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Maize nutrient yield response and requirement in the maize belt of Nigeria

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Abstract

Absence of site-specific nutrient recommendation and high spatial variability of soil fertility are major factors affecting maize response to applied nutrients in Nigeria. In this study, we assessed maize response to applied nutrients and nutrient use efficiency in different management zones (MZs), for designing site-specific nutrient management recommendations for maize in the maize belt of Nigeria. The maize belt in Nigeria was earlier delineated into four MZsMZs (MZ1 to MZ4) based on soil properties. In the current study, data from two different trials, nutrient omission trials ($N = 293$) and fertilizer response trial ($N = 705$), conducted in the years 2015–2017, were extracted for MZ1 to MZ3; to analyze maize yield responses to application of N, P and K, and secondary and micro-nutrients. Maize yield response to K application was only positive in MZ1. Responses to N and P application were positive for all MZs. However, the magnitude of maize response to P varied between the MZs, indicating a differentiation in the degree to which P is limiting maize production in the study area. Average nitrogen requirement was higher for MZ3 (138 kg ha^{-1}), than for MZ2 and MZ1 (121 and 83 kg ha^{-1}, respectively). Average P requirement was higher for MZ3 (45 kg ha^{-1}) than for the other zones. Potassium requirement was 26% and 28% higher in MZ2 and MZ3 compared with MZ1 (~15 kg ha^{-1}). The use of the specific nutrient rates for the MZs may reduce risks and uncertainties in crop production. The delineated MZs of the maize belt of Nigeria that incorporates spatial variability in soil fertility conditions are useful for nutrient management for larger areas.

1. Introduction

Maize is one of the most important staple crops in Nigeria as well as in many other African countries (Ekpa *et al* 2018, Oyinbo *et al* 2019). Breeding efforts by IITA and its' partners which led to the development and release of improved maize varieties with high yielding potential, moisture stress-tolerance and adaptation to various agro-ecological zones (Adnan *et al* 2017, Kamara *et al* 2019), promoted production in Nigeria and in other African countries; ahead of traditionally cultivated sorghum and millets (Fakorede *et al* 2003, Rurinda *et al* 2014). Nigeria became the second most important maize producer in Africa after South Africa, contributing about 13% of the continent's total production (FAOSTAT 2019). The Maize belt presents the highest potential (Aliyu *et al* 2020), and accounts for nearly 80% of the total maize produce in Nigeria (Fakorede and Akinyemiyu 2003). Despite the potential of this region, yield per unit area is still low, at <1.8 t ha^{-1}, against an attainable yield of >5 t ha^{-1} reported for well managed experiments (Tofa *et al* 2020).

Low (Jibrin *et al* 2012) and variable soil fertility (Aliyu *et al* 2020), which is compounded by improper management strategies to sustain soil nutrient stocks, and improve yield response to nutrients (Shehu *et al* 2018) are considered the most critical factors limiting maize productivity in Nigeria's maize belt region. In addition, poor access to and high prices of fertilizers (Liverpool-Tasie *et al* 2017), and low nutrient recovery efficiency (Tabi *et al* 2008) are considered the fundamental reasons for low fertilizer use among smallholder farmers (Kamara *et al* 2013). Suboptimal application of fertilizer through the existing blanket recommendations that ignores spatial variability in crop nutrient requirement additionally contribute to the poor soil nutrient status and low fertilizer-nutrient use efficiency in the region (Shehu *et al* 2018, Garba *et al* 2020).

In effort to optimize maize productivity in Nigeria, several studies have been carried out to understand and quantify variability in soil characteristics and associated maize yield response (Kihara *et al* 2016, Shehu *et al* 2019, Garba *et al* 2020). Such studies found a strong spatial variability in soil nutrient content in farmers' fields and suggested that nutrient recommendations should be tailored toward field-specific conditions. They further indicated that a research gap still exists in understanding and quantifying maize yield response and associated nutrient use efficiency for the entire region. In the same vein, a computer and mobile phone-based decision support tool called Nutrient Expert (NE) has been developed for maize nutrient recommendation tailored towards field-specific conditions in some part of the maize belt of Nigeria (Rurinda *et al* 2020). However, we observed three constraints to effective use and scale-up of the NE among small-holder farmers in the Nigeria's maize belt: (i) low understanding of computer or smart mobile phone, (ii) limited knowledge of some agronomic and soil related terms that are required when running the NE, and (iii) soil testing. Therefore, from the preceding discussion we observed that two studies are needed to fill the stated research gaps; (i) evaluation of yield response and associated nutrient use efficiency for the entire maize belt of Nigeria, (i) development of nutrient recommendations for larger areas that considers the NE use's constraints.

GIS is a widely used technology for spatial analysis of physical and chemical properties of soils (e.g. Behera *et al* 2018). Furthermore, GIS is used to delineate sections of the target landscape with similar production potentials and constraints (Omamo *et al* 2006, Rubiano *et al* 2016) referred to as the management zones (MZs) (Tripathi *et al* 2015, 2019). These serve as focal and distinct zones requiring different priority for use and management strategies. Management strategies developed for MZs are more likely to achieve greater impact (Muthoni *et al* 2017) because of their consideration of dynamics of spatial variability over a larger area. The maize belt of Nigeria has been delineated by Aliyu *et al* (2020) into four distinct nutrient MZsMZs based on soil fertility. The current study was built on these delineated fertility MZs to quantify maize yield response to nutrient application, nutrient use efficiency, and assess the corresponding nutrient requirements for the entire maize belt of Nigeria. Therefore, the current study sought to address the following specific objectives: (i) estimate yield response to nutrient application, (ii) assess the nutrient use efficiencies, (iii) quantify the requirements of nitrogen (N), phosphorus (P) and potassium (K), and compare these parameters between the MZs to determine whether the MZs are useful to provide targeted fertilizer recommendations. Our focus was on the maize belt of Nigeria, which is the most suitable region (in terms of the required biophysical conditions) for maize production in the country.

2. Materials and methods

2.1. Experimental setup and procedure

Data from two types of field experiments (nutrient omission trials—NOTs, and fertilizer response trial—FRT) carried out in the maize belt of northern Nigeria were used to evaluate maize yield response to nutrients N, P and K, and assess their requirements. The NOTs and FRT were established on farmers' fields across eight administrative states (i.e. Kano, Kaduna, Katsina, Bauchi, Nasarawa, Niger, Taraba and Plateau) within the maize belt of northern Nigeria (figure 1).

2.1.1. The nutrient omission trials (NOTs)

The NOTs were conducted between 2015 and 2017. Locations for the trials were selected to represent heterogenous maize growing conditions in the area (figure 1). For the 2015 and 2016 experiments, the trial sites were identified by selecting one or two $10\times$ 10 km grid cells in some targeted parts of the study area using ArcGIS 10.2.2 (Environmental System Research Institute, Redlands, CA, USA). Within each of the $10\times$ 10 km grid, a 1×1 km sub-grids were generated, from which five grid cells were selected and within each of them a field for experimentation was randomly selected. A total of 263 fields (95 and 35 both established in 2015, 103 established in 2016, and 30 in 2017 rainy seasons) were used to estimate yield response to applied nutrients. The procedure for the site selection of the 95 and 103 fields are also described by Shehu *et al* (2018). The establishment of the other 35 fields in 2015 was described by Shaibu *et al* (2018).

