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Economically Optimal Rates and Nutrients Use Efficiency Indices of Maize to the Application of Different Rates of Nutrients in Central Rift Valley of Ethiopia

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Abstract

The use of balanced fertilizers in adequate amount is very important to increase crop productivity and production in Ethiopia. The study was executed to quantify maize (*Zea mays* L.) grain yield response to different rates of nitrogen (N), phosphorus (P), potassium (K) and sulfur (S) under balanced fertilization of other nutrients. On farm trials were conducted at seven sites on 8 farmers' fields in Negele Arsi districts, west Arsi zone of Oromia region for three consecutive cropping seasons (2014-2016). Six rates of N, P, S and eight rates of K treatments established separately for each nutrient were laid out in randomized complete block (RCB) design with three replicates per farm. Nutrient response function modelling showed that 184, 20 and 80 kg·ha^{-1} were the agronomic optimum rate for N, P, and K, respectively. Mean agronomic efficiency (AE) of N, P and K were recorded at the lower rates of these nutrients, application of 46, 10 and 20 kg·ha^{-1} N, P and K resulted in 19.1, 61.0, and 24 kg additional grain yield·kg^{-1} N, P and K, respectively. Also, the mean partial factor productivity (PFP) of N, P and K were 77.6, 370 and 158 kg additional grain·kg^{-1} applied N, P and K respectively. Economically optimal rate (EOR) of N, P and K were 48 - 114 kg·ha^{-1} N with CP 8 - 3.5, 12 - 20 kg·ha^{-1} P with CP 18 - 4.5 and 32 - 53 kg·ha^{-1} K with CP 8-4, from these rates net returns of US$487.23 - 143.30, US$698.16 - 498.3 and US$359.31 - 193.63 could be obtained respectively. To conclude, application of 84, 12 and 40 kg·ha^{-1} N, P and K could be recommended for the production of maize.

Keywords

Agronomic Efficiency, Balanced Fertilization, Economic Optimal Rate, Maize Yield, Nutrient Response Function, Partial Factor Productivity

1. Introduction

In Ethiopia, Maize (*Zea mays* L.) was ranked second in total area coverage and first in production [1]. About 86% of the cropland was covered by cereal production with major cereals such as teff, maize, sorghum and wheat accounting for an estimated 24%, 17%, 15% and 13%, respectively, use during the main cropping season in 2015 [2]. Maize, Teff, Sorghum and Wheat accounts 31%, 20%, 19% and 18% in production respectively [1] [3]. The national average for maize yield in 2016/17 was 3.67 $t \cdot ha^{-1}$ [1], which is lower than the experimental yield of over 4.9 $t \cdot ha^{-1}$ [4]. However, a yield of up to 10.1 $t \cdot ha^{-1}$ could be obtained if maize crops are properly managed. The low yields have been attributed partly to the limited use of external inputs and low nutrient status especially nitrogen (N), phosphorus (P), potassium (K) and sulfur (S) resulting from the mono-cropping and excessive leaching of the soil nutrients [5]. Therefore, it is important to apply adequate amounts of fertilizer to replenish the soils and enhance crop productivity.

Improper plant nutrient management is a major factor contributing to low yield. As Tarfa *et al.* [6] described, low fertilizer use efficiency can result from inappropriate fertilizer recommendations that should account for the cash constraints and risks affecting resource-poor farmers. The recent fertilizer use in Ethiopia is focused on a blanket recommendation of DAP and Urea for all crops [7] which are sources of only N and P. However, recently it is perceived that the production of cereals like wheat and legumes can be limited by the deficiency of S and other nutrients. Sulfur is a macro-nutrient that is taken up by crops in amounts similar and sometimes exceeding those of P, 10 - 30 kg/ha [8], and is considered to be one of the most limiting nutrient elements for crop production. It is essential not only for plant growth and quality produce, but also enhances other nutrients use efficiency and ranks second only to N in importance for optimum crop $yield \cdot quality^{-1}$ [9]. However, S is a nutrient most overlooked in Ethiopian agriculture [10]. According to Xinbing *et al.* [11], it is necessary to determine key factors influencing maize response to N, P, K and S rates and evaluate the potential benefits of alternative N, P, K and S management strategies first.

Optimizing Fertilizer Recommendations for Africa (OFRA) was introduced the way of excluding the use of blanket recommendations in 2012. Optimizing fertilizer use to obtain the optimum economic yield reduces nutrient loss to the environment [12] and is therefore an important strategy to improve nutrient use efficiency in crops. This is because most of the recommended rates of fertilizer application have been found to be generally high as compared to the economically optimal rates (EOR) of nutrients determined from the results of field research conducted across the 13 sub-Saharan African countries [13]. In many developing countries, there is still a large gap between the economically achievable yield and the average yield [14]. This is mostly due to the fact that fertilizer recommendations are not sufficiently profit-oriented and do not consider the economic status of the smallholder farmer [15]. For instance, the yield limits attained from applying optimum fertilizer rates to maize crops were 148% - 248%

greater than using regional recommendation [16].

Most sub-Saharan Africa countries like Kenya, Tanzania, and Uganda adopted fertilizer optimization tool at the early stage and have considerable experience in this domain [17]. Various scholars, Jansen *et al.* [18], Wortman and Sones [19], numerous reports intended to predict the application of economically viable nutrients to crop applications: curvilinear response functions, quadratic-plus-plate models, asymptomatic curvilinear-plate models are best fitted.

Several indices are commonly used in agronomic research to assess the applied nutrient efficiency mainly for purposes that stress crop response to nutrients [20]. The comprehensive measure of NUE is the ratio of yield to the amount of applied nutrient, also called the partial factor productivity [PFPN] of applied nutrient, which declines with increasing nutrient application [21]. The PFP is an aggregate efficiency index that includes contributions to crop yield derived from uptake of indigenous soil nutrient, nutrient uptake efficiency, and the efficiency with which nutrient acquired by the plant is converted to grain yield. In addition to N uptake by the crop and N losses, a portion of the N applied is retained in soil as residual inorganic N (either ammonium or nitrate) or incorporated into various organic N pools-including microbial biomass and soil organic matter [21]. Such retention should be considered a positive contribution to N input efficiency only when there is a net increase in total soil N content. Because more than 95% of total soil N is typically found in organic N pools, an increase in soil organic matter (*i.e.* carbon sequestration) is required to achieve increases in total soil N. Sustained increases in organic matter in cropping systems practiced on aerated soils (e.g. maize- and wheat-based systems without irrigated rice) result in greater indigenous N supply from decomposition of the organic N pools, which can reduce N fertilizer requirements to maintain yields and thereby increase PFPN [22] [23]. Crop NUE may be low, even with low N application rates, because of limited plant growth due to biotic or abiotic constraints, possibly including deficiencies of P and other essential nutrients [24].

This current study in Ethiopia, information on fertilizer optimization and partial factor productivity in the central rift valley are lacking. The present study though assumes that the fertilizer optimization model uses a nonlinear regression function (asymptotic quadratic-plus-plateau model) to predict EOR of N, P, K and S for maize. Therefore, objectives of the research were to 1) determine the yield response functions of maize to N, P, S and K fertilizers; 2) quantify N, P, K and S use efficiency indices of maize; 3) determine the net returns to fertilizer use of N, P, K and S; and 4) determine the economically optimal rates for N, P, K and S (EOR) in the central rift valley of Ethiopia.

