springer, pp. 117–150.

Beaufils ER. 1973. *Diagnosis and recommendation integrated system (DRIS): a general scheme for experimentation and calibration based on principles developed from research in plant nutrition; an extension of the physiological diagnosis (P.D.) techniques developed by the same author for improving plant production* (Soil Science Bulletin 1). Pietermaritzburg: University of Natal, Department of Soil Science and Agrometeorology.

Bell PF, Hallmark WB, Sabbe WE, Dombeck DG.1995. Diagnosing nutrient deficiencies in soybean, using m-DRIS and critical nutrient level procedures. *Agronomy Journal* 87: 859–865.

Beverly RB, Sumner ME, Letzsch WS, Plank CO. 1986. Foliar diagnosis of soybean by DRIS. *Communications in Soil Science and Plant Analysis* 17: 237–256.

Blevins DG, Hiatt AJ, Lowe RH, Leggett JE. 1978. Influence of K on the uptake, translocation, and reduction of nitrate by barley seedlings. *Agronomy Journal* 70: 393–396.

Carneiro A, Pereira Ó, Cunha M, Queiroz J. 2015. The diagnosis and recommendation integrated system (DRIS)-first approach for the establishment of norms for vineyards in Portugal. *Ciência e Técnica Vitivinícola* 30: 53–59.

Castamann A, Escosteguy PAV, Berres D, Zanella S. 2012. Diagnosis and recommendation integrated system (DRIS) of soybean seed oil content. *Revista Brasileira de Ciência do Solo* 36: 1820–1827.

Chabi FO, Dagbénonbakin GD, Agbangba CE, Oussou B, Amadji GL, Ahoton EL, Saïdou A. 2019. Soil fertility level and cropping practices determining soybean yield in Northern East and Center of Benin. *International Journal of Plant and Soil Science* 30: 1–10

Coleman MD, Chang SX, Robison DJ. 2003. DRIS analysis identifies a common potassium imbalance in sweetgum plantations. *Communications in Soil Science and Plant Analysis* 34(13-14): 1919–1941.

Dagbénonbakin GD. 2005. Crop productivity and water use efficiency of important crops in the Upper Ouémé Catchment. PhD thesis. University of Bonn, Germany.

Dagbénonbakin GD, Agbangba CE, Glèlè Kakaï R, Goldbach H. 2010. Preliminary diagnosis of the nutrient status of cotton (*Gossypium hirsutum* L.) in Benin (West Africa). *Bulletin de Recherche Agronomique du Bénin* 67: 32–44.

Dagbénonbakin GD, Agbangba EC, Kindomihou V, Akpo LE, Sokpon N, Sinsin B. 2012. Preliminary DRIS model parameterization to access groundnut (*Arachis hypogaea* L.) nutrient status in Benin (West Africa). *International Journal of Current Research* 4(4): 108–115.

Dagbénonbakin GD, Kindomihou V, Agbangba EC, Sokpon N, Sinsin B. 2013. Diagnosis and recommendation integrated system (DRIS) model establishment for diagnosing sorghum (*Sorghum bicolor*) nutrient status in Benin (West Africa). *Scientific Research and Essays* 8(32): 1562–1569.

Elwali AMO, Gascho GJ, Sumner ME. 1985. DRIS norms for 11 nutrients in corn leaves. *Agronomy Journal* 77: 506–508.

Elwali AMO, Gascho GJ. 1984. Soil testing, foliar analysis and DRIS as guides for sugarcane fertilisation. *Agronomy Journal* 76: 466–470.

Epstein E, Bloom AJ. 2006. *Nutrição mineral de plantas: princípios e perspectivas* (2nd edn). Londrina: Planta.

Fageria NK, Baligar VC. 2005. Growth components and zinc recovery efficiency of upland rice genotypes. *Pesquisa Agropecuária Brasileira* 40(12): 1211–1215.

FAO. 1998. *Guide to efficient plant nutrition management*. Rome: Food and Agriculture Organization of the United Nations.

FAO. 2015. *World reference base for soil resources, International soil classification system for naming soils and creating legends for soil maps*. Rome: Food and Agriculture Organization of the United Nations.

FAOSTAT. 2018. *FAOSTAT Data*. Rome: Food and Agriculture Organization of the United Nations. http://faostat.fao.org/default.aspx. (Accessed 18 July 2020.)

Fisher RA. 1934. *Statistical methods for research workers* (5th edn). Edinburgh: Oliver and Boyd.

Foyer CH, Siddique KHM, Tai APK, Anders S, Fodor N, Wong FL, et al. 2019. Modelling predicts that soybean is poised to dominate crop production across Africa. *Plant, Cell & Environment* 42: 373–385.

Giller KE, Dashiell KE. 2007. *Glycine max* (L.) Merrill. In: van der Vossen HAM, Mkamilo GS (eds), *Plant resources of tropical Africa 14. Vegetable oils*. Wageningen/Leiden: PROTA Foundation/Backhuys Publishers, pp 74–78.