The 30 sites in 2017 were selected by overlaying 250 m resolution gridded datasets for total N, organic carbon, pH and sand contents obtained from African Soil Information Service, and that of total annual rainfall obtained from Climate Hazards Group InfraRed Precipitation with Stationof the study area. These datasets were then rescaled to a uniform range of 0–100. The rescaled grids of the listed

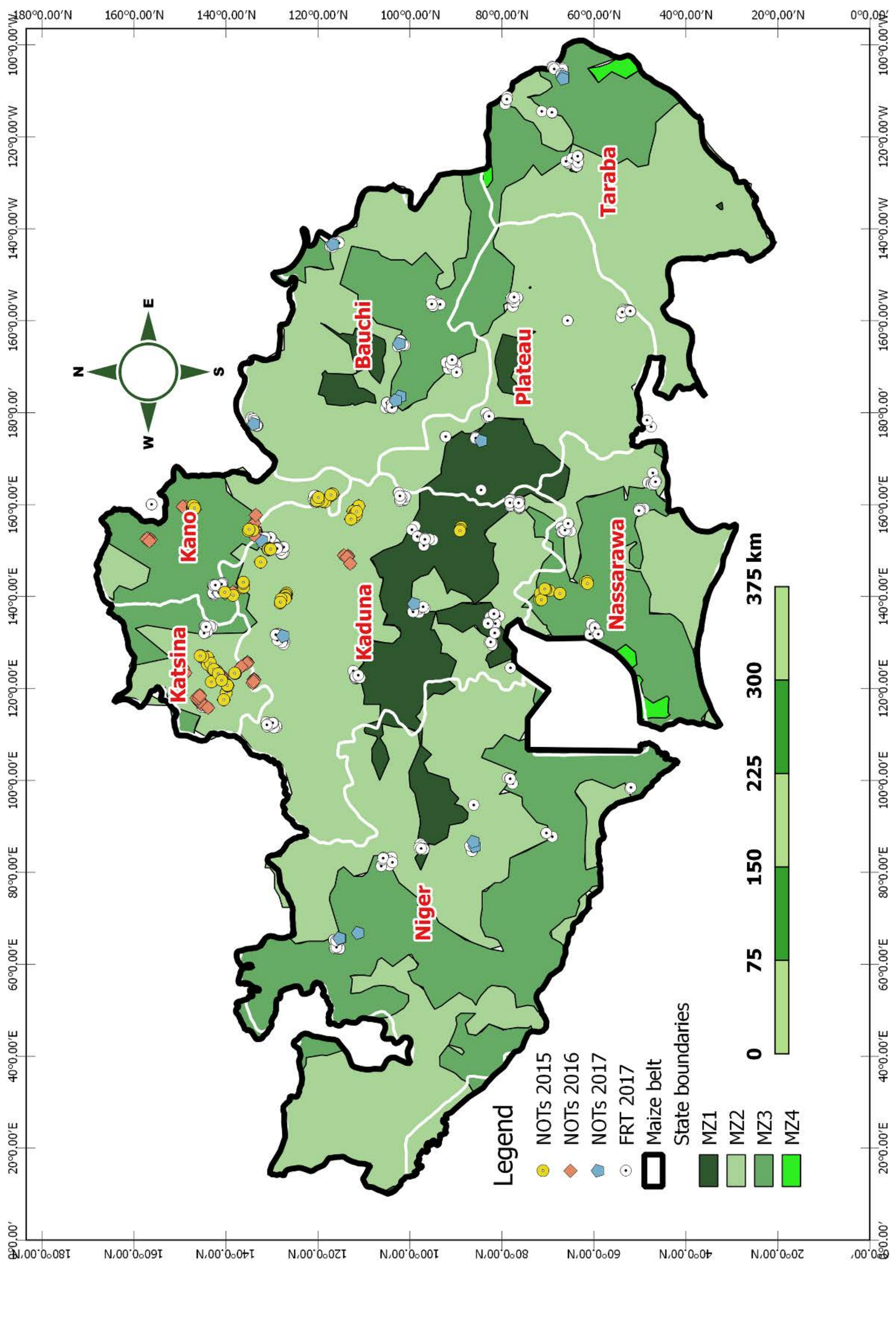

Figure 1. Map showing the maize belt region in Nigeria and location of fields where nutrient omission trials (NOTs) and fertilizer response trial (FRT) were conducted from 2015 to 2017.

variables were combined to derive a single grid. The grid which inherited the rescaled value (0–100) was further refined by conducting focal majority statistics (within a radius of 1 km) to minimize the inherent neighborhood noise and assign most occurring value to each pixel within the neighborhood, and the output grid was clustered using Jenks natural breaks. Five clusters across the area were defined based on the breaks. Each cluster is assumed to be a homogeneous growing environment. To have a fair representation of each cluster, the reclassified grid was converted to polygon. The number of trial sites per cluster was determined based on the relative proportion of land covered by the cluster.

The NOTs consisted of at least six nutrient treatments (NTs), including a Control (no nutrient was applied), PK; (only P and K applied), NK (N and K applied), NP (N and P applied) and NPK in which N, P and K were all applied. Another NPK treatment ('NPK+') with addition of Mg, Ca, S, Zn and B nutrients was used to estimate response to secondary macro- and micronutrients (SMNs). The N, P and K nutrients were applied uniformly at 140 kg N ha^{-1}, 50 kg P ha^{-1} and 50 kg K ha^{-1} respectively at all trial sites. Nitrogen (N) was applied in three equal splits, i.e. at planting, 21 and 42 d after emergence when the soil moisture was adequate. Full dosage of P and K were applied at the planting. The nutrients S, Ca, Mg, Zn and B were applied at planting at the rates of 10–24, 10, 10, 5–10 and 5 kg ha^{-1}, respectively. The maize variety used was SAMMAZ 15; which is an open pollinated, intermediate maturing (105–110 maturity days) variety. Two seeds per hole sown at 0.25 m spacing were thinned to one plant per hill to give an average plant population of 53 333 plants per hectare in all the studies.

The experiment was laid out in plots of six ridges constructed 0.75 m apart, each measuring 5 m long given a gross plot size of 22.5 m^2. Net plot area was determined from a 9 m^2 area across the four inner rows. All cobs and stover in the net plot area were harvested and weighed fresh. Five cobs and stover were then sub-sampled at random for determining moisture content, shelling percentage, and harvest index. Grain yield was expressed on a dry weight basis at 15.0% moisture content adjustment using a grain moisture tester. The sub-sampled grain and stover were dried and subsequently analyzed for nutrients concentration.

2.1.2. The fertilizer response trial (FRT)

This set of trial was established on-farm in 2017 across the maize belt. The trial sites were selected (figure 1) from the soil sampling locations ($n = 3000$) described by Aliyu *et al* (2020). From the soil sampled sites, the trial was established in 935 farms. After screening of data, 705 fields were used in this study. Treatments for the FRT included plots of NPK, NPKSZnB, and a Control where no nutrient was applied. Fertilizer application and crop management practices remained the same as for the NOTs.

Plot dimensions were 10× 15 m for the NPKs and 5× 15 m for the Control in the FRT experiment. In both treatments, ridges were constructed at 0.75 m spacing. The net plots were determined by leaving out the first two and last two ridges of each plot and 1 m each from both ends of each ridge. This resulted in a net plot area of 3× 12 m = 36 m^2 for the Control plot, and 8× 12 m = 96 m^2 for the NPK plots. The same maize variety used in the NOTs was used in this experiment. Planting, spacing and other management practices were also the same as in the NOTs. Grain and stover yields were determined by harvesting and weighing all cobs and stover in the net plot area. The cobs were harvested such that the husk still remains on the plant and the plant remains standing. The cobs were harvested in batches using bags until they are full and then weighed using the electronic portable scale. The procedure for yield determination was also the same as in the NOTs.

