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Implication of blanket NPK application on nutrient balance of maize based on soil and tissue diagnosis approaches in the savannas of northern Nigeria

Kamaluddin T Aliyu[1,*], **Alpha Y Kamara**[1], **Jeroen Huising**[1], **Adam M Adam**[2], **Bello M Shehu**[3] and **Jibrin M Jibrin**[2,3]

[1] International Institute of Tropical Agriculture, PMB 5320, Ibadan, Oyo, Nigeria
[2] Centre for Dryland Agriculture (CDA), Bayero University Kano, Kano 70001, Nigeria
[3] Department of Soil Science, Bayero University Kano, Kano 70001, Nigeria
[*] Author to whom any correspondence should be addressed.

E-mail: K.Tijjani@cgiar.org

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Abstract

Improper nutrient management reduces the yield and affects the nutrient status of crops. This study aimed to diagnose the nutrients limitation in maize. A three-year multi-location (348 sites) nutrient experiments were conducted in randomized block design to analyse nutrients limitation for maize production under conventional fertilizer recommendation system in Nigeria using DRIS, and to identify soil factors that influence DRIS indices using random forest model. DRIS indices for nutrients were calculated from the results of ear leaf samples collected from the experimental plots. The DRIS indices were summed, and used to cluster plots using k-means cluster algorithm. The results show large differences in average yield between the clusters. The clusters also differed based on frequency with which nutrients are most limiting. B was the most limiting in cluster one and three, Mn in cluster two and K in cluster four. Random forest results show that soil pH, B and Mg had the largest influence on DRIS indices in cluster one. DRIS indices were most influenced by soil N and B in cluster two. To a lesser extent, the soil Fe, K, Mg and S contents also influenced DRIS indices in cluster two. Soil K, B and Zn were the most significant factors influencing the DRIS indices in cluster four. Bulk Density, Fe, Na, ECEC, and organic carbon had a moderate influence on the indices in this cluster. Nutrient limitation in plants can be diagnose using the DRIS. Soil properties have a definite influence on maize nutrient status.

1. Introduction

The area where maize is cultivated in Nigeria has remarkably increased over the last three decades (FAOSTAT 2019) due to availability of different stress-tolerant varieties (Kamara *et al* 2019). Consequently, maize cultivation has become more preferred among dominantly sorghum and millet farming communities. The northern Nigeria region (the savannas) is the foremost maize production zone in the country due to relatively more favorable production conditions (Shehu *et al* 2018). The region is characterized by sufficient solar radiation, optimum temperature and well-defined rainy season which allows for adequate drying of maize. This region produces a combined 80% of the 10–11 million metric tons of maize annually produced in the country (Knoema 2021).

While several studies (Garba *et al* 2020, Rurinda *et al* 2020) have reported potential yields of > 6 t ha^{-1} in experimental fields particularly within the savannas of Nigeria, national average maize yield for long has been ranging from < 1.8 to 2.5 t ha^{-1}; equivalent to $< 30\%$ of the potential yield of the area (FAOSTAT 2019). Low soil fertility in the area (Jibrin *et al* 2012, Aliyu *et al* 2020) which is compounded by improper management strategies to maintain soil nutrient stocks, and to improve yield response to nutrient application (Shehu *et al* 2018) are considered the most critical factors limiting maize productivity in the region and in Nigeria as whole. Following existing blanket recommendation which ignores spatial variability in soil nutrient (or soil fertility) status and the sub-optimal application of fertilizers may further contribute to depletion of soil nutrient stock and low fertilizer use efficiency in the region (Garba *et al* 2020). Studies by Shehu *et al* (2019) and Rurinda *et al* (2020) showed that fertilizer recovery efficiency was $< 20\%$ for nitrogen (N), $< 15\%$ for phosphorus (P), and $< 30\%$ for potassium (K) in some parts of the northern savanna areas. Low nutrient use efficiency reflects that a substantial portion of the nutrient(s) applied through fertilizer is not taken by the crop and either lost through leaching or being fixed in the soil.

Although the blanket recommendation acknowledges the application of secondary macronutrients and micronutrients (SMNs), most of emphasis are directed mainly towards three main essential macronutrients; nitrogen, phosphorous and potassium (FFD 2012). In long-term experiments in the savannas of Nigeria, Togo and Benin, Nziguheba *et al* (2009) reported that Ca, Mg and Zn are principally deficient as indicated by their strong negative DRIS (Diagnosis and Recommendation Integrated System) indices. Biwe (2012) also similarly reported that the levels of Zn (0.26 mg kg^{-1}) and Cu (0.36 mg kg^{-1}) in soils of Bauchi state of North-eastern Nigeria, are far below the levels required for maize production. Weil and Mughogho (2000) reported the deficiency of S in most parts of the Guinea savanna of Nigeria, especially under the current intensifying agricultural systems. The deficiency of those nutrients can be partly attributed to the observed suboptimal response of crops like maize to NPK fertilizers leading to a reduction in crop quality and yields.

Addressing the low maize yield in Nigeria should therefore target identification of the limiting soil nutrients and applying them in a balanced manner. Soil testing can indicate potential soil supplying capacity of nutrients, however, it is not a good indicator of actual nutrient uptake by plants, as other factors interplay with nutrient uptake process (Fixen *et al* 2005). Therefore, to effectively diagnose limiting plant nutrients, soil test needs to be complemented with plant tissue nutrient diagnosis (Roy *et al* 2006, Mugo *et al* 2020). Plant tissue nutrient diagnosis is based on the fact that maximum yields are associated with an optimum concentration of nutrients in the plant tissue (Maia 2012, Mangale *et al* 2016). But because nutrient concentration in plant tissues is growth stage dependent (Reuter *et al* 1997), and also affected by the availability of other nutrients (nutrient interaction), nutrient diagnosis based on single nutrient concentration (absolute concentration), e.g., the case of critical value approach and sufficiency range, cannot be confidently applied to diagnose plant nutrient disorder (Beaufils 1987). To overcome this defect, a bivariate nutrient diagnosis method 'Diagnosis and Recommendation Integrated System' (DRIS) was proposed by Walworth and Sumner (1987). The DRIS methods diagnose nutrients in dual ratios (relative concentration), to reflect nutrient status as a function of interaction with other nutrients (Walworth and Sumner 1987). Also, because nutrient ratios in plants are fairly constant throughout crop development stages, the sensitivity of changes in nutrient concentration due to plant age is reduced using the DRIS (Singh *et al* 2000, Harger *et al* 2003).

Moving away from the conventional method of generating fertilizer recommendation alone based on yield response to fertilizer application, soil or foliar analysis respectively, this study aims to complement the tissue diagnosis using the Diagnosis and Recommendation Integrated System (DRIS) with soil analysis under the conventional blanket fertilizer recommendation of NPK in the savanna zones of northern Nigeria. Combining the two approaches will give the opportunity of applying nutrients in a balanced manner, and promote synergistic uptake of plant nutrients for better productivity of crops and soils. The specific objectives of this paper were: (i) to diagnose the nutritional status of maize under conventional blanket NPK recommendation, and (ii) to identify the principal soil properties influencing the maize DRIS indices in the savanna zones of northern Nigeria.