Gott RM, Aquino LA, Clemente JM, Santos LPD, Carvalho AMX, Xavier FO. 2017. Foliar diagnosis indexes for corn by the methods diagnosis and recommendation integrated system (DRIS) and nutritional composition (CND). *Communications in Soil Science and Plant Analysis* 48: 11–19.

Hafeez B, Khanif Y M, Saleem M. 2013. Role of zinc in plant nutrition – a review. *American Journal of Experimental Agriculture* 3(2): 374–391.

Hallmark WB, de Mooy CJ, John P. 1987. Comparison of two DRIS methods for diagnosing nutrient deficiencies. *Journal of Fertilizer Issues* 4(4):151–158.

Horneck DA, Sullivan DM, Owen JS, Hart JM. 2011. *Soil test interpretation guide*. Oregon: Oregon State University Extension Service. https://extension.oregonstate.edu/catalog/pub/ec-1478-soil-test-interpretation-guide

Jones CA. 1981. Proposed modifications of the diagnosis and recommendation integrated system (DRIS) for interpreting plant analyses. *Communications in Soil Science and Plant Analysis* 12 (8): 785–794.

Jones JB Jr. 1993. Modern interpretation system for soil and plant analysis in the USA. *Australian Journal of Experimental Agriculture* 33: 1039–1043.

Kalra Y (ed). 1997. *Handbook of reference methods for plant analysis*. London: CRC Press.

Kamanga BCG, Waddington SR, Robertson MJ, Giller KE. 2010. Risk analysis of maize–legume crop combinations with smallholder farmers varying in resource endowment in Central Malawi. *Experimental Agriculture* 46: 1–21.

Khojely DM, Ibrahim SE, Sapey E, Han T. 2018. History, current status, and prospects of soybean production and research in sub-Saharan Africa. *The Crop Journal* 6: 226–235.

Kihara J, Bolo P, Kinyua M, Rurinda J, Piikki K. 2020. Micronutrient deficiencies in African soils and the human nutritional nexus:

opportunities with staple crops. *Environmental Geochemistry and Health* 42: 1–19.

Kim TK. 2015. T test as a parametric statistic. *Korean Journal of Anesthesiology*, 68(6): 540–546.

Kindomihou MV, Saïdou A, Sinsin BA. 2014. Response to fertiliser of native grasses (*Pennisetum polystachion* and *Setaria sphacelata*) and legume (*Tephrosia pedicellata*) of savannah in Sudanian Benin. *Agriculture, Forestry and Fisheries* 3: 142–146.

Kpènavou CS, Okry F, Santos F, Hounhouigan DJ. 2018. Efficacité technique des producteurs de soja du Bénin. *Annales des Sciences Agronomiques* 22: 93–110.

Llanderal A, Lao MT, Contreras JI, Segura ML. 2018. Diagnosis and recommendation integrated system norms and sufficiency ranges for tomato greenhouse in Mediterranean climate. *HortScience* 53: 479–482.

Mackay DC, Carefoot JM, Entz T. 1987. Evaluation of the DRIS procedure for assessing the nutritional status of potato (*Solanum tuberosum* L.). *Communications in Soil Science and Plant Analysis* 18: 1331–1353.

Marschner H. 1995. *Mineral nutrition of higher plants*. London: Academic Press.

McCray J, Rice R, Ezenwa I, Lang T, Baucum L. 2013. *Sugarcane plant nutrient diagnosis*. Gainesville: University of Florida, IFAS Extension.

Meldal-Johnson A, Sumner ME. 1980. Foliar diagnostic norms for potatoes. *Journal of Plant Nutrition* 2: 569–576.

Melsted SW, Motto HL, Peck TR. 1969. Critical plant nutrient composition values useful in interpreting plant analysis data1. *Agronomy Journal* 61: 17–20.

Moreno JJ, Lucena JJ, Carpena O. 1996. Effect of the iron supply on the nutrition of different citrus variety/rootstock combinations using DRIS. *Journal of Plant Nutrition* 19: 689–704.

Mourão Filho FAA. 2004. DRIS: concepts and applications on nutritional diagnosis in fruit crops. *Scientia Agricola* 61: 550–560.

Nachtigall GR, Dechen AR. 2007. DRIS norms for evaluating the nutritional state of apple tree. *Scientia Agricola* 64: 282–287.

Ohyama T, Tewari K, Ishikawa S, Tanaka K, Kamiyama S, et al. 2017. Role of nitrogen on growth and seed yield of soybean and a new fertilisation technique to promote nitrogen fixation and seed yield. In: Kasai M (ed.), *Soybean: The Basis of Yield, Biomass and Productivity*. London: InTechOpen, pp. 153-185. Chapter link: https://doi.org/doi:10.577266743

Page AL, Keeney DR, Baker DE, Miller RH, Roscoe Ellis Jr, Rhoades JD (eds), 1982. *Methods of soil analysis, Part 2: Microbiological and biochemical properties. Number 9*. Madison, Wisconsin, USA. 1160p

Payne GG, Rechcigl JE, Stepherson RL. 1990. Development of Diagnosis and Recommendation Integrated System Norms for Bahia grass. *Agronomy Journal* 82: 930–934.