2.2. Estimation of nutrient response and nutrient requirement

Soil data from the study area have been used to delineate nutrient MZs, which are reported in Aliyu *et al* (2020). Four MZs were identified (MZ1–MZ4) based on soil fertility (figure 1). MZ2 has the largest area and covers more of the central parts. MZ3, the second largest, is found more around the boundaries of the study area. Whereas MZ1 is the third largest and is located predominantly around the central part of the area. MZ4 comprises of only a very small area and seems to be in the form of spots within MZ3. The MZs, MZ1 and MZ4, are the more fertile; having relatively higher contents of all nutrients (except available P) and ECEC value. The MZ2 is potentially more fertile than MZ3; but has lower Ca and K contents. The nutrient response and nutrient requirement of maize were determined from the two experiments (i.e. NOTs and FRT) for each of the identified MZs. The geographic coordinate of all the fields for the two experiments were overlaid on the MZs, and fields belonging to each MZ were extracted using 'extract values to points' in Spatial Analyst toolbox of ArcMap. None of the fields fall under MZ4, and therefore no analysis was computed for the zone. Datasets from all the experiments were separately subjected to descriptive statistics such as minimum, maximum, mean, standard deviation, coefficient of variation, skewness and kurtosis using JMP Pro version 14 statistical package (SAS Institute Inc. 2017). Analysis of outliers for the yield was conducted for each MZ separately using the quantile method in JPM Pro version 14. In addition to the outlier analysis, fertilized plots with harvest index <0.4 were considered to be limited by one or more growth factors other than nutrients as described by Hay (1995) and Xu *et al* (2019), therefore, such plots were excluded from the data. After the data curation, the data from all the experiments in the same MZ were combined and used for the estimation of nutrient yield response and nutrient requirement for each zone.

2.3. Estimating yield responses and requirements of N, P and K in the MZs

Yield response to nutrients N, P and K for the NOTs were calculated as the yield difference between NPK treatment and nutrient omission treatments (PK, NK and NP) at corresponding sites using equation (1). The responses to N, P and K in the FRT were calculated by first averaging the yields of PK, NK, and NP (from the NOTs) in each MZ, and then the average yields were subtracted from each NPK plot of the FRT within the same MZ.

$$\mathrm{YR}_i = Y_{\mathrm{NPK}} - Y_o. \quad (1)$$

YR_i is yield response (in kg ha^{-1}) to application of nutrient i (i = N, P or K); Y_{NPK} is grain yield of NPK plot (in kg ha^{-1}); Y_o is grain yield at NOT site or MZ average of PK, NK or NP treatments (in kg ha^{-1}) in case of the FRT.

The N nutrient requirement was estimated based on yield response and agronomic efficiency using equation (2).

$$\mathrm{NR_N} = \mathrm{YR_N}/\mathrm{AE_N}. \quad (2)$$

Agronomic efficiency which is an indicator of yield gain as a result of nutrient application, was calculated using equation (3).

$$\mathrm{AE_N} = (Y_{\mathrm{NPK}} - Y_{\mathrm{PK}})/F_{\mathrm{N}}. \quad (3)$$

AE_N is the nitrogen agronomic efficiency, Y_{PK} is yield of the PK (N omitted) treatment at corresponding NPK site, F_N is the amount (in kg ha^{-1}) of nitrogen fertilizer applied.

The equations for estimating P and K requirements have been modified to consider the nutrient recovery efficiency, nutrient uptake requirement and indirectly soil P and K nutrient supply. These were calculated with equations (4) and (5):

$$\mathrm{NR_P} = (\mathrm{YR_P} \times \mathrm{RIE_P}/\mathrm{RE_P}) + (Y_{\mathrm{NK}} \times \mathrm{RIE_P}/\mathrm{RE_P}) \quad (4)$$

$$\mathrm{NR_K} = (\mathrm{YR_K} \times \mathrm{RIE_K}/\mathrm{RE_K}) + (Y_{\mathrm{NP}} \times \mathrm{RIE_K}/\mathrm{RE_K}). \quad (5)$$

$\mathrm{NR_N}$ (equation (2)), $\mathrm{NR_P}$, and $\mathrm{NR_K}$ are nutrient requirements of N, P, and K (in kg ha^{-1}) respectively. $\mathrm{RIE_P}$ and $\mathrm{RIE_K}$ are respectively the required uptake amounts of P and K (in kg ha^{-1}) to produce 1 kg of grain. It is computed as the amount of nutrient i in aboveground tissues (in kg ha^{-1}) for P or K omitted treatment divided by the grain yield of NK and NP respectively. $\mathrm{RE_P}$ and $\mathrm{RE_K}$ are recovery efficiencies of applied P and K respectively. Y_{NK} and Y_{NP} are the yields of the NK and NP treatments at corresponding NPK site, and were considered as proxies for estimating soil supply of P and K respectively. The recovery efficiency is calculated as the difference between *ith* nutrient in the aboveground tissues of the NPK and that in the nutrient omitted plot (equation (6)).

$$\mathrm{RE}_i = U - U_i^0/F_i \quad (6)$$

where U is total amount of nutrient i in aboveground tissues of NPK plot; U_i^0 is total amount of nutrient i in aboveground tissues of i nutrient omission treatment, and F_i is the amount of i fertilizer applied.

All calculations for input values (YR, AE, RIE and RE) were done first with the NOTs dataset at plot level. The average values of these at MZ-level were then used and applied to the FRT at respective plot level. The estimated nutrient responses and requirements were then combined for each MZ and analysed.

2.4. Data analysis

Variance component analysis was used to estimate the percent contribution of random factors to the spatial and temporal variability in the NOTs dataset. The NT was treated as a fixed factor in the model. The random effect model comprised of the MZ and year (Y) as spatial and temporal random effects respectively, and their two (MZ × NT, Y × NT and MZ × Y), and three-way interactions (MZ × Y × NT) and with NT. Analysis of variance (ANOVA) was used to analyze the nutrient use efficiency indicators and nutrient requirements. Significant difference between and within the MZs for the nutrient use efficiency and requirement between zones were compared and separated using LSD procedure at 0.05 level probability. All the statistical analyses were done in JMP Pro Version 14 software (SAS Institute Inc. 2017).

3. Results

3.1. Maize grain yield response to nutrient application across fertility management zones (MZs)

Table 1 show the existence of larger spatial than temporal variation in the NOTs dataset. Variation caused by the MZs was at least 27.5% for all the analyzed factors except for N response, which was just 12.0%. MZ effect was higher among the factors, and contributed to 38.0%, 38.9% and 54.0% of total variations in yield responses to SNMs and K, and $\mathrm{RE_K}$ respectively. This further indicates that environment is the main determinant of the effect of SMNs and K application on maize. Variation caused by year was greater for the nutrient use efficiency indicators than for the yield responses to the nutrient applications. Year affected $\mathrm{RE_N}$ (12.1%) more than $\mathrm{RE_K}$ (6.3%) and $\mathrm{RE_P}$ (3.6%). The two-way interactions also accounted for more variation in the nutrient efficiency indicators than for

Table 1. Variance components and percent contribution of random factors (management zone, year and interactions) on grain yield, response to K, P, N, and SNMs, and some selected nutrient use efficiency indicators.

