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Research Paper

Simulation of major soil nutrients requirement for maize production using the QUEFTS model in the Northern region of Ghana

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Fertilizer requirement identification at specified Districts is necessary to increase applied fertilizers efficiency. The aim of this study was to estimate promising nitrogen (N), phosphorus (P) and potassium (K) nutrients requirements for maize production in 13 Districts of the Northern region, Ghana, using the Quantitative Evaluation of fertility of tropical soils (QUEFTS) model. Soil samples were collected from 104 locations and analysed for N, P and K contents. The QUEFTS model was calibrated using the required maize cultivation data from farmers' fields to obtain the necessary input parameters. The model predicted linear increase in maize grain yield if nutrients are recovered in balanced amounts of 0.49 kg kg^{-1} N, 0.33 kg kg^{-1} P and 0.67 kg kg^{-1} K with internal efficiencies of 35 kg N kg^{-1} and 77 kg N kg^{-1}, 145 kg P kg^{-1} and 509 kg P kg^{-1}, and 32 kg K kg^{-1} and 114 kg K kg^{-1} to obtain about 60 – 70 % of the potential maximum yield. Maize grain yield showed a good correlation with N (92%), P (92%) and K (71%). Results from the study could be used to enhance soil fertility and maize crop yields in the study area.

Key words: Nutrient requirement, fertilizer recommendation, maize yields, major soil nutrients, smallholder farmers, nutrient simulation

INTRODUCTION

The main economic activity in the Northern region of Ghana is agriculture. Hence majority of the population in the region are smallholder farmers and about 80% of the land area is used for cropping, as reported by Food and Agriculture Organisation (AQUASTAT, 2005). Wairegi, (2011) reported that soils in Sub-Saharan Africa, of which Ghana is one, are however poor especially in nutrient levels and therefore cannot sustain increased crop yields. Poor nutrient management (Nkonya, 2004) and continuous cropping (Martey *et al.*, 2014) have led to persistent low crops in the Northern Region of Ghana. To increase the productivity of these soils for enhanced crop yields and incomes of smallholder farmers in the region therefore requires a model approach of recommending balanced location based nutrients requirement.

The quantitative evaluation of fertility of tropical soils (QUEFTS) is a model that describes the quantitative evaluation of the indigenous fertility of tropical soil by using calculated yields of unfertilized maize fields as a measure (Janssen *et al.*, 1990). The model is used to evaluate the fertilizer demands of soil to produce an estimated potential yield (Liu *et al.*, 2006). All other growth conditions are considered optimal, with the exception of fertilizer application which is considered in the model to affect the fertility of the soil (Janssen *et al.*, 1990). In this regard, the fertility of a soil will be based on the capacity of the soil to provide plants with adequate nitrogen, phosphorus and potassium, although other nutrients are required to facilitate these nutrients provision. The model has been used by a number of researchers to recommend fertilizer requirements for maize and wheat in China (Liu *et al.*, 2006); and also for rice in tropical and sub-tropical Asia (Witt *et al.*, 1999).

The approach will improve soil fertility management results in terms of nutrient application and increase the interest of smallholder farmers to invest more in the agricultural sector. This study therefore aimed at calibrating the QUEFTS model according to the specifications required for the model to operate in order to estimate and recommend balanced N, P and K nutrients that could improve maize grain yields in the 13 Districts. The findings of the study could be used to identify promising and adequate N, P and K nutrients as input for smallholder farmers in the study area.

MATERIALS AND METHODS

Description of study area

The study was carried out in the Northern Region of Ghana (Figure 1), which is one of the regions classified as the “breadbasket” areas of Ghana (Motoyoshi *et al.*, 2007). It is the largest of the ten regions and covers an area of about 70,384 km² with 22 Districts within the region. It lies in a geographical location of latitudes N9° 30’ and N10° 00’and longitudes W0º 51’and W1º 00’ with a mean elevation of 149 m above sea level (Getamap, 2006). The mean annual rainfall of the area ranges from 750 mm to 1050 mm and the mean temperature is 28°C. The region is located in the Guinea-Savanna agro-ecological zone. The major soils of the region are Lixisols, Luvisols, Acrisols and Gleysols as described in the World reference Base for Soil Resources, World Soil Resources, report number 84 (Dedzoe *et al.*, 2001) and are mostly poor in soil nutrients (Wairegi, 2011). Most of the major food crops in Ghana are cultivated in this region and they include rice, maize, millet, sorghum, yam and cowpea. However, only maize farms were targeted in this study because it is one of the widely cultivated cereals in the region which according to Sauer *et al.* (2006) is anticipated to remain as one of the prime crops even if the agricultural economy is modified.

