Validation of the QUEFTS model: A case study of field–specific fertilizer recommendations to maize smallholder farmers in western Kenya.

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Validation of the QUEFTS model: A case study of field–specific fertilizer recommendations to maize smallholder farmers in western Kenya.

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Contact office.pp@wur.nl for access to data, models, and scripts used for the analysis.

Abstract.

Response to fertilizer application on most maize smallholder farms in western Kenya is low and variable. This can be majorly attributed to blanket fertilizer recommendations. The aim of the present study was to test the accuracy of the QUEFTS model in predicting grain yield, and internal utilization efficiency (IE) resulting from use of Geodatics tailored package (i.e. field specific fertilizer, improved maize seeds and agronomic advice) on maize smallholder farms. On farm experiments, under farmer management, were set up in the 2017 and 2018 long rain seasons. For 2018 experiment involving a fertilizer and control plot, the mean of observed and predicted grain yields (at 12 % moisture) in fertilizer plots was 4.9 t ha $^{-1}$ and 4.0 t ha^{-1} respectively. Observed control plot grain yield was 3.0 t ha $^{-1}$ compared to predicted yields of 2.5 t ha^{-1}. Generally, for all treatments, the model was good in predicting grain yields (IOA=0.66, RMSE= 1.7 t ha-1, n=70). Observed IE borderlines fit well with the model's default IE borderlines. On most farms, increase in maize grain yield obtained per unit of nutrient applied was considerably higher than that commonly reported under typical smallholder farmer conditions. This indicates that the Geodatics tailored package had a substantial positive impact on farm productivity.

The 2017 experiment involved nutrient omission plots i.e. NPK 1, NPK 2, NP, NK, PK and control plots. Percent yield reduction with reference to NPK 2 plot grain yield due to the omission of N (i.e. PK treatment) and P(i.e. NK treatment) were 38% and 32%, respectively. This result suggests that N and P were the most limiting on the smallholder farms considered. K and S deficiencies were found negligible for maize production on some farms.

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Contents

1. Introduction

Spatial and temporal variation in soil fertility both between and within smallholder farms is recognized across sub-Saharan Africa (Giller et al.), yet the use of blanket fertilizer recommendations is common (Haefele et al., 2003; Tittonell et al., 2008). Some blanket recommendations are developed from a few trials and plots on research stations which often are not representative of the indigenous soil nutrient stocks found in smallholder farms (Haefele et al., 2003). Other blanket recommendations are based on soil series (i.e. large soil zones with relatively similar properties) identified from regional soil property maps and soil geographic databases such as SoilGrids (Hengl et al., 2015; Hengl et al., 2017). Sadly, these maps have very low resolution and are rarely up to date to capture existing soil fertility variations within a smallholding. Besides, nutrient deficiencies associated with a particular soil series can occur at a regional scale, yet deficiencies due to management can vary at a smaller spatial scale (Vanlauwe et al., 2011). As a result, farmers may be liable to apply excessive or insufficient or unbalanced fertilizers in some fields. Over application of fertilizers results into wastage, low profits, risks to human health (Albornoz, 2016; Santamaria, 2006), and losses to the environment with risks of eutrophication and greenhouse gas emissions (Pathak & Bhatia, 2017). Under- and unbalanced fertilizer application not only causes low yields, but also local soil nutrient mining (Roy et al., 2006). For these reasons, it is important that fertilizer advice is tailored to field specific needs in order to increase its efficiency and at the same time, reduce risks to the environment. Efficiency, as used here, refers to an increase in maize grain yield obtained per unit of nutrient applied. This is referred to as Agronomic efficiency (AE). AE of an applied nutrient indicates the nutrient's short term impact on the productivity of a cropping system (Dobermann, 2007).

Spatial and temporal variation in soil fertility is mainly a result of differences in soil formation factors and management. Variation due to soil formation factors is usually dominant on a regional scale. Soil is formed by the interaction of five factors i.e. parent material, time, climate, topography and relief, and organisms. From one zone to another, the factor(s) and or the relative effect of each factor varies and so does the resulting soil type formed (Deckers, 2002; Giller et al., 2006). At a more smaller scale e.g. farm or field level, management factors gain substantial influence on soil fertility variation (Zingore et al., 2007). Management practices in this regard, include a farmer’s past cropping system, use and allocation of inputs both organic (e.g. animal manure, crop residues) and inorganic (e.g. fertilizers, soil amendments such as lime). The type of field management strategies employed are majorly dependent on the resources available to the farmer and also his/her production objective (Vanlauwe et al., 2014). For instance, farmers with moderate input endowments preferably apply homestead residues (e.g. wood ash, organic residues) and manure to infields (i.e. fields near the homestead) than to outfields (Chikuvire, 2000; Misiko et al., 2011; Prudencio, 1993; Tittonell et al., 2013). Consequently, on a single farm two fields with contrasting soil fertility status can be observed – a more fertile infield and less fertile outfield. Such field variation has important implications on fertilizer application rates and crop yield response to fertilizer application. Njoroge et al. (2019) reported that accounting for farmers historical manure use in deriving fertilizer advise reduces P and K crop fertilizer requirements and risks to poor yield response. This example emphasizes the need to tailor fertilizer recommendations.

Several approaches have been developed to tailor nutrient management practices. One such approach is soil testing. Through soil testing, existing soil fertility and its variation between fields can be better understood to derive field-specific fertilizer requirements. A soil test chemically extracts and quantifies plant available nutrients in the soil. In addition, a soil test measures other soil property such as pH that influences nutrient availability and suitability of the soil to support crop growth. Interpretation of soil test results to recommend fertilizers is based on the empirical correlations between the soil test value of a nutrient and crop response to its application (Shand, 2007). Unfortunately, these relationships are site-specific and therefore require many region-specific re-calibration experiments to create. Efforts by smallholder farmers to conduct soil testing are often undermined by the high costs, delay in getting soil test results as the onset of planting approaches, and limited access to reliable soil laboratories. Further, to capture the large nutrient stock variation over short distances in a field requires many soil samples which is costly. Use of single composite soil samples has been linked to poor correlations between soil test value and yield response (Njoroge et al., 2017). Besides, soil-based recommendations rarely consider interactions between nutrients (Tabi et al., 2008). These issues have questioned the reliability of soil test values for the prediction of yield response on smallholder farms. A few simple soil test kits have become available for use by farmers or local experts. Simple soil test kits give immediate analysis results, but, their results are often doubtful (Shand, 2007).

An alternative approach developed to tailor fertilizer recommendations in regions where smallholder farmers can't access soil testing facilities is the site-specific nutrient management (SSNM). SSNM uses a plant-based approach to provide a field-specific fertilizer advice. Simply, the approach determines the fertilizer requirements as the crop nutrient requirement for a target yield minus the indigenous nutrient supply (i.e. measured as the total nutrient uptake in a nutrient omission plot). The crop nutrient requirement is determined from the grain yield- nutrient uptake empirical relationship. A few tools such as nutrient expert for hybrid maize (NEHM) have been developed to implement SSNM principles at a farm level. NEHM is a mobile phone or computer-based decision support tool, that requires answers to a set of simple questions about the farmer's site and farming practices to quickly generate field specific fertilizer recommendations. The input information is processed in an agronomic database that runs on algorithms and decision rules developed from several nutrient omission trials. The output; fertilizer application advice, is instant and its shared to farmers as a text message on android based mobile platforms. NEHM has been applied with success, for instance, in small scale hybrid maize production systems in Philippines, Ethiopia, Kenya, and Tanzania (Pampolino et al., 2012). Mobile phone based tools are progressively utilized to customize fertilizer management practices to farmers' fields, particularly in areas where blanket fertilizer recommendations prevail (Beza et al., 2017). Mobile technology facilitates information sharing with farmers either directly or through extension agents and well-informed local community members (Schut et al., 2018).

Use of mobile data technology has been acquired in the Geodatics project. The Geodatics project generates site-specific fertilizer recommendation, as an alternative to the generic recommendations available to smallholder maize farmers in western Kenya. The Geodatics nutrient management recommendations considers the four key principles common with the 4R stewardship; applying the right type of fertilizer, at the right rate, at the right time and right place (Zingore et al., 2014). The Geodatics project is managed by four partners one of which is the Agrics social enterprise. Agrics operates in Western Kenya. Agrics provides generated field-specific fertilizer and improved seeds to smallholder farmers on credit. Farmers receiving this package (i.e. here referred to as Geodatics farmers) are offered agronomic advice e.g. about fertilizer management, and weed, pest and disease control during the growing season either through community Agrics staff, SMS text or phone call. The Geodatics approach to generating field-specific fertilizer advice involves the use of mobile phones to; first, obtain farm and field data. Second, link the geo-reference of the farmer's field to soil geographic and satellite (Modis-NDVI) databases. Thirdly, run a crop simulation model to obtain agro-ecological zone yield potentials under rainfed conditions which are further corrected using adjustment factors to obtain a final target yield. Adjustment factors downscale or maintain the target yield with regard to; (i) soil quality as by the farmer's judgment on a scale of good, average and bad. The soil quality parameter indirectly captures the field's history e.g. of organic and inorganic fertilizer use and crop yields, (ii) correction for variation in NDVI amplitude during the growing season. Lastly, all the data is integrated into the QUEFTS model (see description in the methodology section) to generate a balanced field-specific fertilizer recommendation. Generated customized fertilizer advice (type and amount) and improved hybrid maize seed bags are delivered to a central community point where Geodatics farmers can pick them.

As mentioned earlier, blanket fertilizer recommendations ignore heterogeneity in soil fertility. This is reflected in the large variation in efficiency of fertilizer application between and within smallholder farms in western Kenya (Kihara et al., 2016; Njoroge et al., 2017; Tittonell et al., 2008). This evidence underscores the need for field tailored fertilizer advice, and the QUEFTS model has been used in this regard. Development of the original QUEFTS model was based on data from rainfed-maize experiments conducted in Kenya and Suriname (Janssen et al., 1990). Later, the original QUEFTS model was tested on independent data obtained from maize fertilizer trials in Kenya and poor correlations between predicted and measured nutrient supply-uptake values were reported. On this comparison, the original QUEFTS model was re-calibrated (Smaling & Janssen, 1993). Similarly, re-calibration and modification of the model to generate site-specific balanced fertilizer recommendation or estimate yield in various environmental conditions have been made (Das et al., 2009; Sattari et al., 2014). These findings highlight the importance of testing and if needed re-calibrating or even modifying QUEFTS to suit different field or ecological conditions. The QUEFTS model works on the assumption that crop growth is only limited by soil fertility and thus other factors such as moisture supply and control of weeds, pests, diseases are optimal. However, in farmer's fields these factors are often not optimum and consequently farmer actual yields are often lower than researcher managed field yields on which QUEFTS is based (Mulder, 2000). Therefore, to ensure the reliability of the application of QUEFTS model, this thesis seeks to validate it under Geodatics farmer conditions. Model validation is defined as "*a demonstration that a model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model,"* (Rykiel Jr, 1996). Validation compares the model predicted output with on-farm observations using input parameters not used in model development. In addition to ensuring its reliability, validating the QUEFTS model will enable a better understanding of growth factors that limit yield production and thus inform on improvements in the Geodatics tailored advice.