	Variance	Contribution (%)	Variance	Contribution (%)	Variance	Contribution (%)	Variance	Contribution (%)	Variance	Contribution (%)
	Grain yield		SMNs response		K response		P response		N response	
Management zonez (MZ)	1121 229.0	27.5	186 928	38.0	202 210	38.9	221 956.2	25.9	132 634.3	12.0
Year (Y)	354 619.0	8.70	2528	0.5	26	0.00	−75 984.1	−8.9	7657.2	0.7
MZ × NT	546.0	0.01	−2874	−0.6	−379	−0.07	161 507.4	18.8	1.2	0.0
Y × NT	0.1	0.00	−22 552	−4.6	−170	−0.03	63 976.7	7.5	−35 172.6	−3.2
MZ × Y	0.5	0.00	−6346	−1.3	−154	−0.03	−797.5	−0.1	−109 989.0	−9.9
MZ × Y × NT	766 581.0	18.8	47 425	9.6	−11 506	−2.21	−13 451.6	−1.6	392 234.7	35.4
Residual	1833 147.0	45.0	286 735	58.3	329 540	63.4	499 847.2	58.3	721 332.2	65.1
Total	4076 122.0		491 844		519 567		857 054.2		1108 698.4	
	AE_N		AE_P		RE_K		RE_P		RE_N	
Management zonez (MZ)	0.451	28.4	0.64	27.8	7.64	54.0	4.80	27.8	7.3	18.6
Year (Y)	0.073	4.2	0.15	6.4	0.90	6.3	0.62	3.6	4.8	12.1
MZ × NT	0.013	0.8	0.01	0.2	3.24	22.8	1.24	7.1	9.7	24.6
Y × NT	0.003	0.2	0.01	0.5	0.36	2.5	1.43	8.2	3.5	9.0
MZ × Y	0.006	0.4	0.07	2.8	0.41	2.9	0.02	0.1	7.8	19.7
MZ × Y × NT	0.002	0.2	0.31	13.6	0.02	0.2	2.91	16.8	4.3	10.8
Residual	1.039	66.0	1.12	48.7	1.62	11.4	6.23	36.4	2.1	5.3
Total	1.6		2.3		14.2		17.14		39.4	

NT: nutrient treatment in the NOTs; SMNs: secondary macro- and micro-nutrients; AE_N and AE_P: agronomic efficiency of N and P respectively; RE_X, K, P and N nutrient recovery efficiency.

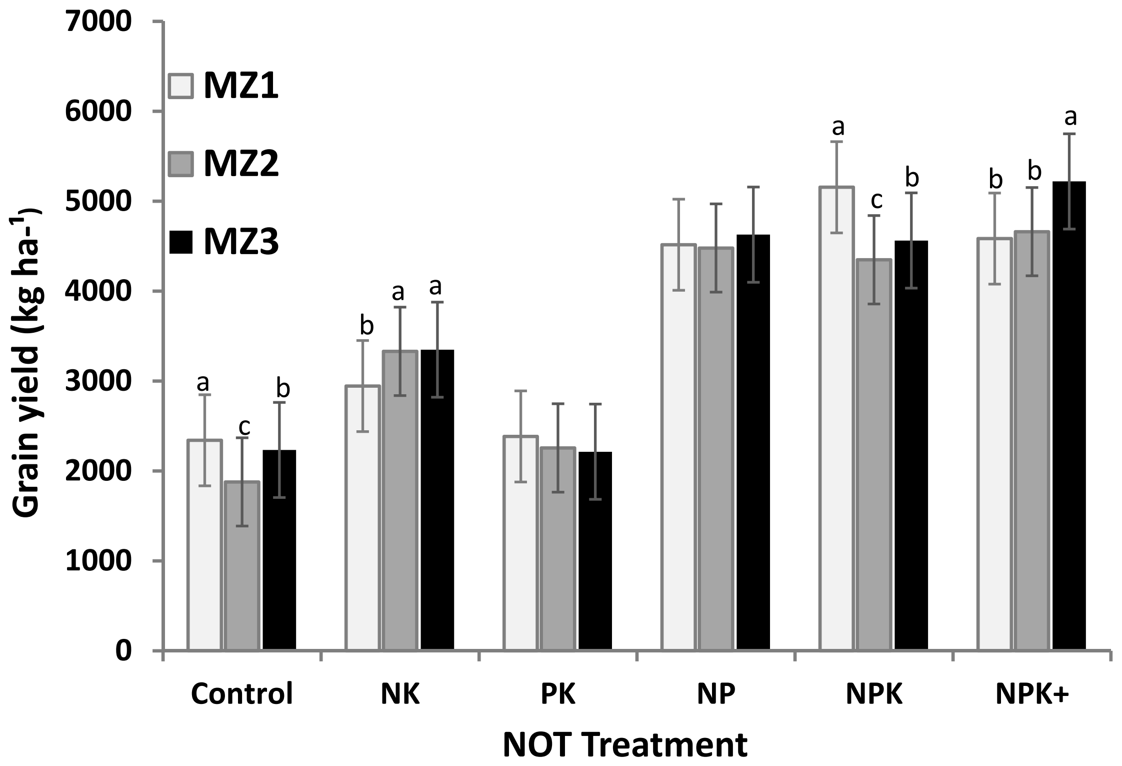

Figure 2. Mean maize grain yield (kg ha^{-1}) of the NOTs treatments in the management zones (MZs). Bars with different lettering under the same NOTs nutrient treatment are significantly different at 5% level of probability. Means were not significantly different among the MZs for PK and NP. Error bars are standard error of means.

the nutrient responses and grain yield. The three-way interaction (MZ × Y × NT) did contribute to larger variations most importantly for N response (35.4%), grain yield (18.8%) and RE_P (16.8%).

Results of the mean maize grain yield of the NOTs treatments indicate a significant variation between the MZs for all NTs, except for NP and PK (figure 2). MZ2 had the lowest grain yield among the MZs for the Control, NP and NPK treatments, whereas highest NPK mean yield (5155 kg ha^{-1}) was observed in MZ1. The NPK+ treatment showed highest yield for MZ3 (5220 kg ha^{-1}). Yields of NP and PK treatments did not differ significantly between the years and the MZs.

The maize grain yield of the NPK and Control treatments in the FRT (figure 3, (I)–(III)) show that yield of NPK ranged from 2508 to 11 508, 1051 to 9199 and 1344 to 7844 kg ha^{-1} respectively for MZ1, MZ2 and MZ3. The yield followed a normal distribution for MZ3; with median (4727) and mean (4618) values being close to each other. Mean grain yield for the Control was lower (2144 kg ha^{-1}) in MZ2 compared with 2381 kg ha^{-1} for MZ1 and 2525 kg ha^{-1} for MZ3 (figure 3, (IV)–(VI)). The data for the Control treatment are normally distributed for MZ3 than for other MZs.

The yield responses to the application of secondary macro- and micro-nutrients (SMNs) over NPK, and responses to application of N, P and K in the NOTs are presented in figure 4. Maize yield response to the application of SMNs relative to the NPK treatment was negative in MZ1 for both the NOTs and FRT. While a positive yield response was observed for the application of SMNs in MZ2 and MZ3, with about 200 kg ha^{-1} and 500 kg ha^{-1} yield increments observed, respectively (figure 4, (I)). Addition of potassium resulted to a yield decrease in MZ2 and MZ3 and yield increase in MZ1 (figure 4, (II)). Yield decrease of about 250 kg ha^{-1} observed in MZ2 due to application of K was significantly higher than that (25 kg ha^{-1}) observed in MZ3. Yield gain of about 350 kg ha^{-1} due to the application of K was observed in MZ1. Application of P (figure 4, (III)) and N (figure 4, (IV)) resulted to a significant yield increase across all the MZs. Yield gain due to application of P was lowest in MZ2 (1300 kg ha^{-1}), followed by MZ3 (1600 kg ha^{-1}) with highest observed in MZ1 (1800 kg ha^{-1}). Yield response to combined application of N, P and K (figure 5) was positive in most experimental sites of MZ1 and MZ3 (figure 5, (I) and (III) respectively). There were specific fields in MZ2 (figure 4, (II)) where the response was below the 1:1 line, implying a negative response to the nutrients.