2. Materials and Methods

2.1. Site Description

Nutrient response function trials were conducted on 8 farmers' fields at Negele-Arsi District, Oromia Region West Arsi Zone (**Figure 1**) for three consecutive cropping seasons (2014-2016). The elevation ranges from 1700 to 1900 m asl, with a mean annual temperature varied between 24˚C and 25˚C and growing period from 146 to 160 days. The rainfall the study site is monomodal dominantly falls from May to September/October. The rainfall in 2014, 2015 and 2016 were 895, 636, 750 mm respectively (Figure 2). The rainfall of 2015 and 2016 cropping seasons less than the 2014 season by 28.9% and 16.2% respectively. The soil of the study area is Vitric Andosols the value of chemical parameters is shown in Table 1.

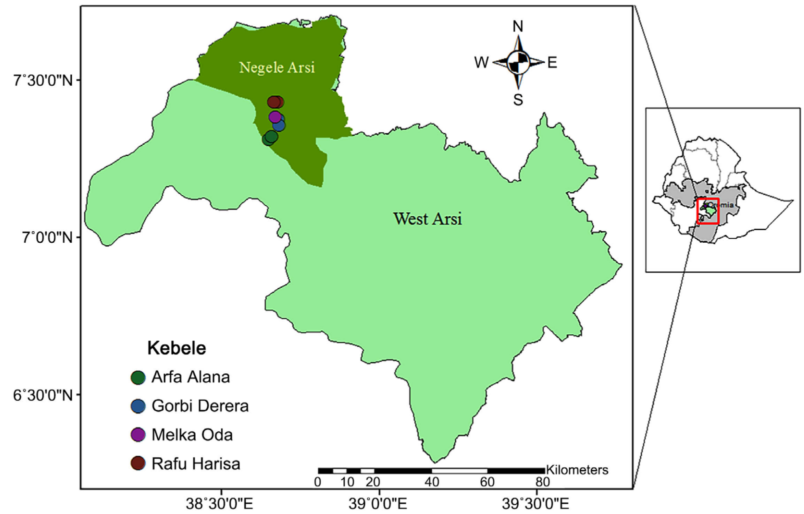


Figure 1. Study site, Oromia Region, West Arsi Zone, Negele Arsi District, Ethiopia.

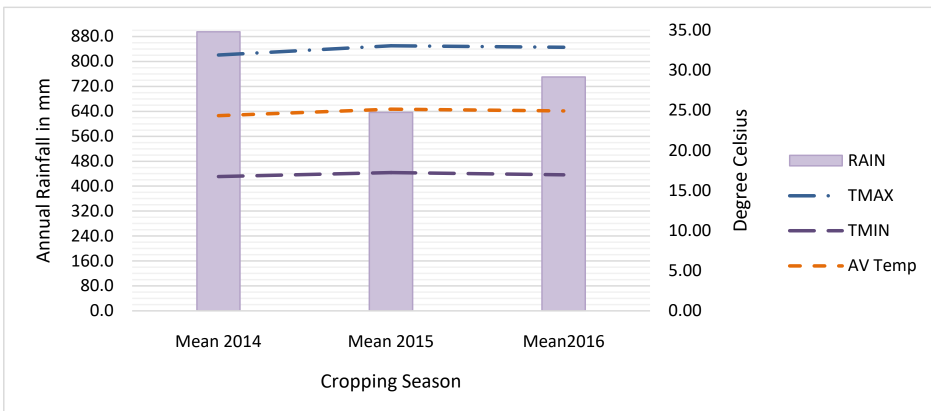


Figure 2. Rainfall and temperature of the cropping seasons.

Table 1. Selected soil chemical properties of the study area (Negele Arsi).

Parameter	Unit	TS_1	TS_2	TS_3	TS_4	TS_5	TS_6	TS_7	Values	Reference
pH		6.3	6.4	6.5	6.7	6.9	6.6	6.6	Slightly acidic-neutral	Jones [25]
SOC	$g\cdot kg^{-1}$	35	27	26	29	25	26	23	High	Charman [26]
Total N		23	22	24	22	18	23	19	Medium	Bruce [27]
Exchangeable K	$mg\cdot kg^{-1}$	769	684	672	668	773	650	787	V. High	FAO [28]
Available P		13.2	11.4	12.3	15	12.2	12	16.1	Marginal	Clements [29]

TS = Testing site.

2.2. Treatments and Experimental Designs

Six rates of Nitrogen (N), Phosphorus (P), Sulfur (S) and eight rates of Potassium (K) treatments with optimum application of other nutrients for each experimental nutrient, including micro-nutrients such as Zinc (Zn) and Boron (B) were evaluated (**Table 2**). All fertilizer treatment combinations were laid out in randomized complete block design on a plot size of 5.1 m by 3.75 m (~19 m^2) and replicated three times in each farmer's field on a total of 8 farmers' fields. The treatment setup for each nutrient is presented in **Table 2**.

Melkassa 2 (M-2) maize variety, was planted at intra and inter-row spacing of 25 cm by 75 cm. Full doses of each of P, K, S, Zn and B were applied in row close to the crop rows at planting, but N was applied in two splits *i.e.*, half at planting and the rest half at 30 days after planting. Nitrogen was applied in the form of urea, Phosphorus as triple superphosphate (TSP), Potassium as potassium chloride (KCl), Sulfur as calcium sulfate ($CaSO_4$), Zinc as zinc sulfate ($ZnSO_4$) and Boron was applied as Borax. The other crop management practices were followed as per the recommendation for the crop.

2.3. Data Collection and Statistical Analysis

Soil sampling and analysis

From all experimental sites composite soil samples were collected from 0 - 20 cm depth before planting using an auger. Following the standard soil sampling procedures three representative sub-samples were collected from each site and mixed in plastic bags to make one composite sample per site that making a total of seven composite samples. Potentiometric method using a glass calomel combination electrode was used to measure pH of the soils in water suspension in a 1:2.5 (soil:water ratio) [30]. The Walkley and Black [31] wet digestion method was used to determine soil organic carbon (OC) content. Total nitrogen content of the soil was determined by the wet oxidation procedure of the Kjeldahl method [32]. Available P was determined using the standard Olsen *et al.* [33] extraction methods. The absorbance of available P extracted was measured using spectrophotometer after colour development. Exchangeable K was determined after percolating and extracting the soil samples by 1N ammonium acetate solution at pH 7 in which exchangeable K+ in the leachate was measured by Flame Photometer [34].

Table 2. Nutrient types and rates used in the trial.

