

Understanding Nutrient Imbalances in Maize (*Zea mays* L.) using the Diagnosis and Recommendation Integrated System (DRIS) Approach in the Maize Belt of Nigeria

Kamaluddin T. Aliyu (✉ K.Tijjani@cgiar.org)

International Institute of Tropical Agriculture (IITA), Oyo Rd, P.M.B. 5320, Ibadan

Jeroen Huising

International Institute of Tropical Agriculture (IITA), Oyo Rd, P.M.B. 5320, Ibadan

Alpha Y. Kamara

International Institute of Tropical Agriculture (IITA), Oyo Rd, P.M.B. 5320, Ibadan

Jibrin M. Jibrin

Centre for Dryland Agriculture, Bayero University, Kano, PMB 70001, Kano

Ibrahim B. Mohammed

Department of Agronomy, Bayero University, Kano, PMB 70001, Kano

Generose Nziguheba

International Institute of Tropical Agriculture (IITA), P.O. Box 30772-00100, Nairobi

Adam M. Adam

Centre for Dryland Agriculture, Bayero University, Kano, PMB 70001, Kano

Bernard Vanlauwe

International Institute of Tropical Agriculture (IITA), P.O. Box 30772-00100, Nairobi

Research Article

Keywords: Diagnostic and Recommendation Integrated System, Mg, Ca, Cu

Posted Date: May 6th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-477739/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Version of Record: A version of this preprint was published at Scientific Reports on August 6th, 2021. See the published version at <https://doi.org/10.1038/s41598-021-95172-7>.

Abstract

Low nutrient use efficiency in maize as a result of imbalanced nutrition has been reported to drastically reduce yield. We implemented, a nutrient omission experiment to assess the effect of nutrient application on maize yield and nutritional balance. Maize ear leaves were analyzed for nutrients, to identify nutrient balance status using the Diagnostic and Recommendation Integrated System (DRIS) approach. Results indicated that omission of N or P resulted in highly imbalanced DRIS indices respectively, and significantly lower grain yield. A strong inverse relationship between K ear leaf content with DRIS index suggests that K application negatively increases K imbalance in many situations. Imbalances of Mg, Ca and Cu were more associated with higher yielding treatments. A Which-Won-Where result show that nutrient imbalances in the diagnosis were systematically frequent when N was omitted. All the diagnosed nutrients were imbalanced even under the highest yielding NPKZn treatment; indicating further opportunity for yield increase with more balanced nutrition. Balanced nutrition of maize in the maize belt of Nigeria should target application of varying amounts of N, P, K, Mg, S and Zn, depending on the soil condition. But because of complexities of nutrient interactions during uptake, it is hardly possible to realize a balanced nutrition. However, differentiating the application of antagonistic nutrients into foliar or soil-based methods is recommended for a more balanced maize nutrition.

Introduction

Genetic improvement of maize (*Zea mays* L.) to tolerate environmental stresses has promoted its cultivation, even into semi-arid and arid parts of Nigeria^{1,2} where growing conditions were less suitable for maize because of high temperature and low rainfall³. Consequently, maize production area in Nigeria increased fourfold from 1960 to 2018⁴. Presently maize occupies 17% of the total arable land and 33% of total area under cereals in the country⁴. Total production has increased over eight-fold within the same time span. As a result, Nigeria became the second most important maize producer in Africa after South Africa contributing about 13% of the continent's total production over the last decade⁴.

Unfortunately, like in many other sub-Saharan Africa (SSA) countries, maize productivity per unit area in Nigeria is low at $< 2 \text{ t ha}^{-1}$ on average, representing 19-21% of the crop's attainable yield ($7-8 \text{ t ha}^{-1}$)⁵. The low yields are in part attributed to inherently low soil fertility condition⁶, limited use of fertilizers and poor nutrient management⁷. Also, apart from the known deficiencies of N, P and K^{8,9}, which are addressed by application of the commonly available fertilizers containing N, P and K⁷, deficiencies of Cu, and Zn¹⁰, B⁵ and S¹¹ are currently reported to constrain maize yields, yet number of studies on micronutrients are just few to support for informed fertilizer policies. Unfortunately, use of NPK fertilizer itself is uniformly prescribed per agroecology, disregarding heterogeneity of soils between fields^{12,13,14}. Continuous adoption of this practice leads to serious nutrient imbalances in the soils, low nutrient use efficiency, low nutrient response and reduced crop performance¹⁵.

Imbalanced nutrient supply affects plant nutrient uptake and utilization, thus reducing crop yield¹⁵. Therefore, diagnosing nutrient status of plants may help in designing efficient nutrient management practices for improved crop yield. Nutrient diagnosis using leaf samples has served to evaluate the nutritional status of plants based on chemical analysis of the leaf tissue; which is highly sensitive to soil nutrient status¹⁶. Maize ear leaf, as one of the sites for greater metabolic activity^{17,18}, has been identified as a useful organ for diagnosing maize nutritional imbalances and guide for fertilizer recommendation¹⁹. The use of maize ear leaf for nutrient diagnosis is based on the established finding that the level of nutrients in the leaf is directly related to nutrient supply and not directly to nutrient concentrations in the soil²⁰. However, plant nutrient content is a composite effect of many factors that interact to affect it. Therefore, to effectively interpret results of leaf tissue analysis, knowledge of nutrient interaction during uptake becomes necessary.

For this purpose, researchers developed different methods to assess the nutritional status of plants, e.g., the critical value approach (CVA) and sufficiency range (SRA). Yet, these methods fail to account for nutrient interactions and magnitude of limitation of each nutrient²¹. In addition to that, SRA is sensitive to the stage of plant development, consequently, implying that diagnosis must be done at the same stage for which the reference sufficiency range was established²². With the aim to correct the defects in the CVA and SRA, Beaufils²¹ developed the "Diagnosis and Recommendation Integrated Systems" (DRIS). The DRIS is based on the calculation of an index for each nutrient, taking into account its interaction with other nutrients²³. The main advantage of DRIS is that it considers the nutrient contents in ratio with other single elements (e.g., N/P, P/N, N/K, K/N...), thereby, nullifying the problem of biomass accumulation and sensitivity in changes of tissue nutrient concentration as they age^{21,24,25}. The use of DRIS in assessing nutritional imbalance of plants also becomes more recognized due to its ability to rank nutrient limitations for plant demand, and herewith making the achievement of nutritional balance possible. The objectives of this paper were to (i) study the effect of nutrient treatments on maize yield, and (ii) diagnose nutrient imbalance using the Diagnosis and Recommendation Integrated System (DRIS) in the maize belt of northern Nigeria.

Materials And Methods

Site description. The field experiments were conducted during 2017 rainy season within the maize belt of northern Nigeria. Due to sufficient solar radiation, a well-defined rainy season and low incidences of pests and diseases, the area is considered of highest maize production potential in Nigeria^{26,27}. The area comprises of five major agro-ecological zones; namely, Derived savanna (DS), southern Guinea savanna (SGS), northern Guinea savanna (NGS), Mid-altitude (MA), and Sudan savanna (SS). Dominant soils are Ferric Luvisols, Acrisols, Cambisols, Nitosols, Leptosols and Lixisols. Rainfall is unimodal and decreases in amount from 1500 mm per annum in the Derived savanna to less than 700 mm in the Sudan savanna, and in

duration from seven to four months northward (FFD, 2012). Mean annual temperatures during the planting season range from 26 to 33 °C respectively throughout the region²⁸.