Results of QUEFTS model validation process will answer the following research question.

1. Does the QUEFTS model make accurate predictions of yields and internal nutrient use efficiencies obtained under farmer conditions.

2. Materials and methods.

2.1. Description of the study site.

The two datasets used in the present study are from experiments conducted in Western Kenya. The region receives annual rainfall ranges from 1,600 to 2,000 mm, spread over two rainfall seasons per year; a Long rain season (LR; from March to July) and a short rain season (SR; from September to December). Major occurring soil types are Ferrasol, Acrisol, and Nitisol (WRB, 2006). Other few non-dominant soil types include Lixisol and Gleysol. Most soils are generally low in fertility, slightly acidic, deep and well drained, and very deficient in N and P. Maize is the staple crop of most people in the area and accounts for 80% of the cropland (Place et al., 2006). Unfortunately, many farmers obtain maize yields of about 1.7 t ha^{-1} per season, despite maximum water-limited yield potentials (i.e. rainfed maize yields achievable on a farmers field with optimal nutrient and crop management practices) of 6 t ha^{-1} (van Ittersum et al., 2013). Major biotic stresses to maize production in western Kenya are witchweed (*striga hermonthica*), and the 2017 outbreak of fall armyworm (*spodoptera frugiperda*).

2.2. Experimental design and treatments.

2.2.1. Experiment 1.

In 2017 LR season, an on-farm experiment was conducted on 30 smallholder farms spread over Eastern and Northern areas of Kakamega county. On each farmer's field six treatments were set up; two full NPK treatments (NPK1 and NPK 2), three treatments with one of the nutrients omitted (NP, NK, and PK) and a control treatment (no fertilizer application). For all treatments except NPK 1 the sources of nutrients were: N: both Diammonium Phosphate (DAP) and Calcium Ammonium Nitrate (CAN) fertilizers except in NK treatment plots, where only CAN was the source. P: DAP except for PK plots where Triple Super Phosphate (TSP) was applied. Source of K: Muriate except in NPK 1 plots. NPK 1 plots had slightly different sources of nutrients than the rest of the plots. NPK 1 plots were treated with a fertilizer blend from Baraka with a composition of P: K of 1.5 and containing some Sulphur. However, N source was DAP and CAN. N was applied in 3 equal splits, i.e. at planting, and at 21 and 35 days after emergence. All other nutrients were applied at planting. Individual plots for the treatments measured 5 m by 5 m except for the full treatments which were 10 m by 10 m. Fertilizer application rates for each farmer were derived from the QUEFTS model using field-specific soil properties obtained from ISRIC soil geographic database. The application rates targeted 80% of water-limited yield for the LR season. Plants were spaced at 25 m by 75 m to result in a population of 53,000 plants per ha. A hybrid maize cultivar was used across all plots. Weeds were managed manually by hand. Fall armyworm infestation was controlled with pesticides application and other cultural practices such as the use of ash, hand picking, and weeding. Fertilization practices were done by a researcher/ field staff, whereas all other field practices were carried out by the farmer. See Table 1 for summary of application rates.

2.2.2. Experiment 2.

This experiment was conducted in the 2018 LR season on fields of 46 smallholder farms. On each field two treatments were set up: Geodatics fertilizer treatment and control treatment (i.e. no fertilizer application). Each treatment was set up in a plot of 5m by 10 m. Each plot was subdivided into two quadrants each measuring 4 m by 3 m in which harvesting was conducted. The setup of the treatments was replicated in 48 farms with each farm served as a complete block. Farms belonged to Geodatics farmers (i.e. maize smallholder farmers using Geodatics fertilizer advice in addition to improved maize hybrid seeds). The Geodatics fertilizer is a field-specific, balanced N, P, and K fertilizer, determined by QUEFTS model using soil characteristics of soil exchangeable K and P from soil analysis results and pH and SOC obtained from African SoilGrids database. The experimental plots were exclusively managed by the farmers. See Table 1 for summary of application rates.

Table 1. Descriptive statistics of fertilizer application rates in experiment 1 (conducted in 2017), and experiment 2 (conducted in 2018). Application was performed by field staff/researcher in experiment 1 and by farmer in Experiment 2. n = number of observations and Q = quantile.

Experiment	Parameter	n	Mean	SD	Minimum	25% Q	Median	75% Q	Maximum
Experiment 1	N	74	455.9	194.9	224.1	224.1	388.6	563.2	1238.5
	P	72	175.0	92.2	60.9	124.0	145.6	215.4	635.4
	K	68	96.2	85.5	10.0	32.9	63.2	141.0	541.8
Experiment 2	N	35	87.9	35.8	31.8	69.6	81.2	97.2	236.5
	P	35	31.9	19.1	11.6	21.7	24.3	39.0	109.9
	K	29	11.5	6.2	4.9	7.2	9.5	13.1	35.7

2.3. Data collection

Soil sampling was conducted in every farmers' field prior to planting. Sampling points, at depths of 0-20 cm, were collected along an "hourglass-shaped path" in a field. About 10-15 soil samples per field were collected, put in a bucket, thoroughly mixed and a single composite sample obtained. Composite soil samples from each field were air-dried, sieved through a 2 mm sieve to get fine soil fractions, and then stored separately in plastic bags for chemical analysis. Geo-reference points of experimental plots were determined using a handheld GPS receiver (Etrex 30x, Garmin limited, Chicago, USA). Further, the distance (i.e. "as the crow flies" distance) from the homestead to the field with plots was determined. Fertilizer applications, field, and crop management practices were monitored by field staff and recorded. Maize was harvested at physiological maturity (experiment 1) and at a farmers' judgment of maturity (experiment 2).

Ears (husks + kernels + cob) were harvested from each plot, counted and their fresh weight determined using a digital scale precise to two decimal places. For each plot, a few harvested ears were shelled to determine the moisture content of grains using a moisture meter (Dickey John Mini GAC, Minneapolis, USA). Using a half-half sampling method, a sample of about 1 kg of harvested ears per plot was collected. Maize stalks in each plot were manually cut by hand at ground level (stubble left belowground was negligible) and weighed. A random sample of about 1 kg of chopped stover (stalks+ leaves) per plot collected. Consequently, two samples were collected from each plot; ear sample and stover sample. The samples were sun-dried until constant weight. The air-dried ears were shelled by hand, and the resulting air-dry grains weighed, and their moisture content determined using a moisture meter (Dickey John Mini GAC, Minneapolis, USA).

2.3.1. Soil analysis.

Soil composite samples were analyzed at CROPNUTS laboratory Nairobi, Kenya (http://www.cropnuts.com/). Available P (Olsen P) and exchangeable base cations (i.e. K, Na, Ca and Mg) were determined using the Mehlich 3 extractant technique (Mehlich,1984). Mehlich 3 technique uses a weak acid mixture to extract macro and micronutrient elements from a soil sample. The extranct solution of available P is acetic acid and fluoride compound mixture while the exchangeable cations (i.e. K, Ca and Mg) are extracted by ammonium nitric and nitric acid extranct. After extraction, P content was determined by conducting the ascorbic-ammonium molybdate method followed by measurement of absorbance of the blue complex formed in a UV-VIS spectrophotometer. K concentration was measured by flame atomic emission spectroscopy, while Ca and Mg was determined by flame atomic absorption spectroscopy procedures. Soil pH was determined in water using a glass electrode pH meter dipped in soil: water mixture of 1:2.5. Soil organic carbon was measured using the Walkley-Black procedure (B. D. Robinson, 2008).To determine soil particle size and thus infer the soil texture, a dispersing liquid was added to 50 g sample of soil after which the hydrometer technique was conducted (Bouyoucos, 1962). Descriptive soil characteristics of the experiment 1 plots used in the present study are shown in (Table 1).

Table 2. Experiment 2: Descriptive statistics of (0-20cm layer) soil properties pH (H_2O), P-Olsen (mg/kg),Soil organic carbon (g/ kg), and Exchangeable potassium (Exc.K, mmol/kg), Clay (%). Each parameter has 70 observations, and Q= quantile.

Parameter	Mean	SD	Minimum	25% Q	Median	75% Q	Maximum
pH	5.7	0.5	5.0	5.3	5.7	6.1	6.9
P-Olsen	6.5	6.0	1.4	2.8	4.4	8.2	28.3
Exc.K	4.8	4.0	0.7	1.9	3.4	5.7	15.6
SOC	18.5	6.4	7.6	13.2	17.2	22.3	33.6

2.3.2. Grain and Stover analysis

For both experiments, subsamples of air-dried grains were analyzed for nutrient concentration by the CROPNUTS Laboratory in Nairobi (http://www.cropnuts.com/). Each grain sample was ground and digested with sulfuric acid, catalysts, and salts. Thereafter, N concentration was determined using the Kjeldahl method while N and P contents were measured using atomic spectrophotometry techniques (Kalra, 1997). Results of the nutrient concentrations were provided on "as is" percentage basis. Unfortunately, the N % was underestimated. A re-analysis of the left over stover (10 samples) and grain was done at Wageningen University and Research environmental science laboratory (WUR), and results provided on a dry matter basis. Consequently, the N% was corrected with the function. N % in DM grain = 0.7614 * (N % in as is grain + 0.4582, N % in DM stover = 0.6446 * N % in as is stover + 0.3857.