Nutrients	Nutrient rates ($kg \cdot ha^{-1}$)	Optimum nutrients					
		N	P	K	S	Zn	B
Nitrogen (N)	0, 46, 92, 138, 184, 230	N_Rates	30	100	30	2	0.5
Phosphorus (P)	0, 10, 20, 30, 40, 50	92	P_Rates	100	30	2	0.5
Potassium (K)	0, 20, 40, 60, 80, 100, 120, 140	92	30	K_Rates	30	2	0.5
Sulfur (S)	0, 10, 20, 30, 40, 50	92	30	100	S_Rates	2	0.5

Crop sampling and measurements

To measure grain yields harvesting took place at mid-November, the central three rows of each plot were harvested at ground level. Grain yield was then recorded. After threshing, seeds were cleaned, weighed, and seed moisture content was measured using a gravimetric method. Grain yields (adjusted to a moisture content of 12.5%) was converted to $Mg \cdot ha^{-1}$ before statistical analysis.

Statistical analysis

A general linear modeling (GLM) framework of SAS protocols to evaluate differences between treatments was used to determine variation in yield with the different levels of N, P, K and S by site and season combining study sites and seasons. Analysis of variance (ANOVA) was done using generalized linear model (GLM) procedure. The fixed effect in the model was nutrient rate, while site and season, were the random effect. In general models, the random component specifies that the linear predictor contains a term that randomly varies with one or more season correlates of crop yield, for example site within a season. The model was of the following form:

$$Y = \mu + \text{rate} + \text{Season} + \text{Site} + \text{Season} * \text{rate} + \text{Site} * \text{rate} + \varepsilon \quad (1)$$

where μ is the grand mean yield ($Mg \cdot ha^{-1}$), rate is the rate of application ($kg \cdot ha^{-1}$) for the nutrient under study, site and season are the random component and ε is the error term.

When differences between treatments were significant, least significant difference (LSD) was used to separate means, with a significant level of 0.1%, 1% and 5%. Least square estimates and their 95% confidence intervals were used for statistical inference.

When significant nutrient rate effects occurred for grain yield, response functions were fitted for each nutrient sites-seasons, an asymptotic quadratic–plateau function, which gave an exponential rise to maximum yield or to a yield plateau.

Nutrient response functions were compared and used as deemed appropriate to determine the optimum rate of the nutrient in question. The asymptotic function for nutrients was grain yield (GY):

$$GY\left(\text{Mg} \cdot \text{ha}^{-1}\right) = a - bc^{X} \quad (2)$$

where a is yield at the plateau (*i.e.*, expected maximum), b is the amplitude (the yield due to nutrient application), and c is a curvature coefficient and X is the nutrient rate applied.

The asymptotic function generally gave the best fit for the N, P and K for all sites-seasons hence, the mean of the predicted yields of the asymptotic functions were used for nutrient rates intermediate between the treatment levels to determine an adjusted asymptotic function. To complement the actual means for 0, 46, 92, 138,184 and 230 $kg \cdot ha^{-1}$ for the determination of the adjusted asymptotic function, predicted values 23, 69, 115, 161 and 207 $kg \cdot ha^{-1}$ N rates were used.

$$GY\left(\text{Mg} \cdot \text{ha}^{-1}\right) = 3.94 - 1.16 * 0.9875^{\text{N rate}} \quad (3)$$

The asymptotic function was also applied for the P and K rates for the sites-seasons. Sulfur rate effects were generally not significant in the analysis and failed to converge using combined sites-seasons. Differences were considered significant at $P \leq 0.05$.

$$GY\left(\text{Mg}\cdot\text{ha}^{-1}\right) = 3.897 - 0.812 * 0.838^{\text{P rate}} \quad (4)$$

Phosphorus rate increments were small enough that the asymptotic function gave good response functions. Potassium rate increments were gave good response functions for combined analysis sites-seasons.

$$GY\left(\text{Mg}\cdot\text{ha}^{-1}\right) = 3.402 - 0.696 * 0.968^{\text{K rate}} \quad (5)$$

The nutrient rates for maximum net returns, or the economically optimal rates (EORs) from nutrients application, were calculated for ranges of CPs for N, P and K. Economic analyses were done with a grain price of US\$0.23 kg^{-1} (21.8 Ethiopian Birr per US\$), and the costs of using fertilizer US\$1.39 kg^{-1} N, US\$3.78 kg^{-1} P, and US\$ 1.28 kg^{-1} K were a function of grain price and the CP. The mean EORs were determined for each CP of the respective nutrient. Equations were developed using nonlinear regression analysis to relate EORN, EORP and EORK to CP. The PCR is defined as marginal net benefit divided by the marginal cost due to the nutrient application. This was also calculated as the value of yield gained due to nutrient application at a given nutrient rate minus the nutrient use cost with this difference divided by the nutrient use cost.

In the second step of analyses, we focused on the assessment of the agronomic efficiency of (AE) and partial factor productivity (PFP) to measure production efficiency. The AE and PFP of N (NAE, NPFP), P (PAE, PPFP) and K (KAE, KPFP) also answer a more direct question [21] [35]: "How much productivity improvement was gained by the use of this nutrient input". Therefore, AEN, AEP and AEK, defined as grain production per unit of N, P or K applied, are more important for decision-making concerning fertilizer use, AE, and PFP were determined using the following formulae as described by [21]:

$$\text{NAE}\left(\text{kg}\cdot\text{kg}^{-1}\right) = \frac{GY_f - GY_u}{N_a} \quad (6)$$

$$\text{PAE}\left(\text{kg}\cdot\text{kg}^{-1}\right) = \frac{GY_f - GY_u}{P_a} \quad (7)$$

$$\text{KAE}\left(\text{kg}\cdot\text{kg}^{-1}\right) = \frac{GY_f - GY_u}{K_a} \quad (8)$$

$$\text{NPFP}\left(\text{kg}\cdot\text{kg}^{-1}\right) = \frac{GY_f}{N_a} \quad (9)$$

$$\text{PPFP}\left(\text{kg}\cdot\text{kg}^{-1}\right) = \frac{GY_f}{P_a} \quad (10)$$

$$\text{KPFP}\left(\text{kg}\cdot\text{kg}^{-1}\right) = \frac{GY_f}{K_a} \quad (11)$$

where GY_f is the grain yield of the fertilized plot (kg), GY_u is the grain yield of the unfertilized plot (kg) for each replicate, and N_a, P_a or K_a is the quantity of N, P or K applied as fertilizer (kg) at the given rate.

3. Results and Discussion

3.1. Maize Yield Response to Nitrogen, Phosphorus, Sulfur and Potassium Fertilizers

The results of this study are presented in the following two Tables. In Table 3 results of N, P and S are presented in Table 4 result of K is presented.

Table 3. Response of maize grain yield to application of **nitrogen**, **phosphorus**, and **Sulphur** rates at different seasons and (Seasons-Sites).