3.2. Nutrient use efficiency

The average fertilizer-nutrient recovery efficiencies were comparable for N and K between the MZs (table 2). The average recovery efficiency of N (RE_N) was 0.50, 0.46 and 0.44, and those of K (RE_K) were 0.41, 0.52 and 0.49, for MZ1, MZ2 and MZ3

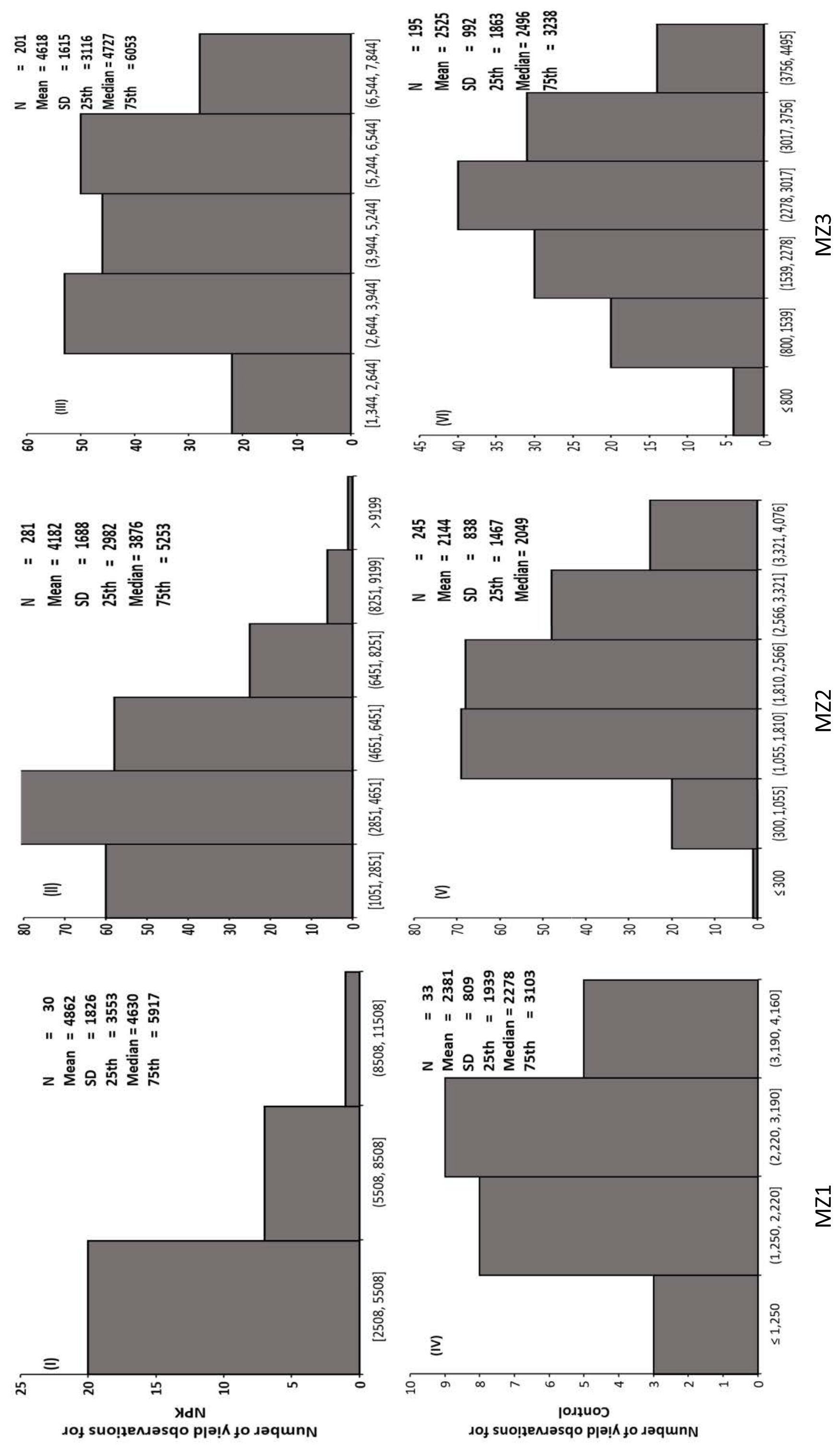

Figure 3. Maize grain yield distribution of the fertilizer response trial (FRT) for the NPK and Control treatments in MZ1 (I) and (IV), MZ2 (II) and (V) and MZ3 (III) and (VI).