Table 3.Experiment 2: Descriptive statistics of grain and stover analysis results in units of dry matter percent. MC represents moisture content percent of both grain and stover at the time of analysis at Cropnuts laboratory. N % results from Cropnuts were underestimated and consequently a re-analysis was performed at WUR laboratory. n = observations and Q = quantile

laboratory	Sample	n	Parameter	Mean	SD	Minimum	25% Q	Median	75% Q	Maximum
Cropnuts	Grain/ stover	74	MC	13.1	1.2	8.0	12.6	13.1	13.7	16.0
	Grain	74	N	0.92	0.26	0.45	0.73	0.86	1.10	1.53
		74	P	0.34	0.11	0.18	0.26	0.31	0.40	0.61
		74	K	0.45	0.12	0.29	0.35	0.41	0.54	0.77
	Stover	74	N	0.41	0.19	0.12	0.27	0.40	0.54	1.03
		74	P	0.11	0.08	0.03	0.06	0.08	0.13	0.37
		74	K	1.04	0.50	0.19	0.73	0.97	1.26	2.77
WUR	Grain	10	N	1.33	0.22	0.92	1.16	1.28	1.48	1.85
	Stover	10	N	0.74	0.14	0.53	0.64	0.74	0.84	1.21

2.4. Calculations

2.4.1. Grain yield, stover yield, and grain yield response.

Grain yield (kg ha^{-1}, at 12% moisture content (MC)) was calculated (using the shelling percent method) as:

$$(GrainsDW/EarsDW) * EarsFW * ((100-\%MC)/88) * (10000/harvest\ area) \quad (1)$$

Where; GrainsDW= Air dry weight of grains in a sample, EarsDW= Air dry weight of ears in a sample, EarsFW=fresh weight of ears in a harvest area (kg/ harvest area) and %MC=percent moisture content of grain at the time of harvest.

Stover yield (kg ha^{-1}, at 12% moisture content) was calculated as follows:

$$PstoverFW* \ (stoverDW/stoverFW)* \ ((100-\%MC)/88) \ *(10000/harvest\ area) \quad (2)$$

Where; stoverFW=stover fresh weight per harvest area, stoverDW=airdry stover weight per sample, stoverFW=stover fresh weight per sample.

Total nutrient uptake (kg ha^{-1}) in crop above-ground biomass at 12MC air dry weight basis was calculated as:

$$((\%nutG.as.is* \ 12\%.MC) \ /100)* \ Grain \ yield \ + \ ((\%nutS.as.is* \ 12\%.MC)/100)*Stover\ yield \quad (3)$$

Where; %nutG.as.is and %nutS.as.is refer to nutrient concentration percent in grain and stover respectively, as obtained from the laboratory, 12%MC refer to correction of as.is MC to 12% MC i.e. ((100-as.isMC%)/ 88).

2.4.2. Apparent recovery efficiency (RE), Internal utilization efficiency (IE), and nutrient uptake.

Keulen (1986), notes that to obtain a yield response to fertilizer application two conditions must be met: First, a fraction of the applied fertilizer must be taken up by the plant. This fraction is referred to as recovery efficiency (RE). Secondly, after uptake, the crop converts the nutrient into economic yield. The capacity of the crop to convert nutrients from both the soil and added fertilizer into economic yield is referred to as internal utilization efficiency (IE). To estimate the RE, IE, and AE the following equations will be used (Dobermann, 2007).

$$RE_{N/P/K}= (U_{N/P/K}-U_0) /F_{N/P/K} \quad (4)$$

$$IE_{N/P/K}=Y/U_{N/P/K} \quad (5)$$

$$AE_{N/P/K}= (Y-Y_0) /F_{N/P/K} \quad (6)$$

where; U=total nutrient uptake in aboveground crop biomass with nutrient applied, U_0=nutrient uptake in aboveground crop biomass with no nutrient applied, Y=Grain yield with nutrient applied, Y_0=Grain yield with no nutrient applied, F=amount of nutrient applied.

2.5. QUEFTS model

The original QUEFTS model was developed by Janssen et al. (1990), as a tool to evaluate the soil fertility aspect of land quality in a quantitative manner. The model uses soil chemical characteristics; pH, organic C content (g C/kg), P-Olsen (mg P/kg), and exchangeable (mmol K/kg) to quantify soil fertility defined as the capacity of the soil to supply the plant with N, P and K nutrients. Based on levels of N, P and K nutrients supplied from the soil and their interaction the model can predict crop yield. The model predicts yield in the following four steps;

1. Calculating potential supply of N, P and K i.e. the maximum quantity of N, P and K that can be taken up by the maize crop, if no other nutrients or growth factors are limiting. Potential supplies indicate the available amounts of nutrients from both soil (i.e. indigenous nutrient supply) and fertilizer. Indigenous nutrient supply is the total amount of a nutrient circulating in the root zone that originates from weathering of minerals and mineralization of stable organic matter during the growing season (Duivenbooden, 1992). For measurement purposes, indigenous nutrient supply is defined as the maximum amount of a nutrient taken up by the crop when all other nutrients and growth factors are optimum (Janssen et al., 1990). This plant-based measure and apparent fertilizer recovery are determined in a nutrient omission plot. Janssen et al. (1990), using data from maize fertilizer trials in western Kenya, made empirical equations (7, 8, 9) below that can be used to estimate potential nutrient supplies. These equations are valid for soils that are deep and well-drained, with pH (H_2O) in the range 4.5 -7, Organic carbon less than 70 g C / kg, and P-Olsen below 30 mg P/ kg observed in the 0-20 cm topsoil depth. In the equations (7, 8, 9), $F_{N/P/K}RE_{N/P/K}$ indicates

nutrient addition resulting from fertilizer application. In case of lack of reliable data of RE from nutrient omission plots, QUEFTS uses standard RE values of 0.5, 0.1, 0.5 for N, P, and K, respectively.

2. Calculating actual uptake of N, P and K. In this step, the model considers nutrient interactions because enhancing supply of one nutrient can positively influence the uptake of the other nutrient(s). Determining actual uptake from the potential supply is based on a theoretical assumption of a linear decrease of the slope of nutrient uptake and supply (dU/ dS) from one to zero. When dU/dS is one, the whole potential supply of a nutrient is taken up by the plant i.e. uptake of the nutrient is equal to and increases linearly with its potential supply. This case occurs when the supply of the nutrient is very limited compared to the supply of the other two nutrients. When the ratio is zero, there is no further uptake of the nutrient i.e. relation between potential supply and actual uptake is at a plateau level. In this case, the nutrient is in a relatively very large supply compared to the other two. In between the linear (dU/dS=1) and plateau (dU/dS= 0) zones, the relation between potential supply and actual uptake is parabolic. This ultimately results in a Linear-parabolic-plateau relationship.

3. Calculating yield ranges. In this step, the yield range (upper and lower) depending on the actual uptake of each nutrient is determined. The upper yield refers to the yield that can be attained when the potential supply of the nutrient is low compared to the other two (dU/dS=1). Here the nutrient is growth limiting, its concentration in plant tissue is low and its regarded as being at maximum dilution (d). Given the low nutrient uptake, the grain yield produced per unit of the nutrient concentration in the above-ground biomass (i.e. IE) is maximum. Values of maximum IE for maize, as reported by Janssen et al. (1990) are 70, 600 and 120 Kg biomass per kg N, P and K respectively. The lower yield refers to the yield that could be obtained when the nutrient is taken up excess compared to other nutrients and thus it is at maximum accumulation (a) (see Fig) IE values at this stage are 30, 200 and 30 kg per kg N, P and K (Janssen et al., 1990). Janssen et al. (1990) suggested that, in an ideal situation where a nutrient is neither limiting nor in excess with respect to the other two nutrients (i.e. balanced fertilization) and when other growth factors are non-limiting, its optimal IE is the average of the maximum and minimum IE values. This suggestion results in a linear- parabolic- plateau relationship between grain yield and nutrient uptake. In other words, linear when nutrient uptake is at its maximum under conditions of limited nutrient supply

(dU/dS=1), parabolic (i.e. IE decrease) when yields tend to approach the climate adjusted potential yield. The parabolic part is further affected by the boundary lines a and b.

4. Calculating the final yield estimate from the yield ranges. The yield ranges are combined in pairs (N and P, N and K, P and K) and the yield estimates determined for the pairs are averaged. The average is the final yield estimate.

$$TS_N=1.7 * (pH-3) * Org.\ C + F_N RE_N \tag{7}$$

$$TS_P=0.35 * (1-0.5* (pH-6)2) * (Org.C + 0.5 * P\text{-}Olsen) + F_P RE_P \tag{8}$$

$$TS_K=F_K RE_K + 0.625*(3.4-0.4*pH) *Kexch/ (2+0.9*Org.C) \tag{9}$$

Where; Where; IS_N, IS_P and IS_K refer to indigenous potential supply of N, P and K respectively, pH= soil pH, Org.C=organic carbon content (g C/kg), Olsen- P = plant available soil P content (mg P/kg), Kexch=exchangeable potassium (mmol K/kg), F_N, F_P and F_K refer to application rates of N, P and K respectively, while RE_N, RE_P, and RE_K refer to apparent recovery efficiencies of N, P and K, respectively.

Besides predicting yield response to soil fertility, QUEFTS has been used, as mentioned earlier, to estimate balanced fertilizer requirements. Important in this regard is predicting the amount of nutrients available from the soil (i.e. potential nutrient supply) and the crop nutrient requirement for a target yield (I.e. determined from the yield- nutrient uptake relationship).

2.5.1. Data analysis.

For experiment 1, statistical data analysis was performed with a linear mixed model (Kamanga et al.) using the lme4 package in R statistical software. The purpose of fitting the lme model was to remove the error in the measured values arising from differences in farmer field location and management and unbalanced design or missing values. The lme model version used was; grain yield ~ treatment + (1/ Farm ID). Test for significance was done by Type III ANOVA with Satterthwaite method (using the lmerTest package) and pairwise comparison was accomplished using the predictmeans package in R. Means are reported at a significance level of 0.05.

2.5.2. Validation of the QUEFTS model

The R version of QUEFTS model was run with input parameters; (i) soil properties (i.e. Soil PH, Organic carbon, Exchangeable potassium, P-Olsen) from the soil analysis results as shown in table 1, (ii) farmer application rates of N, P and K fertilizer, (iii) default QUEFTS model RE values of 0.5 for N and K, and 0.1 for P fertilizer, (iv) default QUEFTS model maximum IE borderline values (i.e. 70, 600, 120 kg biomass per kg N,P and K respectively) and minimum IE borderline value (i.e. 30, 200, and 30 kg biomass per kg N, P and K, respectively, (v) maximum LR season yield potential yield for western Kenya; 12 t DM/ ha, (vi) average temperature of 18 ^{o}C. Model outputs were predicted grain yield (at 12 MC) and nutrient uptake. To test the accuracy of QUEFTS, predicted values were plotted against observed values. Root mean square error (RMSE) and index of agreement (IOA) were also used to judge model accuracy. RMSE and IOA were determined from the following equations:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{n}} \tag{10}$$

$$IOA = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \tag{11}$$

Where; O, $\bar{O}$, P refers to observed, mean of observed, and predicted value, respectively.