Nitrogen Rate									
Season	0	46	92	138	184	230	CV	P > F	SE
$Kg \cdot ha^{-1}$			GY ($Mg \cdot ha^{-1}$)				(%)		
N_14 + Sites (n = 3)	2.72^{d}	4.35^{ab}	3.55^{c}	3.47^{c}	4.65^{a}	3.81^{bc}	20.69	***	0.37
N_15 + Sites (n = 3)	2.20^{d}	2.50^{cd}	3.00^{abc}	2.71^{bcd}	3.22^{ab}	3.30^{a}	20.00	***	0.27
N_16 + Sites (n = 2)	3.36^{c}	3.98^{bc}	3.98^{bc}	3.80^{bc}	5.31^{a}	4.47^{b}	13.86	***	0.33
(Sites-Seasons) (n = 8)	2.69^{e}	3.57^{c}	3.45^{cd}	3.27^{d}	4.28^{a}	3.79^{b}	11.00	***	0.39
Phosphorus Rate									
$kg \cdot ha^{-1}$	0	10	20	30	40	50			
P_14 + Sites (n = 3)	3.72^{b}	3.83^{b}	4.68^{ab}	5.02^{a}	5.04^{a}	4.43^{ab}	24.3	*	0.51
P_15 + Sites (n = 3)	2.58^{c}	3.72^{a}	3.35^{ab}	3.16^{b}	3.11^{b}	2.91^{bc}	15.58	***	0.23
P_16 + Sites (n = 2)	2.90^{b}	3.47^{ab}	3.97^{a}	3.85^{a}	4.10^{a}	2.99^{b}	18.72	*	0.38
(Sites-Seasons) (n = 8)	3.09^{c}	3.70^{ab}	4.00^{a}	4.03^{a}	4.09^{a}	3.50^{bc}	19.3	*	0.72
Sulfur Rate									
S_14 + Sites (n = 3)	5.16	4.85	4.65	4.95	4.60	4.79	25.02	ns	0.57
S_15 + Sites (n = 3)	2.16	1.75	2.21	1.85	2.22	2.33	33.23	ns	0.33
S_16 + Sites (n = 3)	3.96	3.76	4.13	4.10	3.81	3.76	16	ns	0.36
(Sites-Seasons) (n = 8)	3.73	3.41	3.60	3.57	3.51	3.61	23.02	ns	0.82

Table 4. Response of maize grain yield to application of potassium rates at different seasons and (Seasons-Sites).

K_Rate ($kg \cdot ha^{-1}$)	0	20	40	60	80	100	120	140	CV	P > F	SE
Season					$Mg \cdot ha^{-1}$				(%)		
K_14 + Sites (n = 3)	3.66^{b}	3.94^{ab}	3.96^{ab}	4.19^{ab}	4.37^{ab}	4.17^{ab}	4.26^{ab}	4.67^{a}	21.33	*	0.89
K_15 + Sites (n = 3)	1.89^{b}	2.09^{ab}	2.44^{ab}	2.46^{ab}	2.44^{ab}	2.65^{a}	2.62^{a}	2.27^{ab}	25.42	*	0.60
K_16 + Sites (n = 2)	2.38^{c}	3.58^{a}	2.64^{bc}	3.26^{ab}	3.33^{ab}	3.40^{a}	3.46^{a}	2.89^{abc}	19.39	*	0.6.0
(Sites + Seasons) (n = 8)	2.68^{b}	3.16^{a}	3.06^{ab}	3.31^{a}	3.39^{a}	3.40^{a}	3.44^{a}	3.33^{a}	22.58	***	0.39

Combined analysis (sites-2014 season) revealed that the application of 184 kg and 46 kg N gave significantly high grain yield as compared to other treatments at ($P < 0.001$) with the corresponding 70.95% and 59.92% yield advantage respectively over the control (0 kg N) (**Table 3**). In the 2015 and 2016 cropping seasons significantly higher yields were observed from higher rates as compared to the lowest rates at ($P < 0.05$) level. The combined analysis across sites in 2015 (sites-season) 230 kg N, 184 kg N and 92 kg N ha^{-1} rates gave significantly higher grain yields as compared to other treatments at ($P \leq 0.001$) level. Subsequent yield advantage of 50%, 46% and 36 % were obtained from these rates over the control (0 kg N) respectively. In 2016 the combined analysis (Sites-Season) the application of 184 kg N ha^{-1} significantly highest grain yield (5.31 $Mg \cdot ha^{-1}$) as compared to other treatments at ($P < 0.001$) level. The pooled mean analysis across sites and over years (all sites-all seasons) revealed that the application of 184 kg N ha^{-1} statistically significant highest yield (4.28 $Mg \cdot ha^{-1}$) were observed as compared to other treatments at ($P < 0.001$) level. This rate had 59.10% yield advantage over the control (0 kg N). In this study, inconsistent maize grain yields (sites-seasons) were observed by the application of N, this is due to the significant field-to-field and within-field variability of indigenous soil N supply (**Table 1**), and these fixed rates will unavoidably result in sub-optimal N management in different fields within a study district [36] [37].

The statistical analysis revealed a significant grain yield response to phosphorus fertilizer application over the two sites in 2014 cropping season at ($P < 0.05$ and $P < 0.001$) levels respectively, however there was no significant difference in the third site at 0.05 probability level (**Table 3**). The combined analysis (all sites-season) showed the application of P above 10 $kg \cdot ha^{-1}$ significantly improved the maize grain yield at ($P < 0.05$) level. High maize grain yields (5.04 Mg followed by 5.02 $Mg \cdot ha^{-1}$) were obtained by the application of 40 kg and 30 P ha^{-1} with yield improvement of 35.5% and 34.9% respectively, however these rates statistically similar yield with 20 kg P ha^{-1} compared to the control without P application. In 2015 cropping season all sites responded well to the small P doses as compared the higher doses. The combined analysis across sites (sites-season) showed the application of P at different rates significantly improved the grain yield at ($P < 0.001$) level. The application of smallest rate (10 kg P ha^{-1}) increased the yield by ~44.2 % compared to the control without P. In the 2016 cropping season the combined analysis across sites the grain yield significantly affected by the application P at ($P < 0.05$) level. The application of 20, 30 and 40 kg P ha^{-1} gave similar grain yields compared to other rates. The pooled analysis (Sites-Seasons) revealed that the application of different rates of P significantly boosted the yield at ($P < 0.05$) level. The application of 20 kg P, 30 kg P and 40 kg P ha^{-1} gave 4.0 Mg, 4.03 Mg and 4.09 $Mg \cdot ha^{-1}$ grain yield with subsequent yield advantage of 29.45, 30.42, 32.36% respectively. This finding agrees with [38], the application of P at low rate appeared to be optimum at the Savanna Zones of Nigeria while yield decreased at higher P rates. Similar to N, significantly higher yields were obtained due to the application P fertilizer, which might be ascribed to variation in overall soil properties, crop growing conditions, such as rainfall, crop management practices and pest management. Soil moisture critically affects the availability of P, particularly in the rift valley of Ethiopia where soil moisture stress is a key constraint for crop production [39].

Unlike other nutrients (N and P) considered in this experiment, maize grain yield did not significantly respond to S application at ($P < 0.05$) level. Surprisingly, the highest grain yield was recorded from the control without application of S. The combined analysis (sites-seasons) revealed that maize grain yield was not significantly affected by the application of S at ($P < 0.05$), this may be due to high concentration of sulfur in this soil. The 2014 season grain yield generally much greater than others seasons (**Table 3**). The insignificant yield variation among the treatments may be due to sufficient amount of sulfur in the soil of the study sites. Itanna [40] and Korb *et al.* [41] observed, based on the surface soil analysis results at plow depth, sulfate concentrations were 8.1 in vitric andosol and Haplic Nitisol 1.8 $mg \cdot kg^{-1}$, indicating that andosols had sufficient sulfate for plant growth.