METHODOLOGY

Model description and requirements

The characteristics of the soil dataset required for the model to operate successfully is a well-drained, deep soil with a pH (H_2O) ranging between 4.5 and 7.0, organic carbon content of less than 70 gkg^{-1}, P-Olsen below 30 $mgkg^{-1}$, and exchangeable potassium below 30 $mmolkg^{-1}$ for which the soils in the study area satisfied the conditions. The chemical properties were analysed for a soil of depth 0-20 cm (Smaling and Janssen, 1993). According to Das et al. (2009), QUEFTS describes the relationship between grain yield and nutrient supply in four steps. These steps are (i) assessment of the potential indigenous nutrient supply on the basis of chemical soil data; (ii) calculation of the actual uptakes of N, P and K based on the potential supplies of N, P and K (iii) identification of yield ranges as functions of the actual uptakes of N, P and K at maximum accumulation and maximum dilution; (iv) estimation of the actual yield taking into account the three yield ranges (Janssen *et al.*, 1990).

Assessment of potential indigenous nutrient supply based on soil laboratory test

The data used in this study refers to the fields of eight farmers chosen from each District that has particulars of farmers regarding their farming activities recorded in the database provided by Savanna Agriculture Research Institute (SARI), Tamale, Ghana, as well as farmers who do not have their particulars included in the database. Each field was selected from different communities within a District to ensure uniformity of dispersion in the distribution of selected fields. Thirteen Districts which have available data on research demonstrations captured in the SARI database were used in this study.

Soil samples were collected from each of these 104 locations previously cropped to maize, between May, 2013 and March, 2014 with the soil auger before planting. Twenty (20) cores of 0–20 cm depth of soil were taken and hand-mixed thoroughly in a bucket to homogenize the sample. A composite sample was then taken from the bulk to represent that location as shown in (Figure 2). The soils were analysed for N, P and K contents at the laboratory. Total N was determined by Kjedahl’s method, available P by Bray I method and exchangeable K by Ammonium Acetate extraction (Matula, 2009).

The N, P and K contents for the Districts were obtained

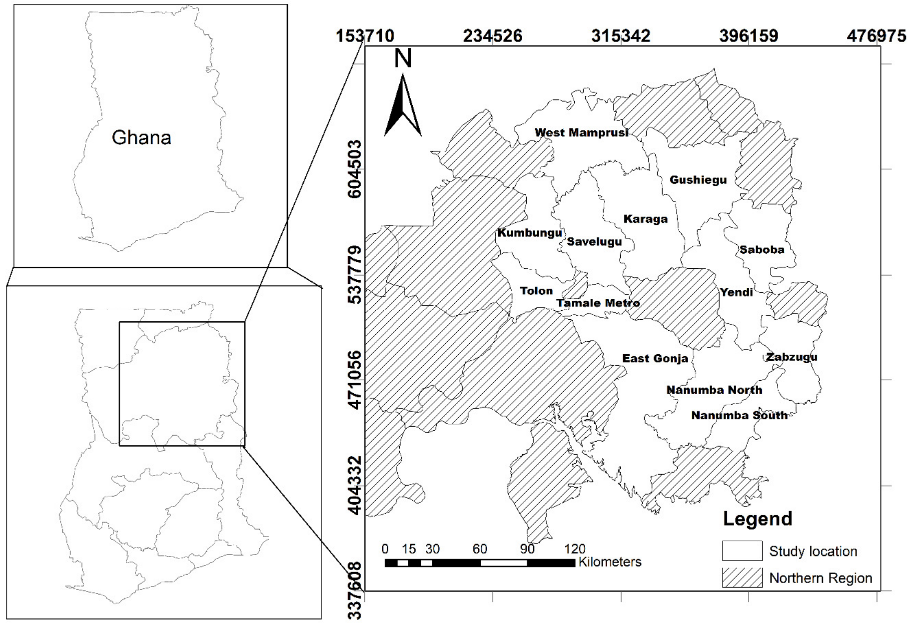

Figure 1. Map of study area.