The index of agreement (IOA) is an index that describes model accuracy. It ranges from 0 to 1, where 0 represents no agreement between predicted and observed values, whereas 1 indicates perfect agreement between observations and predictions(Willmott, 1981). The index was used by Tabi et al. (2008) in his study to validate the QUEFTS model. In the present thesis, the IOA value of 0.5 will be a threshold for good or poor model performance.

To test the validity of standard IE borderlines, the observed maximum and minimum IE values (IE borderlines) will be determined as the 2.5th and 97.5th percentiles of the calculated IE values of each nutrient (Eqn 1). By excluding 2.5% of the lowest and highest observed IE values, it is expected that observations, where other factors other than nutrients could have been limiting yield production, will be removed (Liu et al., 2006; Witt et al., 1999).

3. Results

3.1. Experiment 1

3.1.1. Grain yield.

NPK 2 treatment was used as a reference for the nutrient omission plots except NPK 1. Higher grain yields were obtained for NPK 2, and NP treatments (Table 4). Grain yields in control, NK and PK plots were not significantly different from each other. Percent yield reduction with reference to NPK 2 grain yield due to the omission of N (i.e. PK treatment) and P (i.e. NK treatment) were 38% and 32%, respectively. This shows that N and P had the utmost effect on grain yield. Yields in NPK 1 treatment were significantly lower than those in NPK 2 implying that K source or addition of Sulphur did not have a significant positive effect on grain yield.

Table 4. Experiment 1. Descriptive statistics of grain yield (t ha -1, at 12% moisture), Indigenous N, P, and K supply (ISN, ISP, ISK; kg ha-1, measured as aboveground plant uptake) for nutrient omission plots set on selected smallholder farms in western Kenya.

Treatment	NPK 2	NP	NPK 1	PK	NK	Control
Grain yield	3.4^{a}	3.3^{ab}	2.6^{bc}	2.3^{c}	2.1^{c}	2.0^{c}
n	16	14	16	9	15	23

Notes; n =number of observations. Mean grain yield values that do not share superscripts are significantly different at $p < 0.05$.

3.2. Experiment 2

Mean of observed grain yields in fertilizer plots was 4.9 t ha -1 (SD = 1.9 t ha $^{-1}$) and in control was 3.0 t ha $^{-1}$(SD = 2.1 t ha^{-1}). However, observed grain yields varied largely across farms. Also, observed yield response (i.e. grain yields in fertilizer plot minus grain yields in control plot) varied between farmers (Fig. 1).

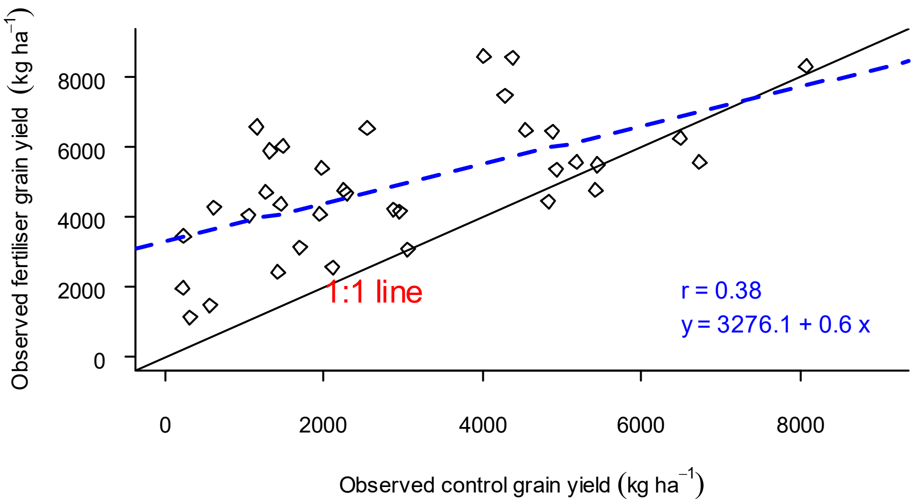

Figure 1. Experiment 2. Relation of observed control and fertilizer grain yield. Points below the 1:1 line (solid line) indicate a negative grain yield response to fertilizer application. The dashed line is a linear regression line with R squared values (r = 0.38) and linear regression equation y = 3276.1 + 0.6 x.

A linear mixed model was fit on the observed data (grain yield and nutrient uptake) using the lme4 package in R statistical software. The purpose of fitting the lme model was to remove the error in the observed values arising from differences in farmer field location and management. The lme model version used was; observed grain yield ~ treatment + (1/ Farm ID) i.e. a lme model with intercepts varying randomly, but slopes being common. Simply, the quantity of the response variable i.e. observed grain yield when the explanatory variable (i.e. Treatment) is zero is different among the random variable terms (i.e. Farm IDs), but the effect of each additional unit of the explanatory variable is the same across each random variable term. The model was also run with observed nutrient uptake as a response variable. The lme model fit well (i.e. Explained much of the variation) with the observed data (Fig.2). The fitted values of the model were extracted. The fitted value for each farm ID is obtained by adding together the fixed factor effect on that farm ID and the estimated random effect for all farm IDs.

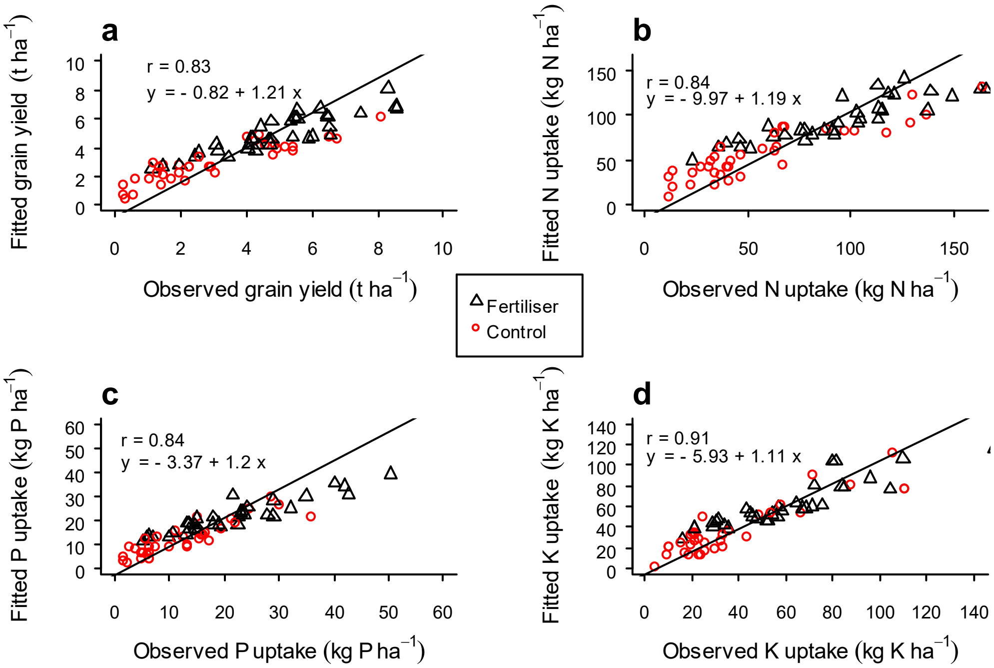

Figure 2. Experiment 2. The accuracy of fitting a linear mixed model to the observed grain yield and nutrient uptake data. Fitted values were obtained after fitting a linear mixed effects model with the explanatory variable as; observed grain yield (plot ***a****), observed N uptake (plot* ***b****), observed P uptake (plot* ***c****) and observed K uptake (plot* ***d****). Treatment and farm ID were fixed and random variables, respectively. Lines are linear regression lines with R squared values (r) and linear regression equations.*

3.2.2. Validation of QUEFTS

Fitted values of grain yield and nutrient uptake were used as indicative of observed values during validation of QUEFTS.

3.2.2.1. Grain yield.

Fitted values of grain yields in fertilizer plots averaged 5.0 t ha $^{-1}$ compared to the predicted average of 4.0 t ha^{-1}. Similarly, the means of fitted values and predicted grain yields in control plots were 3.0 t ha^{-1} and 2.5 t ha^{-1}, respectively. Fitted values and predicted grain yields in both fertilizer plots (Fig. 3b; IOA= 0.56) and control plots (Fig. 3**Error! Reference source not found.**c; IOA= 0.55) were in good agreement. Generally, for the full dataset, the model was good in predicting fitted values of grain yields (Fig. 3a; IOA=0.66, RMSE= 1.7 t ha^{-1}, n=70). An overview of descriptive statistics of various parameters is presented in (Table 5).

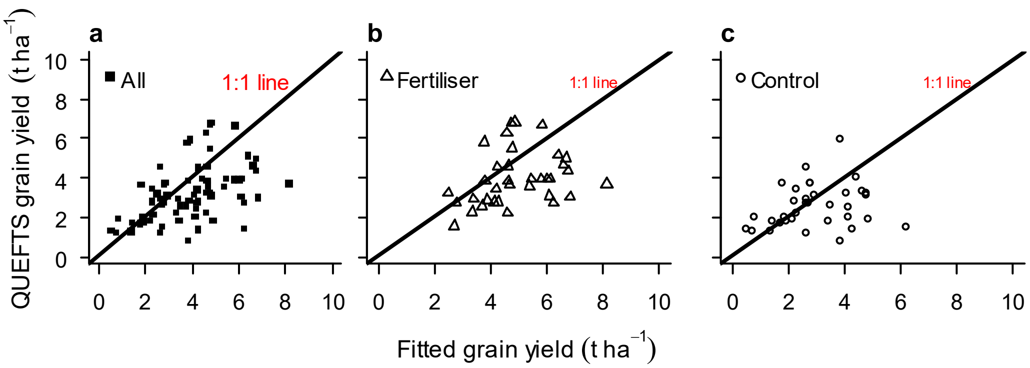

*Figure 3. Experiment 2. Performance of QUEFTS model (original version) in predicting fitted maize grain yields obtained under farmer management in Western Kenya: for all treatments (**a**), for fertilizer plots(**b**), and in control plots(**c**). Grain yield is expressed at 12% moisture content. QUEFTS model was run with RE values of 0.5, 0.1, 0.5 for N, P and K. Maximum and minimum IE borderlines were 30 and 70 for N, 200 and 600 for P, and 30 and 120 for K.*

3.2.2.2. Internal utilization efficiency (IE)

Janssen et al. (1990), fixed minimum and maximum IE borderlines, respectively, at 30 and 70 for N, at 200 and 600 for P, and at 30 and 120 for K (solid lines Fig. 2). For the present study, the maximum and minimum fitted values IE values (IE borderlines) were determined as the 2.5th and 97.5th percentiles of the calculated fitted values IE values of each nutrient (Eq. 1). By excluding 2.5% of the lowest and highest fitted values IE values, it is expected that observations, where other factors other than nutrients could have been limiting yield production, will be removed (Liu et al., 2006; Witt et al., 1999). Consequently, suitable minimum and maximum fitted values IE limits were fixed, respectively, at 37 and 71 for N, at 172 and 398 for P, and at 33 to 177 for K (dashed lines in Fig. 4). The percent change in fitted values IE borderline values of N, P and K is below 50% and thus comparable to those in QUEFTS as set by Janssen et al. (1990). Hence, in the present study, the data points left out by the solid lines in Fig. 4 x, y, z, are regarded as outliers. Considering the median lines that represent balanced fertilization (blue dot dashed lines), P was generally over-supplied (Fig. 4 y) whereas K was under-supplied (Fig. 4 z). Summary statistics of fitted values IE values based on observed grain yield and nutrient uptake data for all treatments are given in (Table 5).