2. Materials and methods

2.1. Description of the study area

The studies were conducted in the southern Guinea, northern Guinea and the Sudan savanna zones across three States in northern Nigeria (Kano, Kaduna and Katsina States, shown in figure 1). The Sudan savanna (SS) has varied range of soil from Regosols to Ferric Luvisols.The SS has a length of growing season of around 120 days lasting from May to October with total of 753 ± 171 mm of rain over 57 ± 9 rainy days. Average minimum and maximum temperatures are 20.0 °C and 33.7 °C respectively. The SS is bordered by the northern Guinea savanna (NGS) in the southern extremes. The NGS climate is characterized by a longer growing season and larger number of rainy days (63 ± 9 days) and higher total annual rainfall amount (998 ± 133 mm) than the SS. It has a growing season of 140 days, and soil is mostly Dystic Gleysols and some Lithosols towards the southern part. Average minimum and maximum temperatures are respectively 19.2 °C and 31.6 °C. Lithosols is the most dominantly found soil type in the southern Guinea savanna (SGS). The SGS is the wettest zone of all the savannas with an annual total rainfall of 1541 ± 270 mm and length of growing season of over 150 days covering April to October. Average minimum (21.1 °C) and maximum (32.4 °C) temperatures are similar to that of the SS. Description of the zones are based on 30 year averages from 1980–2009 as reported by Tofa *et al* (2021). These zones together present the most suitable maize growing area in Nigeria and are part of the larger maize belt of Nigeria as described by Aliyu *et al* (2020).

2.2. Experimental procedures

Two different field experiments were conducted across the study area from 2015–2017 rainy seasons. The first set of experiment was the nutrient omission trials (NOTs) that were conducted is the three consecutive experimental years. The sites for the NOTs were selected such that the varying maize cropping conditions across the study area are well represented. The site selection was explicitly reported in Shehu *et al* (2018, 2019) for 2015 and 2016. Modification of the spatial sampling frame work for 2017 is reported in Aliyu *et al* (2021).

Ninety-five (95), 103 and thirty (30) experiments were established on farmer fields in 2015, 2016 and 2017 growing seasons respectively. The experiments in 2015 and 2016 consisted of six nutrient treatments (field layout is shown as supplementary material figure S1), which comprised of a Control (no nutrient application), PK, NK, NP, NPK and NPK+ treatment which had Mg, Ca, S, Zn and B nutrients added to NPK. In 2017, the NPK+ treatment was split into NPKS, NPKB, NPKZn and NPKSZnB in addition to the treatments in 2015 and 2016. During each year, the N, P and K nutrient were applied uniformly at 140 kg N ha^{-1}, 50 kg P_2O_5 ha^{-1} and 50 kg K_2O ha^{-1} respectively at all trial sites. Nitrogen (N) was applied in three equal splits, i.e., at planting (basal), at 21 and 42 days after sowing (DAS), while full dosages of P and K were applied at planting. The nutrients S, Ca, Mg, Zn and B were basally applied at the rates of 10–24, 10, 10, 5–10 and 5 kg ha^{-1} respectively, (more description of the NOTs is provided in table S1). The maize variety SAMMAZ 15 is the most widely adopted variety within the experimental area because of its' tolerance to drought, *Striga* and maize streak virus infestation was used throughout the study. Two seeds per hole were sown at 0.25 m spacing, and later thinned to one plant per in all the studies.

In each year, each treatment plot consisted of six ridges constructed 0.75 m apart, each measuring 5 m long given a plot area of 22.5 m^2. Yield was estimated from a plot area of 9 m^2, defined by disregarding 1 row from each side of the plot and 1 m from either row side of the four middle rows. All cobs and stover in the net plot area were harvested and weighed fresh. Five cobs were then sub-sampled at random for determining moisture content, shelling percentage, and harvest index. Grain yield (in kg ha^{-1}) was expressed on a dry weight basis at 15.0% moisture content adjustment using a grain moisture tester.

In the second experiment, a fertilizer response trial (FRT) was established in the 2017 rainy season. This experiment was conducted across the larger maize belt of the Nigeria savannas across eight States with site selection procedure fully described by Aliyu *et al* (2020). The trial was established in 935 farms from which 120 sites which belong to the focal area for this study were considered in this study. The FRT treatments included NPK, NPKSZnB, NPSZnB and a Control where no nutrient was applied. The whole plot for the NPK was made up of 20 rows of 10 m × 15 m lengths spaced at 0.75 m (field layout is shown as supplementary material figure S3). The net plot was determined by leaving out the first two and last two rows of each plot and 1 m each from both ends of each row. Thus, maize yield was estimated from a plot area of 8 m × 12 m = 96 m^2. The same maize variety used in the NOTs was used in this experiment. Planting, fertilizer application and crop management practices were the same as the NOTs.

The NPK treatment was common between the two studies because it is the dominant/recommended fertilizer management practice in the study area (FFD 2012). Therefore only data of the NPK treatment across the experiments were used and reported in the study.

2.3. Soil and ear leaf sampling and analysis

Prior to establishment of the fields, soil samples were collected at 20 cm depth from representative spots at each experimental site and analyzed for physical and chemical properties. Total soil organic carbon (OC_{tot}) was determined using modified Walkley & Black chromic acid wet chemical oxidation and spectrophotometric method (Heanes 1984). Total nitrogen content (N_{tot}) was measured using micro-Kjeldahl digestion method (Bremner 1996). The pH (soil/water ratio of 1:1) was measured using a glass electrode pH meter. Available phosphorus, available sulphur, exchangeable cations (K, Ca, Mg and Na) and micronutrients (Zn, Fe, Cu, Mn and B) were extracted by Mehlich-3 procedure (Mehlich 1984) and read through inductively coupled plasma optical emission spectroscopy (ICP-OES, Optima 800, Winlab 5.5, Perkin Elmer Inc., Waltham, MA, USA). Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable cations (K, Ca, Mg and Na) and exchangeable acidity (H + Al). Soil texture was analyzed using hydrometer method (Gee and Or 2002).

For ear leaf analysis, ten maize ear leaves were randomly collected from the second and fifth rows immediately at the beginning of silking stage (female flower initiation stage) in the NOTs. For the FRT, first ear leaf was sampled from a plant selected arbitrarily at the centre of the plot. The second and third ear leaves were sampled from the fifth plants to the left and right in reference to the first sampled plant. Two rows perpendicular to the first sampled row from both sides were selected and same procedure was repeated. The tenth sample was randomly collected from within the plot.

The samples were washed with distilled water and air dried. The dried samples were then ground with agate pestle and mortar and analysed for nutrient contents. Nitrogen was analyzed by digesting the samples in hot sulphuric acid solution in the presence of Se as catalyst, followed by colorimetric N analysis using autoanalyzer (Technicon AAII, SEAL Analytical Inc.) following indophenol blue method. For the determination of Sulphur, ball-milled samples were digested with nitric acid (HNO_3) and the nutrient contents in the digest were determined in Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES Optima 3300 DV, Perkin Elmer, Norwalk, USA). Phosphorus (P), K, Ca and Mg and micronutrients (Zn, Fe, Cu, Mn and B) were analyzed by first dry-ashing the samples for four hours at 550 °C and then prepared and read on ICP-OES Optima 800, Winlab 5.5 (manufactured by PerkinElmer Inc., Waltham,MA, USA).