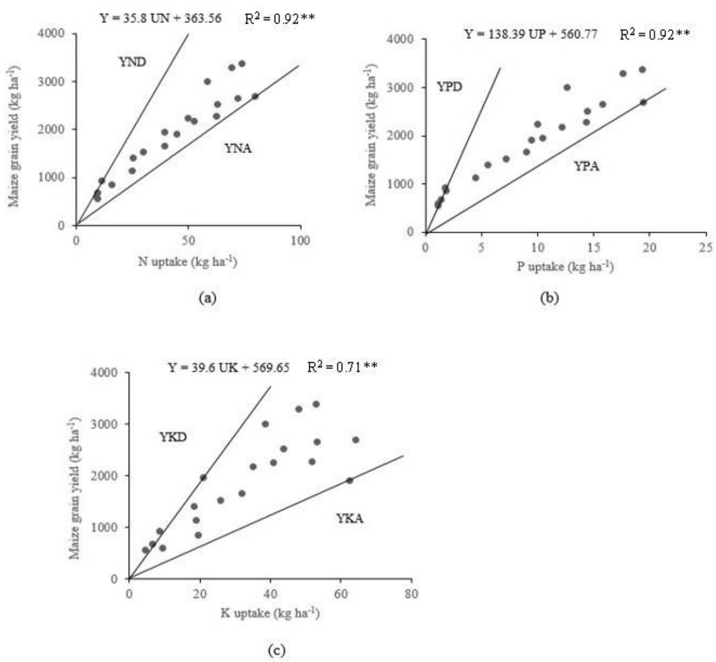

Figure 2. Relationship between grain yield of maize and nutrient uptake (U) of (a) N, (b) P and (c) K. The upper (YND, YPD, and YKD) and lower (YNA, YPA, and YKA) lines indicate yields of maximum dilution and maximum accumulation respectively. Data are based on research trials from Savanna Agricultural Research Institute, Tamale covering 20 demonstration sites from five Districts in Northern Region of Ghana.

**Significant at 0.01 probability level.

from the aggregate N, P and K contents from the soil laboratory analysis from the eight selected communities within each of the chosen District. The nutrient variability in the chosen 13 Districts were then classified under very low and low (N < 0.05 % and N < 0.1, P < 6 mg kg^{-1} and K < 0.1 $cmol_c$ kg^{-1}), adequate (moderate) (N > 0.1 %, P = 6 – 25 mg kg^{-1} and K = 0.1 – 0.25 $cmol_c$ kg^{-1}) and high (good) (N > 0.1 %, P > 25 mg kg^{-1} and K > 0.25 $cmol_c$ kg^{-1}) contents (Wopereis *et al.*, 2009).

Calculation of actual uptakes of N, P and K by the harvested maize

The amount of N, P and K nutrient contents removed from the soil through harvested maize grains were then computed to determine the amounts of nutrients needed to be replaced based on the level of nutrients already in the soil as classified. The N, P and K uptake by the maize crops were determined using the equation by Opoku (2011) as follows:

$$Uptake = (Grain\ yield\ kg\ ha^{-1}) \times Nu\ (kg\ kg^{-1})\ in\ grain + (stover\ yield\ kg\ ha^{-1}) \times Nu\ (kg\ kg^{-1})\ in\ stover \quad (1)$$

The nutrients in percentages were expressed in $kgkg^{-1}$ in order to assess the amount of N, P and K uptake in kg ha^{-1} from the field. The QUEFTS model was then used to determine an estimated amount of nutrients needed to be replaced and compared with the computed. Data obtained from omission plots (NP, NK, and PK plots) calculated from the model was used to obtain parameters that were used to calibrate the model. The potential nutrient supply from the soil, denoted by the recovery efficiency (RE) was estimated with the QUEFTS model; and it was expressed based on the equation given by Liu *et al.* (2006) as:

$$RE = \frac{Uptake\ of\ Nu\ from\ Nu\ fertilsed\ soil - Nu\ Uptake\ from\ Nu\ unfertilised\ soil}{Amount\ of\ Nu\ applied\ or\ available} \quad (2)$$

where Nu is the nutrient (N, P, or K) of interest.