The statistical analysis indicated that maize grain yield significantly varied with application of K at different rates combined sites in different seasons and sites-seasons at ($P < 0.05$) (**Table 4**). Grain yield steadily increased with the increase in K rates up to 80 kg ha^{-1}. However, there is no significant yield difference among each other at ($P < 0.05$) level. The application of 140 kg K ha^{-1} gave significantly higher yield (4.67 $Mg \cdot ha^{-1}$) compared to the unfertilized control with K at ($P < 0.05$) level, with the subsequent yield advantage of ~27.6% in (all sites-2014 season). In 2015 and 2016 cropping seasons both seasons in all sites significantly affected by the application of different rates of K compared to the unfertilized control with K at ($p < 0.05$). Sites-2015 season the mean grain yield generally low as compared to other seasons. In this season the grain yield significantly improved by the application of K, with the subsequent yield advantage of 10% to 40% as compared to the zero control (**Table 4**). In 2017 season-sites, the application of K significantly increased the grain yield as compared to the zero control at ($P < 0.05$) level. The smallest dose much improved the yield than the higher doses. The application of 20 kg K ha^{-1} gave the highest grain yield 3.58 $Mg \cdot ha^{-1}$ with the corresponding 50.4% yield advantage. The pooled mean analysis (sites-seasons) revealed that the application of different rates of K fertilizer significantly boosted the grain yield from 15% to 28% by the application of 10 kg to 120 kg K ha^{-1} compared to the unfertilized zero control at ($P < 0.001$) level (**Table 4**). The availability of the three top elements potassium (K^+), nitrogen (N) and phosphorous (P) strongly determine the crop yield [42]. K^+ is the most abundant element and plays a crucial role in growth, development, yield, quality, quantity and stress resistance of all plant crops [43] [44].

The grain yield of 2014 was generally lower than the others seasons, this is due to the occurrence of El Niño during the season (**Figure 2**). This is supported by

[3] Ethiopia's agriculture has been hit hard by the El Niño effect in 2015 and, to a lesser extent, in 2016.

3.2. Nutrient Response Curve

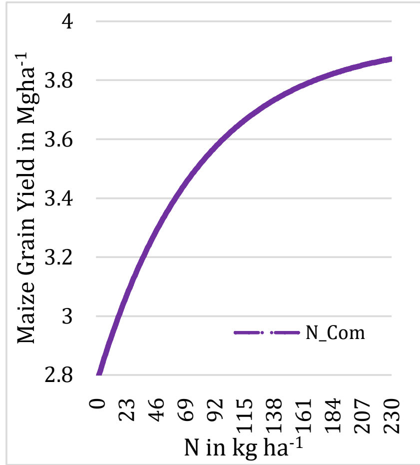
Nitrogen is the most limiting plant nutrient for the production of maize. This analysis compared yield responses to various rates of nitrogen (N) fertilizer with maize grown without N fertilizer. The nutrient response-function model markedly showed that application of 184 kg N, 20 kg P and 80 kg K ha^{-1} were agronomically the optimum rates (AOR) for maize production. As indicated in **Figure 3(a)**, the optimum nitrogen response curve was met at the higher N rate, while slight yield increments were observed with the increase in the N rates.

The response function curves were steep increased in maize grain yield to nitrogen, phosphorus and potassium fertilizers rates up to 84 kg N, 12 kg P and 40 kg K ha^{-1} combined (sites-seasons), followed by succeeding small yield increments (**Figure 3**, **Table 5**). The grain yield of maize increased with increasing N, P and K rates till plateau were reached at 184 kg, 20 kg and 80 kg·ha^{-1} respectively after which the grain yield smoothened (**Figure 3**) in predicted yields. The increases in observed grain yield with N, P and K applications ranged from 0.88

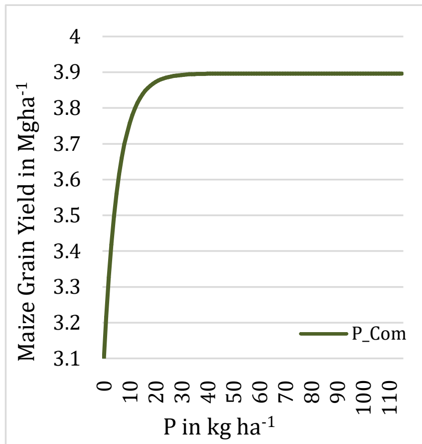
Table 5. Asymptotic nonlinear regression coefficients (*a*, *b*, and *c*) for grain yield response to N, P and K rate and economically optimal N, P and K rates (EORs) for maize, determined across all sites and season, with a cost of fertilizers use (US$·kg^{-1}) to price of grain (US$·kg^{-1}) ratios (CPs) and profit to cost ratio (PCR).

	Coefficient			Recommended nutrient rate			EORs at five N, P and K/grain price ratios				
	a	b	c	EOR†	Rec‡		CP = 8	CP = 6	CP = 5	CP = 4.5	CP = 3.5
Season	Mg·ha^{-1}			kg/ha		Nitrogen	kg·ha^{-1}				
N_2015	3.85	1.62	0.995				1	48	87	110	164
N_2016	6.16	2.74	0.997		92		9	105	166	201	285
N_Comb S_S	3.94	1.16	0.988	82			48	71	85	96	116
PCR (US$)	3.94	1.16	0.988				0.38	0.62	0.81	0.90	1.22
						Phosphorus	CP = 18	CP = 10	CP = 7	CP = 5.5	CP = 4.5
P_2014	4.91	1.30	0.937				24	33	38	44	45
P_2015	3.25	0.67	0.049				2	2	2	2	2
P_2016	3.71	0.82	0.834		20		12	15	17	18	19
P_Comb S_S	3.90	0.81	0.838	16			12	15	17	18	20
PCR (USD)	3.90	0.81	0.838				2.33	4.07	5.55	6.88	7.78
						Potassium	CP = 8	CP = 6	CP = 5	CP = 4.5	CP = 4
K_2014	5.21	1.49	0.995				0	44	80	101	125
K_2016	3.22	0.85	0.273		0		4	4	4	4	4
K_Comb S_S	3.40	0.70	0.968	44			32	41	46	50	53
PCR (USD)	3.40	0.70	0.968				0.76	1.07	1.35	1.44	1.69

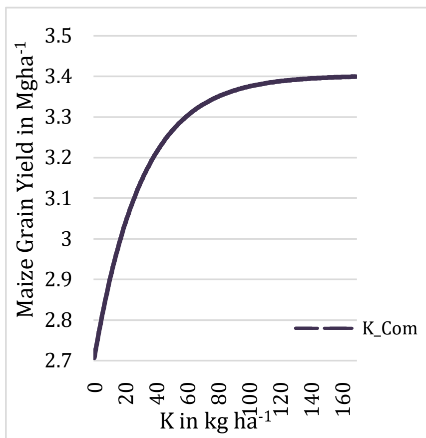
† Economically optimal rate of N, P and K, ‡ Blanket recommended rate.



