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Research Article

Response of Maize to Secondary Nutrients and Micronutrients in the Guinea Savanna of Nigeria

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Abstract

Background and Objective: In order to address the inadequacy of the current blanket fertilizer recommendation in the Guinea Savanna of Nigeria, the effect of other nutrients in addition to N, P and K in limiting maize productivity must be assessed. This study aimed to quantify the effects of the addition of secondary macronutrients and micronutrients on maize grain yield, nutrient uptake and N, P and K use efficiencies in the Guinea Savannah of Nigeria. **Materials and Methods:** The experiment consisted of 12 treatments: A control, an NPK treatment and 10 other treatments in which secondary macronutrient (Mg, S) and/or micronutrients (B, Zn) (SMNs) were added to the NPK. These were set across 4 locations with 3 replications. **Results:** Maize yield response to the addition of SMNs showed wide variation. The highest yield advantage over recommended NPK fertilizers was highest with the addition of Mg in Lere (2.4 t ha^{-1}), S+B+Zn in Faskari (2.8 t ha^{-1}), S+B in Doguwa (1.5 t ha^{-1}) and S+Zn in Toro (2.4 t ha^{-1}). The uptake, agronomic use efficiency, internal utilization efficiency and apparent recovery efficiency of N, P and K were significantly increased with the addition of SMNs but were not improved with Zn application beyond NPK alone. **Conclusion:** These results indicated that nutrient limitations to maize in the Guinea Savannah go beyond N, P and K. Therefore, S, Mg and B are needed to improve maize productivity and engender improved use efficiencies of NPK fertilizers.

Key words: Nutrient management, fertilizer use, interaction, yield response, macronutrients, micronutrients

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

In Nigeria, maize (*Zea mays* L.) is a strategic staple crop on which many households depend on for domestic consumption. Additionally, it provides many industrial uses in flour mills, breweries, confectioneries and animal feed mills. The bulk of maize production is in the Guinea Savanna of Nigeria where the most favourable climatic conditions suitable for its production exist. Despite the favourable growing conditions, yields obtained by smallholder farmers are far below the attainable yields for most improved varieties and high variability in yield exists between farms. Average farmer yields in 2016 were 2.0 t ha⁻¹ although actual yields obtained in farmers' fields, could range between 0.5-4.0 t ha⁻¹, depending on fertilizer and agronomic practices¹.

The major reason for the low maize yields in Nigerian Guinea Savanna has been attributed to several constraints, such as poor soil fertility and low nutrient availability^{2,3}, non-use of improved seeds, herbicides and fertilizer, lack of proper adherence to good agronomic practices⁴ and increased levels of abiotic and biotic constraints such as the recent outbreak of fall armyworms⁵ and Striga. Poor soil fertility and low nutrient availability have been singled out as the most serious biophysical constraints that result in poor yields in sub-Saharan Africa (SSA) countries including Nigeria⁶⁻⁸.

In Nigeria, regional blanket fertilizer recommendations have been used as one of the intervention strategies for tackling poor soil fertility and improving crop yields and nutrient use efficiencies. This recommendation focused on the three primary nutrients (N, P and K) as the most limiting in crop production⁹. Although the use of the current fertilizer recommendation has increased crop yields, it has been established that it may have also accelerated the depletion of other nutrients not supplied, leading to nutrient deficiencies and imbalances. Indiscriminate use of these imbalanced NPK aggravates micronutrient disorders which act additively along with biotic and abiotic stresses to limit crop productivity¹⁰⁻¹². Part of the reasons why attainable yields are rarely realized despite NPK applications is the limitations of other nutrients¹³. In fact, other nutrients (apart from N, P and K) have been reported to be constraints for maize production in Sub-Saharan African countries including Nigeria¹⁰⁻¹². Such nutrients include secondary macronutrients especially sulphur^{10,11,14} and micronutrients especially zinc, boron, copper and molybdenum¹⁵⁻¹⁷.

Recently, several studies have shown the need to revisit the current understanding of crop nutrients need and fertilizer recommendation programs under the current crop intensification systems. A report by Shehu *et al.*¹⁰ using

diagnostic nutrient omission trials in the Northern Guinea and Sudan Savannas of Nigeria highlighted the need for more diagnostic trials involving the omission of secondary macronutrients and micronutrients to understand their distinctive role in limiting maize yield and the link with underlying soil characteristics. In a meta-analysis reported by Kihara *et al.*¹¹, secondary nutrients such as S and micronutrients like Zn and B are indicated to limit crop productivity in SSA, especially in soils with low response to macronutrients and that more research is needed to unravel the conditions under which application of secondary macro and micronutrients could improve crop yields¹¹. This study aimed at quantifying the effects of the addition of secondary macronutrients and micronutrients on maize yield, nutrient uptake and use efficiencies of N, P and K. The specific objectives were to (1) Analyze the interactive effect of secondary macro and micronutrients on maize grain yield and nutrient uptake in the Guinea Savannah of Nigeria and (2) Assess the effect of the addition of secondary macronutrients and micronutrients on N, P and K use efficiencies.

MATERIALS AND METHODS

Site Selection and description: This study was conducted during the 2017/2018 rainy season (June-October) in the Guinea Savanna of Nigeria across 4 locations (Faskari, Doguwa, Lere and Toro) of Nigeria (Fig. 1). The study locations cut across 4 political State boundaries (Katsina, Kano, Kaduna and Bauchi). In each study location, a representative farming domain was selected based on the intensity of maize production, the similarity in soil base and farmer-resource endowment. Three sites were randomly selected in each location and on-farm researcher-managed multi-nutrient omission trials (MNOT) were established.