The values of the internal efficiencies (IE), from which the maximum accumulation (a) or minimum nutrient use efficiency (the lowest IE value obtained from the calculations) and maximum dilution (d) or maximum nutrient use efficiency of nutrients in the soil (the highest IE value obtained) were calculated using the equation by Witt *et al.* (1999) as:

$$IE(Nu) = \frac{Grain\ yield}{Uptake(Nu)} \quad (3)$$

The IEs were obtained using data from demonstration trials from five Districts. The field experiment for the trials were comparable to smallholder farming systems which were conducted in the 2013 cropping season. Crops were grown under typical tropical rainfed system. Weeds control were done by hand picking whiles pests and diseases control were done based on plant protection measures such as spraying pesticides. Basically farmers apply their own doses of fertilizers based on the choice of fertilizer applied. Fertilizers used on the fertilized plots include Urea (46 % N), triple superphosphate (50% P_2O_5) and potassium sulfate (44 % K_2O). The planting density for the maize was 50 × 10^3 plants ha^{-1}. Half of the N was applied to the base of the plant and the other half was applied after about 45 days after planting. Phosphorus and K were applied to the base of the crop at planting. The control plot received no fertilizer application, but was treated the same as the fertilized plots. Harvesting was done by hand after about 90 days when the crops were matured. Grain and stover samples were collected from both fertilized and unfertilized plots. The grain was separated from stover by hand.

Model calibration and identification of maize yield ranges

Data from four demonstrations were taken from each of the five Districts, making a total of twenty different trials, and this data was used to calibrate the QUEFTS model (Maiti *et al.*, 2006). In calibrating the model, the maximum yield (Y max) was set to 10000 $kgha^{-1}$, which is the standard yield capacity of the model, while the potential grain yield for the area was set to 60% of the maximum yield. The value for potential yield of maize grain was considered appropriate based on the potential yield of maize in Ghana, which according to Sallah *et al.* (1997) is about 6 tha^{-1} in the Guinea Savannah zone where this study was situated. Total P of the study area was estimated as 155 $mgkg^{-1}$, which was the general phosphorus status of the study area (Owusu-Bennoah *et al.*, 1995). The available P within the study area was analysed using Bray 1 method. However, the requirement for soil P analysis to be used in the QUEFTS model was P-Olsen method. Mowo *et al.* (2006) explained that P Bray 1 is about 0.75 to 2.5 times P-Olsen. Therefore the values of the two extremes were both used in the calculation of available P-Olsen in the study area and the obtained average values (which correlated highly to the Bray 1 values, r = 0.82), that met the requirement of the maximum P-Olsen value that can be used in the model and pertains to the available P in the study area was used.

Three sets of constants were generated for ‘a’ and ‘d’ to test the sensitivity of the model after calibration. The first, second, and third sets were taken from the 5^{th}, 7.5^{th}, and 10^{th} percentile of the smallest generated IE from the twenty trials to obtain ‘a’ while the 95^{th} , 92.5^{th} and 90^{th} percentile of the maximum IE was used to obtain ‘d’. The first set was used for the model, and the 5^{th} and 95^{th}

Table 1. Classification of soil N, P and K nutrient contents in 13 Districts within the study area.

District	N (%) level	P (mg kg^{-1}) level	K (cmolc kg^{-1}) level
Savelugu	(0.04) very low	(3.2) low	(0.1) adequate
Yendi	(0.04) low	(2.1) very low	(0.1) adequate
West Mamprusi	(0.07) low	(5.1) low	(0.1) adequate
Kumbungu	(0.05) low	(2.4) very low	(0.1) adequate
Zabzugu	(0.07) low	(5.6) low	(0.1) adequate
Gushegu	(0.07) low	(3.1) low	(0.2) adequate
Saboba	(0.08) low	(7.2) adequate	(0.2) adequate
Karaga	(0.07) low	(2.1) very low	(0.3) high
Tamale Metropolitan	(0.08) low	(5.0) low	(0.21) adequate
East Gonja	(0.05) low	(2.3) very low	(0.2) adequate
Tolon	(0.05) low	(5.5) low	(0.1) adequate
Nanumba South	(0.04) low	(2.9) very low	(0.1) adequate
Nanumba North	(0.06) low	(3.9) low	(0.1) adequate

Classification: very low and low (N < 0.05 % and N < 0.1, P < 6 mg kg^{-1} and K < 0.1 $cmol_c$ kg^{-1}), adequate (moderate) (N > 0.1 %, P = 6 – 25 mg kg^{-1} and K = 0.1 – 0.25 $cmol_c$ kg^{-1}) and high (good) (N > 0.1 %, P > 25 mg kg^{-1} and K > 0.25 $cmol_c$ kg^{-1}) contents (Wopereis *et al.*, 2009).

percentiles were excluded in order to remove outliers from the data (Das *et al.*, 2009).