Raj GB, Rao AP. 2006. Identification of Yield- Limiting Nutrients in Mango through DRIS Indices. *Communications in Soil Science and Plant Analysis* 37: 1761–1774.

Ramakrishna A, Bailey JS, Kirchhof G. 2009. A preliminary diagnosis and recommendation integrated system (DRIS) model for diagnosing the nutrient status of sweet potato (*Ipomoea batatas*). *Plant and Soil* 316: 107.

Rathfon RA, Burger JA. 1991. Diagnosis and recommendation integrated system modifications for Fraser Fir Christmas trees. *Soil Science Society of America Journal* 55: 1026–1031.

Ronner E, Franke AC, Vanlauwe B, Dianda M, Edeh E, Ukem B, Balaf A, van Heerwaardena J, Giller KE. 2016. Understanding variability in soybean yield and response to P-fertiliser and rhizobium inoculants on farmers' fields in northern Nigeria. *Field Crops Research* 186: 133–145.

Saïdou A, Balogoun I, Ahoton EL, Igué AM, Youl S, Ezui G. 2018. Fertiliser recommendations for maize production in the South Sudan and Sudano-Guinean zones of Benin. *Improving the Profitability, Sustainability and Efficiency of Nutrients Through Site Specific Fertiliser Recommendations in West Africa Agro-Ecosystems*. Springer, Cham 215–234.

Sanchez CA, Sera GH, Burdine HW. 1991. DRIS evaluation of the nutritional status of crisphead lettuce. *HortScience* 26: 274–276.

Serra AP, Marchetti ME, Bungenstab DJ, da Silva MAG, Serra RP, et al. 2013. Diagnosis and recommendation integrated system (DRIS) to assess the nutritional state of plants. In: Matovik MD (ed.), *Biomass now: sustainable growth and use*. London: InTechOpen, pp 129–146.

Singh NP, Awasthi RP, Sud A. 2000. Diagnosis And Recommendation Integrated System (DRIS) norms for apple (*Malus* x *domestica* Borkh L. CV. Starking Delicious) in Himachal Pradesh. *Indian Journal of Horticulture* 57: 196–204.

Shapiro SS, Wilkk MB. 1965. An analysis of variance test for normality. *Biometrika* 52(3): 591–599.

Snyder GH, Kretschmer AE. 1988. A DRIS analysis for bahia grass pastures. *Proceedings – Soil and Crop Science Society of Florida* 4: 56–59.

Ståhle L, Wold S. 1989. Analysis of variance (ANOVA). *Chemometrics and Intelligent Laboratory Systems*, 6(4): 259–272.

Sumner ME. 1977a. Effect of corn leaf sampled on N, P, K, Ca and Mg Content and Calculated DRIS Indices. *Communications in Soil Science and Plant Analysis* 8: 269–280.

Sumner ME. 1977b. Application of Beaufil's Diagnostic Indices to maize data published in the literature irrespective of age and conditions. *Plant and Soil* 46: 359–369.

Sumner ME. 1979. Interpretation of foliar analysis for diagnostic purposes. *Agronomy Journal* 71: 343–348.

Szücs E, Kállay T, Szenci G. 1990. Determination of DRIS indices for Apple (*Malus domestica* Borkh). *Acta of Horticultarae* 274: 443–721.

Teixeira LAJ, Quaggio JA, Zambrosi FCB. 2009. Preliminary DRIS norms for 'Smooth Cayenne' pineapple and derivation of critical levels of leaf nutrient concentrations. *ActaHort* 822: 131–138.

Uchida R. 2000. Essential nutrients for plant growth: nutrient functions and deficiency symptoms. In: JA Silva, and Uchida R (eds), *Plant nutrient management in Hawaii's soils, approaches for tropical and subtropical agriculture*. Manoa: College of Tropical Agriculture and Human Resources, University of Hawaii at Manoa, pp 31–55.

Ujwala RM. 2001. Interaction of micronutrients with major nutrients with special reference to potassium. *Karnataka Journal of Agricultural Science* 24: 106–109.

Wadt PGS, Novais RD, Alvarez VVH, Fonseca S, Barros ND. 1998. Valores de referência para macronutrientes em eucalipto obtidos pelos métodos DRIS e chance matemática. *Revista Brasileira de Ciência do Solo* 22: 685–692.

Walworth JL, Sumner ME. 1986. Foliar diagnosis: a review. In: Tinker BP (ed), *Advances in plant nutrition*. New York: Elsevier, pp 193–241.

Westfall DG, Whitney DA, Brandon DM. 1990. Plant analysis as an aid in fertilising small grains. In: Westerman RL (ed.), *Soil testing and plant analysis* (3rd edn). Madison: Soil Science Society of America. pp. 495–519.

Yan S, Jianfeng Y, Hua W, Chao Z, Can W, Gang W, Tan L. 2015. Diagnosis and recommendation integrated system norms for jackfruit (Artocarpus heterophyllus Lam.) nutrient status evaluation. *Journal of Agricultural Science*. 7(11): 245–253.

Received 29 March 2021; revised 28 July 2023; accepted 28 July 2023
Associate Editor: Endalkachew Woldemeskel