2.4. Data analyses

2.4.1. DRIS *analysis*

Diagnosis and Recommendation Integrated System (DRIS) (Beaufils 1987) was used to assess the nutrient balance index in maize using the results of the ear leaf analysis. First step in DRIS analysis is the establishment of DRIS nutrient norms. The norms are the average nutrient pair ratios of the high yielding (reference population). The reference population was determined by sorting the data according to yield in decreasing order and a cut-off yield was determined. In this study, the cut-off point was determined at mean yield $+0.5 \times$ standard deviation (Aliyu *et al* 2021). Using this criterion, plots with yield $\geqslant 5645$ kg ha^{-1} were considered high yielding and were used as the reference. The reference sub-population constituted 27% of the entire dataset. The Mean value for each nutrient pair, their corresponding coefficient of variation (CV), and variance (σ^2) were then calculated separately for the two sub-populations. The mean value of each nutrient pair ratio in the high-yielding population were considered as the norms (Walworth and Sumner 1987). For calculating the DRIS index, we expressed all possible forms of nutrient pair expressions i.e., A/B, B/A and A×B. Accuracy of DRIS diagnosis depends on the variability of the nutrient pair ratios for the high versus the low yielding sub-populations. Thus, we again calculated the variance (σ^2) for each form of nutrient pair expression separately for each sub-population. It is hypothesised that the data of the low yielding sub-population is more imbalanced and therefore should have larger variance than the high yielding one. Therefore, we divided the variance of the low yielding sub-population by that of the high yielding sub-population. Finally, the nutrient pair ratio expression that present the highest variance ratio between the low and high yielding sub-population was selected among the three nutrient pair expressions, and was used for calculating the DRIS index. The DRIS index for each nutrient was calculated as bivariate relationship between that nutrient and all other nutrients.

As explained by Walworth and Sumner (1988), If we consider hypothetical nutrients A, B through N, then:

$$A\ index = \frac{f\left(\frac{A}{B}\right) + f\left(\frac{A}{C}\right) + f\left(\frac{A}{D}\right) + \ldots + f\left(\frac{A}{N}\right)}{N} \tag{1}$$

$$B\ index = \frac{-f\left(\frac{A}{B}\right) + f\left(\frac{B}{C}\right) + f\left(\frac{B}{D}\right) + \ldots + f\left(\frac{B}{N}\right)}{N} \tag{2}$$

$$N\ index = \frac{-f\left(\frac{A}{N}\right) - f\left(\frac{B}{N}\right) - f\ldots - f\left(\frac{M}{N}\right)}{N} \tag{3}$$

For, if $A/B \geqslant a/b$;

$$f\left(\frac{A}{B}\right) = \left[\frac{\left(\frac{A}{B}\right)}{\left(\frac{a}{b}\right)} - 1\right] \times \frac{1000}{CV} \tag{4}$$

or, if $A/B < a/b$;

$$f\left(\frac{A}{B}\right) = \left[1 - \frac{\left(\frac{a}{b}\right)}{\left(\frac{A}{B}\right)}\right] \times \frac{1000}{CV} \tag{5}$$

Where a/b is the norm for the ratio of nutrients A and B, and CV is the coefficient of variation associated with that norm expressed as percentage. A/B denotes the ratio of average concentration of the ten ear leaves collected per plot for nutrients A and B, n is the number of nutrients considered in the diagnosis, and $f(A/B)$ is a function of nutrients A and B ratio. The 1000 multiplier in equations (4) and (5) comprises of a factor 10 to give the resultant indices a convenient magnitude and a factor 100 to express the CV as fraction rather than as percentage.

A DRIS index value for given nutrient close to zero ('0') indicates nutritional balance for that given nutrient relative to other nutrients in the diagnosis. A negative index value for a given nutrient, indicates lower amount relative to other nutrients and further indicates that the nutrient is yield limiting. On the other hand, positive index value of a nutrient indicates excess presence of that nutrient relative to others and could also affect yield negatively (Walworth and Sumner 1986).

2.4.2. Statistical analysis

After generating the DRIS nutrient index value for each nutrient, the values were summed across all the diagnosed nutrients for each plot to obtain overall nutrients DRIS index value for each plot. K-means cluster analysis was performed on the summed DRIS index of each field so that, fields with similar overall nutrient DRIS values are grouped to allow for an in-depth analysis of major soil properties influencing the DRIS index values for each cluster. Selection of optimal number of clusters used in this study was guided by highest cubic clustering criterion. This analysis was done in JMP Pro version 14 statistical package (SAS Institute Inc. 2017). Between each of the identified clusters, analysis of variance was used to compare the average levels of soil properties. The mean contents of the soil properties were separated using least significant difference (LSD) method.

Random forest (RF) regression was used to assess the major soil properties influencing maize DRIS indices in each of the identified clusters. The model considered all the analyzed soil properties as predictor variables using random forest regressor in XLSTAT statistical software. The RF model was trained with 50% of the observations, 30% was used for model validation and 20% for model testing. Feature importance was used to explain the influence of various soils properties on overall DRIS index values for each cluster. Errors in the models training were monitored using out-of-bag (OOB) (Janitza and Hornung 2018). Choice of the two models here, that is, the K-means and RF for this study is largely due to their robustness in handling large data set; especially of multivariate nature.

3. Results

3.1. Characteristics of the soils across the experimental fields

Apart from soil pH and texture, other chemical properties of the soils across the environmental fields varied widely (table 1). Average value of the pH (5.88) is considered moderately acidic using Esu (1991) classification of Nigerian savanna soils. About 77% of the fields however varied within the moderate to slightly acidic conditions. Few fields (19%) with pH values ranging from 4.80 to 5.50 fell within the strongly acidic condition, while the remaining 4% were either of neutral or slightly alkaline class. Average soil textural class across the sites is sandy loam according to USDA (1975) classification, this is common in about 40% of the fields. The CVs of sand (23.3%), silt (27.2%) and clay (26.4%) indicate a fairly consistent distribution pattern across the study fields. Although there was a moderate variation in total N, organic carbon, available P and ECEC contents, their average values indicate that they in low levels across the sites. Only less than 8% of the fields have moderate contents of these properties. The average contents of K, Mn, Zn and Fe are rated high, but this was highly inconsistent across the fields.