Experimental design and treatment structure. The experiment was established in thirty farms selected across the study area. Each site was considered as a replicate. The treatments were nine different fertilizer nutrient combinations, which consisted of a Control which received no applied nutrients, NK, NP, PK, NPK, and NPK + treatments; NPKB, NPKS, NPKZn and NPKSZnB. It is a special design for a nutrient omission trials in which N, P and K are alternately omitted from the NPK application and single micronutrients (including S, B or Zn) alternately added to the NPK treatment, with one treatment having all nutrients applied (NPKSZnB). The plots were laid out in a randomized complete block design; with 3 blocks each consisting 3 plots. Each plot consisted of 6 ridges (spaced at 0.75m apart) of 5 m length to give a gross plot area of 22.5 m². The plots were separated by an unplanted ridge or 1 m when ridge spacing was not applicable. The nutrients N, P and K application rates were 140 kg N ha⁻¹, 50 kg P₂O₅ ha⁻¹ and 50 kg K₂O ha⁻¹ respectively. Nitrogen (N) was applied as urea in three equal splits, i.e., at planting (basal), at 21 and 42 days after emergence (DAE), while full doses of the other nutrients were applied during planting. P was applied from SSP, while K was applied using muriate of potash (MOP). Elemental S and Zn (using ZnSO₄) were applied at the rate 10 kg ha⁻¹ while B was applied at 5 kg ha⁻¹ using and Borax.

Maize variety, sowing and harvesting. Sammaz 15; the most commonly grown maize variety in the study area was used in the experiment. The variety is open pollinated, *Striga*, streak virus and drought tolerant/resistant, with 105–110 maturity days. Sowing was done within the best window for planting maize (June and July) of the area. Two seeds per hole sown at 0.25 m intra-row and 0.75 m inter-row spacings were thinned to one plant per hill between 10 to 14 days after sowing to give an average recommended plant population of 53,333 plants ha⁻¹. Plants within a net plot area (two innermost rows minus 1m from both ends of each row) of 2.25 m² were harvested at full maturity. The harvested plants were separated into stems and cobs, and dried. The dried cobs were shelled and the grains weighed for yield determination. The grain yield was expressed in kg ha⁻¹ after weighing the shelled grains and adjusting the moisture to 15% using grain moisture tester as reported by Kamara et al.².

Ear leaf sampling and analysis. Ten maize ear leaf samples were randomly collected from the second and fifth ridges immediately at the beginning of silk stage (female flower initiation stage). The samples were washed with distilled water and allowed to air dry. The dried samples were then ground with agate pestle and mortar and analyzed 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 on a Technicon autoanalyzer using the indophenol blue method. For the determination of available Sulphur, ball-milled samples were digested with nitric acid (HNO₃) 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). Available Phosphorus, cations (K, Ca and Mg) and micronutrients (Zn, Fe, Cu, Mn and B) were analyzed by first dry-ashing the samples for 4 hours at 550°C and then prepared and read on ICP-OES. All the methods used in this study for plant sampling are in compliance with the IUCN policy on Research Involving Species at Risk of Extinction, and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

DRIS analysis. For establishing the DRIS norms, the data was divided into two sub-populations i.e., a low (non-reference) and high yielding (reference) populations. This was done by first sorting the plots according to yield in decreasing order and then portioning the data into the two sub-populations. The high yielding population comprised plots having grain yield higher than the Mean + 0.5* standard deviation – the mean and the standard deviation were calculated from the entire dataset. Thus, plots with yields ≥ 3,766 kg ha⁻¹ were considered high yielding, and they constituted 31% of the entire dataset. DRIS norms and coefficients of variations (CVs) were derived according to the procedure by Walworth and Sumner²⁴. Mean value for each nutrient pair (example, A/B), their corresponding CV, and variance were then calculated separately for the two sub-populations. The mean value of each dual nutrient ratio in the high-yielding population were used as DRIS norms²⁴. To select the dual nutrient ratio order (A/B or B/A) for calculating the DRIS indices (Eqs. 1 and 2, or 3 and 4), the variance of the low yielding sub-population was divided by that of the high yielding sub-population. It is theoretically expected that the data of the low yielding population would be more unbalanced and therefore should have larger variance than the high yielding one. The dual nutrient ratio with higher variance ratio value were therefore selected and used in the diagnosis. The DRIS indices were calculated based on ratios of each nutrient relative to all other nutrients using the equations below by Walworth and Sumner²⁹.

The DRIS index is the mean deviation of the dual nutrient ratios of a given nutrient from their respective norm values. The nutrients were ordered based on their DRIS index value, to determine the order of the degree of limitation to produce the nutrient limitation diagnosis. 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 more negative index value for a given nutrient, indicates lower amount or shortage relative to other nutrients. Alternatively, higher positive index value of a nutrient indicates excess presence of that nutrient relative to others³⁰.

If we consider hypothetical nutrients A, B through N, then:

$$A \text{ index} = \frac{f\left(\frac{A}{B}\right) + f\left(\frac{A}{C}\right) + f\left(\frac{A}{D}\right) + \dots + f\left(\frac{A}{N}\right)}{n} \quad (1)$$

$$B \text{ index} = \frac{-f\left(\frac{A}{B}\right) + f\left(\frac{B}{C}\right) + f\left(\frac{B}{D}\right) + \dots + f\left(\frac{B}{N}\right)}{n} \quad (2)$$

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

$$f\left(\frac{A}{B}\right) = \left[\frac{\left(\frac{A}{B}\right)}{\left(\frac{a}{b}\right)} - 1\right] \times \frac{1000}{CV} \quad (3)$$

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

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

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, and $f(A/B)$ is a function of nutrients A and B ratio. The 1000 multiplier in equations 3 and 4 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.

Statistical analyses. Descriptive statistics was carried out to study the distribution of the soil, yield and ear leaf data using mean, range and coefficient of variation (CV). Relationship between respective nutrient ear leaf content and DRIS index was studied using a regression analysis, with nutrient ear leaf content as the independent variable and the DRIS index as the dependent variable. Simple scatter plot of the DRIS indices was plotted to study the relationships among the nutrient DRIS indices. Comparison GGE biplot was drawn with sectors to demarcate most responsible nutrient treatment which influence nutrient DRIS indices based on mean and stability. All statistical analyses were done in GenStat 17th edition statistical package.

Results

Physico-chemical soil properties at the experimental sites. Soil properties across the experimental sites showed wide variation, except for pH which has a low coefficient of variation (CV) of 7.9% (Table 1). Average pH value (6.6) indicated that the soils can be generally regarded as slightly acidic. Total soil organic carbon (SOC_{tot}) was very low, and this condition seem to be moderately consistent across the sites. Average total nitrogen (N_{tot}) (0.65 g/kg) and available phosphorus ($P_{avail.}$) (2.4 mg/kg) are rated 'very low' according to Nigerian National Special Programme on Food Security NSPFS³¹ and Esu³² fertility classification of Nigerian Savanna soils. According to the same fertility rating, average K (0.79 $cmol_c\ kg^{-1}$) is considered optimum to high, Mg (1.25 $cmol_c\ kg^{-1}$) is considered 'low' to 'moderate', and Ca (3.67 $cmol_c\ kg^{-1}$) Zn (5.02 $mg\ kg^{-1}$), Fe (118.8 $mg\ kg^{-1}$), and Mn (151.2 $mg\ kg^{-1}$) all fall under the 'optimum' sufficiency range. Boron (0.09 $mg\ kg^{-1}$ on average) is rated as 'very low'. However, the CVs of Mg (66%), B (103 %), and Zn (69%) were the highest among the soil properties and further indicate high variation across the sites. Percentage sand was on average was 54.7 % and did not vary too much, with the texture classes predominantly sandy clay loam and sandy loams.

Maize grain yield. Maize grain yield ranged from 101 to 7,450 $kg\ ha^{-1}$ across the nutrient treatments (Tables 2a and 2b). Except under NPKB plots, average grain yield of the NPK and NPK + treatment plots were above 3,000 $kg\ ha^{-1}$. The NPKZn treatment increased grain yield by 28% compared to NPK. Omission of either N or K (in PK and NP treatment respectively) both reduced yield by 59%, and that of P (NK treatment) reduced yield by 56% compared to that of the NPK treatment. On average, yield for the Control plot was below 1,500 $kg\ ha^{-1}$. The highest coefficient of variation (66% and 65%) of yield under Control and NP respectively indicated that the experimental fields were highly variable in terms of fertility status.