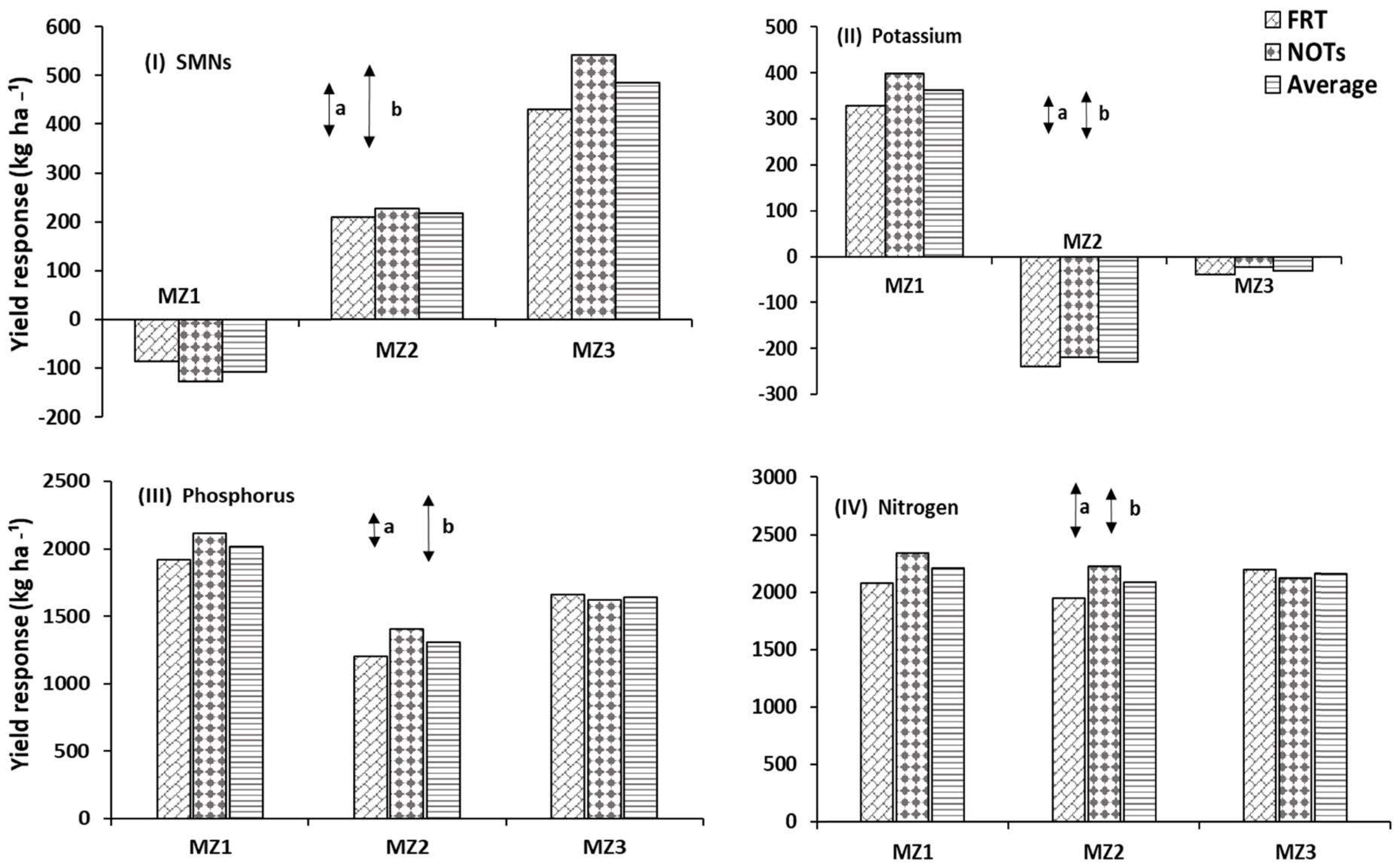

Figure 4. Comparison of maize yield response to (I) secondary macro and micro-nutrients—SMNs, (II) potassium, (III) phosphorus and (IV) nitrogen across the nutrient management zones (MZs). Double headed arrows a and b indicates least significant difference at 5% probability level between the two experiments and among MZs respectively.

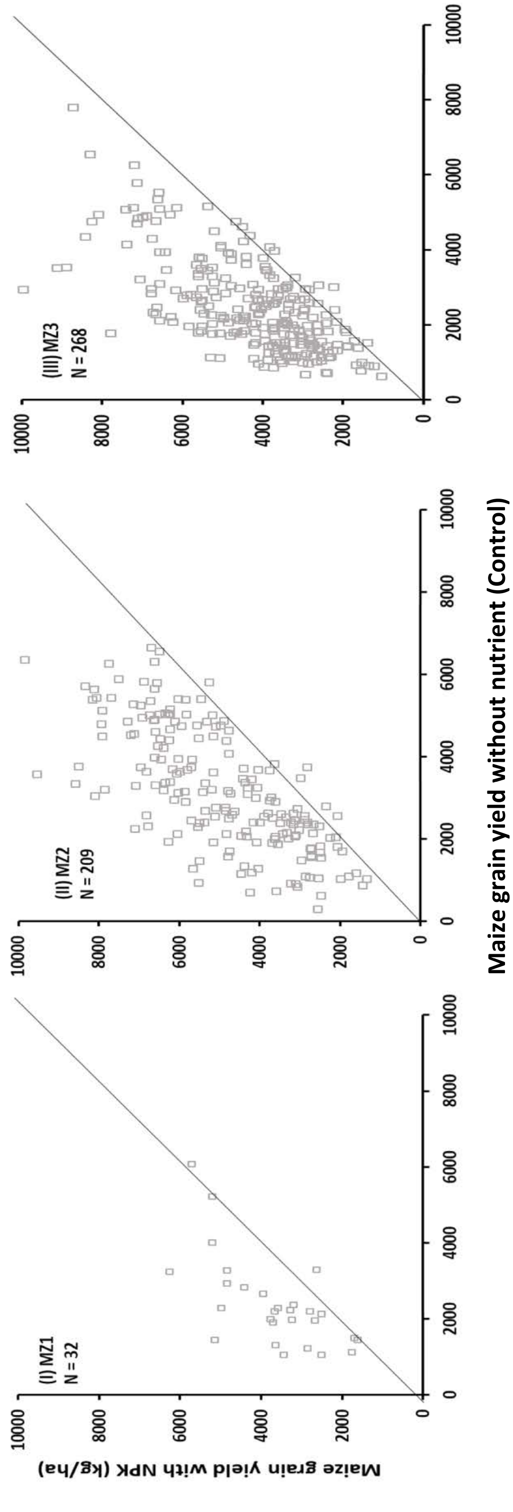

Figure 5. Maize grain yield response to combined N, P and K nutrients relative to maize grain yield for the control (with no nutrient applied) in MZ1 (I), MZ2 (II), and MZ3 (III).

Table 2. N, P and K nutrient recovery efficiency (REx), agronomic efficiency (AEx) across the management zones (MZs).

Treatment	RE_N	RE_P	RE_K	AE_N	AE_P	AE_K
MZ1	0.50	0.26	0.41	18.9	37.4	11.3
MZ2	0.46	0.11	0.52	14.8	29.4	6.2
MZ3	0.44	0.30	0.49	15.5	35.5	9.4
Mean	0.46	0.20	0.49	15.4	33.1	8.26
LSD	0.10	0.23	0.20	2.93	7.92	2.37

Aboveground nutrient contents were not analyzed for the FRT; thus, these values were determined only from the NOTs. LSD: least significant difference at 5% probability level.

Table 3. N, P and K nutrient requirements across the respective management zones (MZs).

	N requirement (kg ha^{-1})		P requirement (kg ha^{-1})		K requirement (kg ha^{-1})	
	NOTs	FRT	NOTs	FRT	NOTs	FRT
MZ1						
N	25	27	22	23	23	28
Maximum	149.6	142.6	49.9	49.1	30.7	36.8
Minimum	30.1	35.1	10.1	11.0	3.7	5.1
Mean	100.0	79.5	30.1	25.2	16.1	13.7
CV (%)	34.8	47.2	34.2	45.0	39.4	45.8
MZ2						
N	151	233	152	239	162	272
Maximum	167.6	166.6	74.0	77.6	40.5	45.4
Minimum	41.6	40.5	12.6	7.7	1.4	4.4
Mean	120.6	118.1	44.6	40.3	21.1	19.1
CV (%)	24.6	27.0	28.8	51.9	33.4	41.8
MZ3						
N	160	183	154	172	168	213
Maximum	164.2	165.2	76.8	76.5	46.9	41.4
Minimum	46.3	47.2	11.8	13.3	1.9	5.8
Mean	138.8	136.4	46.9	43.6	20.4	20.6
CV (%)	17.3	17.9	31.7	34.6	42.8	36.6

NOTs: nutrient omission trials; FRT: nutrient response trial; CV: coefficient of variation; MZ: management zone; N: number of sites in MZ.

respectively (table 2). Average phosphorus fertilizer recovery efficiency (RE_P) of 0.30 observed in MZ3 was higher than that of the other two MZs (i.e. 026 for MZ1 and 0.11 for MZ2). Agronomic efficiency of the three nutrients (N, P and K) were comparable among the MZs. Higher values were observed in MZ1 (18.9% for N, 37.4% for P and 11.3% for K), followed by MZ3 (15.5% for N, 35.5% for P and 9.4% for K) and a lowest in the MZ2 (14.8% for N, 29.4% for P and 6.2% for K).

3.3. Nutrient N, P and K requirements

Table 3 show that the maximum N requirement across the MZs was 168 kg ha^{-1}, while the minimum requirement was 30 kg ha^{-1}. N requirement for MZ1 was 100 kg ha^{-1} based on estimation using the NOTs and 79.5 kg ha^{-1} using the FRT. The coefficient of variation which translates to relative variability, shows that average (from the NOTs and FRT) variation in N requirement within MZ1 (CV = 41%) was larger compared to the other MZs.