3.2. Variation of ear leaf nutrient concentrations across the experimental fields

According to the CV values, the variation in ear leaf concentration of all the analyzed nutrients is of moderate nature according to Wilding (1985) procedure. The kurtosis and skewness values of all the nutrients were also within the acceptable limits of asymmetric data dispersion (table 2). For N, the mean concentration was 23.89 g kg^{-1}. This value was also quite similar to those of the other measures of central tendencies (median = 23.85, mode = 23.0). These values were below the critical level of N in the ear leaf. The skewness and kurtosis were respectively −0.12 and −0.33. Average ear leaf concentration of P was 2.43 g kg^{-1}, and this also seem to be moderately consistent (CV = 28.6%) across the sites. Average K ear leaf concentration was 18.2 g kg^{-1} with slight difference across the data set. Concentration of ear leaf ranged from 2.3–9.70 g kg^{-1} for Ca, 0.3–4.96 g kg^{-1} for Mg and 0.0–3.10 g kg^{-1} for S. Among the micronutrients, average ear leaf concentration of Cu was 6.05 mg kg^{-1}, 74.39 mg kg^{-1} for Mn, 13.69 mg kg^{-1} for Zn, 3.27 mg kg^{-1} for B, and 139.43 mg kg^{-1} for Fe.

Table 1. Descriptive statistics of the chemical and physical properties of the soils at the experimental sites.

Soil Property	Mean	Median	Mode	Minimum	Maximum	Standard deviation	Kurtosis	Skewness	CV (%)
pH (Water) 1:1	5.88	5.88	5.80	4.80	7.20	0.41	0.12	0.17	6.9
Total Organic Carbon (g kg^{-1})	6.81	6.31	7.84	2.02	18.0	2.71	1.20	0.96	39.7
Total N (g kg^{-1})	0.50	0.48	0.50	0.14	1.48	0.19	4.76	1.62	37.9
Available P (mg kg^{-1})	2.80	2.36	2.88	0.64	9.35	1.59	2.83	1.53	56.8
K (cmol$_c$ kg^{-1})	0.48	0.44	0.17	0.06	1.52	0.33	-0.03	0.79	69.8
Available S (mg kg^{-1})	9.08	8.28	15.7	4.11	38.36	3.67	16.50	2.94	40.4
Ca (cmol$_c$ kg^{-1})	2.63	2.47	2.02	0.24	9.78	1.23	3.66	1.18	46.7
Mg (cmol$_c$ kg^{-1})	0.94	0.81	1.37	0.08	3.53	0.52	4.32	1.72	55.7
Cu (mg kg^{-1})	1.48	1.45	1.66	0.13	5.12	0.84	2.94	1.34	56.8
Mn (mg kg^{-1})	63.2	58.1	88.6	3.71	180.7	40.4	0.58	0.97	63.9
B (mg kg^{-1})	0.05	0.03	0.10	0.00	0.25	0.05	2.83	1.74	94.2
Zn (mg kg^{-1})	4.47	1.32	3.28	0.62	69.06	6.31	31.60	4.17	141.2
Fe (mg kg^{-1})	139.7	126.4	101.5	43.4	527.2	59.7	8.90	2.24	42.8
Na (cmol$_c$ kg^{-1})	0.13	0.10	0.07	0.04	0.55	0.09	5.07	2.17	67.3
ECEC (cmol$_c$ kg^{-1})	5.27	4.79	7.60	0.82	18.35	2.48	2.06	1.07	47.1
Sand (%)	48.11	45.60	40.00	26.00	77.20	11.18	−0.47	0.43	23.2
Silt (%)	29.76	31.20	39.20	9.20	44.00	8.11	−0.67	−0.42	27.2
Clay (%)	22.13	20.80	20.80	11.60	41.60	5.83	0.21	0.74	26.4

Table 2. Descriptive statistics of the concentration of macro nutrients and micro nutrients in the ear leaves.

Statistical terms	Macro nutrients (g kg^{-1})						Micro nutrients (mg kg^{-1})				
	N	P	K	Ca	Mg	S	Cu	Mn	Zn	B	Fe
Mean	23.89	2.43	18.20	5.88	2.28	1.45	6.05	74.39	13.69	3.27	139.43
Median	23.85	2.40	17.80	5.80	2.20	1.45	5.80	67.50	12.81	3.15	132.75
Mode	23.00	2.00	11.60	4.60	1.90	1.20	4.60	80.23	9.57	2.00	195.76
Minimum	8.90	0.80	5.90	2.30	0.30	0.00	1.59	16.23	3.69	0.48	43.31
Maximum	36.70	4.50	32.57	9.70	4.69	3.10	13.44	181.14	28.35	7.61	305.04
Standard Deviation	5.18	0.70	4.99	1.47	0.73	0.43	2.32	33.96	4.92	1.27	51.61
Kurtosis	−0.33	0.12	−0.52	−0.55	0.09	0.47	−0.27	0.40	0.39	0.62	−0.11
Skewness	−0.12	0.41	0.21	0.11	0.54	0.12	0.37	0.89	0.84	0.77	0.56
CV (%)	21.7	28.6	27.4	25.1	31.9	29.6	38.4	45.7	35.9	38.7	37.0

3.3. The DRIS analysis

For establishing the DRIS norms, nutrient dual ratios that present the highest variance among the three possible expressions (direct, indirect and product) were selected for every nutrient pair combination (table 3). The direct and Indirect forms of expression were selected in equal cases (46.7%) for the nutrient pairs. In just 6% of the cases, the product form of the dual ratio expression (Mg × Ca, Mg × Fe and K × Zn) was selected. The results of the variances calculated for each nutrient dual ratio across the fields indicated a higher variance ratio in the low yield sub-populations than in the high yield sub-population group. This resulted in a variance ratio $\geqslant 1$ when the variance of the low yield was divided by that of the high yield sub-population (table 3). The variance ratio was usually higher when macro and micro nutrients were paired. The CVs were also likewise higher when a micro nutrient was involved, and again the CV of Mn/B for the low yield sub-population was the highest (76.71%) among all the (table 3).

The results of the DRIS nutrient diagnosis indicate that the average indices for the individual nutrients widely varied across the experimental sites (figure 2). Although in few cases, nutrients like Mg, K, Ca, S, and Zn have the near '0' DRIS indices, they however show negative DRIS indices in many cases across the fields. The average index of N was only positive in one field across the experiment; however, N was only the most limiting nutrient in just 3% of the fields (figure 3). The DRIS indices of Mg and Zn were the most inconsistent across the experimental fields, with values range of 1.9 to −10.5. Copper (Cu), Mn and B had the most negative DRIS indices across the fields. Across the experiments, the DRIS analysis indicated that nutrients which were not applied (B, Mg, Mn, S and Zn) showed a consistently negative DRIS indices at individual sites (figure 3). In most cases (31%), Zn was found to have the most negative DRIS index among the nutrients (figure 3). Magnesium

Table 3. Selected forms of nutrient dual ratios, DRIS norms, variance (σ^2) for low and high yield sub-populations and variance ratios.