Ear leaf nutrient concentration. Ranges of nutrient ear leaf concentrations across the treatments is shown in Tables 2a and 2b. All treatments with N application resulted in higher N ear leaf concentration compared to the Control and PK treatments. Phosphorus (P) concentration ranged from 0.04% in Control treatment to 0.39% in NPK and NPKZn treatments. Higher average P ear leaf concentrations were observed for the NP, PK and all NPK treatments, and were significantly different from that of the Control (0.16%) and the NK (0.20%). For K, there was no significant differences between the various treatments, though the NK and NPK + treatments had slightly higher ear leaf K concentrations. The omission of K did not reflect in lower average ear leaf concentration. The highest average K ear leaf concentration was observed for the NK treatment. There was no indication that K application in itself led to higher K concentrations in the ear leaf. Average ear leaf concentration of Ca was below 1.23% across the treatments. However, Ca concentration was higher in NPK and NPK + treatments. Magnesium (Mg) concentration ranged from 0.01 to 1.46%. There was little difference in the average Mg and Ca concentrations for the various treatments, only that the Control had a lower concentration for the elements. Sulphur concentration ranged from 0.01 to 1.2 % across all treatments. With the exception of NPKSZnB treatments (0.05%), the S ear leaf concentration for all the NPK related treatments was slightly elevated (ranging from 0.71–0.84% on average) compared to the Control, NP, NK and PK treatments, which seems to suggest there some relationship to the yield level.

There was no clear link between the micronutrients in the ear leaf to any of the treatments. Highest concentration of Cu was 11.25 $mg\ kg^{-1}$ for the Control treatment and the lowest concentration of 2.24 $mg\ kg^{-1}$ was found for the NPKB and PK treatments. Manganese (Mn) concentration was generally higher in plots where N was applied. There was an average of 35% increase of Mn ear leaf concentration across N treatments compared to when N was omitted and for the Control. Among the NPK and NPK + treatments the mean Zinc (Zn) concentration was highest for the NPKZn (23.5 $mg\ kg^{-1}$) and the NPKSZnB (19.9 $mg\ kg^{-1}$) treatments, but not different from the NP and NK treatments (~ 24.0 $mg\ kg^{-1}$). This suggest a possible effect of the Zn application, whereby the dilution of the Zn concentration in the higher yielding treatments was compensated by the Zn application under the NPKZn and NPKSZnB treatments. Boron (B) concentration in the ear leaves ranged from 0.33 to 5.85 $mg\ kg^{-1}$. Surprisingly lower B concentrations were

found for the NPKB and NPKZn treatments. Concentration of Fe was averagely high across the treatments, with highest means recorded with NPKS and NPKZn treatments.

DRIS indices. The DRIS ratios were selected based on higher variance ratio between the low and high yielding sub-populations. The variance ratios of all the selected dual ratios of the low against the high yielding sub-populations were ≥ 1 , which indicate relative higher variance of the low yielding sub-population. The variance ratios of N/K (153.7) and B/Zn (118) (Table 3) were the highest among the ratios.

Percentage of plots with negative DRIS indices for the nutrient treatments (Table 4) indicates that PK, NPKS and NPKZn treatments have highest percentage of plots with negative DRIS nutrient indices. Among the nutrients, B had the lowest percentage of plots with negative index values across the nutrient treatments, while Fe had the highest number of negative index plots. Among the nutrient omission treatments, the PK treatment showed the highest frequency of plots with negative N index which reflects the impact of the N limitation on the DRIS index value. The NK, NP and NPK treatments showed lower percentage (33.3 and 40.0% respectively) of plots with negative N DRIS index indicating that N was imbalance due to higher concentrations of other nutrients. The percentage of plots with negative N DRIS index for the NPK and NPK + treatments ranged from 40.0 to 64.3% apart from the NPKS treatment which had 84.6% of plots with a negative N DRIS index value. The slightly higher percentage for the NPKZn treatment indicates a possible dilution of the N concentration on the ear leaf because of the higher yield.

The percentage of negative P DRIS index value plots was lowest for the 'Control' treatment (*viz.* 58.3%) and for the other treatments the percentage did not differ much, with the percentage ranging between 64.3 to 84.6%, indicating that for all treatments the relative P concentration is lower than for the reference population. There was no marked decrease in percentage of the plots with negative P DRIS Index value for the NP and PK treatments or a marked increase in percentage for the NK treatment (P-omission treatment).

Omission of K (NP treatment) resulted in a reduced percentage (33%) of negative K index plots, contrary to what would be expected and the NK treatment showed an unexpected high percentage of plots with negative K DRIS index values. Otherwise, the percentage of negative plots varied between 46.75 and 76.9% indicating that the relative K concentration was generally lower than for the norms where K was involved. The NPKS increased number of plots with negative Fe index by 19% and that of B by 13% compared to NPK. Ca index however, becomes increasing negative in plots where Zn was applied or N was omitted from NPK. Both the PK and NPKZn treatments resulted to relatively higher percentages of plots with negative DRIS index scores for most of the nutrients. For the NPKZn, this was also true for most nutrients except for the N and P DRIS indices and to lesser extent for the S DRIS index score. The generally lower percentage of plots with negative B DRIS index values, across the various treatments, indicates that the relative B ear leaf concentrations of the low sub-populations was not much different, which probably indicates that the B concentration was low across the board. On the other hand, the percentage of negative plots with negative Fe DRIS index values was relatively high, irrespective of the treatment, indicating that the reference population of plots with high yields have relatively lower Fe concentration in the ear leaves. The same applies to Mg, where we find high percentages of plots with negative DRIS scores across the treatments, indicating that the reference population has a relatively low Mg ear leaf concentration, indicating a possible nutrient limitation.

Table 5 shows the ranking of the nutrient limitations based on the DRIS index value for each treatment. For the interpretation one has to take account of the treatment and the nutrients. N ranked high (2nd) in the order of nutrient limitations for the PK treatment, while it ranked lower for other treatments where N was applied, indicating N was highly limiting. For P and K, the pattern was less clear and also not ranking highly in terms of nutrient limitations for the respective nutrient omission treatments. Sulphur ranked high in the order of nutrient limitations for the NK, NP and PK treatments as well as for the NPK and NPKSZnB treatments. It ranked low for the NPKS and the NPKZn. This suggest that S was clearly a limiting nutrient, with the low ranking for the NPKZn explained by the possible positive effect of Zn application on the availability of S. Zinc ranked high in the order of nutrient limitations for the 'Control', NK and NP treatments, but did not seem to be specifically prominent for the other high yielding treatments. Boron ranked lowest based on its DRIS index value for seven of the nine treatments and ranked highest for the NPKZn treatment. Note that the NPKZn treatment generated the highest yields and the corresponding plots will therefore constitute a large part of the reference population. The negative interaction with B thus explains the generally low percentage of plots with negative B DRIS index scores and consequently low ranking in the order nutrient limitation for the remaining treatments other than NPKZn. Therefore, the low ranking in order of nutrient limitation in this case does not necessarily signify that B is not a limiting nutrient.

With regards to the nutrients that are not included in any of the treatments, Mg ranked high in the order of nutrient limitations for all the treatments (often ranking first, second or third). This is also consistent with the relatively high percentage of plots with negative Mg DRIS index values. Therefore, among this group Mg is considered the most important yield limiting nutrient. Secondly, Fe ranked relatively high, ranking second to sixth depending on the treatment. Also, in this case it is consistent with the generally high score of plots with negative Fe DRIS index values across the treatments. No particular evidence of Mn limitation was observed in any of the treatments. Noteworthy is the high ranking in order of nutrient limitation for the NPK (3rd) and the NPKZn treatment (2nd), indicating possible interaction with Zn application. A similar observation was made for Ca and Cu, in that there was no particular evidence that the nutrients might be limiting, but that for particular treatments the high ranking is noteworthy. In this case the NPKS, NPKB and the NPKSZnB treatments show high ranking of Ca and Cu (Table 5) suggesting an interaction with S and B on the availability of these nutrients.