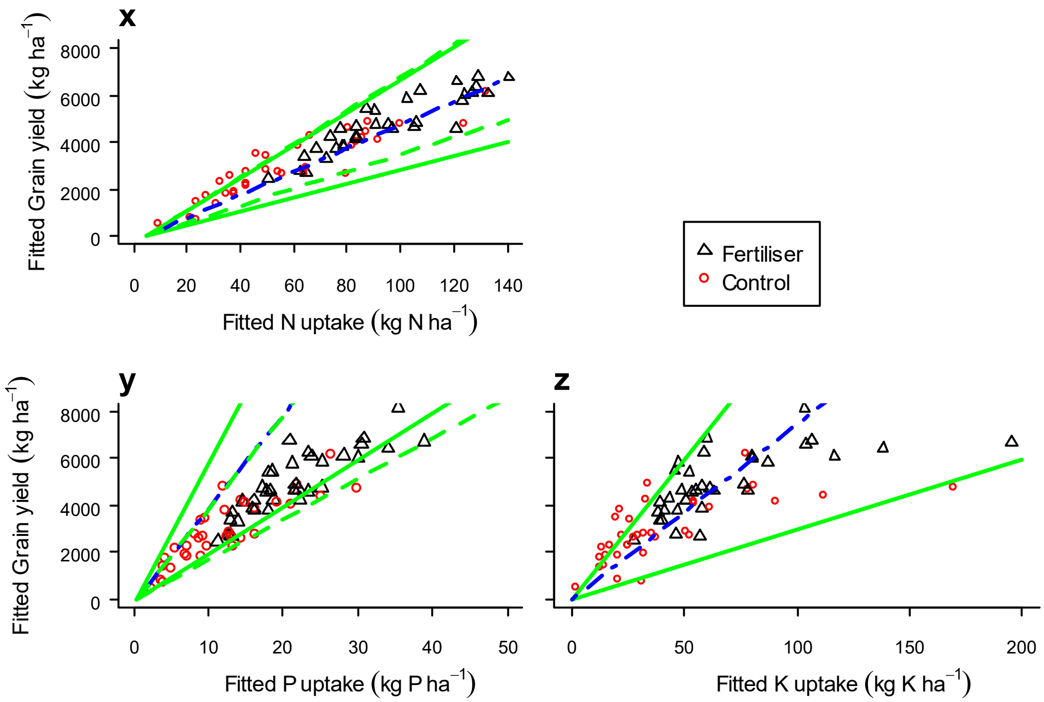

*Figure 4. Experiment 2. The relationship between fitted values of grain yield and aboveground plant N (plot **x**), P (plot **y**), and K (plot **z**) uptake. The upper and lower boundary lines indicate fitted IE at maximum nutrient dilution (d) and maximum nutrient accumulation (a), respectively, according to Jansen et al (1990) (solid lines) and as fitted at 2.5th and 97.5th percentile of this data (dashed lines). The blue dot dashed lines indicate the median of the solid line borderlines i.e. balanced nutrient uptake. Minimum nutrient uptake before any grain yield formation can occur was set at 5, 0.4, 2 kg for N, P and K, respectively(Jansen et al, 1990).*

3.2.2.3. Apparent fertilizer recovery efficiency (RE)

Mean of fitted RE-N, RE-P and RE-K were 0.55, 0.39, and 2.93, respectively (Table 5). The mean of fitted RE- N recovery was similar to the default QUEFTS RE-N (0.5). Generally, fitted RE-P and RE-K was higher than their respective default QUEFTS RE values. Drawing from the equation of RE, a RE-K of above 1 indicates that in the fertilizer plot, more indigenous K was taken up than in the control plot.

3.2.2.4. Agronomic Efficiency (AE)

Generally, grain yield increased with increase in nutrient application (Fig. 5). However, the grain yield gain per kg application was lower at high nutrient application rates than at a low application rates (Fig.6). Simply, AE was high at lower application rates, and subsequently decreased with increasing application rates. AE-P decreased with increasing plant – available soil P (Fig. 7b) but no clear trend was observed with soil clay content (Fig. 7d). Relationship of AE-N and AE-K with respective soil properties did not yield a clear pattern (Fig. 7a, b, c). Mean of fitted AE-N, AE-P and AE-K was 26.2, 84.0 and 221.0, respectively (Table 5). The predicted mean of AE-N, AE-P, and AE-K was 16.4, 49.5 and 151.9, respectively. As expected PAE was highest at lower application rates. For K, the lower application rates (and thus high AE-K values) were associated with a high amount of K taken out of the field through grain compared to the amount of K applied (i.e. partial nutrient balance of greater than 1). A general response function between grain yield (kg ha^{-1}, at 12 % moisture) and fertilizer application rates (kg ha^{-1}) for the present study was found to be: *Grain yield = (3058.3 + random intercept) + 16.7 N + 17.5 P -26.0 K.* The random intercept varied among farms from -2464.0 to 2934.6 kg ha^{-1}.

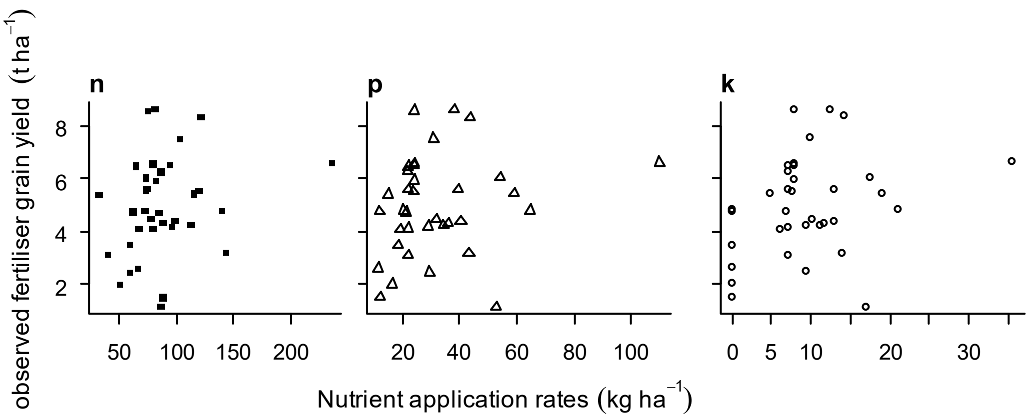

Figure 5. Experiment 2. Relation of grain yield and fertilizer application rates of N (plot n), P (plot p) and K (plot k). zero application of K was on fields that were found sufficient in Exchangeable K levels from the soil analysis results.

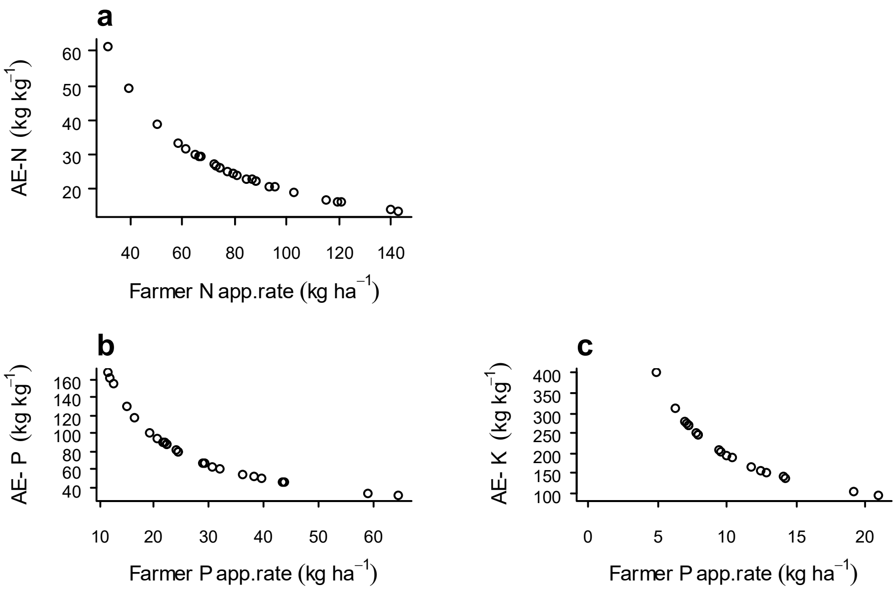

Figure 6. Experiment 2. Relation of agronomic efficiency and nutrient rates applied by the farmer. app.rate = application rate. Data points represent 28 observations for AE-N and AE-K, and 23 observations for AE-K.