	High yield sub-population			Low yield sub-population					High yield sub-population			Low yield sub-population			
Form of expression	Norm	CV (%)	σ^2_{high}	Norm	CV (%)	σ^2_{low}	$\sigma^2_{low}/\sigma^2_{high}$	Form of expression	Norm	CV (%)	σ^2_{high}	Norm	CV (%)	σ^2_{low}	$\sigma^2_{low}/\sigma^2_{high}$
Mg/N	0.09	35.86	0.00	0.10	37.42	0.00	1.27	S/Ca	0.27	31.56	0.01	0.25	39.12	0.01	1.38
K/N	0.80	29.42	0.06	0.79	34.80	0.08	1.36	Ca/Cu	0.01	45.29	0.00	0.12	54.23	0.00	1.75
Ca/N	0.24	29.40	0.00	0.26	31.16	0.01	1.39	Mn/Ca	1.37	50.19	46.96	1.49	62.58	71.23	1.52
N/P	10.24	23.44	5.76	10.47	32.60	11.64	2.02	Ca/Fe	0.00	45.58	0.00	0.00	55.43	0.00	1.40
S/N	0.06	28.31	0.00	0.63	31.00	0.00	1.31	Zn/Ca	2.57	40.66	1.09	2.46	48.57	1.43	1.31
N/Cu	0.05	47.02	0.00	0.05	54.28	0.00	1.34	Ca/B	0.02	36.14	0.00	0.22	64.50	0.00	4.40
Mn/N	0.35	40.08	1.49	0.29	50.03	2.71	1.82	S/P	6.14	27.48	0.03	0.64	41.05	0.07	2.43
Fe/N	0.52	40.78	4.57	0.39	46.18	8.71	1.91	Cu/P	0.25	35.27	0.80	2.69	46.76	1.58	1.98
N/Zn	0.02	27.97	0.00	0.19	34.78	0.00	1.52	Mn/P	3.12	44.80	195.79	34.65	66.53	531.5	2.71
N/B	1.62	39.00	0.00	0.87	65.41	0.00	3.14	P/Fe	0.00	39.80	0.00	0.00	54.21	0.00	1.57
Mg/K	0.12	35.44	0.00	0.41	48.18	0.00	2.43	Zn/P	0.58	34.88	4.03	6.15	48.85	9.03	2.24
Mg*Ca	0.14	47.72	0.00	0.14	49.21	0.00	1.09	P/B	0.01	43.35	0.00	0.09	63.97	0.00	2.48
Mg/P	0.93	32.18	0.09	1.04	43.54	0.20	2.26	S/Cu	0.00	44.36	0.00	0.00	53.70	0.00	1.50
Mg/S	1.63	45.89	0.39	1.68	37.24	0.56	1.44	Mn/S	53.12	50.43	717.57	5.66	58.03	1043.3	1.45
Mg/Cu	0.00	37.01	0.00	0.00	49.67	0.00	2.15	Fe/S	4.56	56.31	2835.3	1.73	52.46	3168.0	1.12
Mg/Mn	0.00	54.21	0.00	0.00	58.79	0.00	1.26	S/Zn	0.00	37.62	0.00	0.00	45.50	0.00	1.48
Mg*Fe	31.3	51.80	262.9	33.0	52.17	295.9	1.13	S/B	0.05	41.20	0.00	0.01	51.52	0.00	1.75
Mg/Zn	0.00	37.60	0.00	0.00	48.91	0.00	1.93	Mn/Cu	1.37	57.93	0.63	1.48	68.66	1.04	1.64
Mg/B	0.01	42.16	0.00	0.01	63.79	0.00	2.97	Fe/Cu	2.33	49.03	1.30	2.76	64.64	3.17	2.43
K/Ca	3.54	36.21	1.64	3.24	43.81	2.02	1.23	Cu/Zn	0.05	44.31	0.00	0.05	51.00	0.00	1.39
K/P	7.96	29.86	5.65	8.04	40.43	10.57	1.87	Cu/B	2.02	46.14	0.01	0.21	68.50	0.02	2.47
K/S	13.99	43.75	32.48	3.53	42.11	37.49	1.15	Fe/Mn	2.07	57.11	1.40	2.29	61.34	1.97	1.41
K/Cu	0.04	51.34	0.00	0.36	64.43	0.00	1.55	Mn/Zn	5.88	50.89	8.96	6.29	67.46	17.98	2.01
K*Mn	147.6	50.87	5475.4	130.41	56.74	5638.1	1.03	Mn/B	25.18	53.88	184.05	28.29	76.71	470.8	2.56
K/Fe	0.00	39.97	0.00	0.00	46.03	0.00	1.02	Fe/Zn	10.33	44.52	21.15	11.84	52.59	38.79	1.83
K*Zn	28.28	45.56	166.00	24.65	54.70	181.88	1.10	Fe/B	42.69	55.52	561.81	52.57	61.61	1049.2	1.87
K/B	0.06	42.78	0.00	0.64	49.62	0.00	1.35	Zn/B	4.76	56.67	7.28	5.04	65.33	10.85	1.49
Ca/P	2.39	29.07	0.48	2.66	38.59	1.05	2.18								

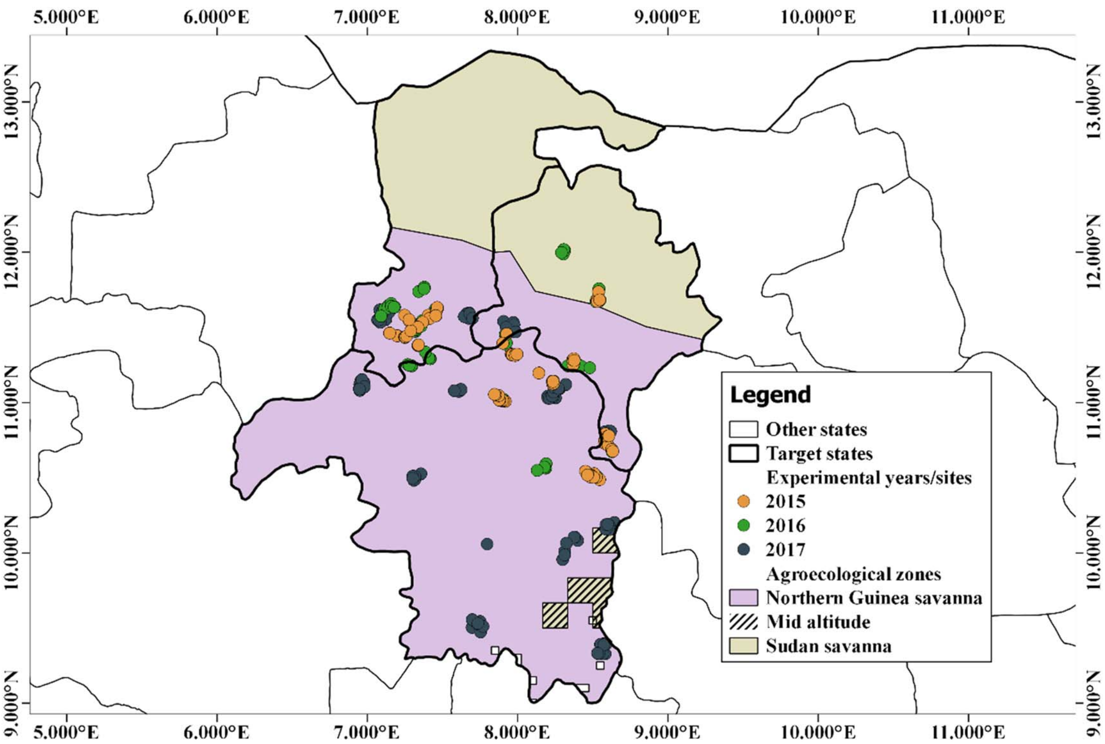

Figure 1. Map showing the study states, agroecologies, experimental sites and years.