Experimental treatments and field procedures: The trials consisted of twelve treatments which were arranged in a randomized complete block design in 3 replicates, with an experimental plot size of 6×5 m. The description of each treatment is shown in Table 1. Maize was planted at 0.75 m inter-row spacing and 0.25 m intra-row spacing, using 2 seeds/planting hole. At two weeks after emergence, the plants were thinned to 1 plant/stand, resulting in a uniform plant density of 53,333 plants ha⁻¹. The variety used was IWD-C2-SYN (SAMMAZ 15) which is recommended for this agroecology. The IWD-C2-SYN is an intermediate maturing, white dent open-pollinated variety with a yield potential of about 10 t ha⁻¹. The nutrients were applied as follows: Primary

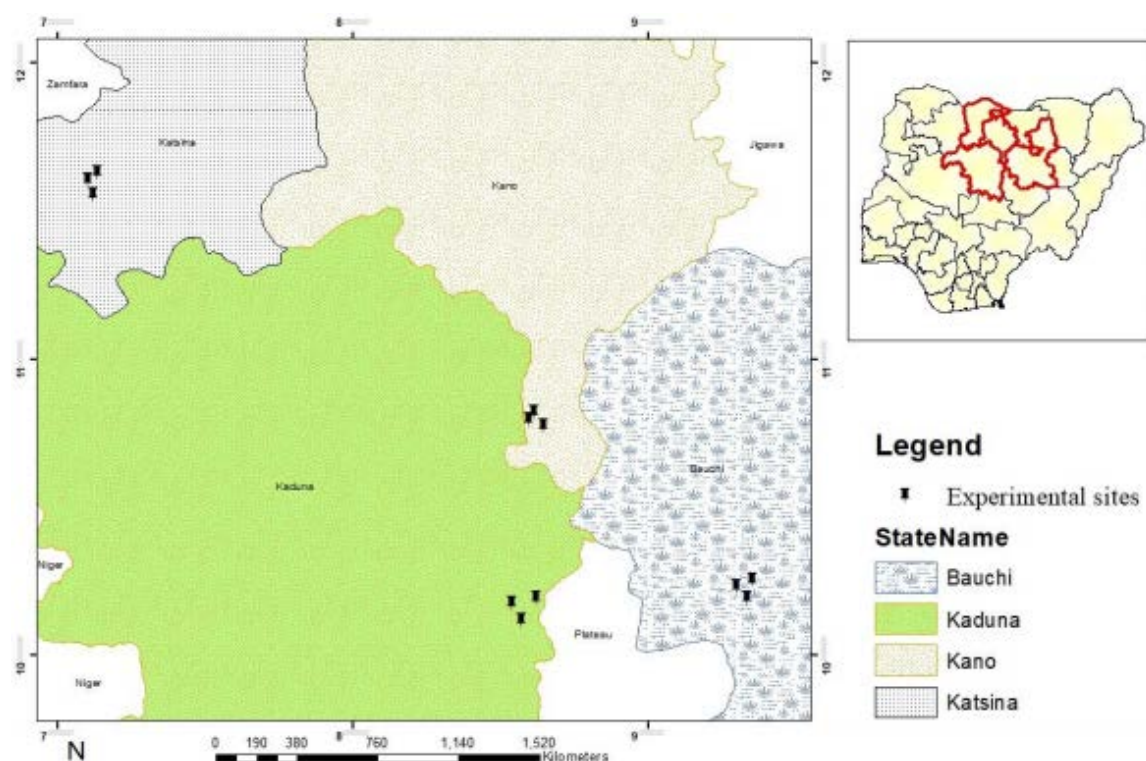


Fig. 1: Map showing experimental fields in the Guinea Savanna of Nigeria
Source: Author

Table 1: Description of the 12 treatments for the study

Codes	Treatments	Descriptions
T ₁	Control	No fertilizer application, used to measure grain yield as an indicator of the effective indigenous N, P, K, S, Zn, Mg and B supply from soil, rainwater, crop residue and or atmosphere
T ₂	NPK	N, P and K applied at the recommended rate (FFD [®]), used to estimate the nutrient-limited yield gap and evaluate agronomic use efficiencies of N, P and K. This treatment served as a check
T ₃	NPK+S	This treatment provides the estimate of the effect of sulphur as a secondary macronutrient on maize productivity in addition to NPK to allow for evaluating the contribution of S to nutrient-limited yield gap
T ₄	NPK+B	This treatment provides the estimate of the effect of boron as a micronutrient on maize yield in addition to NPK to allow for evaluating the contribution of B to nutrient-limited yield gap
T ₅	NPK+Zn	This treatment provides the estimate of the effect of zinc as a micronutrient on maize yield in addition to NPK to allow for evaluating the contribution of Zn to nutrient-limited yield gap
T ₆	NPK+Mg	This treatment provides an estimate of the effect of magnesium as a secondary macronutrient in addition to NPK to allow for evaluating the contribution of Mg to nutrient-limited yield gap
T ₇	NPK+B+Mg	This treatment provides the estimate of the interactive effect of boron and magnesium on maize yield in addition to NPK
T ₈	NPK+S+B	Used to measure grain yield to measure the combined effect of macro and micronutrients on maize productivity
T ₉	NPK+S+Mg	This treatment has recommended N, P, K, S and Mg rates applied, used to measure grain yield to estimate the combined effect of primary (NPK) and secondary (S and Mg) macronutrients on maize productivity
T ₁₀	NPK+S+B+Zn	This treatment was used to assess the interactive effects of N, P, K, S, B and Zn and their contribution to maize productivity
T ₁₁	NPK+S+B+Mg	Recommended rates of these nutrients will be applied, the treatment provides an estimate of the interactive effects of S, B and Mg in addition to NPK on maize
T ₁₂	NPK+S+B+Mg+Zn	S, B, Zn and Mg will be applied at recommended rates in addition to NPK to provide an estimate of their effect on maize productivity