Relationship between nutrients ear leaf concentration and DRIS indices. Figure 1 show varied strengths of relationship between ear leaf nutrient concentration and corresponding DRIS index values from weak to strong. The Figure show that ear leaf nitrogen concentration is a poor indicator of N index in DRIS with a low R^2 value (0.24). The figure also shows a strong proportionate increase in DRIS index values of S and Cu at corresponding higher ear leaf nutrient concentrations. The DRIS index values of K, S and Zn were the most strongly explained by ear leaf concentration among the analyzed nutrients ($R^2 = 0.73$). Higher ear leaf nutrient levels of K, Mg, Ca, and Zn correspondingly showed strong influence for consistent decrease (negativity) in DRIS indices.

GGE biplot analysis. Figure 2 show relationships among the nutrient DRIS indices on a biplot. PC1 explained 34 % of the total variation in the data. The PC1 was strongly influence by the positive correlations with the DRIS indices Mn, N, Fe, P and B. Additional 22.3 % of the variance was explained by PC2; and was positively correlated with index of Zn with negative correspondence with Cu index. Indices of P, B, Mn, N, B, K, and S were positively correlated with each other; indicating a synergistic relationship. Indices of Zn and Mg were positively correlated with each other and negatively with Cu and Ca. indicating a possible antagonistic association between them.

The 'Which-Won-Where' view of the GGE biplot (Fig. 3) show the degree of influence of nutrient treatments on the nutrients DRIS indices. The general rule in GGE is that nutrient indices that share the same sector with a particular nutrient treatment are the most associated with that treatment. The indices of Zn and Mg formed a cluster and share the same sector with Control and NK treatments. The largest cluster was formed by the indices of K, S, P, Mn, Fe, B and N, and found in the sector of PK treatment. This sector is bordered closely by Control, indicating that these two treatments have similar DRIS index values for most of the nutrients within that cluster. In the diagnosis, Cu and Ca indices became more consistently important yield limiting under NPKZn and NPKSZnB. The DRIS nutrient indices associated with NPK, NPKS and NPKB did not show any consistent pattern of occurrence.

Discussion

Maize yield was significantly affected by the nutrient treatments. The results reflected the responsiveness of maize to the applied nutrients compared to when no nutrient was applied. As reported by Shehu et al.⁵, maize yield can reach > 5 tons per hectare in northern Nigeria when nutrient deficiencies are properly addressed. Application of NPKZn gave the highest yield. This indicates relative response to Zn in the study area. The result confirmed the findings of Garba et al.³³, that Zn application increased maize yield in some parts of Nigeria. The low CV of yield under NPKZn treatment in this study also confirmed the stability of maize yield response to Zn in the study area. This may be due to the improvement of fertilization uptake caused by Zn application³⁴. Yield decrease due to B application observed in this study has also been previously reported by Shehu et al.⁵. Results of the soil analysis also confirmed B deficiency in the soils in this study, however, since there is dearth information about B application rates, it is possible that the B application rate used in this study was higher than required, and might have resulted to B toxicity, or lower than required for significant B response. In this sense it can be argued that the high amount of soil Zn might have countered B expression as similarly reported by Rehman et al.³⁵.

Occurrence of negative DRIS index of N was higher in the treatments where no nitrogen was applied (Control and PK) or when other nutrients were applied with NPK (especially NPKS and NPKZn). A significant increase in ear leaf concentration of N beyond the critical level of 2.6% when N was applied also indicated that maize responded to N treatments. The relationship between N DRIS index and N ear leaf concentration discovered in this study indicated a proportionate increase in N balance index at higher ear leaf concentrations. But since this relationship is weak, emphasis could not be made concerning the negativity of the N balance index in some plots where N was applied. In a similar study, Reis Júnior et al.³⁶, Silveira et al.³⁷, Nachtigall and Dechen³⁸ observed very low correlation coefficients for N and S between their ear leaf concentrations and respective DRIS balance indices, indicating that other important factors play role in the nutrient balance. The current study was on-farm that cut across wide range of cropping potentials. This could have possibly caused a large variation in the ear leaf content of nutrients due to different previous nutrient management which affected the N balance. In progressive diagnosis, Sumner³⁹ discovered that negative N index was not an indication of deficiency, but an imbalance caused by continuous application of P, S and K. Similarly, the high percentage of negative N index plots of NPKS and NPKZn treatments (compared to the NPK) might not directly be related to N deficiency, rather an imbalance as a result of S and Zn additions. This can be attributed to the very low variance between the dual nutrient ratios (N/S and Zn/N) of the sub-populations⁴⁰. It can therefore be concluded that N diagnosis using these treatments is likely ineffective in this study. The K ear leaf contents for NK and NPKZn were within the sufficiency range (1.2–1.7%) for the region reported by Reuter et al.⁴¹, this thus indicates some level of K response. However, K application under PK and NPK, showed a significantly lower K leaf concentration below the critical limit. Therefore, it can be concluded that K response is likely a site-specific scenario. The strong inverse relationship between K ear leaf content with DRIS index indicates that K application negatively increase K imbalance in many situations. Further, the table for order of nutrient limitation indicated that K was limiting in both scenarios of omission and application. As indicated by Kihara et al.⁴² response to K may be very patchy. Though the lower yield of NP observed indicates the significance of K, the large variation in the results (CV is 65%) further confirmed variable response to K in the area. Shehu et al.⁵ and Nziguheba et al.¹⁰ both indicated that K is not a limiting nutrient for maize production in some soils within the study area. Inconsistent response to K could be attributed to the large deposit of K-feldspars as the dominant mineral²⁷ in rocks of the basement complex and dust deposition of K during the harmattan¹⁰ which resulted in inherent high K concentrations in the soil, but these may have been depleted depending on the type of land use and land use history and caused variable response.

The ear leaf concentration of P was below the critical limit (0.27%) established by Reuter et al.⁴¹, apart from those of NPK and NPKS treatments (0.28% and 0.27% respectively). Effect of P application did not directly reflect in the P balance index except for the NPKS where P was the second least important limiting nutrient. The higher ear leaf content and lower limitation order of P under the NPKS is not surprising as P and S interact in synergy to

influence uptake of each. Studies in Nigeria by Ogunsola and Adetunji⁴³ recommended S application for enhanced P uptake by maize. The high recurrence of negative DRIS P balance index and increased order of P limitation for NPK and NPKB treatments is more difficult to explain, especially as P uptake is reported to be positively influenced by B application⁴⁴. But since B is not an important limiting nutrient in most of the diagnosis results, it is likely that rate of B applied in this study might have affected the P balance. The strong positive correlation between P and B indices in this study further confirms the effect of B on P. Also, most of selected dual nutrient norms that involved P for the high yielding sub-population (which were used for the diagnosis) were not much higher than their corresponding low yielding sub-population. This means that the DRIS index calculated for P involved some samples from high yielding but unbalance sub-population, and this must have affected the P DRIS index. Though the norms involving P in this study are in most cases higher than those obtained by others like Serra et al.⁴⁵ and Anabela et al.⁴⁶ in other continents, yet the ear leaf P contents were below the sufficiency limit, this therefore suggest that nutrient norms cannot be universally adopted.