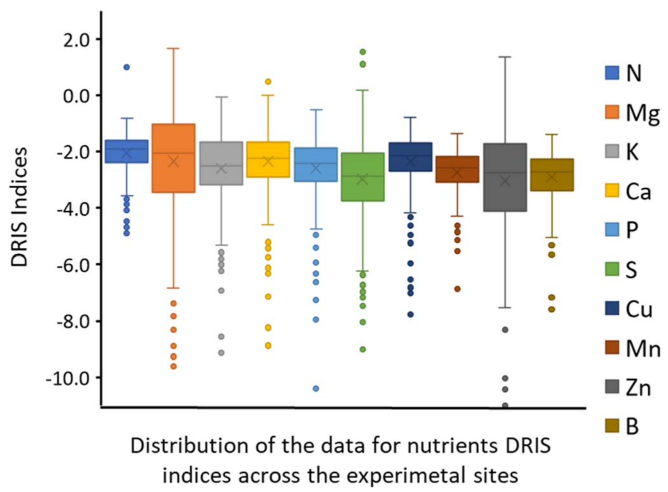

Figure 2. Variation in the distribution of the nutrients DRIS indices across the experimental fields.

(Mg) and Mn with 15.4 and 14.4% respectively were the second most limiting set of nutrients, and followed by B in around 10% of the fields.

3.4. Cluster analysis

Based on attaining high cubic clustering criterion, four distinct clusters were selected using the multivariate k-means cluster analysis to best represent the highest homogeneity and heterogeneity within and between the clusters respectively. Cluster one and cluster two were the largest with 139 and 119 fields respectively. Cluster four was the third largest with 98 fields while cluster three was the smallest with 18 fields. Below are the attributes of the selected clusters in terms of soil, grain yield and DRIS indices.

Results of analysis of variance on the soil (table 4) indicated that levels of pH, ECEC, available P and S, Ca and B did not significantly vary among the clusters. The pH condition on average was moderate across the clusters. In general, ECEC, available P and S, and B were low, while Ca level was moderately high across the clusters. Although the contents of N and Mg in cluster four were below the critical soil levels, the cluster seem to have the

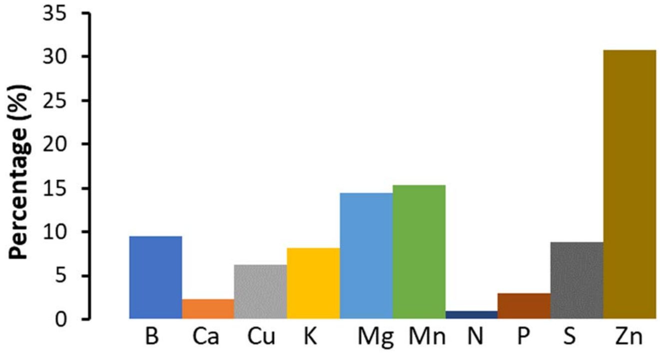

Figure 3. Percentage of occurrence of nutrients as having the most negative DRIS index value across all the sites.

Table 4. Analysis of variance results comparing soil properties of different clusters across the study.

Cluster	pH (water) 1:1	ECEC ($cmol_c$ kg^{-1})	OC (g kg^{-1})	N (g kg^{-1})	Available P (mg kg^{-1})	K ($cmol_c$ kg^{-1})	Ca ($cmol_c$ kg^{-1})	Mg ($cmol_c$ kg^{-1})	S (mg kg^{-1})	Cu (mg kg^{-1})
1	5.91	5.13	6.21ab	0.47ab	2.83	0.44b	2.44	0.88b	8.85a	0.58b
2	5.88	5.05	7.50a	0.51ab	2.94	0.44b	2.73	0.91b	8.97a	0.53b
3	5.90	5.16	5.33bc	0.44abc	2.75	0.34b	2.76	0.79b	7.48ab	0.40b
4	5.85	5.78	7.40a	0.53a	2.62	0.59a	2.74	1.07a	9.78a	0.74a

Cluster	Mn (mg kg^{-1})	Zn (mg kg^{-1})	B (mg kg^{-1})	Na (*$cmol_c$ kg^{-1}*)	Fe (mg kg^{-1})	BD (g/cm^3)	Sand (%)	Silt (%)	Clay (%)
1	58.39b	1.00b	0.05	0.13b	140.49	0.90	49.76b	28.29b	21.95a
2	59.96b	1.02b	0.05	0.12b	135.83	0.96	44.87b	32.75a	22.39a
3	65.55ab	1.40a	0.05	0.11b	153.41	0.96	60.45a	21.46c	18.1b
4	73.55a	1.03b	0.06	0.16a	141.12	0.75	47.69b	29.24b	23.07a

The means under each soil property with different letter(s) across the clusters indicates significant difference. Means within the same column not followed by any letter are not significantly different. All means comparisons were made at 5% level of probability.

higher contents of K, Cu, Mn and Na. Cluster two is the second more fertile environment with dominantly higher organic carbon level, although the organic carbon was also yet below the critical level. Cluster three had higher Zn level among the clusters. This cluster had the highest and lowest contents of sand and clay respectively. The cluster is rated the least fertile and it is characterized by lowest contents of organic carbon, N, K, Mg, S, Cu, and Na.

Grain yield generally varied moderately within each cluster except cluster one which varied widely (figure 4). Highest yield was obtained from cluster two, with a mean yield of approximately 7,000 kg ha^{-1}. Yield of cluster one and four did not significantly vary. Also statistically, distribution of yield was identical between the two clusters. The cluster three had yield between 2,000–8,000 kg ha^{-1}, and mean yield of 4,700 kg ha^{-1}, which make it the second highest yield cluster after cluster two (figure 4).

When the DRIS indices for the nutrients were clustered, the result show that Mn and B were the most important limiting nutrients with lowest DRIS indices (most negative indices) occurring in 27.34% and 25.18% instances respectively in cluster one (table 5). Mg (18.71%), P (13.67%) and K (10.07%) were also found to limit maize productivity in this cluster. For cluster two, Mn (26.89%) and Mg (21.01%) were the dominant limiting nutrients according to the DRIS analysis. Boron (B) and Fe were the second important yield limiting nutrients in 13.45 and 10.08% of the sites in the cluster two. The third group of limiting nutrients in this cluster include P, K, Ca, S and Cu. Cluster three had the lowest number of limiting nutrients. In this cluster, B was the most important limiting nutrient in 43.75% of the fields. Each of P and Mn was found as most limiting in 25% of the fields in cluster three. Yield is indicated to be limiting by almost all nutrients in the same magnitude in cluster four. The indices of K were the most negative in 18.37% percent of the fields in the cluster. That of P, Zn and Fe were second after K with each recurring in 12.24% of the case.