The CV for P requirement ranged 28.8%–51.9% across the MZs for both experiments. The variation was generally higher when the requirement was estimated using the FRT in all MZs (CV = 45.0% for MZ1, 51.9% for MZ2 and 34.6% for MZ3). On average, P requirement was more consistent in MZ3 (CV = 33.3%). Maximum P requirement among the MZs was 77.6 kg ha^{-1} for MZ2. Minimum P requirement was estimated for MZ1 (7.7 kg ha^{-1}) using the FRT. Variation of K requirement in overall was higher compared with those of N and P across all the MZs.

ANOVA on the average nutrient requirements estimated from the combination of NOTs and FRT datasets shows that N requirement (figure 6, (I)) was significantly higher ($p < 0.05$) for MZ3 (138 kg ha^{-1}), than that of MZ2 and MZ1 (119 and 89 kg ha^{-1} respectively). Average P requirement was also higher for MZ3 (38 kg ha^{-1}) than for other zones. K requirement for MZ2 and MZ3 (19.8 and 20.5 kg ha^{-1} respectively) were similar, and significantly higher than that for MZ1 (14.7 kg ha^{-1}) (figure 6, (III)).

4. Discussions

4.1. Grain yield and nutrient response

The variation in grain yield among the MZs is expected as each zone presents a peculiar growing environment and supposedly a different maize yield potential. In the absence of other yield limiting factors, the

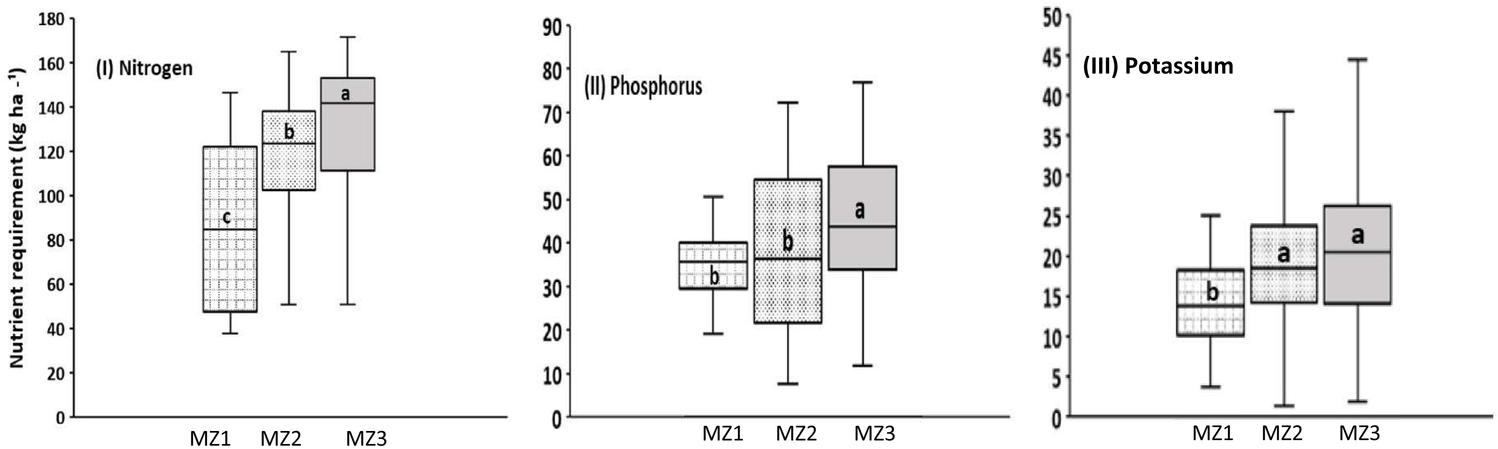

Figure 6. Box plot showing N (I), P (II) and K (III) nutrient requirement (kg ha^{-1}) for the management zones. Different letter in each box plot indicates significant mean difference nutrient requirement between the management zones at $p \leqslant 0.05$.

Table 4. Soil fertility and related characteristics of the management zones (MZs).

MZs	Area covered (%)	pH (H_2O)	SOC_{tot} (g kg^{-1})	N_{tot} (g kg^{-1})	Av. P (mg kg^{-1})	Ca (cmolc kg^{-1})	Mg (cmolc kg^{-1})	K (cmolc kg^{-1})
1	17	5.83c	11.7a	1.02a	3.18c	4.24a	1.81a	1.01a
2	52	5.73d	7.80c	0.69c	3.79b	1.87d	0.79c	0.50d
3	29	6.07b	5.50d	0.42d	3.43c	2.20c	0.78c	0.59c
4	2	6.13a	10.07b	0.86b	8.46a	3.35b	1.50b	0.95b
LSD	—	0.043	0.390	0.035	0.230	0.182	0.081	0.034

MZs	Na (cmolc kg^{-1})	ECEC (cmolc kg^{-1})	Zn (mg kg^{-1})	Cu (mg kg^{-1})	Mn (mg kg^{-1})	Fe (mg kg^{-1})	B (mg kg^{-1})	Av. S (mg kg^{-1})
1	0.19a	9.25a	1.29b	1.25a	79.97a	121.9c	0.15a	13.18a
2	0.13c	6.58c	1.05c	1.20a	61.64b	164.6a	0.07b	10.64b
3	0.14b	5.67d	1.01c	0.57c	60.69b	102.2d	0.04c	7.49c
4	0.14b	7.89b	1.42a	1.08b	79.93a	142.6b	0.15a	10.02b
LSD	0.009	0.267	0.038	0.064	3.621	3.739	0.010	0.447

Different lettering within the same column indicates significant mean difference at 1% level of probability using LSD. LSD: least significant difference between means.

MZs: managementm zones; SOC_{tot}: total soil organic carbon; N_{tot}: total nitrogen; Av. P: available P; ECEC: effective cation exchange capacity; Av. S: available sulphur.

Source: Aliyu *et al* (2020).

lower the soil indigenous nutrient supply, the higher the yield response (Tabi *et al* 2008). Phosphorus (P) was the second yield limiting nutrient for maize production especially in MZ1; suggesting that efficient P management can enhance maize productivity in the zone. The lower yield of NK in MZ1 can be related to the lower soil available P of the MZ1 relative to MZ2 and MZ3 (see table 4). Yield response to secondary macro- and micro-nutrients (SMNs) was negative for MZ1 indicating that these nutrients are not significantly limiting maize production in the zone. This is also supported by the higher levels of the nutrients in the soil as shown in table 4. Studies by Kihara *et al* (2016) indicated that large response to nutrients are likely when the soil nutrient supply is severely deficient.

The positive yield response to N and P throughout the maize belt can be related to the generally low total nitrogen and available phosphorus in the soils (table 4). Deficiencies of N and P in the maize belt of Nigeria has been reported in many studies (Nziguheba *et al* 2009, Kihara *et al* 2016, Shehu *et al* 2018) and were recognized to critically reduce maize yield (Tabi *et al* 2008, Kamara 2017). The smaller recovery efficiency (11.0%) and lower agronomic efficiency (29.4) of P observed in MZ2 may be explained by the relatively higher available P soil content. The relative lower pH value and highest Fe content of MZ2 might have favored conversion of the available P into less soluble form by reacting with the Fe compared to the other management. This situation had also been reported by Shehu *et al* (2019) to affect P soil supply. High yield response to P in other parts of the area was similarly reported by Kihara *et al* (2016) and Shehu *et al* (2018) and both attributed to the P soil content which is below the critical level.