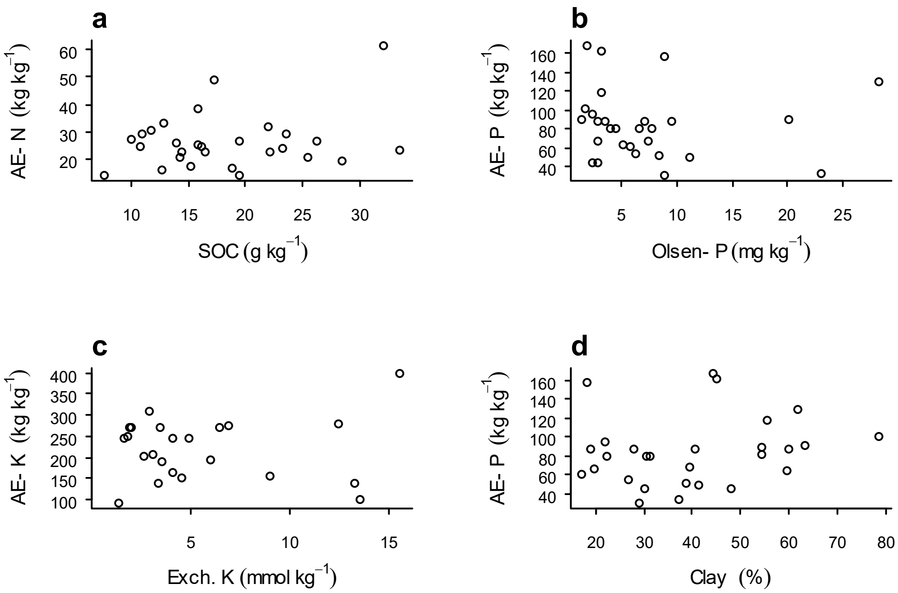

Figure 7. Experiment 2. Relation of agronomic efficiency and soil properties: soil organic carbon (plot a), plant-available soil phosphorus (plot b), Exchangeable potassium (plot c), and soil clay content (plot d).

Table 5. Experiment 2. Descriptive statistics of grain yield (t ha^{-1}, at 12% moisture), Internal efficiency (IE, kg grain per kg nutrient uptake), Agronomic efficiency (AE, kg grain per kg nutrient applied) and Apparent recovery efficiency (RE, kg nutrient taken up per kg nutrient applied). Data is categorized into FITTED (indicative of observed data) and QUEFTS (predicted) values.

Parameter	Data type	Treatment	n	Nutrient	Mean	SD	Minimum	25% Q	Median	75% Q	Maximum
Grain yield	FITTED	Fertilizer	35		4.9	1.3	2.5	4.0	4.7	6.0	8.1
		Control	35		3.0	1.3	0.5	2.1	2.7	4.1	6.2
	QUEFTS	Fertilizer	35		4.0	1.4	1.5	2.9	3.8	4.6	6.8
		Control	35		2.5	1.1	0.8	1.7	2.5	3.2	5.9
IE	FITTED	All	70	N	51.6	8.6	32.3	46.8	59.8	56.7	76.1
			70	P	251.3	60.0	159.3	211.9	234.5	280.5	425.2
			70	K	88.5	39.8	24.2	63.5	83.3	102.5	278.8
AE	FITTED	Fertilizer	28	N	26.2	10.2	13.7	20.8	24.6	29.2	61.4
			28	P	83.96	36.3	30.1	59.5	80.8	92.0	167.6
			23*	K	221.0	73.2	92.8	161.6	247.0	270.9	399.9
	QUEFTS	Fertilizer	28	N	16.0	5.1	3.6	13.8	16.0	20.7	26.7
			28	P	49.5	12.9	25..5	42.6	48.7	53.4	80.2
			23*	K	151.9	36.8	90.2	129.9	145.7	151.9	246.9
RE	FITTED	Fertilizer	28	N	0.55	0.21	0.29	0.44	0.51	0.62	1.29
			28	P	0.39	0.17	0.14	0.28	0.38	0.43	0.78
			23*	K	2.93	0.97	1.23	2.14	2.93	3.59	5.30

Notes; n = number of observations * lesser observations due to zero application of K on some fields found sufficient in K. Q =quantile, SD =standard deviation.

4. Discussion.

4.1. Experiment 1

Results in table 4 suggest that grain yield response to N was enhanced due to the application of P and vice versa i.e. grain yield responses to N and P were linked. The omission of potassium (i.e. NP treatment) did not have a significant reduction in yield relative to NPK 2 treatment. NPK 1 and NPK 2 differed in their source of K; Muriate was used in NPK 2 whereas a fertilizer blend 1.5PK with some Sulphur was used in NPK 1 plots. However, yields in NPK 1 treatment were significantly lower than those in NPK 2 implying that K source or addition of Sulphur did not have a significant positive effect on grain yield. N and P are the most limiting and thus important nutrients on the smallholder farms in Western Kenya considered in the present study. K and S deficiencies were found negligible for maize production on some farms. This result is contrary to the results of Kihara and Njoroge (2013) which indicated significant importance of S.

4.2. Experiment 2

Both observed grain yield means were higher than the Kenyan national maize yield average of 1.7 t ha^{-1} (FAO, 2019), indicating that data in the present study is from fertile fields. Variation in control grain yields can be attributed to variation in factors related to soil characteristics i.e. soil fertility between farms (Table 2, Fig.13 in appendix), and management practices during the season. The reason for few negative grain yield responses to fertilizer application (data points below 1:1 line in Fig.1) can be attributed to error : e.g. a mistake in data collection, human/ animal interference with harvestable yields in the fertilizer plot during or at end of season, etc. However, for his negative AE values, Vanlauwe et al. (2011) suggested that in dry soil conditions a seed maybe scorched by a closely placed fertilizer. This can limit uptake of indigenous nutrients (e.g. due to death of seeds or weak seedling establishment) in the fertilizer plot compared to uptake in an adjacent control plot. Consequently, resulting yield in fertilizer plot is decreased. In addition to fertilizer application practices, another factor that can affect crop yield response is related to soil. Some soils give no or little response to fertilizer application and thus yields in these soils are not significantly different from those in control plots. Such kind of soils were referred to as poor, non-responsive soils by Vanlauwe et al. (2010). He further stated that soils can be relatively fertile such that addition of external inputs results in a small increment in yield. Such soils he referred to them as good, non-responsive soils. Both these soil categories can be observed in Fig 1.

Generally, according to the indicators for model accuracy used in the present study, the model was good in predicting fitted grain yield. However, from Fig 3, the model underestimated much of the fitted grain yields. The same result was observed with plotting QUEFTS against observed grain yield values (Fig.8 in appendix). This accuracy gap between the judgement indicators and graphical plotting could be a shortfall in the computation of the indicators used e.g. as reported by Pereira et al. (2018) for the index of agreement (IOA) . Probable reasons for QUEFTS underestimating much of the grain yield observed could be that: (i) the hybrid maize cultivar used in the present study has a higher production potential than that used to calibrate the original QUEFTS model in 1990 ((Janssen et al., 1990). Several studies have reported differences in grain yield gains between modern and old hybrid maize cultivars. For example, Ciampitti and Vyn (2012) reported that on an area basis and relatively similar N input levels, modern maize genotypes (1990 – 2011) had greater yield potential than old era (1940-1990) maize genotypes. They largely attributed this to enhanced tolerance to higher plant density from 5 to 7.6 per m^2. In the present study, plant density observed in farmers' fields averaged 3.6 and 3.9 per m^2 in fertilizer and control plots, respectively (see Fig.9 in appendix). Following Geodatics recommended practices (i.e. spacing: 70 by 25 cm, seeding rate: one seed per hole), the targeted plant density in the present study was about 5.6 per m^2 (56,000 plants / ha). However, at harvest, this target was not achieved on almost all farms (Fig 9).This indicates significant low germination percentages or post-germination plant deaths on farmers' fields. Optimal plant density is important in maximizing maize grain yield. At a sub-optimal plant density, resources such as nutrients, light, soil moisture are not effectively utilized, whereas, at supra optimal levels individual plants can be deprived of resources due to intense competition (Sangoi, 2001; Tetio-Kagho & Gardner, 1988). Both these situations can result in lower grain yields per hectare than would be obtained. It is thus important that causes of lower plant population densities in farmers field at harvest be identified and addressed. It can be assumed that such actual lower plant densities at harvest can drive, as was observed in few instances, some farmers to increase plant densities in excess of the recommended levels. The observed plant densities observed in the present study are less than the average of about 5 per m^2 used in calibration of QUEFTS (Janssen et al., 1990). Therefore, yield differences (between QUEFTS and fitted) could be at an individual plant level- higher yield per plant. See observed individual plant yield characteristics in Fig. 10, and 11 in appendix. Individual plant physiological improvements attributed to modern genotypes include; single-cross hybrids with superior tolerance to stress e.g. drought and N deficiency (Ciampitti & Vyn, 2012; Edmeades, 2013), sustained higher rates of photosynthesis in their leaves during grain filling stage, increased post-silking N uptake with the main fate of the N taken being grains (Echarte et al., 2008). Unfortunately, verifying whether the modern maize genotypes used in the present study are genetically distinct and have a yielding advantage over those used for calibration of QUEFTS was not possible, (ii) soil analysis results might not be fully representative of soil properties on actual farmers field used for the experiment. This could be a result of : (a) improper soil sampling procedures as regards appropriate sampling tools, sampling depth and sampling point patterns. In a few monitored instances, field staff did not conduct sampling satisfactorily to the issued instructions for field activities, (b) a farmer applying the Geodatics package, and subsequently the experiment setup on a different field than the one offered by the farmer for soil testing, (c) the soil laboratory results, as with the plant analysis results, could have an error, (iii) the half-half sampling method for harvested ears, as written in field activities instructions was rarely followed. For this reason, there could have been a bias towards sampling good filled ears resulting in the higher yields observed.

Internal utilization efficiency (IE) is a crop specific parameter and indicates the capacity of the crop to convert nutrients obtained from all sources into grain yield. The fitted IEs for the present data were within the standard IE borderlines fixed by Janssen et al. (1990). However, K and to a small extent N, were slightly deficient in the maize crop in farmers' fields (i.e. data points are slightly close to the solid line of maximum N and K dilution, Fig.4a and c. Indeed, there were a few visible N deficiency symptoms (e.g. light green leaf color, stunted plants, poor kernel development) observed on a few fertilizer plots. P was slightly available in excess (Fig.4b). This finding implies imbalanced crop nutrition. Imbalanced crop nutrient uptake is mainly caused by imbalanced nutrient supply or fertilization and results in grain yield decrease. Imbalanced fertilization could mainly be a result of farmers not following the Geodatics recommended fertilizer application rates and practices. It was observed that some farmers applied either excess or short of advised amounts (Fig. 12 in appendix). Some farmers applied lower rates of fertilizer to save the remainder for other fields or next season. Other causes for this deviation can be attributed to, lack or improper training of farmers, lack of proper tools e.g. table spoon or plastic scoops to use in applying fertilizer correctly, conservativeness of some farmers in use of tools to apply fertilizer as an alternative to use of hands, hiring of untrained labor. IEs are important in determining crop nutrient requirements, and consequently fertilizer requirements for a given target yield. As suggested by Janssen et al. (1990), averages of maximum and minimum IE values indicate balanced crop nutrient requirements. To this end, considering QUEFTS IE borderline median for each nutrient (Fig 4), balanced nutrient uptake of maize to produce 1000 kg of grain yield is 20, 2.5 and 13.3 kg of N, P and K, respectively.