Range of Ca concentration in the ear leaves was small as indicated by a low CV (< 25%) for most of the treatments. The average concentration of Ca was obviously above the critical concentration levels of 0.21% and 0.30% established by Reuter et al.⁴¹ and Nziguheba et al.¹⁰ respectively. Although, Ca was not a treatment in this study, some amount of Ca (~ 15 %) is contained in TSP fertilizer that was used as source of P in this study, which might be the reason for the high Ca ear leaf concentrations, especially where P was applied. Negative DRIS Ca index is also confirmed to be associated more with the NPK treatments as shown in the Which-Won-Where plot. The percentage fields with negative Ca index was also lowest in the NK confirming the earlier suggestion. In the WBE experiment, Nziguheba et al.¹⁰ also reported negative Ca index, even though ear leaf concentration of Ca was above the critical limit, and they concluded that the negativity indicated Ca was imbalanced not deficient. Therefore, we conclude also that the negative Ca index observed in this study translates to imbalance. This further confirmed by the high level of Ca content in the soil observed in this study. Adequate amount of Ca was reported by Agbenin⁴⁷, in most soils in West African savanna except in case of long-term continuous cultivation and without Ca application. Negative S indices was more associated more with PK treatment and less with NPKS and other treatments. Contrary to the conclusion made by Nziguheba et al.¹⁰ that pronounced imbalances of Mg and Ca hide S effect, our results revealed that S is next most critical nutrient after deficiencies of N, P and K were addressed.

The average B ear leaf concentration for all the treatments was within the sufficiency range of 2–5 mg kg⁻¹ established for maize by Kelling⁴⁸. The B treatments resulted in relatively higher B DRIS index. However, it did not reflect in the B leaf concentration, which was relatively lower for the NPKB treatment. The results were similar to that of Aref⁴⁴, where the Control and B treatments were not significantly different for ear leaf concentration. The occurrence of negative index of B across the treatments was however lower compared to those of the other nutrients. B was also shown to be least important limiting nutrient except under NPKZn. Though previous studies⁴⁹ have showed widespread deficiency of B in the soils within this study area, but considering the very narrow range (0.3-1 mg kg⁻¹) between deficiency and excess levels for soil B, it could be assumed that the B application rate (5 kg ha⁻¹) used in this study might have been high enough to have caused B toxicity, and subsequently, the low yield of the B treated plots. The Zn ear leaf concentrations were higher than those reported by Nziguheba et al.¹⁰ in the same region. Our findings seem to suggest an effect of Zn application on the ear leaf content, with the NPKZn and the NPKSZnB treatments showing slightly elevated Zn ear leaf concentrations among the NPK treatments. The Zn ear leaf concentration for the NK and NP treatments were relatively high (though not significantly different from the other treatments) which also seems to be reflected in the higher Zn DRIS index values (- 8.4 and - 3.1 respectively – not shown). The pronounced limitations by Ca and Cu seem to have masked the effect of Zn in many of the treatments. Other analyzed micronutrients (Cu, Mn and Fe) in this study were mostly above their critical concentration levels with all treatments except when N was not applied, or when B was applied.

Conclusions

The nutrient treatments used in this study significantly affected the ear nutrient concentration, DRIS indices, and maize yield. Omission of any of the major macro nutrient (N, P and K) resulted in lower yield than when they were applied. Ear leaf concentrations of most nutrients correlated well with their corresponding DRIS indices. The DRIS method identified nutrient imbalance for maize production in the maize belt of Nigeria. The diagnosis indicated consistent imbalances of unused secondary macro and micronutrients (Mg, Cu and Ca) in most NPK treatments; revealing their relative importance in maize nutrient management in the area. The Which-Won-Where showed that the frequent occurrence of negative imbalances of nutrients associated with PK treatment is systematic rather than random. None of the diagnosed nutrients is within the balance range of -1 to +1 even under the highest yield treatment (NPKZn); indicating that yield can be further increased when nutrient imbalances are further addressed. DRIS diagnosis is complementary to soil analysis in diagnosis of nutrient limitations and to making recommendations on balanced crop nutrition. Balanced nutrition of maize in the maize belt of Nigeria should target the application of varying amounts of N, P, K, Mg, S and Zn, depending on the soil condition. Because of complexities of nutrient interactions during uptake, it is hardly possible to realize a balanced nutrition. However, differentiating the application of antagonistic nutrients (especially the divalent cations) into foliar or soil methods is recommended for a more balanced maize nutrition.

Declarations

Acknowledgements

This work was funded by the Bill and Melinda Gates Foundation (BMFG) through the 'Taking Maize Agronomy to Scale in Africa (TAMASA)' project managed by the International Institute of Tropical Agriculture (IITA), and the Centre for Dryland Agriculture (CDA) of Bayero University Kano. Additional fund through the CDA under the Africa Center of Excellence (ACE) project is also acknowledged.

Author contributions

Conceptualization, K.T.A., A.Y.K. and J.M.J.; methodology, K.T.A. and G.N.; formal analysis, K.T.A.; investigation, K.T.A.; resources, A.Y.K., B.V. and J.M.J.; data curation, K.T.A.; writing—original draft preparation, K.T.A.; writing—review and editing, J.H., A.Y.K., J.M.J., G.N., A.M.A., I.B.M. and B.V.; visualization, K.T.A.; supervision, I.B.M.; project administration, J.M.J. and A.Y.K.

Competing interests

The authors declare no competing interests.

Additional information

Request for data and any material used in this study should be directed to K.T.A.

e IUCN Policy Statement on Research Involving Species at Risk of Extinction and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

References

1. Adnan, A. A. *et al.* CERES-maize model for determining the optimum planting dates of early maturing maize varieties in northern Nigeria. *Front. Plant Sci.* **8**, 1118 <https://doi.org/10.3389/fpls01118> (2017).
2. Kamara, A. Y., Ewansiha, S. U., Tofa, A. I. & Yield N uptake N utilization of early maturing, drought and striga-tolerant maize varieties under low N conditions. *Commun. Soil Sci. Plant Anal.* <https://doi.org/10.1080/00103624> (2019).
3. Jibrin, M. J., Kamara, A. Y. & Friday, E. Simulating planting date and cultivar effect on dryland maize production using CERES maize model. *Afr. J. Agric. Res.* **7**, 5530–5536 (2012).
4. FAOSTAT. *Production Statistics (Prodstat)* (Food and Agriculture Organization of the United Nations, Rome, 2018).
5. Shehu, B. M., Merckx, R., Jibrin, J. M., Kamara, A. Y. & Rurinda, J. Quantifying variability in maize yield response to nutrient applications in the Northern Nigerian Savanna. *Agronomy*. **8**, 18 <https://doi.org/10.3390/agronomy8020018> (2018).
6. Shehu, B. M. *et al.* Balanced nutrient requirements for maize in the Northern Nigerian Savanna: Parameterization and validation of QUEFTS model. *Field Crop. Res.* **241**, 107585 <https://doi.org/10.1016/j.fcr> (2019).
7. Rurinda, J. *et al.* Science-based decision support for formulating crop fertilizer recommendations in sub-Saharan Africa. *Agric. Syst.* **180**, 102790 <https://doi.org/10.1016/j.agsy> (2020).
8. Vanlauwe, B., Six, J., Sanginga, N. & Adesina, A. A. Soil fertility decline at the base of rural poverty in sub-Saharan Africa. *Nature Plants*. **1**, 15101 (2015).
9. Kamara, A. Y., Ekeleme, F., Jibrin, J. M., Tarawali, G. & Tofa, I. Assessment of level, extent and factors influencing Striga infestation of cereals and cowpea in a Sudan savanna ecology of northern Nigeria. *Agric. Ecosyst. Environ.* **188**, 111–121 (2014).
10. Nziguheba, G. *et al.* Assessment of nutrient deficiencies in maize in nutrient omission trials and long-term field experiments in the West African Savanna. *Plant Soil*. **314**, 143–157 (2009).
11. Weil, R. & Mughogho, S. Sulphur nutrition of maize in four regions of Malawi. *Agron. J.* **92**, 649–656 (2000).
12. Chikowo, R., Zingore, S., Snapp, S. & Johnston, A. Farm typologies, soil fertility variability and nutrient management in smallholder farming in Sub-Saharan Africa. *Nutr. Cycl. Agroecosyst.* **100**, 1–18 (2014).
13. Giller, K. E. *et al.* Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agric. Syst.* **104**, 191–203 (2011).
14. Tiftonell, P., Vanlauwe, B., Corbeels, M. & Giller, K. E. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. *Plant Soil*. **313**, 19–37 (2008).
15. Bado, V. & Bationo, A. Integrated management of soil fertility and land resources in sub-Saharan Africa: involving local communities. *Adv. Agron.* **150**, <https://doi.org/10.1016/bs.agron> (2018).
16. Shaibu, A. S., Jibrin, M. J., Shehu, B. M., Abdulrahman, L. B. & Adnan, A. A. Deciphering the stability and association of ear leaves elements with nutrients applied to grain yield of maize. *Pertanika J. Trop. Agric. Sci.* **41** (3), 1275–1287 (2018).
17. Parent, L. E. Diagnosis of the nutrient compositional space of fruit crops. *Revista Brasileira de Fruticultura*. **33** (1), 321–334 (2011).
18. Urano, E. O. M. *et al.* Avaliação do estado nutricional da soja. *Pesquisa Agropecuária Brasileira*. **41** (9), 1421–1428 (2006).
19. Serra, A. P. *et al.* Establishing DRIS norms for cotton with different selection criteria for the reference population. *Pesquisa Agropecuária Brasileira*. **48**, 1472–1480 (2013).
20. Maia, C. E. Fertilization response likelihood for the interpretation of leaf analyses. *R. Bras. Ci. Solo*. **36**, 437–445 (2012).
21. Beaufils, E. R. *Diagnosis and Recommendation Integrated System (DRIS). A general scheme for experimentation and calibration based on principles developed from research in plant nutrition.* 1–132 (Soil Science Bulletin No. 1, University of Natal, 1973).