macronutrients were applied at 140 kg N ha⁻¹, 60 kg P₂O₅ ha⁻¹ and 60 kg K₂O ha⁻¹, secondary macronutrients and micronutrients in all the sites were applied at 20 kg S ha⁻¹, 10 kg Mg ha⁻¹, 5 kg Zn ha⁻¹ and 5 kg B ha⁻¹. Nitrogen (N) was applied in 3 splits, one-third at planting together with all other nutrients and the other two one-thirds at 21 and 42 days after

sowing (DAS). The N, P and K were applied in the form of urea (46% N), triple superphosphate (20% P₂O₅) and muriate of potash (60% K₂O), respectively. Sulphates of magnesium and zinc were used as the sources of Mg, Zn and sulphur. Elemental S was also used to augment the balance of S in MgSO₄ and ZnSO₄. Borax was used as the source of boron.

Soil characterization and laboratory analyses: Before the trial establishment, soil samples were taken from each experimental field and analyzed for initial nutrient status. The soil samples were collected using auger from at least 5 points in a W-shape to have a representative sampling. The samples were taken from 0-20 cm from each plot and then bulked together and passed through a 2 mm sieve to form a composite sample. The composite samples were prepared using standard procedures and analyzed for physical and chemical properties. Total organic carbon was measured using modified Heanes¹⁸ chromic wet chemical oxidation and spectrophotometric method. Total nitrogen (total N) was determined using the micro-Bremner digestion method¹⁹. Soil pH (S/W ratio of 1:1) in water was measured using the glass electrode pH meter and particle size distribution using the hydrometer method²⁰. Available phosphorus, available Sulphur, exchangeable cations (K, Ca, Mg and Na) and micronutrients (B, Cu, Mn, Fe and Zn) were analyzed based on Mehlich extraction procedure²¹ and reading with inductively coupled plasma optical emission spectroscopy (ICP-OES). Exchangeable acidity ($H^+ + Al^{3+}$) was determined by shaking the soil with 1N KCl and titration with 0.5N NaOH²². Effective cation exchange capacity (CEC) was calculated as the summation of exchangeable cations (K, Ca, Mg and Na) and exchangeable acidity ($H^+ + Al^{3+}$). All the laboratory analyses were carried out at the Analytical Services Laboratory of the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria.

Maize yields and nutrient uptake: At physiological maturity, plants were harvested from a net plot of 9 m² from the four central rows. All the plants in the net plot were harvested and the total fresh weights of cobs and stover were taken in the field using a sensitive digital scale. Ten cobs were randomly selected as subsamples, dried over 8 days and then shelled. Thereafter, the yield was determined as a function of grain weight, shelling percentage and measured grain moisture. Grain yield was finally expressed on a dry weight basis at 15.0% moisture content. Five stover sub-sample also were taken from thoroughly mixed plants from the net plot and then dried in a forced-air oven at 60°C for 48 h, after which stover dry weights were determined. Subsamples of grain and stover were ground to 2 mm and digested using nitric acid and 50% hydrogen peroxide mixture to determine P, K, Ca, Mg, Cu, Fe, Mn and Zn. Total N was determined by the micro-Kjeldahl method. These ground and digested samples were analyzed in the laboratory using standard methods²².

Statistical analysis: Soil physical and chemical properties were subjected to descriptive statistics to provide the estimate

of the mean, standard error and coefficient of variation (CV) values at location level using JMP® Pro Version 14.0 (SAS Institute Inc., 2018). Variation in soil properties was assessed using the CV values and rated as low (<20%), moderate (20-50%) and high (>50%) based on Aweto²³.

Nutrient application strategy effects on maize grain yields and nutrient uptake were examined using a mixed model with nutrient management strategy as a fixed effect; replication nested in location and interaction between location and nutrient application strategy as a random effect. In addition, the yield difference of each of the nutrient application strategies relative to the check treatment (i.e., NPK) was explored to assess yield gain/loss when a nutrient was omitted or applied across the four locations.

To evaluate the nutrient use efficiencies of maize, the following parameters were calculated using the equations described in Dobermann²⁴.

Agronomic use efficiency (AE) of applied nutrient (kg yield increase per kg of nutrient applied):

$$AE \text{ (kg kg}^{-1}\text{)} = \frac{Y - Y_0}{F} \quad (1)$$

Apparent crop recovery efficiency (RE) of applied nutrient (kg increase in N uptake per kg N applied) as:

$$RE \text{ (kg kg}^{-1}\text{)} = \frac{U - U_0}{F} \quad (2)$$

where, RE was then expressed in percentage (%) to reflect its dependency on the congruence between plant demand and nutrient release from the applied nutrient.