Model validation and estimation of actual maize yield

The model was validated by running it with data from twenty previous research demonstration trials by SARI, Tamale, Ghana, in selected locations of the study area using the established parameters obtained from the calibration. The predicted maize yields for the Districts were based on the maximum potential grain yield and the nutrient uptake of maize for the region. The predicted yields by the QUEFTS model were then compared with the measured yield output from these selected locations to assess the accuracy of the predicted yield outcomes using U- Theil statistic. Theil's U statistic is a relative measure of accuracy that compares predicted results with measured results of minimal historical data (Makridakis, 1993). It was expressed based on the equation by Wijayanto and Prastyanto, (2011) as:

$$U = \frac{\sqrt{\frac{1}{T}\sum_{1}^{T}(Y_t^s - Y_t^a)^2}}{\sqrt{\frac{1}{T}\sum_{1}^{T}(Y_t^s)^2} + \sqrt{\frac{1}{T}\sum_{1}^{T}(Y_t^a)^2}} \quad (4)$$

where T = the number of samples, Y_t^s is the predicted value of the model, Y_t^a is the measured value. When U is less than 1 or close to zero, the model is said to be better in prediction, and when it more than 1, the model is said to be poor in prediction (Wijayanto and Prastyanto, 2011).

RESULTS

N, P and K nutrient status of the Districts within the study area

Results obtained after comparing the laboratory soil nutrient analysis of the Districts to the nutrient needed for effective maize production showed that 12 out of the 13 Districts had their N and P nutrient contents below average for maize cultivation. The nutrients contents of K, however, ranged from high to adequate in all the 13 Districts. Classification of the status of the nutrient levels has been presented in (Table 1).

Calculated recovery efficiency and internal nutrient efficiency for maize production in the study area

The RE and the IE parameters obtained from the twenty trials used to calibrate the QUEFTS model have been presented in (Tables 2 and 3). The average RE (kg kg^{-1}) used to calibrate the model were: N = 0.49, P = 0.33 and K = 0.67. The three sets of values for 'a' and 'd' used for the sensitivity test are shown in (Table 3). These three sets represent different extremes of internal efficiencies which excluded outliers to test the sensitivity of the model.All three sets provided similar nutrient requirements for maize, with the exception of yield levels close to the potential. Set 1 of 'a' and 'd' with values 35 kg N kg^{-1} and 77 kg N kg^{-1}, 145 kg P kg^{-1} and 509 kg P kg^{-1}, and 32 kg K kg^{-1} and 114 kg Kkg^{-1} was therefore used in the standard version of the QUEFTS model, as this set of values included the maximum range of variability in the data. The relationship established between uptake of nutrients and maize grain yield by plotting nutrient uptake of maize against maize grain yields from the demonstration sites are presented in

Table 2. Recovery efficiencies (RE) obtained from the calculations from nutrient omission plots with the QUEFT model

Partition	Recovery efficiency (kg kg^{-1})		
	N	P	K
No NPK	0	0	0
NPK	0.65	0.41	0.84
NP	0.38	0.39	-
NK	0.44	-	0.62
PK	-	0.20	0.56
RE	0.49	0.33	0.67

N – nitrogen, P – phosphorus, K - Potassium

Table 3. Sets of constants 'a' (maximum accumulation) and 'd' (maximum dilution) obtained as related to increase in maize grain yields and uptake of N, P and K nutrients.

Soil nutrient	Set I kg kg^{-1}		Set II kg kg^{-1}		Set III kg kg^{-1}	
	5th percentile	95th percentile	7.5th percentile	92.5th percentile	10th percentile	90th percentile
	a	d	a	d	a	d
N	35	77	36	75	37	73
P	145	509	148	496	152	482
K	32	114	33	111	34	104

(Figure 2). This was a linear relationship and it determined estimation of maize grain yields based on uptake of nutrients from the soil with a good correlation (N = 92%, P = 92% and K = 71%).The validated model gave an accuracy of 0.18, based on U-Theil calculation of accuracy using Eq. (4).

Calculated N, P and K requirements and estimated maize yields by the QUEFTS model for smallholder farms in the study area

The nutrients applied within the fertilizer application methods on farmers' fields, with its observed yield and the calculated actual uptake of nutrient to be applied with its estimated maize grain yields have been presented in (Table 4).