Apparent RE indicates the fraction of the applied nutrient that is taken up by the crop. The fraction that is not taken up follows the fate of (i) loss by erosion and run-off, leaching (N, K, P), volatilization (for N), denitrification (for N) (ii) irreversible fixation into soil organic matter, microbial biomass (iv) incorporation in the soil mineral fraction (for P and K) (v) residual inorganic forms which becomes available in subsequent seasons/ years after application (Dobermann, 2005; Duivenbooden, 1992). Fitted RE were higher for P and K than the default QUEFTS values. Mean of fitted RE-P (0.39) was close to that (0.35) reported by (Wasonga et al., 2008) for western Kenya. Fitted RE- K of above 100%, suggest that soil K uptake in the fertilizer plot was considerably greater than that in the control plot. Given the NPK application in the fertilizer plot, crop root system could have been enhanced to explore a larger soil mass and hence a larger uptake of soil K. If this is true, it could mean that, farmers need to utilize balanced fertilizers so they could reap from the available soil K. Like IE, RE is important for generating field specific fertilizer recommendations. However, RE is often variable between fields as is in the present study (Table 5). This variation results from a multitude of issues categorized into; fertilizer application practices (i.e. 4Rs, indigenous nutrient supply inclusive) and factors that determine the crop nutrient demand e.g. variety specific seasonal potential yield, climate (e.g. rainfall), crop management (e.g. weeding, pest and disease incidence) and cropping system (e.g. monoculture vs intercropping) (Dobermann 2005; Duivenbooden 1992). These numerous factors reemphasis the need for specific fertilizer recommendations, but also present difficulties in predicting applied nutrient uptake or response to fertilizer application and consequently accurate tailoring of RE values for each field. Therefore, its more feasible to conduct zonal experiments and establish a standard representative mean for the nutrient RE. Besides being a useful parameter for fertilizer recommendation, RE is an indicator of nutrient loss or accumulation in the field.

Agronomic efficiency (AE) is an indicator of the increase in grain yield resulting from the use of fertilizers, and thus shows a short-term influence of the fertilizers applied on the productivity of the cropping system. Generally, observed mean AE were higher than those commonly reported for farmer managed fields across SSA (Ichami et al., 2019). For instance, mean AE-N of 26.2 kg grain [kg N applied]$^{-1}$ observed in the present study, is higher than AE-N value of 14 kg grain [kg N applied]$^{-1}$ reported for Malawian smallholder farmers following a nationwide fertilizer and improved seed subsidy program (Chinsinga, 2008). Observed AE-N mean is, however, still relatively lower than AE-N means reported for western Kenya under researcher management and hybrid maize varieties e.g. 34 kg grain [kg N applied]$^{-1}$ by Vanlauwe et al. (2011) for a metanalysis study across SSA, and 33,33,39 by Ngome et al. (2013) for treatments NP (each nutrient applied at a rate of 100 kg ha^{-1}) and control treatments on Nitisol, Acrisol and Ferrasol dominant soil types respectively. Mean observed AE-P (mean 84) is higher than AE-P values searched in literature for western Kenya. Mean AE-P for western Kenya under researcher management, hybrid maize variety and in consideration of NP and control treatments was reported by Kihara and Njoroge (2013) as 16 kg grain [kg N applied]$^{-1}$ (at range of P application range 4- 250 kg P ha^{-1}), and by Ngome et al. (2013) as 33, 39, 39 for the three dominant soil types Nitisol, Acrisol and Ferrasol respectively. Literature on AE-K values for western Kenya is scarce. Nevertheless, Fixen et al. (2015) reported that for cereals typical AE-K values range between 8-20 which is very far below the AE-K of 221.0 observed in the present study. AE is affected by soil fertility and application rates (see Fig. 6 and 7 in appendix). A common expectation is that a higher crop yield response is obtained at lower levels of soil fertility. Available P on most farmers' fields was below critical levels of 10 and 15 mg kg-1 as suggested by Nandwa and Bekunda (1998) and Okalebo et al. (2009), respectively (table 2). Consequently, a relatively high (though variable) yield response to P application was observed. Plant available soil P in western Kenya is limited due to the slightly high acidic soils which have moderate to high fixation of P (Kihara & Njoroge, 2013). Much of the applied P is fixed by adsorption on Fe and Al hydroxides and oxides and consequently its immediate availability for uptake by the plant is reduced (Baligar & Bennett, 1986). K deficiency in much of western Kenya is negligible, hence a higher AEK could be due to low application rates. Whilst this shows that soils are not deficient in K, as confirmed by Experiment 1 and the soil analysis results, omitting or meager K application would result in soil K depletion in the long run given that , in this study, K removal from the field through grain was considerably higher compared to K input. As most farmers harvest ears (grains), some also remove crop residues from the field as feed for livestock. Given the lower efficiency in livestock manure collection, re-cycling of K back to the field is hardly achieved. Therefore, replacement or maintenance application of K is required. The gap between farmer and researcher managed field AE-N values is always attributed to a lesser degree of crop and field management under farmer conditions (Cassman et al., 2002). This signifies a need to further enhance extension services to smallholder farmers. Many technologies to improve, and help bridge this AE-N disparity have been reported and can be distinguished into (i) those that increase the crop demand and uptake of N (i.e. use of improved genotypes) and (ii) those that enhance the availability of soil and fertilizer N for crop uptake (i.e. management, including field-specific fertilizer recommendations) (Cassman et al., 2002; Giller et al., 2004). In the latter category, the factors in the present study that could have fallen short under some fields and present an avenue for improving AE-N values include; (i) lower plant densities at harvest time, (ii) deviation of farmer fertilizer application rates and placement practices from advised practices, (ii) planting and weeding on recommended time. Late planting by some famers was because of delay in delivering farm inputs to nearby pick-up points.

Some limitations to the present study are as follows; (i) A few issues with the determination of NUE values by the difference method using nutrient uptake in fertilized and control plots i.e. (a) overestimation of REP and REK. RE of a nutrient is best determined by the difference in its uptake between full NPK plot and its corresponding nutrient omission plot (i.e. where it is the only limiting nutrient and thus will be maximally taken up by the plant). In the present study, given the assumption that N is always limiting on the farmers' field, its uptake in the control plot signifies its maximum supply. This, however, doesn't hold when considering uptake of P and K which are rarely limiting. As a result, the crop in the control plot takes up fewer amounts of P or K than what is potentially available. Therefore, observed REP and REK could be overestimated whereas REN is considerably reliable. (b) cofounding effects e.g. applied fertilizer N in the fertilizer plot can reduce rates of mineralization of soil organic matter and crop residues unlike in the control plot (Ladha et al., 2011), (c) since NUE terms used are ratios of many measurements or fitted values, sampling, measurement or model fit accuracy errors can cause significant errors, (ii) Residual effects of nutrients from previous nutrient applications and their effect on calculating uptake differences cannot be captured. Also, nutrients in the roots were not accounted for, (iii) The method of determination of AE values for specific nutrient ignore the relative contribution of other nutrients, (iv) some plots set up did not have data to collect because e.g. they had been washed away by heavy rains, their demarcations had been tampered with, farmer had replanted with own variety following poor germination, had very few harvestable ears (e.g. due to theft, in season harvest, bird damage, poor germination etc.), were harvested by farmers without the presence of the field staff to record harvest data, some farmers wanted their maize to be harvested earlier than the potential harvest dates for a physiologically mature maize as such separating maize grains from cobs for moisture analysis was difficult, application rates were not recorded, etc.

5. Conclusion

According to the model accuracy indicators used (IOA and RMSE), QUEFTS model was fairly good in predicting grain yields attained on smallholder farmers’ fields. However, considering graphical plotting, model accuracy on individual fields was poor i.e. predicted yields were below or above corresponding observed yields. Inaccuracy of the QUEFTS model in predicting grain yield resulting from individual field soil fertility, puts a limit on its application in generating field specific fertilizer for Geodatics farmers. This is important because farmers are interested in knowing the level of AE to expect for a given quantity of fertilizer purchased and subsequently applied. With this knowledge farmers can make informed decisions to maximize their return on fertilizer investment.

The AE of most Geodatics farmers was considerably higher than AE commonly reported under typical smallholder farmer conditions, which shows that the Geodatics package (i.e. field-specific fertilizer, improved and agronomic advice) can have a substantial positive impact on farm productivity. This positive impact, in light of most Geodatics farmers deviating from the recommended field-specific fertilizer application rates, suggests that not the tailoring of fertilizer application rates but the NPK package was important. The subsequent benefit to farmers in terms of money after selling of maize produced was not investigated in the present study. However, both grain yield and economic returns are important for continued use and adoption of the Geodatics package by smallholder farmers in Western Kenya.

Appendix.

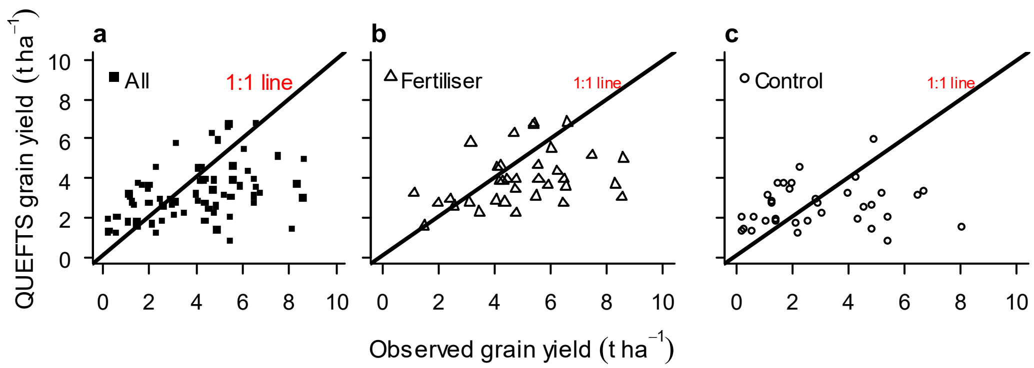

*Figure 8. Experiment 2. Performance of QUEFTS model (original version) in predicting maize grain yields observed under farmer management in Western Kenya: for all treatments (**a**), for fertilizer plots(**b**), and in control plots(**c**). Grain yield is expressed at 12% moisture content. QUEFTS model was run with RE values of 0.5, 0.1, 0.5 for N, P and K. Maximum and minimum IE borderlines were 30 and 70 for N, 200 and 600 for P, and 30 and 120 for K.*

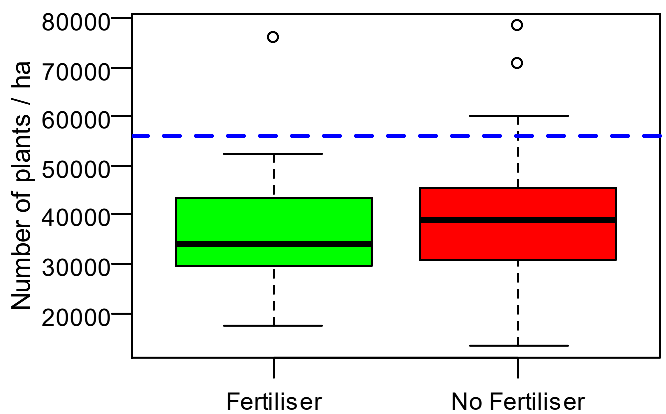

Figure 9. Experiment 2. Plant density observed in treatments conducted farmers' fields at harvest. At onset of planting, the targeted planting density was 56,000 (indicated by the dashed horizontal line). Each treatment had 35 observations.