Internal utilization efficiency (IE) of a nutrient (kg yield kg⁻¹ nutrient uptake):

$$IE \text{ (kg kg}^{-1}\text{)} = \frac{Y}{U} \quad (3)$$

Partial factor productivity (PFP) of applied nutrient (kg harvested product per kg nutrient applied):

$$PFP = \frac{Y}{F} = \frac{Y_0}{F} + AE \quad (4)$$

Where:

U = Total plant nutrient uptake in aboveground biomass at maturity (kg ha⁻¹) in a plot that received fertilizer

U₀ = Total nutrient uptake in aboveground biomass at maturity (kg ha⁻¹) in the control plot

Y = Maize yield with applied nutrients (kg ha⁻¹)

Y₀ = Maize yield (kg ha⁻¹) in a control treatment

F = Amount of nutrient applied (kg ha⁻¹)

RESULTS

Variation in soil physical and chemical properties of the study area:

Most soil physical and chemical properties showed moderate to wide spatial variability across the study sites (Table 2). Soil pH showed moderate variability with most of the sites having pH and exchangeable acidity within the range considered optimum for most crop growth and development. In Lere, the available Fe concentration was high with the pH being strongly acidic implying the potential of low P availability due to fixation by Al and Fe. Mean total N, effective cation exchange capacity (ECEC) and organic carbon in the soils fell within low fertility status. Available S varied moderately across sites and fell within low fertility class in Toro and Doguwa while in Lere and Faskari. Exchangeable K was moderate to high in all the sites. Boron concentration was lowest in Toro (0.019 mg kg⁻¹) and highest in Doguwa (0.045 mg kg⁻¹). The concentration of Cu varied widely and was low in Toro and Lere and medium in Doguwa and Toro. Very high Mn concentration was observed in all the sites.

Maize response to nutrient management strategies: There was a wide variation in the response of maize to the addition of a single macronutrient or micronutrient or when used in combination as indicated by gain or loss in grain yield. This

indicates the wide diversity and heterogeneity in soil and maize growing conditions in the study areas. The variance components and percent contributions of the random terms specified in the model are presented in Table 3.

Table 4 shows the effects of nutrient application strategies on maize grain yield and nutrient uptake in the Guinea Savanna of Nigeria. Maize grain yield was significantly ($p < 0.05$) influenced by nutrient application strategy. In all cases, the addition of secondary macronutrients and/or micronutrients to NPK led to an about a 4-fold increase in grain yield relative to the control. Figure 2 show the interactive effect of the addition of nutrients on maize grain yield across the four locations in the Guinea Savannah of Nigeria. There was a wide variation among the locations in terms of loss or gain in grain yield resulting from the addition of SMNs. The addition of secondary macronutrient (S and/or Mg) to NPK led to an over 1 t ha⁻¹ increase in grain yield compared to NPK alone. Yield gains due to sulphur application in addition to the recommended NPK were highest in Lere (1.8 t ha⁻¹) and lowest in Toro (0.1 t ha⁻¹). This represented 25% yield increment over the values obtained using there commended NPK fertilizers. In the case of Mg, higher gains in grain yield more than that with S were obtained in all the four locations with the highest gain of about 2 t ha⁻¹ observed in Faskari. The addition of B showed a variable response across locations,

Table 2: Soil physical and chemical properties of the experimental sites

	Locations					
Soil properties	Toro	Lere	Doguwa	Faskari	CV (%)	±SE
Particle size (%)						
Clay	8.60	10.60	23.90	17.30	55.95	2.439
Silt	11.90	19.90	29.30	31.20	43.86	2.925
Sand	79.50	69.50	46.80	51.50	27.72	4.945
Soil reaction						
Ph	5.90	5.4	6.10	5.80	5.95	0.099
Total nitrogen (g kg ⁻¹)	0.42	0.41	0.36	0.40	26.34	0.03
Available P (mg kg ⁻¹)	18.12	5.84	8.45	15.14	47.11	1.62
Available S (mg kg ⁻¹)	3.88	5.5	3.67	5.86	43.78	0.029
Organic carbon (g kg ⁻¹)	2.43	2.65	3.60	1.30	39.87	0.29
Micronutrients (mg kg⁻¹)						
Zn	9.61	6.64	16.01	1.32	99.78	2.42
Cu	1.66	1.07	1.17	2.55	55.78	0.26
Mn	39.70	57.31	47.31	30.64	38.65	4.88
Fe	114.44	125.28	111.43	104.20	22.91	7.53
B	0.019	0.030	0.045	0.023	39.81	0.003
Exchangeable cations (cmol⁺ kg⁻¹)						
Na	0.27	0.33	0.32	0.37	25.39	0.024
K	0.35	0.49	0.46	0.32	26.59	0.03
Mg	1.74	1.14	1.31	0.68	0.91	0.21
Ca	1.55	2.86	2.95	1.07	60.93	0.37
Effective CEC	3.37	3.38	5.09	2.35	43.59	0.45
Exchangeable acidity	0.01	0.00	0.00	0.001	39.20	0.001

CV: Coefficient of variation, SE: Standard error

Table 3: Variance components and percent contribution of random factors to grain yield, total macronutrients and micronutrients nutrient uptake of maize in the Guinea Savanna of Nigeria

Random effects	Grain yield		Total N uptake		Total P uptake		Total K uptake		Total Ca uptake		Total Mg uptake		Total Cu uptake		Total Fe uptake		Total Mn uptake		Total Zn uptake	
	Variance	Percentage	Variance	Percentage	Variance	Percentage	Variance	Percentage	Variance	Percentage	Variance	Percentage	Variance	Percentage	Variance	Percentage	Variance	Percentage	Variance	Percentage
Location (L)	135629	15.5	19.9	2.3	0.5	2.40	-34.0	-4.1	4.8	4.2	-0.00001	-0.06	-0.690	1.4	-0.024	-4.8	0.0008	3.4	-0.00035	-0.7
Rep (Location)	37668	4.3	-22.6	-2.6	0.1	0.60	30.0	3.7	3.4	2.9	-0.008	-6.30	1.163	2.4	0.039	8.0	-0.0004	-1.6	-0.00205	-4.2
Location×treatment	403852	46.1	121.9	14.1	-0.2	-0.08	227.0	27.9	0.8	0.7	-0.011	-8.01	-5.212	10.6	-0.011	-2.1	0.0005	2.0	0.001054	2.2
Residual	298164	34.1	746.3	86.2	19.2	97.80	591.0	72.6	105.4	92.1	0.132	100.00	54.074	85.6	0.487	95.0	0.022	96.2	0.049864	92.9
Total	875312		865.5		19.6		814.4		114.5		0.132		49.300		0.500		0.0232		0.050919	