(a) GY ($Mg \cdot ha^{-1}$) = $3.94 - 1.16 \times 0.9875^{\text{N rate}}$



(b) GY ($Mg \cdot ha^{-1}$) = $3.897 - 0.812 \times 0.838^{\text{P rate}}$



(c) GY ($Mg \cdot ha^{-1}$) = $3.402 - 0.696 \times 0.968^{\text{K rate}}$

Figure 3. Nutrient response functions and optimum nutrient rates of maize (a) Nitrogen, (b) Phosphorus and (c) Potassium (Sites-Seasons).

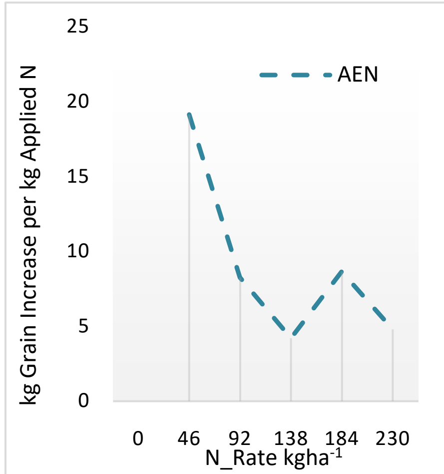
to 1.59, 0.41 to 1.0 and 0.38 to 0.76 $Mg \cdot ha^{-1}$ corresponding to relative increment of 32.7% to 59 %, 13.2% to 25.6% and 14.2% to 28.3% over the control in the combined (sites-seasons) respectively. The resulting yield response functions with respect to N, P, and K applications were 0.7 Mg GY increased with the application of 0 - 84 kg N and 0 - 10 kg P, 0.5 Mg GY with the application of 0 - 40 kg K however, by the application of more than 84 kg N, 10 kg P and 40 kg K fertilizers the yield increments were only 0.3, 0.1 and 0.2 $Mg\cdot ha^{-1}$ respectively. Low response to N fertilizer may also be caused by erratic distribution of rainfall, especially in semi-arid areas, such as the rift valley of Ethiopia [39]. Crops efficiently use N fertilizer when rainfall is suitable. Even in normal years, sub-optimal rainfall during critical stages of crop growth that is, the stage immediately before and after anthesis may significantly reduce N-uptake and use efficiency [45].

3.3. Effect of N, P and K Fertilization on Nutrient Use Efficiency Indices

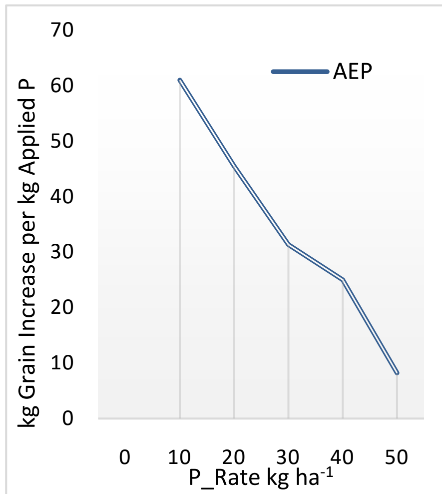
Results indicated that mean agronomic efficiency of N (AE_N) in the combined (sites + seasons), ranged from 4.2 - 19.1 kg additional grain $yield\cdot kg^{-1}$ N applied (**Figure 4(a)**). The AE_N values decreased consistently with the increasing N rate until 138 kg N and want up at 184 kg N which is AOR, where the highest AE_N value of 19.1 kg additional grain $yield\cdot kg^{-1}$ N was obtained from the lowest rate of 46 kg N ha^{-1} and the lowest AE_N value of 4.2 kg additional grain $yield\cdot kg^{-1}$ N was recorded from the higher rate of 138 kg N ha^{-1}. Therefore, a unit kg of applied N increased maize grain yield from 4.2 to 19.1 kg by the application of 138 kg and 46 kg N ha^{-1} respectively. The high AEN values, 46 kg N ha^{-1} was found to be economically optimal rate for maize production. According to Jama *et al.* [46], agronomic efficiency and partial factor productivity of N were higher with 50% of the recommended N rate. Meisinger *et al.* [47] indicated that most components of nitrogen use efficiency were estimated to be higher at the economically optimum N rate compared with higher N rates, confirming the findings.

Mean agronomic efficiency of P (AE_P) in the combined (sites-seasons) varied between 8.2 to 61.0 kg additional grain $yield\cdot kg^{-1}$ P applied. The highest and lowest values of AE_P were obtained from the lowest rate of 23 kg P ha^{-1} and the highest rate of 115 kg P ha^{-1} (**Figure 4(b)**). Berge *et al.* [48], results of TAMASA and OFRA in current agronomic nutrient use efficiency of maize were compared in Sub-Saharan Africa on N and P, the mean observed AE_N values were 14.3 kg additional grain yield per kg N applied and mean observed AE_P 23.9 kg additional grain yield per kg P applied. The agronomic efficiencies of N and P obtained in this study were higher than the average observed for maize by TAMASA and OFRA in East Africa. Pelá *et al.* [49]; Tarekegne and Tanner [50] reported a decrease in phosphorus use efficiency with the increase in P doses.

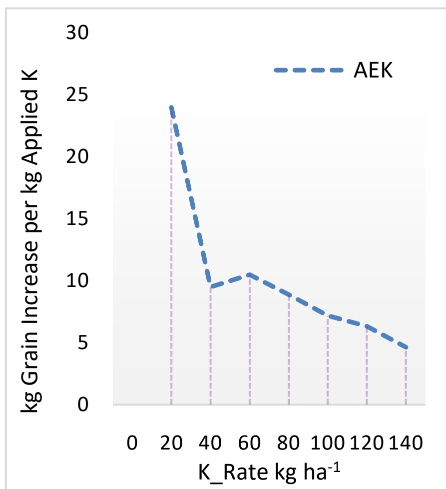
In the combined analysis (sites-seasons) mean AE_K of K ranged from 4.6 - 24.0 kg additional grain $yield\cdot kg^{-1}$ K applied. The highest and lowest values of AE_K were recorded from application of 20 and 140 kg K ha^{-1}, respectively (**Figure 4(c)**). TAMASA and OFRA observed, no significant K response was found in any of the three East Africa countries as reported by [48].



(a) Nitrogen



(b) Phosphorus



(c) Poassium

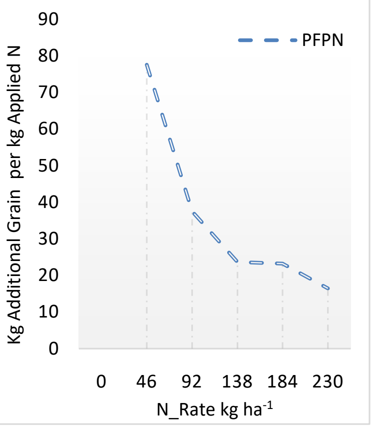
Figure 4. Agronomic use efficiency of (a) nitrogen, (b) phosphorus and (c) potassium for maize grain yield.