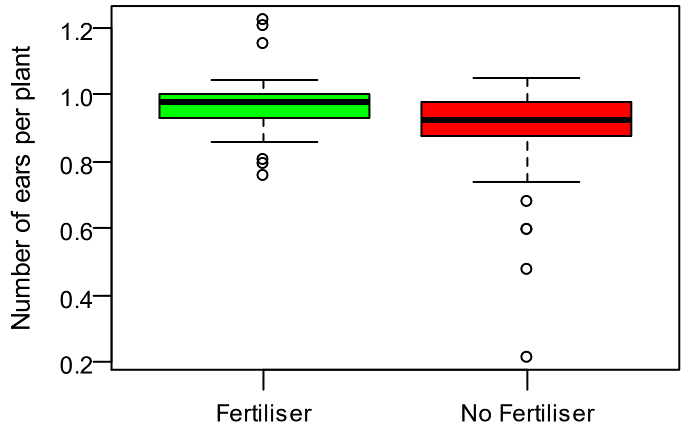

Figure 10. Number of ears per plant observed for different treatments in farmers fields. Each treatment had 35 observations. Expected number of ears per plant at planting were 0.5 – 2 .

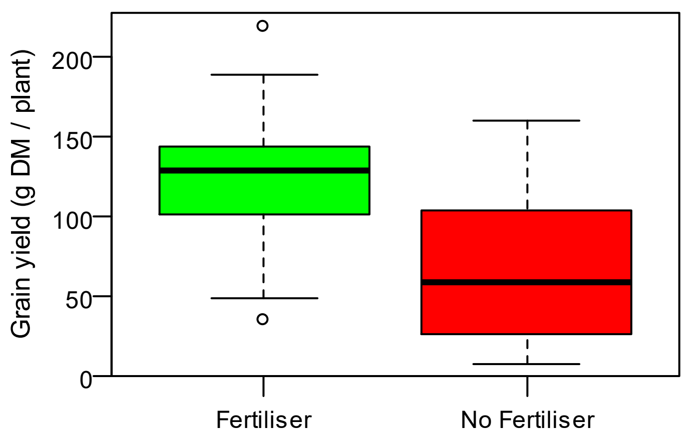

Figure 11. Grain yield per plant observed for different treatments in farmers' fields. Each treatment had 35 observations.

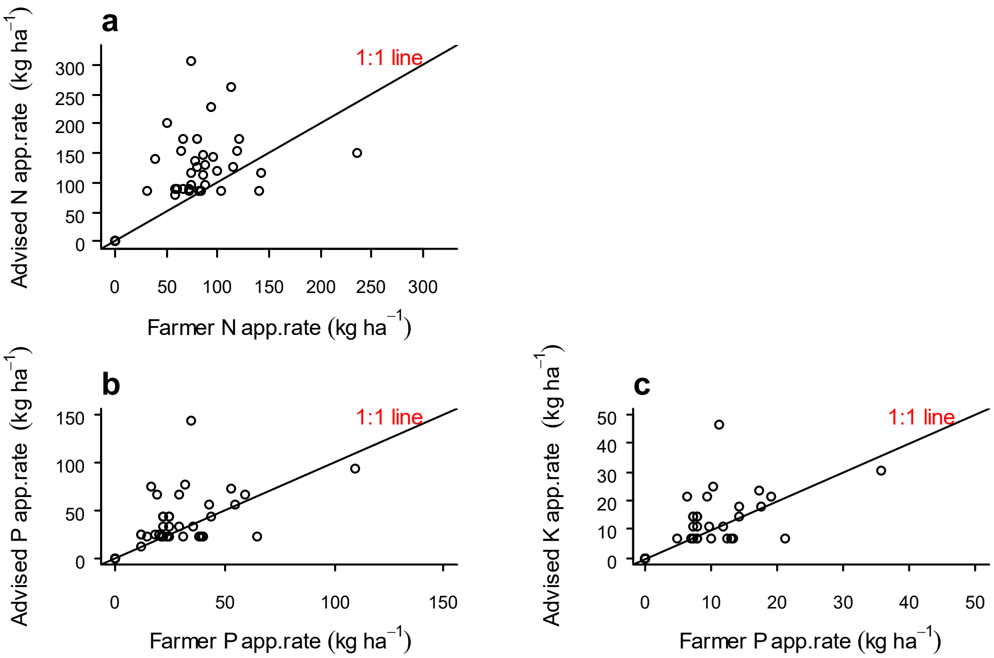

Figure 12. Relation of advised nutrient application rates to actual farmer applied nutrient rates. Data points in each plot represent 70 observations. app.rate = application rate.

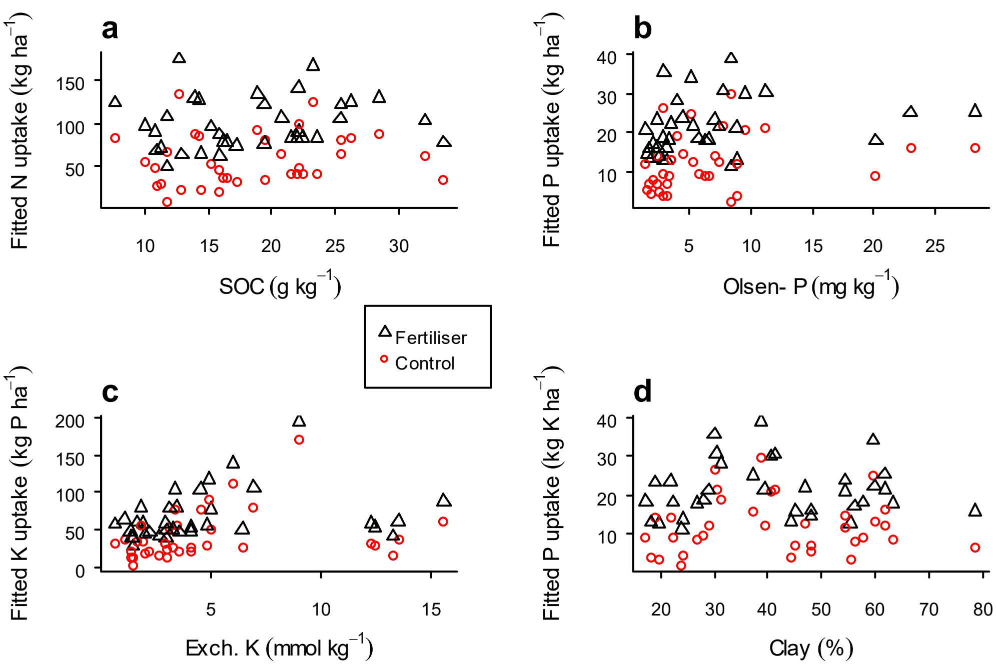

Figure 13. Relation of nutrient uptake and soil properties in control and fertilizer plots. SOC = soil organic carbon, Olsen -P = plant soil available phosphorus, Exch.K = Exchangeable potassium.

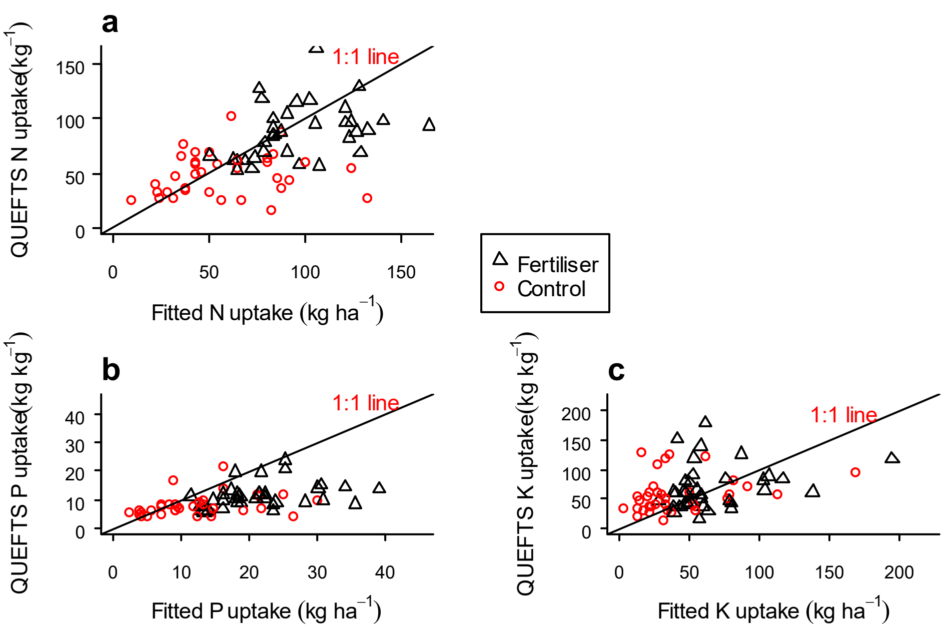

Figure 14. Experiment 2. Performance of QUEFTS model (original version) in predicting nutrient uptake in aboveground maize biomass at 12 % moisture content observed under farmer management in Western Kenya. QUEFTS model was run with RE values of 0.5, 0.1, 0.5 for N, P and K. Maximum and minimum IE borderlines were 30 and 70 for N, 200 and 600 for P, and 30 and 120 for K.

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