Table 4: Maize grain yield and uptake of macronutrients and micronutrients as influenced by nutrient management strategies

Nutrient management strategy	Grain yield (t ha ⁻¹)	Total N		Total P		Total K		Total Ca		Total Mg		Total Cu		Total Fe		Total Mn		Total Zn	
		uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	uptake (kg ha ⁻¹)	
Control	0.42±0.309 ^e	25.0±11.5 ^c	8.0±1.6 ^{bcd}	54.0±11.5 ^{ab}	12.0±1.7 ^{abc}	72.0±11.9 ^{ab}	11.0±3.8 ^{de}	5.3±2.33 ^c	0.32±0.24 ^b	0.03±0.056 ^{cd}	0.27±0.11 ^b	0.14±0.080							
NPK	3.79±0.309 ^d	76.0±11.9 ^{abc}	12.0±1.7 ^{abc}	72.0±11.9 ^{ab}	13.0±4.0 ^{de}	12.2±2.55 ^{abc}	13.0±4.0 ^{de}	12.2±2.55 ^{abc}	0.54±0.26 ^{ab}	0.19±0.059 ^{a-d}	0.48±0.12 ^{ab}	0.22±0.085							
NPK+B	4.20±0.309 ^d	99.0±9.8 ^{ab}	12.0±1.3 ^{abc}	94.0±10.0 ^a	31.0±3.1 ^{ab}	20.7±1.77 ^a	31.0±3.1 ^{ab}	20.7±1.77 ^a	1.15±0.19 ^{ab}	0.04±0.046 ^d	0.85±0.09 ^a	0.30±0.064							
NPK+Mg	5.72±0.309 ^a	128.0±10.1 ^a	14.0±1.4 ^{ab}	101.0±10.3 ^a	34.0±3.2 ^a	23.0±1.88 ^a	34.0±3.2 ^a	23.0±1.88 ^a	1.18±0.19 ^{ab}	0.15±0.048 ^{a-d}	0.77±0.09 ^{ab}	0.35±0.068							
NPK+S	4.73±0.309 ^{a-d}	111.0±9.8 ^{ab}	17.0±1.3 ^a	80.0±10.0 ^{ab}	26.0±3.1 ^{a-d}	16.3±1.77 ^{ab}	26.0±3.1 ^{a-d}	16.3±1.77 ^{ab}	1.09±0.19 ^{ab}	0.31±0.046 ^{ab}	0.77±0.08 ^{ab}	0.28±0.064							
NPK+S+B	5.17±0.317 ^{abc}	110.0±9.8 ^{ab}	13.0±1.3 ^{abc}	100.0±10.0 ^a	29.0±3.1 ^{abc}	18.2±1.77 ^{ab}	29.0±3.1 ^{abc}	18.2±1.77 ^{ab}	1.57±0.18 ^a	0.10±0.046 ^{bcd}	0.81±0.08 ^a	0.37±0.064							
NPK+S+B+Mg	4.97±0.309 ^{abc}	97.0±10.1 ^{ab}	15.0±1.4 ^{ab}	75.0±10.3 ^{ab}	24.0±3.2 ^{a-e}	17.5±1.88 ^{ab}	24.0±3.2 ^{a-e}	17.5±1.88 ^{ab}	1.06±0.19 ^{ab}	0.27±0.048 ^{abc}	0.64±0.09 ^{ab}	0.27±0.068							
NPK+S+B+Zn	5.65±0.309 ^{ab}	103.0±9.8 ^{ab}	16.0±1.3 ^a	82.0±10.1 ^{ab}	23.0±3.1 ^{a-e}	14.8±1.77 ^{abc}	23.0±3.1 ^{a-e}	14.8±1.77 ^{abc}	1.18±0.18 ^{ab}	0.34±0.046 ^a	0.63±0.08 ^{ab}	0.22±0.064							
NPK+S+B+Zn+Mg	4.59±0.309 ^{bcd}	118.0±10.5 ^{ab}	7.0±1.4 ^{cd}	85.0±10.6 ^{ab}	22.0±3.4 ^{a-e}	14.7±2.02 ^{abc}	22.0±3.4 ^{a-e}	14.7±2.02 ^{abc}	1.47±0.21 ^{ab}	0.05±0.05 ^{cd}	0.82±0.10 ^{ab}	0.41±0.072							
NPK+S+Mg	4.72±0.309 ^{a-d}	110.0±10.1 ^{ab}	9.0±1.4 ^{bcd}	63.0±10.3 ^{ab}	21.0±3.2 ^{a-e}	13.5±1.88 ^{abc}	21.0±3.2 ^{a-e}	13.5±1.88 ^{abc}	1.13±0.19 ^{ab}	0.13±0.048 ^{a-d}	0.57±0.09 ^{ab}	0.20±0.068							
NPK+S+Zn	4.75±0.317 ^{a-d}	97.0±9.8 ^{ab}	10.0±1.3 ^{bcd}	63.0±10.0 ^{ab}	17.0±3.1 ^{b-e}	11.2±1.77 ^{bc}	17.0±3.1 ^{b-e}	11.2±1.77 ^{bc}	0.70±0.18 ^{ab}	0.24±0.046 ^{a-d}	0.46±0.08 ^{ab}	0.09±0.064							
NPK+Zn	3.88±0.309 ^d	68.0±11.0 ^{bc}	4.0±1.5 ^d	37.0±11.1 ^b	9.0±3.6 ^e	6.2±1.4 ^c	9.0±3.6 ^e	6.2±1.4 ^c	0.51±0.22 ^b	0.06±0.053 ^{cd}	0.59±0.11 ^{ab}	0.10±0.076							
Prob > F	<0.0001	<0.0001	<0.0001	0.0061	<0.0001	<0.0001	<0.0001	<0.0001	0.0064	<0.0001	0.0081	0.0521							