3.5. Major soil factors influencing the DRIS indices

Results of the random forest regression analysis show that the algorithm stopped growing trees for clusters 1, 2 and 4 when the trees reach 200. For cluster four, the prediction error reduces and stabilized after more than 800

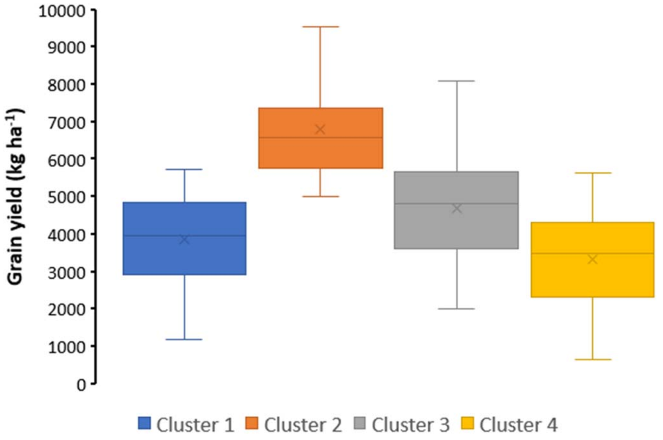

Figure 4. Distribution of grain yield by cluster.

Table 5. Percentage of fields with negative DRIS indices of nutrients for each cluster.

Nutrient	Cluster 1 (*N* = 131)	Cluster 2 (*N* = 109)	Cluster 3 (*N* = 19)	Cluster 4 (*N* = 89)
	Percentage of fields			
P	13.67	7.56	25.00	12.24
K	10.07	6.72	0.00	18.37
Ca	0.72	5.04	0.00	5.10
Mg	18.71	21.01	6.25	10.20
S	0.72	4.20	0.00	2.04
Cu	0.00	4.20	0.00	6.12
Mn	27.34	26.89	25.00	11.22
Zn	1.44	0.84	0.00	12.24
B	25.18	13.45	43.75	10.20
Fe	0.72	10.08	0.00	12.24

trees were grown in the forest (results not shown). The variable importance features for each cluster are presented in figures 5(a)–(d). The results indicated that nutrient DRIS indices are influenced by unique soil factors for respective clusters. For cluster one, pH appears to have the largest influence on nutrient DRIS indices (figure 5(a)). Boron and Mg were the second most important soil variables which affected the DRIS indices. Other important factors were ECEC, sand content, available P and organic carbon. Nutrient DRIS indices were most influenced by N and then by B contents in cluster two (figure 5(b)). Soil contents of Fe, K, Mg and available S also influenced the nutrients DRIS indices at similar magnitude in this cluster. For cluster three, pH was the major variable, and Na as the second (figure 5(c)). Bulk density (BD) and Cu were also critical influencers of the DRIS indices. More than in any cluster, multiple variables influenced the DRIS indices of the nutrients in cluster four (figure 5(d)). Potassium (K), B and Zn seem to be the most significant factors in this cluster. Iron (Fe) and Na, ECEC, BD and organic carbon had a moderate influence on the nutrient's indices in descending order respectively.

4. Discussion

In this study, some of the diagnosed nutrients which were found in lower levels (negative DRIS indices) in the maize plant tissues were actually in sufficient levels in the soils. This finding is relatively novel in the study area as previous studies on plant, soil, and nutrients interaction are few in Nigeria, and the focus was mainly on outcome produced by individual factor. How these factors interact to produce a given outcome have not received a significant attention. Aliyu *et al* (2021) concluded that tissue nutrient diagnosis should be complemented with soil analysis for targeting a proper nutrient recommendation. Sampling population in previous studies on nutrient diagnosis is either formed from different nutrient treatments (Aliyu *et al* 2021), or from a farm survey across different cropping systems (Serra *et al* 2014, Carneiro *et al* 2015). Using those type of

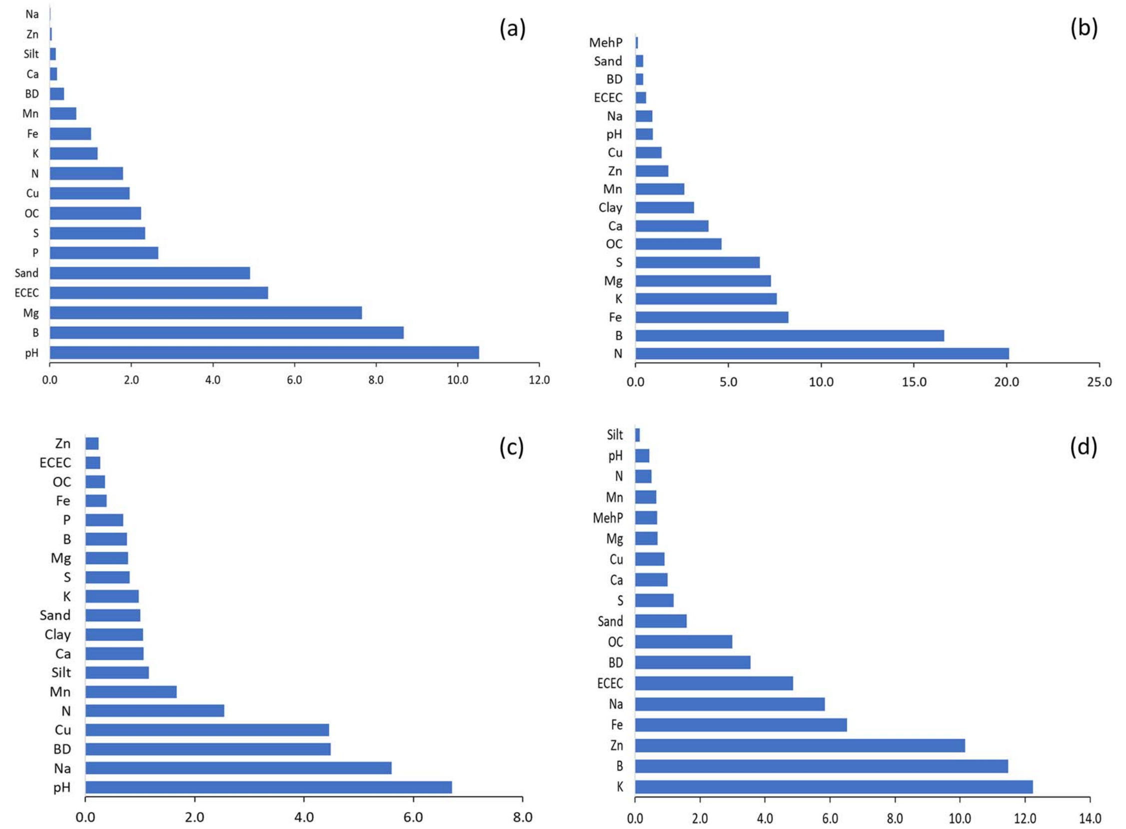

Figure 5. Major soil factors influencing maize DRIS indices of nutrients for cluster one (a), cluster two (b) cluster three (c) and cluster four (d).