Dobermann and Achim [21], defined the partial factor productivity (PFP) is an aggregate efficiency index that includes contributions to crop yield derived from uptake of indigenous soil nutrients, NPK fertilizer uptake efficiency, and the efficiency with which NPK acquired by the plant is converted to grain yield. **Figure 5(a)** showed that the highest PFP_N of 77.6 kg additional grain·kg^{-1} applied N at the smallest dose 46 kg N and the smallest PFP_N 16.5 kg additional grain·kg^{-1} N at the highest dose 230 kg N ha^{-1} in combined (sites-seasons). In line with this study [51] at Measso district West Hararge Zone Oromia region in Ethiopia, the highest PFP of N 101/99 kg grain sorghum·kg^{-1} N at the smallest dose 23 kg N and the smallest 23.9/26.6 kg grain sorghum·kg^{-1} N at the highest dose 92 kg N ha^{-1} in 2014 season/combined (all sites and both seasons) were observed. This result is slightly higher than the world average 70 kg grain·kg^{-1} N as described by [21]. The higher the PFP_N may be due to the adequate soil total nitrogen and organic carbon pool of the study site (**Table 1**). As described by Bell [22] and Kolberg *et al.* [23] higher indigenous N source from decomposition of the organic N pools, which can reduce N fertilizer requirements to maintain yields and thereby increase PFP_N. The combined (sites-seasons) as **Figure 4(b)** indicated that the highest PFP_P of 370 kg additional grain·kg^{-1} applied P at the smallest rate 10 kg·ha^{-1} P and the smallest PFP_P 70.0 kg additional grain·kg^{-1} P at the highest rate 50 kg·ha^{-1} P applied. **Figure 5(c)** showed the smallest rate 20 kg K gave the highest PFP_K 158 kg additional grain·kg^{-1} applied K and the lowest PFP_K 23.8 kg additional grain·kg^{-1} applied K from the highest rate 140 kg K ha^{-1} applied.

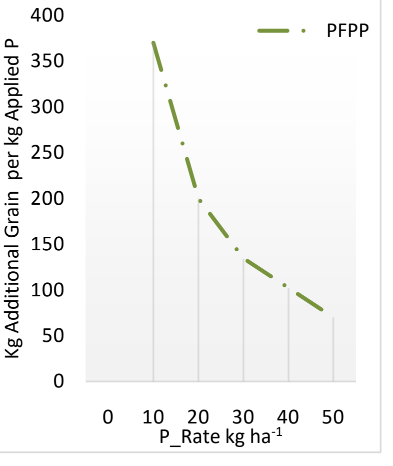
3.4. Net Returns to Fertilizer Use

The results of net returns to fertilizer use are presented in **Figure 6**. Generally, there were proven that the net returns to N, P and K fertilizers use increased with an increase in N, P and K application rates until a point where further application of nutrients resulted in insignificant increment in net returns and consequently leading to financial loss. The optimum N net return at 84 kg N, P return at 14 kg P and K at 48 kg K ha^{-1}. After applying N, P and K fertilizers of US$116.76, 52.92 and 61.44 to maize, earned net returns of US$91.50, 151.30 and 89.5 respectively. The benefit to cost ratio of N is minimal as compared to P and K.

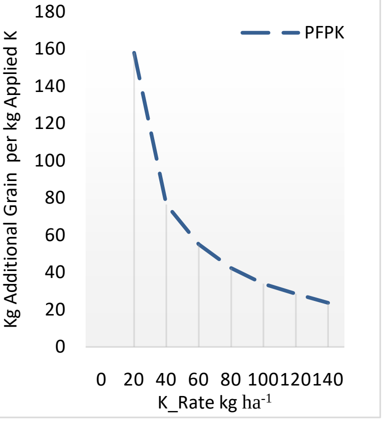
Wortmann and Sones [19] described that financially constrained smallholder farmers therefore require high net returns to validate their use of fertilizer on their crops. Based on the results, the economically poor farmer can get the highest net profit by applying low nutrient rate. As can be observed from **Figure 3**, the steeper the slope of the curve, the higher the net returns to fertilizer use. Therefore, as the amount of budget invested in purchasing fertilizer increases, the slope decreases until it reaches a plateau and finally declines leading to profit reduction. Generally, as the nutrient fertilizers application rate exceeds the EOR the net benefit to nutrient fertilizers uses decreases. The results obtained from this study is similar to a finding reported by [52] in Northern Tanzania who described that as nutrient application rates get further away from the optimum, net return and value cost ratio decrease.



(a) Nitrogen

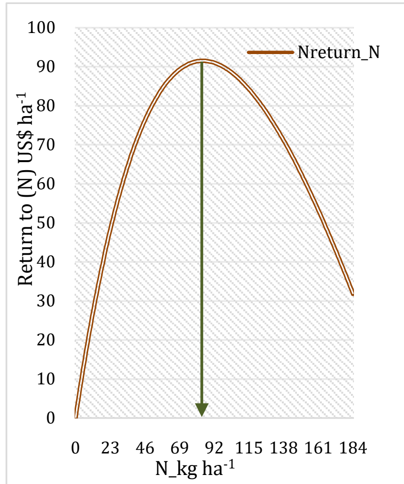


(b) Phosphorus

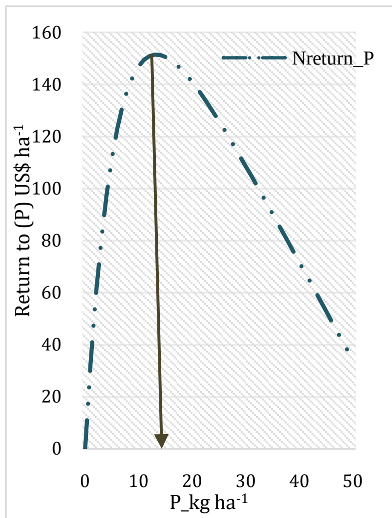


(c) Poassium

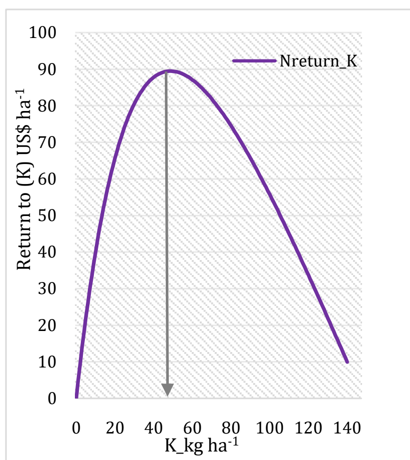
Figure 5. Partial Factor productivity of (a) nitrogen, (b) phosphorus and (c) potassium for maize grain yield.