22. Baldock, J. O. & Schulte, E. E. Plant analysis with standardized scores combines DRIS and sufficiency range approaches for corn. *Agron. J.* **88**, 448–456 (1996).
23. McCray, J., Rice, R., Ezenwa, I., Lang, T. & Baucum, L. Sugarcane Plant Nutrient Diagnosis, 12 (University of Florida – IFAS Extension (Ed.), Florida 2013).
24. Walworth, J. L. & Sumner, M. E. The Diagnosis and Recommendation Integrated System (DRIS). *Adv. Soil Sci.* **6**, 148–185 (1987).
25. Singh, N. P., Awasthi, R. P. & Sud, A. Diagnosis and recommendation integrated system (DRIS) norms for apple (*Malus x Domestica* Borkh. L. CV. Starking Delicious) in Himachal Pradesh. *Indian J. Hortic.* **53** (3), 96–204 (2000).
26. Adewopo, J. B. Smallholder maize-based systems Multifunctional land uses in Africa: sustainable food security solutions In: Earthscan Food and Agriculture series. (ed. Elisabeth, S. & Madelene, O.) 114–129(Routledge, 2019).
27. Aliyu, K. T. *et al.* Delineation of soil fertility management zones for site-specific nutrient management in the maize belt region of Nigeria. *Sustainability.* **12**, 9010 <https://doi.org/10.3390/su12219010> (2020).
28. FFD. *Fertilizer use and management practices for Nigeria.* (4th edition) (Federal Fertilizer Department, Federal Ministry of Agriculture and Rural Development, Abuja, Nigeria, 2012).
29. Walworth, J. L. & Sumner, M. E. Foliar diagnosis: A review In: *Advances plant nutrition* (ed. Tinker, B. & Lauchli, A. V.)193–241(Praeger Publishers, NY, 1988).
30. Walworth, J. L. & Sumner, M. E. Foliar diagnosis-A review. In: *Advances in Plant Nutrition* (ed. Tinker, B. P.) (Elsevier, New York, 1986).
31. NSPFS. *Nigerian soil fertility rating and thematic fertility maps. National Special Programme for Food Security (NSPFS)* (Abuja, Nigeria, 2005).
32. Esu, I. E. Detailed soil survey of NIHORT farm at Bunkure Kano state, Nigeria. Page 27–37 (Ahmadu Bello University Zaria; Kaduna, Nigeria 1991).
33. Garba, I. I. *et al.* Response of maize to secondary nutrients and micronutrients in the Guinea savanna of Nigeria. *J. Agron.* **19**, 120–130 (2020).
34. Cakmak, I., McLaughlin, M. J. & White, P. Zinc for better crop production and human health. *Plant Soil.* **411**, 1–4 (2017).
35. Rehman, A., Farooq, M., Ozturk, L., Asif, M. & Siddique, K. H. M. Zinc nutrition in wheat-based cropping systems. *Plant Soil.* <https://doi.org/10.1007/s11104-017-3507-3> (2017).
36. Reis Junior, R. A., Corrêa, J. B., Carvalho, J. G. & Guimarães, P. T. G. Diagnose nutricional de cafeeiros da região sul de Minas Gerais: normas DRIS e teores foliares adequados. *Revista Brasileira de Ciência Solo.* **26** (3), 801–808 (2002).
37. Silveira, C. P., Nachtigall, G. R. & Monteiro, F. A. Testing and validation of methods for the diagnosis and recommendation integrated system for signal grass. *Scientia Agric.* **62** (6), 520–527 (2005).
38. Nachtigall, G. R. & Dechen, A. R. DRIS use on apple orchard nutritional evaluation in response to potassium fertilization. *Commun. Soil Sci. Plant Anal.* **38** (17), 2557–2566 (2007).
39. Sumner, M. E. Diagnosing the Sulphur requirements of corn and wheat using foliar analysis. *Am. J. Soil Sci. Soc.* **45**, 87–90 (1981).
40. Mourão Filho, F. A. A. & DRIS Concepts and applications on nutritional diagnosis in fruit crops. *Sci. Agric.* **61** (5), 550–560 (2004).
41. Reuter, D. J. *et al.* Temperate and tropical crops. (In: *Plant analysis: an interpretation manud.* Reuter, D.J. & Robinson, J. B.) 83–284(CSIRO, Australia, 1997).
42. Kihara, J. *et al.* Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agric. Ecosyst. Environ.* **229**, 1–12 (2016).
43. Ogunsola, K. E. & Adetunji, M. T. Effects of phosphorus and sulphur on dry matter yield of maize (*Zea mays*) in some soils at Abeokuta, Ogun state, Nigeria. *J. Trop. Agric, Food, Environ. Ext.* **15** (2), 1–8 (2016).
44. Aref, F. Iron, copper and manganese concentration in maize leaf as influenced by soil and foliar application of zinc sulfate and boric acid. *Int. J. Academic Res.* **3**, 1080–1087 (2011).
45. Serra, A. P. *et al.* Diagnosis and Recommendation Integrated System (DRIS) to assess the nutritional state of cotton crop in Brazil. *Am. J. Plant Sci.* **5**, 508–516 (2014).
46. Anabela, C., Óscar, P., Mário, C. & Jorge, Q. The diagnosis and recommendation integrated system (DRIS) – first approach for the establishment of norms for vineyards in Portugal. *Ciência Téc. Vitiv.* **30** (2), 53–59 (2015).
47. Agbenin, J. O. Soil saturation extract composition and sulfate solubility in a tropical semiarid soil. *Soil Sci. Soc. Am. J.* **67**, 1133–1139 (2003).
48. Kelling, K. A. Soil and applied boron. Downloaded from <http://corn.agronomy.wisc.edu/Management/pdfs/a2522.pdf> (2010).
49. Oyinlola, E. Y. & Chude, V. O. Status of available micronutrients of the basement complex rock – derived Alfisols in northern Nigeria savanna. *Trop. Subtrop. Agroecosyst.* **12**, 229–237 (2010).

Tables

Table 1. Selected physico-chemical properties of top soil (20cm) layer in the experimental fields.