The absence of significant difference in response to N among the MZs could be related to soil contents of organic carbon and total N being below the critical values of <10 g kg^{-1} and 1.0 g kg^{-1} respectively, in most parts of the study area as reported in Esu (1991) soil fertility rating. Previous studies in the maize belt (Vanlauwe *et al* 2011, Kamara *et al* 2014, Adnan *et al* 2017), have also highlighted nitrogen as the most yield limiting nutrient. The relatively higher N response of MZ1 compared to the other MZs could be explained by higher soil organic carbon which enhances soil nutrient exchange capacity (Zingore *et al* 2007). N may be deficient in the soils due to low organic carbon content and losses through leaching, denitrification and volatilization. This may have contributed to the greater yield response to N fertilizers in the present study. Reason for the negative response to K in MZ2 and MZ3, and a small positive K response observed in MZ1 which had higher K soil contents cannot be precisely explained in this study. However, Kihara *et al* (2016) and Shehu *et al* (2018) also observed pockets of K response in this area, even though the soil K amount was high.

The positive response to the SMNs in the MZ2 and MZ3 may be likely due to their low concentrations in the soil. Different studies have reported contrasting results concerning response to SMNs application in the maize belt of Nigeria. Shehu *et al* (2018) reported positive response to SMNs application in only one of four clusters they delineated within this region. Garba *et al* (2020) also reported variable response of maize to SMNs application within the maize belt. They reported about 25% yield increase compared to NPK in Lere in which is part of MZ2 in this study, and a very minimal response in Toro which is an area under MZ1. But since all the SMNs (S, B, Zn, and Cu) used in our study were applied together along with NPK, no clear explanations could be provided regarding which micro/macro nutrient is critical and responsible for the yield increase, where and why. Although there was in general a positive response to the SMNs in MZ2 and MZ3 of up to 500 kg ha^{-1}, Garba *et al* (2020) indicated that additional yield of 1600 kg ha^{-1} could be obtained when only S and B are applied with NPK in MZ2, and up to 2000 kg ha^{-1} in MZ1 when only S and Zn are applied with NPK.

4.2. Nutrient use efficiency

Average N recovery efficiency across the region is comparable to those reported by Shehu *et al* (2019) and Rurinda *et al* (2020) within the same area. These values were however relatively lower than those reported by Janssen *et al* (1990) in other parts of Africa. Higher N recovery efficiency in MZ1 could be related to the higher amount of organic carbon, which normally enhances recovery of applied nutrients (Tabi *et al* 2008). The P recovery in all the zones were higher than the defaults for QUEFTs (Janssen *et al* 1990). Specifically, higher P recovery in MZ1 could be linked to the availability of organic carbon in the zone compared to other zones. The overall high P recovery in the area could be traced to soil P content below the critical value (7–10 mg kg^{-1}). The recovery efficiency of K in MZ2 is comparable to that (0.54) reported by Rurinda *et al* (2020) in the northern Guinea savanna located withing the maize belt of Nigeria. The agronomic efficiency of N in all the MZs was far below the 30 kg kg^{-1} African regional benchmark (Fixen *et al* 2015), and 36 kg kg^{-1} reported in well managed farmers' fields (Kurwakumire *et al* 2014). Lower levels of the nutrient use efficiencies in this study (specifically the low N recovery 'in MZ2 and MZ3' and low N agronomic efficiency 'in all the zones'), might suggest substantial losses of the applied N (Fixen *et al* 2015); through leaching, erosion, among others, owing to the high sand fraction in the soils and small organic matter coupled with high rainfall intensity.

4.3. Nutrient requirements

The clear variability in N, P and K requirements (figure 6) among the MZs could be attributed to the variations in soil conditions, nutrient responses and other factors which influence nutrient use efficiency (Tittonell *et al* 2008). Lower N requirement of MZ1 is the result of higher yield response due to higher N use efficiency, higher soil N and organic carbon contents compared with the other MZs. The average N requirement for MZ2 (119 kg ha^{-1}) is comparable with that (123 kg ha^{-1}) reported by Rurinda *et al* (2020) using the soil-based test. Our N recommendation for MZ2 is also comparable with the blanket recommendation for N (120 kg ha^{-1}) in Nigeria for most part of the zone (FFD 2012). Average P requirement for MZ1 and MZ2 are respectively comparable and higher relative with the 26 kg P ha^{-1} regional recommendation for low P soils (Federal Fertilizer Department (FFD) 2012). However, average P requirement across all zones is higher than 15 kg P ha^{-1} recommended by Rurinda *et al* (2020) using the NE tool. For all the zones, the range of the yield response for NPK from the FRT is wide, and with no clear peaks for MZ1 and MZ3. This may suggest the presence of factors that could explain the difference in response. The MZ2 in particular had clearer peak and a lower mean value, and striking is that it had relatively higher percentage of fields with low response. Though this needs to be verified by studying the respective yields of the NPK and the Control treatments of the same site. However, corresponding low yields of both the Control and NPK in the same site would suggest the likelihood of non-responsiveness. Under such conditions fertilizer application becomes a risky investment, and this could be the reason for the lower recommended P rate for the MZ2 in this study.

4.4. Overall nutrient management strategy for the MZs

Nutrient requirement for maize depends on soil, climate and seed type used for planting. These factors interact together at spatial and temporal scales to influence recovery efficiency of applied nutrients. Understanding and analyzing spatial heterogeneity of yield response will help to reasonably determine fertilizer application rates at scale. Nutrient use efficiency can be further improved by recommending reasonable application of soil organic matter through cereal-legume rotation (Kamara *et al* 2020), application of manure and preserving crop residues on the field after harvest (Kihara *et al* 2016). This is especially more important for MZ2 and MZ3, where the soil organic carbon is extremely low. Use of secondary macro- and micro-nutrients may also be useful in enhancing maize yield in the area. Addition of Sulphur was reported to increase yield significantly in MZ2 (Nziguheba *et al* 2009, Garba *et al* 2020), and the same result may likely be achieved with MZ3 that also has lower available S. However, the results of combined application of the SMNs are not consistent across many studies. There is the need therefore to study the effects of individual nutrient in combination with NP or NPK. Conversely, the NP or NPK compound fertilizers should contain higher amount of P than K.

5. Conclusions

A strong variation in yield response to nutrients was observed among the soil fertility MZs. N response did not substantially vary across the MZs owing to the generally low N soil content below the established critical levels for maize. This justifies the larger requirement for the nutrient especially in the much soil N deficient zones of MZ2 and MZ3. Despite the wide range of soil P deficiency across the zones, response to P varied with higher response observed in MZ1, followed by MZ3 and lowest in MZ2. Response to K was small and only observed in MZ1 suggesting that K is not a major limiting nutrient in most parts of the study area. Average N:P:K requirement is 89:34:15, 119:38:20 and 138:45:21 kg ha^{-1} respectively for MZ1, MZ2 and MZ3. The positive yield response of maize yield to application of SMNs observed in MZ2 and MZ3, indicates that SMNs are critical to optimize nutrient related maize productivity in the region. The general high variability in maize response to the applied nutrients and nutrient requirements within each zone is a reflection of the inherent variation between farmers' fields mainly due to management. Nevertheless, that still did not mask the differences in nutrient response and requirement between the MZs. Therefore, the zones seem to represent a relevant level of stratification of the area for making better targeted nutrient recommendations.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.25502/pakr-y904/d.

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Author contributions

Huising E J, Jibrin M J, Rurinda J and Kamara A Y designed the research and managed the project. Husing E J, Rurinda J and Aliyu K T facilitated the research and manage the data. Aliyu K T prepared the manuscript with contributions from all co-authors.

Conflict of interest

The authors declare no conflict of interest.

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