Values not connected by the same letter(s) are significantly different at p<0.05 using Student Newman-Keuls test

Levels not connected by the same letter(s) are significantly different at p<0.05 using Student Newman-Keuls test

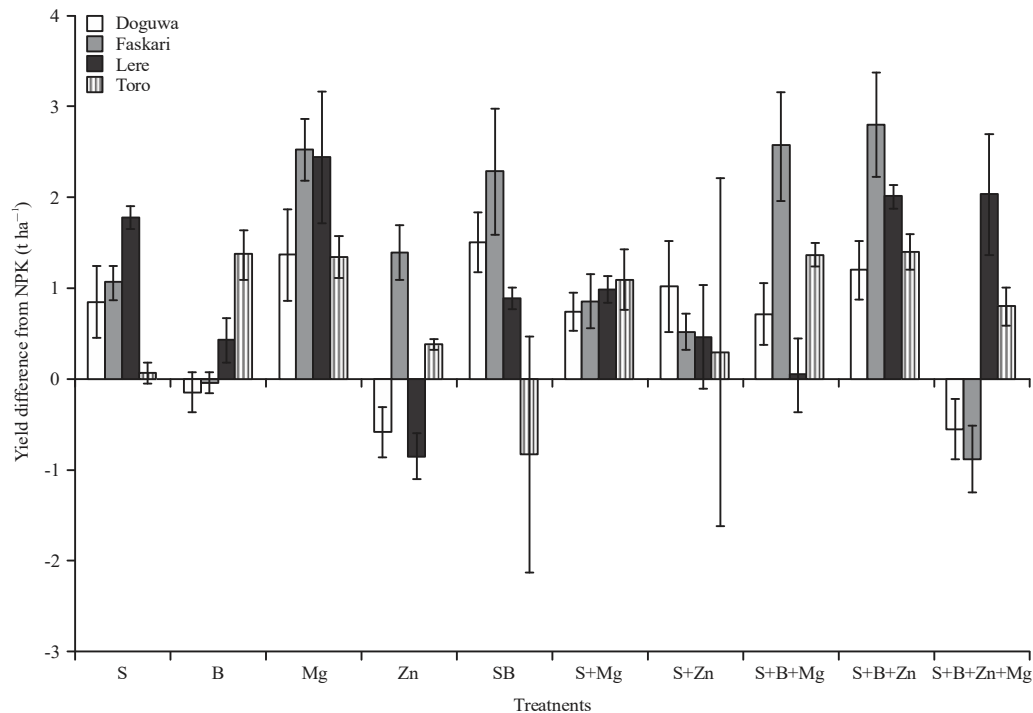


Fig. 2: Maize yield response to the application of SMNs as a yield difference relative to NPK

yield gains of 0.4 and 1.4 t ha⁻¹ were observed in Toro and Lere, respectively. In Doguwa and Faskari however, a yield reduction of 0.1 t ha⁻¹ was observed with the addition of B. A similar response was observed with the addition of Zn where a negative yield response (yield reduction of 0.6 and 0.8 t ha⁻¹) were recorded in Doguwa and Lere, respectively. The combined effects of SMNs addition showed a general yield gain of >1 t ha⁻¹ in all locations except in Doguwa where the addition of S+B+Zn+Mg resulted in a yield reduction of 0.5 t ha⁻¹. Highest yield gains were observed with the addition of S+B in Doguwa (1.58 t ha⁻¹), S+B+Zn in Faskari (2.8 t ha⁻¹), Mg in Lere (2.48 t ha⁻¹) and S+Zn in Toro (2.08 t ha⁻¹).

Nutrients uptake and use efficiencies: Across all nutrient management strategies, there were differences in the total uptake of both macronutrients and micronutrients. The treatments had a positive significant effect ($p < 0.05$) on total N, P, K, Ca, Mg, Cu, Fe and Mn uptakes but did not significantly influence Zn uptake ($p > 0.05$) as presented in Table 3. Treatment groups that have Mg had the highest uptake of N, P, K, Ca and Mg uptakes (128, 17, 34 and 24 kg ha⁻¹, respectively). The total Cu uptake was highest for NPK+S+B (1.57 kg ha⁻¹) while total Fe uptake was highest for NPK+S+B+Zn (0.34 kg ha⁻¹).