The estimated maize yields for Kumbugu, Zabzugu, East Gonja, Tolon and Nanumba South Districts were lower than the observed/measured maize yields even though the predicted N and P rates were lower than the observed N and P rates; and observed K rates lower in the Zabzugu District. Districts like Savelugu, Yendi, West Mamprusi, Gushegu and Nanumba North obtained higher maize yield estimates even though the predicted N and P fertilizer rates were lower than the observed. However, Districts like Saboba and Karaga obtained higher maize yield estimates with higher N, P and K fertilizer rates, except Tamale Metropolitan where estimated higher N, P and K fertilizer rates resulted in lower estimated maize yields as compared to the observed.

DISCUSSION

Estimation of N, P, and K nutrients for maize production

Nutrients removed from the soil through harvested crops need to be replenished so that the soil can regain its fertility to continue supporting crop production. The right amount, however, is needed to be replaced to sustain and increase yields. Maize removes an average of about 1.38 % of N, 0.35 % of P and 0.47 % of K from the soil; and the maize stover contains about 0.46 % N, 0.04 % P and 1.03 % K (Opoku, 2011).

Validity of calculated N, P, and K nutrients requirements and estimated maize yields

The calibration of the QUEFTS model used to predict the needed nutrients to replace the removal conformed to the nutrient RE for maize production in Ghana. This is because, according to IFDC, (2012), the RE for maize in Ghana is 0.50 kg N kg^{-1}, 0.35kg P kg^{-1}, and 0.70kg K kg^{-1}. The obtained values of RE indicate that uptake of nutrients of maize in the study area is 0.49kg N kg^{-1}, 0.33kg P kg^{-1} and 0.67kg K kg^{-1} (Table 3), which conformed to the RE of N, P and K nutrients for maize in Ghana. Maize grain yields showed a good correlation with nutrient uptake in maize (Figure 2). The lower lines (YNA, YPA and YKA) indicate situations whereby a specified nutrient (N, P, or K) is excessively accumulated in the plant; and the upper lines (YND, YPD and YKD) indicate situations where the nutrient (N, P or K) is the main yield limiting factor and that the obtained yield is the highest possible given the amount of nutrient taken up by the plant (Janssen *et al.*, 1990). In such situations, the nutrient is said to be 'maximally diluted' in the plant (Smaling and Janssen, 1993). The correlation between nutrient uptake and maize grain could therefore be used to calculate maize grain yield using the established relationship (Figure 2). The calculated Theil's U of 0.18 also indicated that the model was accurate in estimating the actual nutrient (N, P and K) uptake needed for replacement and the corresponding yield that could be obtained (Wijayanto and Prastyanto, 2011).

Necessity of calculating N, P and K requirements for the study Districts

In all the study Districts, it was observed that the amount of nutrients needed to replace the lost nutrients were different, and therefore would not be appropriate to recommend a blanket fertilizer formulation for maize production, for instance 120 N, 90 P, and 90 K (kg ha^{-1}) (Tetteh and Nurudeen, 2015), for all the Districts. In addition, the estimated yields also differed for all Districts based on the fertilizer application. These occurrences in the predictions showed that variations exist in the soil nutrients of the Districts, and these variations were considered by the QUEFT model to calculate the fertilizer requirement based on the IE of maize in the study area that was used by the model (Wijayanto and Prastyanto, 2011).

Conclusion

About 90% of the study Districts recorded N and P nutrients contents below average requirement for maize cultivation, which confirmed that the soils are poor and variable in nutrients contents and needed to be managed differently. The QUEFTS model was therefore used to accurately (Theil's U = 0.18) predict N, P, and K nutrient requirements for the Districts resulting in a linear increase in maize yield when nutrients were recovered in balanced amounts of 0.49 kg kg^{-1} N, 0.33 kg kg^{-1} P and 0.67 kg kg^{-1} K with internal efficiencies of 35 kg N kg^{-1} and 77 kg N kg^{-1}, 145 kg P kg^{-1} and 509 kg P kg^{-1}, and 32 kg K kg^{-1} and 114 kg K kg^{-1}. Maize grain yield in the Districts also showed a good correlation with the observed N (92 %), P (92 %) and K (71 %) nutrients used by the model to make the estimation.

The observed and estimated N, P, and K nutrients for maize production in the study area could serve as a guide for proper allocation of fertilizer input to these locations, and the calibrated QUEFTS model used to estimate nutrient needs for the other Districts in the region based on their nutrient contents.

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