populations for nutrient diagnosis may likely complicate the diagnosis and compromise its' quality and reliability. In this study we used population which had received similar nutrient treatment so that the difference in performance of the crop may be attributed more to variation in soil properties. Our findings indicated a wide variation in inherent soil properties across the experimental fields. Previous studies on soils (Aliyu *et al* 2020) indicated a wide variability of soil nutrients within the major maize production domain in Nigeria. Relative response to nutrient application has also been reported with a high variation across a study area by Shehu *et al* (2018), Garba *et al* (2020) and Aliyu *et al* (2022). Nziguheba *et al* (2009) used the DRIS to diagnose nutrients that limit maize yield in Nigeria. Variation in pH is the lowest among the soil properties. Over 77% of the fields are within the suitable pH limit for maize production (Shehu *et al* 2019). The fields with lower pH values (strongly acidic condition) are few across the study fields and could have resulted from improper application of mineral nitrogen fertilizer over time which usually leads to soils becoming more acidic (Schumann 1999). These specific fields have high sand content, and it is possible the situation would worsen with continuous application of high nitrogen since sandy soils have low buffering capacity (Nelson and Su 2010). Our study environment is generally low in nitrogen, organic carbon and P contents. This finding is consistent with that of Ekeleme *et al* (2014). Aliyu *et al* (2020) reported a high correlation between organic carbon and N, and highlighted that their availability is dependent on pH condition of soil. The same study also attributed the variability of the N, P and K to inherent soil forming minerals. Therefore, our sites present a suitable environment for conducting nutrient experimentation.

Deriving our experimental data from the uniform treatment set had helped in reducing variability in ear leaf nutrients across the fields. However, the small variability was also sufficient to allow for data categorization in the diagnosis process. The ear leaf concentrations of N, P, B, Zn and S were below the critical levels established by Reuter *et al* (1997). The concentrations of K, Mg, Ca, Fe and Cu are notably within the sufficiency levels established by Reuter *et al* (1997). While some of the values for the ear leaf nutrients; N, P, Cu and B were similar to those reported by Aliyu *et al* (2021), those of K, Ca and Fe were significantly higher in this study.

The overall variability of the DRIS indices across the experimental fields could be attributed to the variability of the soil and ear leaf nutrient concentration. Nutrient DRIS index is direct reflection of tissue concentration of the nutrient (McCray *et al* 2013). Magnesium had the highest variation in of the DRIS index across the experiment and this can be related to higher range of distribution of the nutrient, both in the soil and ear leaf across the fields. On the contrary, lower variation in N DRIS index across the fields is attributed to the low variation of soil nitrogen across the fields. The highest occurrence of Zn as the most negative nutrient in the diagnosis is contrary to the findings of Aliyu *et al* (2021) under the NPK treatment. However, this is possible because Zn had the most consistent negative DRIS indices distribution across the sites. In addition, the soils across the fields were uniformly low in Zn content. A similar finding of low Zn in these soils was also reported by Huising and Mesele (2021). Zn was predominantly the most negative nutrient irrespective of treatments in the long-term experiment reported by Nziguheba *et al* (2009). Aliyu *et al* (2021) also reported that application of Zn did not significantly increase Zn ear leaf content, thus resulting in negative DRIS index of Zn in many cases. The case of negative B and Mg indices corresponds to low soil contents of the nutrient as also reported in other studies (Garba *et al* 2020). The high percentage of negative Mn DRIS index despite high amount of Mn in the soil could be attributed to high antagonistic effect of Fe (content of Fe in our experiment fields was high) on Mn during uptake as discovered by Kobraee and Shamsi (2011).

4.1. Cluster analysis

The DRIS indices for the nutrients in cluster one was mainly influenced by pH and B, and to larger extent Mg, ECEC and Sand. Highest number of negative DRIS index of B could be linked to the low soil B content of the cluster. Cluster one is the least fertile among the four clusters and it is therefore not surprising to also found that almost all nutrients have negative DRIS indices in this cluster. The ECEC and soil pH are highly correlating soil properties (McKenzie *et al* 2004). Low ECEC in this cluster is the result of high sand content which easily leach away the cations, this is the reason that this cluster is associated with low levels of the cations. The yield limitation and high negative DRIS indices of Mg could have been created by the low Mg levels in the soil. In addition to that, the cluster has sufficient levels of K and Ca and both have stronger binding affinity which gives them edge over Mg at the exchange site during uptake. This situation was more aggravated because of the higher level of pH of the cluster (René *et al* 2017).

Nitrogen and B appears as the major influencers of the DRIS indices of cluster two. This cluster had a sum of −22.94 (not shown) DRIS balance index. It is clear that this cluster is responsive to nutrients going by the highest mean yield recorded. The high nutrient response in this cluster seems to be related with low amount of nutrients and the ability of the soil to hold nutrients due to higher clay content. Boron being another important influencer of the DRIS indices could also be explained by its very low content in the soil. The pH is the most important soil property in cluster three. The nutrients with highest number of negative DRIS indices in this cluster were P, Mn and B. These nutrients were in low supply in the soil and they therefore contributed to the cluster having the highest overall negative DRIS balance index of −155.

Cluster four had the second lowest grain yield though it has the highest contents of most of the soil fertility properties. Soil K, B and Zn were the dominant factors that influenced the DRIS indices of the nutrients. Low yield in this cluster could be related to luxury consumption of nutrients by the maize. This is reflected in the overall nutrient balance index of this cluster going up to 27.4. Luxury nutrient consumption had been reported to decrease nutrient use efficiency in maize (Janssen *et al* 1990, Shehu *et al* 2019). The roles of K and B in plants are similar and they interact synergistically to influence the uptake of each other (René *et al* 2017). In this cluster, K was in very high amount in the soil and possibly upset the nutrient balance of the other nutrients in the diagnosis.

5. Conclusion

In this study, we understand that nutrient diagnosis using both soil and plant tissue methods are compliments to holistic insight on plant-soil interaction as regard to maize nutrition. Most of the results of the DRIS diagnosis in this study agrees with that of the soil. For example, nutrients (like nitrogen) which were found in low amounts in the soil showed consistent negative DRIS indices. Also, nutrients (B, Mg, Mn, S and Zn) which were not part of the treatments of this study continuously showed negative indices, indicating their relative lower availability in the soil. Due to the high variation of the nutrients across sites and DRIS indices, the cluster analysis on the DRIS indices helped to group fields with similar DRIS indices, thereby providing a more precise dimension on the nutrient limitations. The clusters differed based on frequency with which nutrients are most limiting. B for example was the most limiting in cluster one and three, Mn in cluster two and K in cluster four. Both high (more positive) and low (more negative) DRIS indices resulted to low maize yield respectively, likely due over and under supply of nutrients respectively. Random forest results show that different soil properties influenced the DRIS indices in different ways depending on the cluster. This indicates that soils at different location varied when it comes to fertility management, thus hinting that the NPK fertilizer recommendation being promoted to farmers need to be reviewed and focus should be more on site-specificity depending on the soil resources.

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Data availability statement

The work which generate the datasets that is used for this study was from collaborated researches which involved many institutions with different data policies. The data that support the findings of this study are available upon reasonable request from the authors.

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethical statement

No ethics approval is required in this study.

ORCID iDs

Kamaluddin T Aliyu https://orcid.org/0000-0003-1613-1147
Jeroen Huising https://orcid.org/0000-0002-5567-5289

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