(a) GY ($Mg \cdot ha^{-1}$) = $3.94 - 1.16 \times 0.9875^{\text{N rate}}$



(b) GY ($Mg \cdot ha^{-1}$) = $3.897 - 0.812 \times 0.838^{\text{P rate}}$



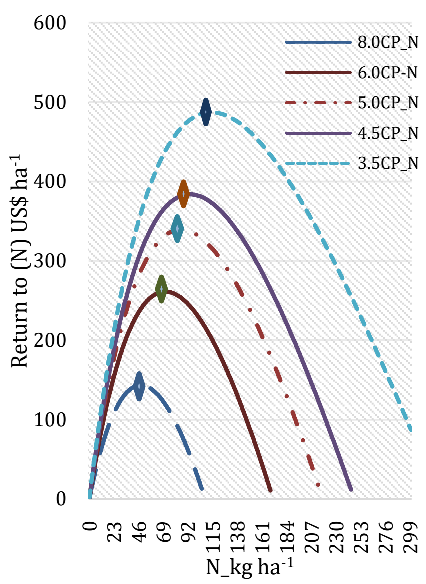
(c) GY ($Mg \cdot ha^{-1}$) = $3.402 - 0.696 \times 0.968^{\text{K rate}}$

Figure 6. Net returns to nitrogen (a), phosphorus(b) and potassium (c) fertilizers use. These figures are dependent on grain values and fertilizer use costs.

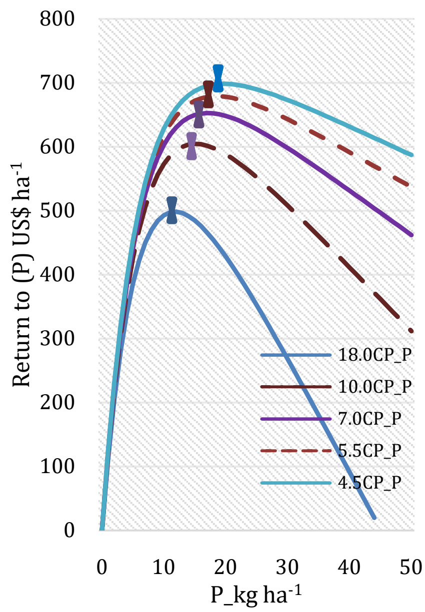
3.5. Economically Optimal Nutrient Rates for N Fertilizer Use Cost to Grain Price Ratios

The EOR of N, P and K in the combined analysis (sites-seasons) were 48 - 114 kg N ha^{-1} with CP = 8 to 3.5 respectively, 12 - 20 kg P ha^{-1} with CP = 18 to 4.5 and 32 - 53 kg K ha^{-1} with CP = 8 to 4 respectively (**Table 5** and **Figure 7**). From these estimated results, net returns of US$487.23 to 143.30 with PCR 1.22 - 0.38, for CP 3.5 to 8 could be obtained at the EOR_N of 114 - 48 kg N ha^{-1} respectively. From the estimated EOR_P combined (sites-seasons), net returns of US$ 698.16- 498.3 with PCR were 7.78 - 2.33 for CP 4.5 - 18.0 could be obtained at 20 - 12 kg P ha^{-1} respectively. The EOR_K, net returns of US$359.31 - 193.63 for the PCR were 1.69 - 0.76 for CP 4.0 - 8.0 could be obtained at 53 - 32 kg·ha^{-1} respectively (**Table 5** and **Figure 7**). The estimated average EOR of N, P and K for maize were 82.4, 16.4 and 44.4 kg·ha^{-1} and the blanket recommended rates of N, P and K fertilizers for the study area were 92, 30 and 0 kg·ha^{-1} respectively. In this study 82 kg N ha^{-1} EOR_N was obtained, which is 12% less than the recommended rate of 92 kg N ha^{-1} required for maize production in the study area. Since application beyond 82 kg N ha^{-1} is uneconomical. Negeash and Bekele [2] reviewed the EOR for N averaged over all crops in all AEZ of Ethiopia was 63 kg·ha^{-1} compared with 51 kg·ha^{-1} for the average of the recommended rates. The EOR for P averaged over all crops in all AEZ was 18 kg·ha^{-1} compared with 20 kg·ha^{-1} for average of recommended rates. The recommended P rate was 20 kg·ha^{-1} in most cases while the EOR P determined from the results of field research was much more variable [2].

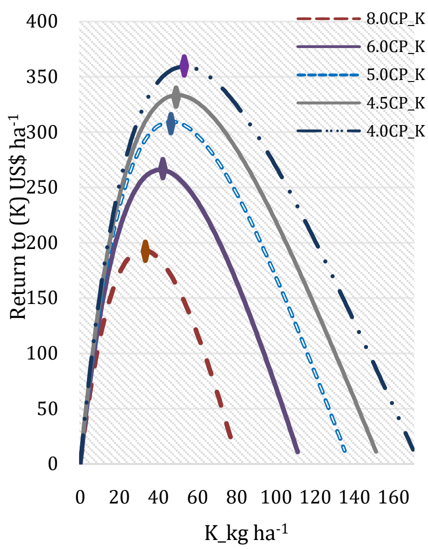
Maize grain yield was not significantly affected by application of sulfur at ($p< 0.05$) thus effect of S did not fit a response function (**Table 3**). Financially constrained smallholder farmers can be benefited at lowest EOR (48 kg N, 12 kg P and 32 kg K ha^{-1}) (**Table 5** and **Figure 6**) this was supported by other study with curvilinear to plateau responses [53].



(a) GY (Mg·ha^{-1}) = $3.94 - 1.16 \times 0.9875^{\text{N rate}}$



(b) GY $(\text{Mg}\cdot\text{ha}^{-1}) = 3.897 - 0.812 \times 0.838^{\text{P rate}}$



(c) GY $(\text{Mg}\cdot\text{ha}^{-1}) = 3.402 - 0.696 \times 0.968^{\text{K rate}}$

Figure 7. Economically optimal N, P and K rates for maize production in Oromia region, west Arsi Zone, Negele Arsi District of Ethiopia for five ratios of (a) Nitrogen, (b) Phosphorus and (c) Potassium the cost of fertilizer use to the grain price (CP). The EOR N, P and K with CPs are indicated by specific symbols at the peak of each curve.

4. Conclusion

In this study balanced fertilization is effective for increasing agronomic efficiency of nutrients and the grain yield, which in turn has meaningful implications for farm profitability and food security. Upon the findings, it is concluded that balanced rates of N, P, and K application with Zn and B gave greater yield increments. Based on the economic optimal rate of nutrients of this finding and economic ability of the smallholder farmers three different recommendations could be given, balanced application of 48 kg N ha^{-1}, 12 kg P ha^{-1}, 32 kg K ha^{-1}, 2 kg Zn ha^{-1} and 0.5 kg B ha^{-1} (financially constrained farmer), 85 kg N ha^{-1}, 17 kg P ha^{-1}, 46 kg K ha^{-1}, 2 kg Zn ha^{-1} and 0.5 kg B ha^{-1} (financially limited farmer), 114 kg N ha^{-1}, 20 kg P ha^{-1}, 53 kg K ha^{-1}, 2 kg Zn ha^{-1} and 0.5 kg B ha^{-1} (financially not constrained) could be recommended for maize in the study area and similar locations. In addition, we also recommend a shift from blanket fertilizer recommendations to yield and profit targeted EOR through soil, crop and agronomic managements.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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Abbreviations

AE Agronomic use efficiency,
CP kg of maize required to equal the cost of 1 kg of nutrient applied
EOR The economically optimal rate of nutrient application or the rate expected to maximize net return per hectare to nutrient application
PCR Profit to cost ratio, or the net benefit divided by the added costs due to application of a nutrient
PFP Partial factor productivity,