The addition of secondary macro and/or micronutrients generally increased N, P and K use efficiencies (Fig. 3a-d). The mean agronomic N use efficiency (AE_N) was highest with

NPK+S+B+Mg treatment (34.6 kg grain kg⁻¹ N applied) and the least from NPK+Zn (21.4 kg grain kg⁻¹ N applied) treatment K (Fig. 3a). Application of Zn alone to NPK did not increase AE_N, AE_P and AE_K beyond that observed in NPK only plots. The internal N utilization efficiency (IE_N) was highest for NPK (53.3 kg grain kg⁻¹ N applied) and lowest for NPK+Zn (31.7 kg grain kg⁻¹ N applied) (Fig. 3b). A different trend was observed in the case of IE_P were the highest values were recorded for NPK+Zn and lowest for NPK. Internal utilization of K (IE_K) was highest for NPK+S+Zn and lowest for NPK+S+B+Zn+Mg (Fig. 3b). The IE_P were mostly lower than IE_N and IE_K. The results further revealed that the highest mean N apparent recovery efficiency (RE_N) was highest for NPK+Mg (75.5 kg yield increased kg⁻¹ N applied) and lowest for NPK+Zn (27.1 kg yield increased kg⁻¹ N applied) whereas, RE_P was highest for NPK+S and lowest for NPK+Zn (Fig. 3c). The RE_N was consistently higher than RE_P and RE_K. The mean of partial factor productivity (PFP) was consistently higher for P than N and K. The PFP_N was highest for NPK+S+B+Zn and lowest for NPK+Zn (Fig. 3d). Similar trends were observed with P and K. Application of secondary macronutrients and/or micronutrients increased N, P and K use efficiencies beyond those observed with recommended NPK only, except for NPK+Zn. All treatments with+Zn had consistently lower nutrient use efficiencies compared to other treatment combinations.

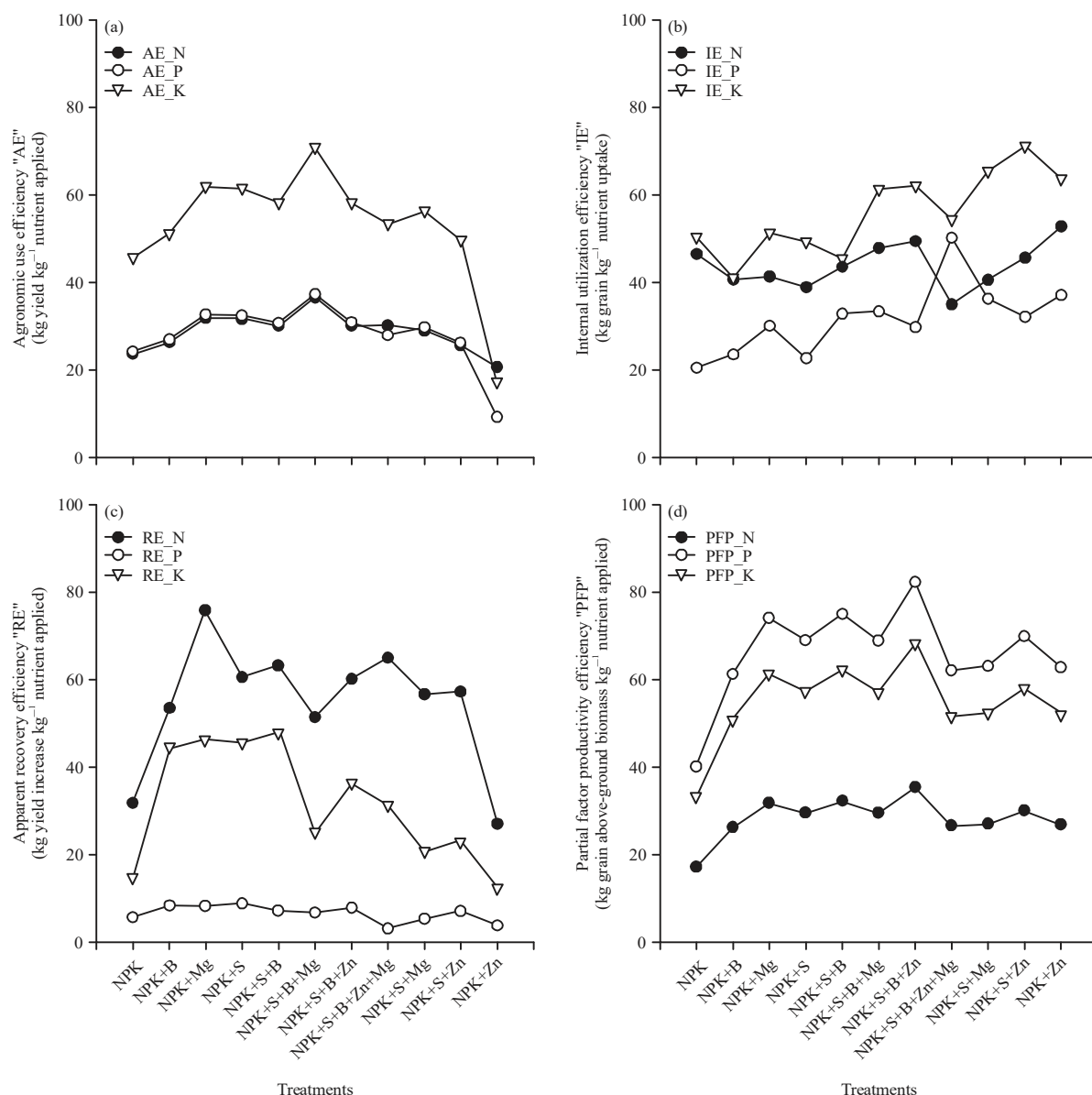


Fig.3(a-d): Effects of nutrient management strategy on (a) agronomic use efficiency, (b) internal utilization efficiency, (c) Apparent recovery efficiency and (d) Partial productivity of N, P and K