Soil property	Average	Minimum	Maximum	CV	Soil property	Average	Minimum	Maximum	CV
pH _{water}	6.63	5.50	7.60	7.9	S _{avail.} (mg kg ⁻¹)	9.80	3.84	48.68	41.7
SOC _{tot} (g kg ⁻¹)	6.06	2.30	11.50	31.8	B (mg kg ⁻¹)	0.09	0.00	0.77	103.1
N _{tot} (g kg ⁻¹)	0.65	0.21	1.15	34.6	Zn (mg kg ⁻¹)	5.02	0.07	14.00	68.9
P _{avail.} (mg kg ⁻¹)	2.40	1.03	7.36	51.8	Cu (mg kg ⁻¹)	2.29	1.47	3.94	34.5
Ca (cmol _c kg ⁻¹)	3.67	0.87	9.17	54.5	Mn (mg kg ⁻¹)	151.2	14.52	333.4	51.9
Mg (cmol _c kg ⁻¹)	1.25	0.29	4.46	66.1	Fe (mg kg ⁻¹)	118.8	77.78	182.9	25.7
K (cmol _c kg ⁻¹)	0.79	0.37	1.42	34.7	Sand (g kg ⁻¹)	540.7	35.0	81.0	21.9
Na (cmol _c kg ⁻¹)	0.10	0.01	0.12	20.3	Silt (g kg ⁻¹)	210.4	9.0	39.0	35.5
ECEC (cmol _c kg ⁻¹)	5.81	1.64	14.58	47.2	Clay (g kg ⁻¹)	230.6	10.0	46.0	38.2

Table 2a. Range of maize grain yield and ear leaf concentrations of macronutrients and micronutrients of fertilizer treatments.

Treatment		Yield (kg ha ⁻¹)	Macronutrients (%)					Micronutrients (mg kg ⁻¹)					
			N	P	K	Ca	Mg	S	Cu	Mn	Zn	B	Fe
Control	Mean	1,445	1.90	0.16	1.03	0.78	0.30	0.63	5.31	111.3	17.7	2.64	39.7
	Min.	101	1.31	0.04	0.02	0.06	0.01	0.05	2.90	61.23	12.5	0.33	25.4
	Max.	3,471	2.61	0.27	1.56	1.03	0.46	1.12	11.25	183.8	27.8	4.09	65.9
	CV (%)	66	17	42	39	29	40	53	42	34	25	39	26
NK	Mean	1,745	2.57	0.20	1.33	0.86	0.35	0.61	5.28	152.6	24.0	2.72	38.6
	Min.	407	2.24	0.07	0.66	0.68	0.17	0.21	3.43	105.0	9.8	1.58	25.3
	Max.	2,697	3.14	0.28	2.52	1.18	0.71	1.03	8.82	202.1	37.1	4.01	55.7
	CV (%)	43	11	31	33	15	49	38	24	21	39	30	24
NP	Mean	1,612	2.69	0.23	1.03	0.96	0.39	0.62	5.78	153.4	23.4	2.94	40.5
	Min.	1,177	2.17	0.10	0.46	0.68	0.23	0.04	2.90	90.0	8.0	1.14	22.8
	Max.	3,465	3.45	0.33	1.91	1.57	0.58	1.25	9.42	225.4	45.5	4.29	68.3
	CV (%)	65	12	24	33	28	29	62	34	23	38	27	27
PK	Mean	1,621	1.77	0.21	1.04	0.98	0.43	0.55	4.27	109.6	14.7	2.74	38.9
	Min.	982	1.28	0.12	0.39	0.62	0.19	0.04	2.25	49.3	8.4	0.96	22.8
	Max.	2,602	2.39	0.29	1.64	1.65	1.46	1.26	7.59	188.0	27.3	3.75	65.9
	CV (%)	28	17	27	33	25	74	55	33	38	39	25	30

Table 2b. Range of maize grain yield and ear leaf concentrations of macronutrients and micronutrients of fertilizer treatments.

Treatment	Yield (kg ha ⁻¹)	Macronutrients (%)						Micronutrients (mg kg ⁻¹)					
		N	P	K	Ca	Mg	S	Cu	Mn	Zn	B	Fe	
NPK	Mean	3,967	2.52	0.28	1.03	1.02	0.34	0.73	5.53	138.0	17.8	2.78	42.0
	Min.	1,419	1.77	0.12	0.53	0.61	0.19	0.04	2.91	93.8	10.7	0.62	25.4
	Max.	5,769	3.37	0.39	1.70	1.61	0.52	1.20	8.84	223.8	30.6	5.85	73.7
	CV (%)	33	15	24	33	28	27	49	35	29	29	43	27
NPKB	Mean	2,386	2.68	0.24	1.13	1.11	0.34	0.76	4.33	156.0	16.1	2.24	38.3
	Min.	599	2.08	0.15	0.51	0.58	0.17	0.15	2.24	98.2	0.6	0.91	25.5
	Max.	3,986	3.59	0.33	1.74	1.73	0.52	1.29	8.19	237.2	24.5	3.95	83.9
	CV (%)	46	16	20	34	27	31	43	41	23	40	38	39
NPKS	Mean	3,776	2.69	0.27	1.18	1.23	0.36	0.71	5.15	145.4	17.4	2.60	51.4
	Min.	1,673	2.19	0.10	0.72	0.78	0.22	0.01	2.84	80.9	7.8	0.80	25.4
	Max.	7,450	3.49	0.37	1.94	2.04	0.51	1.18	8.82	203.5	26.4	4.54	148.6
	CV (%)	38	15	23	30	25	22	42	37	23	28	35	59
NPKZn	Mean	5,097	2.62	0.24	1.24	1.15	0.34	0.84	5.54	142.7	23.5	2.20	51.9
	Min.	3,122	2.07	0.14	0.82	0.69	0.20	0.33	2.83	88.3	17.1	0.47	35.4
	Max.	6,535	3.21	0.39	1.79	1.70	0.53	1.28	10.04	202.7	40.8	3.49	73.5
	CV (%)	22	11	29	24	24	27	39	35	20	28	45	22
NPKSZnB	Mean	4,093	2.52	0.23	1.16	1.19	0.39	0.50	4.79	158.8	19.9	2.84	44.3
	Min.	2,004	2.09	0.15	0.43	0.58	0.17	0.01	2.83	100.4	11.5	1.83	25.4
	Max.	6,887	2.89	0.32	1.97	2.16	0.78	1.16	8.21	241.0	36.9	4.39	85.9
	CV (%)	43	11	24	33	33	39	72	32	21	34	22	35

Table 3. Some selected maize DRIS norms, dual ratios and variance used in the nutrient diagnosis.

Form of expression	Low yielding sub-population			High yielding sub-population			Variance ratio $\sigma^2_{low} / \sigma^2_{high}$
	Norms	CV (%)	σ^2_{low}	Norms	CV (%)	σ^2_{high}	
N/Mg	8.889	158.3	197.968	8.530	33.3	8.051	24.59
N/K	3.615	319.1	133.064	4.460	37.8	0.866	153.72
N/Ca	2.869	118.0	11.452	2.420	20.9	0.257	44.64
N/P	12.126	50.5	37.532	14.199	29.8	11.142	3.37
N/Zn	0.150	219.0	0.155	0.168	37.4	0.003	50.91
Mg/K	0.403	72.1	0.084	0.627	53.7	0.031	2.72
Mg/Ca	0.384	42.2	0.026	0.481	33.4	0.011	2.49
P/Mg	0.787	126.6	0.993	0.821	39.9	0.107	9.26
S/Mg	2.358	161.9	14.569	2.497	51.3	1.643	8.87
Cu/Mg	0.210	256.4	0.289	0.177	45.7	0.007	44.37
Mn/Mg	5.345	208.5	124.179	4.730	34.6	2.681	46.32
Fe/Mg	1.524	153.2	5.456	1.571	54.0	0.718	7.59
B/Mg	0.111	242.7	0.072	0.718	47.9	0.001	60.80
K/Ca	1.189	42.7	0.257	1.609	36.1	0.160	1.61
P/K	0.307	262.1	0.648	0.332	39.8	0.009	75.97
S/K	0.705	321.5	9.049	0.936	58.3	0.169	53.58
Fe/K	0.606	312.5	3.592	0.472	72.2	0.116	30.96
P/Ca	0.258	93.7	0.059	0.337	39.3	0.009	6.76
S/Ca	0.767	123.1	0.893	0.793	51.9	0.141	6.35
Fe/Ca	0.481	115.7	0.309	0.517	36.9	0.026	11.90
B/Ca	0.026	180.0	0.004	0.041	50.3	0.000	38.42
S/P	3.377	107.2	13.092	3.383	57.1	3.563	3.67
Cu/P	0.250	61.9	0.026	0.265	43.2	0.009	2.75
Mn/P	6.976	47.1	10.814	6.431	42.8	7.582	1.43
P/Zn	0.011	277.2	0.003	0.019	43.0	0.000	72.02
Fe/P	2.074	51.6	1.145	2.122	42.9	0.754	1.52
B/P	0.142	53.1	0.006	0.094	48.1	0.002	2.79
S/Zn	0.045	158.5	0.005	0.046	54.6	0.001	9.48
Fe/Zn	2.811	164.7	2.930	2.811	71.3	4.023	5.79
B/Zn	0.245	307.9	0.571	0.313	55.6	0.005	117.97
B/Fe	0.035	41.6	0.001	0.054	54.4	0.001	1.12

Table 4. Percentage of fields with negative DRIS indices for various nutrient treatments.

Nutrient negative index (%) plots											
Treatment	N	P	K	Mg	Ca	S	Cu	Mn	Zn	Fe	B
Control	58.3	58.3	66.7	100.0	50.0	50.0	41.7	66.7	83.3	83.3	16.7
NK	33.3	75.0	91.7	66.7	25.0	66.7	58.3	66.7	58.3	66.7	33.3
NP	40.0	73.3	33.3	73.3	33.3	53.3	46.7	60.0	80.0	66.7	33.3
PK	78.6	78.6	64.3	85.7	85.7	71.4	71.4	85.7	50.0	100.0	14.3
NPK	40.0	80.0	53.3	66.7	40.0	53.3	60.0	66.7	46.7	73.3	33.3
NPKB	46.7	66.7	46.7	60.0	60.0	53.3	80.0	60.0	53.3	66.7	40.0
NPKS	84.6	76.9	61.5	76.9	61.5	61.5	61.5	76.9	53.8	92.3	46.2
NPKZn	64.3	64.3	71.4	78.6	71.4	57.1	71.4	78.6	92.9	85.7	42.9
NPKSZnB	53.8	84.6	76.9	76.9	46.2	46.2	61.5	53.8	61.5	92.3	30.8

Table 5. Order of nutrient limitation for the nutrient treatments.

Treatment	Order of nutrient limitation
Control	B > P > S > Cu > Ca > N > Fe > Mn > K > Zn > Mg
NK	B > Cu > N > Ca > Mn > Fe > P > Mg > K > S > Zn
NP	B > Cu > K > Ca > N > Mn > P > Fe > Zn > Mg > S
PK	B > Ca > P > Zn > Cu > Mn > K > S > Fe > N > Mg
NPK	B > Zn > Ca > K > N > Cu > Mg > P > Mn > Fe > S
NPKB	B > Mn > S > N > Zn > K > Fe > P > Ca > Mg > Cu
NPKS	B > P > S > Zn > N > K > Mn > Fe > Ca > Mg > Cu
NPKZn	S > Ca > Cu > P > N > Mg > Zn > Fe > K > Mn > B
NPKSZnB	K > Zn > N > B > Mn > P > Cu > Fe > S > Mg > Ca

Figures

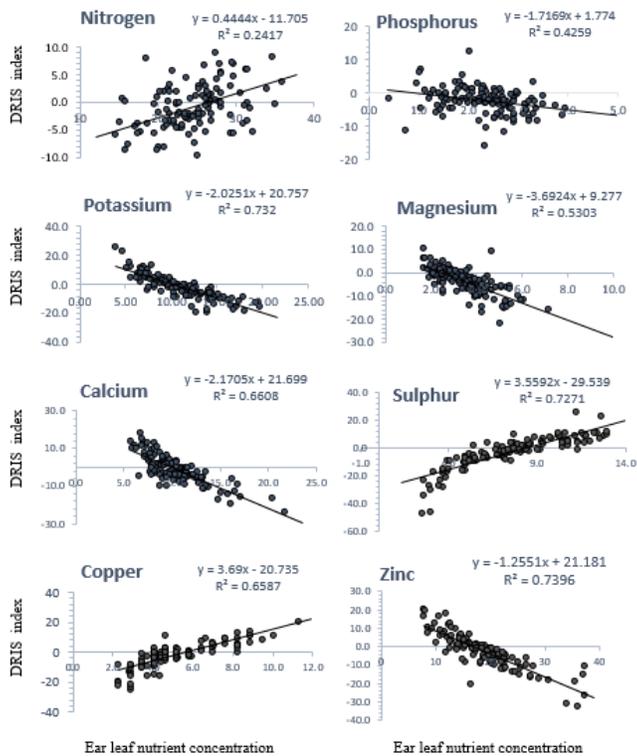


Figure 1

Relationship between ear leaf nutrient concentration and corresponding nutrient DRIS index.

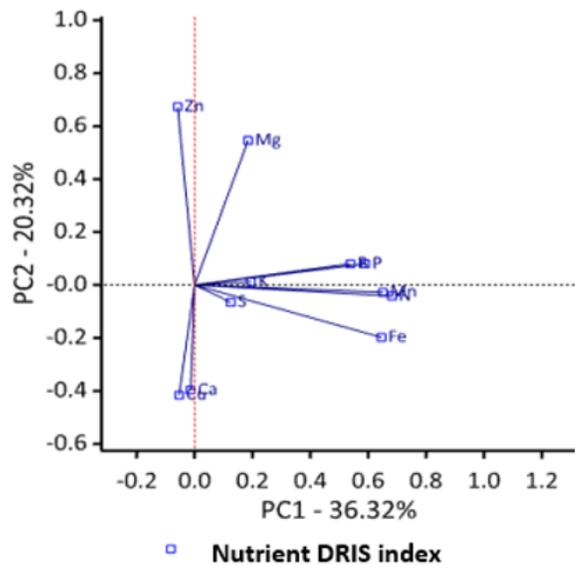


Figure 2

Relationship among nutrients DRIS indices and maize grain yield.

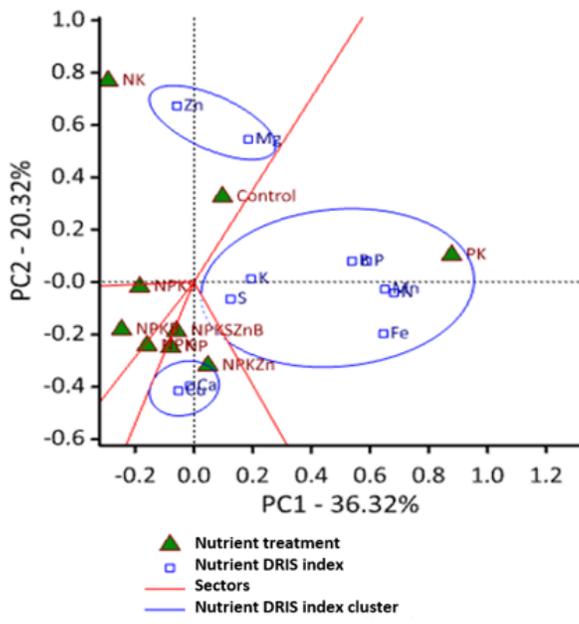


Figure 3

Which-Won-Where biplot showing the effect of nutrient treatments on DRIS indices and yield.