DISCUSSION

The mean available S and exchangeable K were within medium to high fertility class based on the classification of Horneck²⁵. The total N, ECEC and total organic C were within low fertility class as described by Esu²⁶ in all sites. The low total N, ECEC and total organic C in all the sites were mainly because Savannas are known to be inherently low in fertility partly because they have low nutrient reserves and as a result of the removal or burning of crop residues at harvest²⁷⁻²⁹. This could be due to historic residual S applied through

S-containing fertilizers such as SSP (with 11-12% S content) and K application through NPK fertilizers and the parent materials with rich K-bearing feldspar minerals. The low Cu concentration in Lere and Toro and low Zn in Faskari indicated the potential development of their deficiencies and this could partly be attributed to their strong sorption capacity and due to nutrient mining through the application of NPK only³⁰. In addition, the soils in those sites have a high sand fraction (%S and >50) making it be highly prone to nutrient leaching due to low water and nutrient holding capacity and consequently have low available Zn and organic carbon^{31,32}.

Previous studies have reported a high degree of variability in crop response to nutrients that are associated with variability in soil characteristics within and across sites in sub-Saharan Africa^{10-11,33,34}. In an experiment in southwestern Nigeria, the application of 12.5 kg ha⁻¹ of Mg was found to increase grain yield of QPM by 18.8% relative to NPK in a single cropping season¹⁵. In 3 years, maize field in SSA, magnesium application led to grain yield gain of 16.5% relative to NPK only³⁵ and this effect was significant under the condition of lower N rate³⁶. This phenomenon can be related to the physiological function of Mg²⁺, which is responsible for nitrate anions uptake by plant roots from the soil solution. Micronutrients also limit maize growth and especially in soils that are continuously cropped without returning these nutrients^{11,12}. The yield loss observed with Zn application in Doguwa and Lere suggested that additional application of Zn would decimate the grain yield. Previous studies in the sites in the Guinea Savannah have reported the sufficiency of Zn in some of the soils³⁷. Similarly, the response of crops to nutrients including micronutrients depends on among other factors (e.g., soil acidity and nutrient interactions), the level of crop available nutrients in the soil¹¹. The response of maize to Zn is low under high P levels as there is an antagonistic interaction between high P levels and Zn. Soils in Doguwa and Lere have high sand content and generally have sandy to sandy loam texture. The soils in these are likely to be easily leached and have low crop available Zn³⁷.

Most researches in SSA investigated secondary macronutrients and micronutrients singly but results from this study suggest that multiple effects are also common^{14,15}. This is similar to report by Vanlauwe *et al.*¹² that multiple rather than individual deficiency are the norms in most part of SSA. Similarly, nutrient interaction influences crop yield as many secondary macronutrients and micronutrients are interrelated in their metabolic functions and uses similar rhizosphere transporters and could, therefore, have an antagonistic or additive relationship^{38,39}. Supplementation by S, Zn and B increases maize yield by 40% over standard NPK recommendation in certain SSA countries¹². In a nutrient omission trial in Mozambique, the application of Mg, S, Zn and B lead to 1.3 t ha⁻¹ more yield than NPK only. Similarly, In Ethiopia, with balanced NPK across 9 sites, yields were 3 t ha⁻¹ but with S, Mg, Zn and B supplementation, the yield of 4.2 t ha⁻¹ was observed¹².

Previous studies reported significant effects of mineral fertilizers on nutrients uptake and accumulation and consequently crop yields⁴⁰. In Doguwa and Toro where pH is moderately acidic, they tend to have low Fe uptake. Organic matter content in the soil mediate Cu uptake in crops⁴¹ and

the low total organic carbon in the study areas could be the reason for low uptake of the micronutrients.

The agronomic use efficiency, internal utilization efficiency and apparent recovery efficiency have frequently been used to characterize the nutrient effects^{24,42-44}. The N, P and K use efficiencies were highest with NPK+Mg treatment. These findings are in conformity with the results of previous studies which reported that adequate soil Mg exhibit favourable effects on N use efficiency^{45,46}. Magnesium is known to assist the crop to access and utilize N and called the phenomenon Mg-induced N uptake⁴¹. Magnesium is mainly transported in the plant by mass flow, any abiotic stress such as moisture stress could inhibit its uptake. The observed enhanced use efficiencies of N, P and K due to the addition of secondary macronutrients and/or micronutrients is in conformity with the observation of Chianu *et al.*³⁹ and Chander *et al.*⁴⁷, who suggested that for better crop yields, a wider range of nutrients other than NPK may be necessary to provide better-balanced nutrient supply through improved agronomic efficiency of the NPK and engender nutrient use efficiencies in some soils.

The findings of this study imply the maize productivity can be increased in the Guinea Savanna of Nigeria when nutrient limitations and imbalances are appropriately addressed through revising the current fertilizer recommendation programmes to include other nutrients that are critical to improve crop yields and use efficiencies of NPK fertilizers.

CONCLUSION

The results of this study demonstrated that the addition of Mg, S and B increase maize yield, agronomic use efficiency, internal utilization efficiency and apparent recovery efficiency of N, P and K relative to the application of NPK only. These improvements were however not realized with Zn application as all treatments with +Zn had consistently lower nutrient use efficiencies compared to other treatment combinations.

SIGNIFICANCE STATEMENT

These results indicated that nutrient limitations to maize in the Guinea Savannah go beyond N, P and K. Therefore, S, Mg and B are needed to improve maize productivity and engender improved use efficiencies of NPK fertilizers. The results provide additional information for establishing an in-depth basis for evaluating the agronomic and economic efficiency of revising current soil fertility management options, based on which recommendations for improved soil management could be rooted.

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