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Variability in yield responses, physiological use efficiencies and recovery fractions of fertilizer use in maize in Ethiopia

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ABSTRACT

Physiological use efficiency (PUE), recovery fraction of applied nutrients and indigenous soil nutrient supply form the basis of site-specific fertilizer recommendations. To derive these parameters, and understand their variability, as well as yield responses and fertilizer use profitability, nutrient omission trials (NOTs) were conducted in farmers' fields across different agro-ecologies in Bako (n = 37), Central Rift Valley (CRV) (n = 66) and Jimma (n = 44) regions of Ethiopia in the main crop growing seasons of 2015 and 2016. The treatments used in the NOTs were control, PK, NK, NP, NPK and NPKSM, where SM refers to secondary and micro nutrients, and applied levels of N, P and K, were 120, 40 and 40 kg /ha, respectively. The results showed that the average yields of the control treatment were 4.5, 3.1 and 2.9 t/ha in Bako, CRV and Jimma, whereas the average yields for the NPK treatment were 8.3, 4.9 and 7.9 t/ha in the respective regions. Nitrogen was limiting grain yield in all the three regions, whereas P limited yield only in CRV and Jimma. The average N agronomic efficiencies in Bako, CRV and Jimma were 25.7, 13.3 and 35.5 kg grain kg^{-1} of applied N, respectively, under NPK fertilizer use. With the levels of fertilizer used in the NOTs, NK, NP and NPK treatments were profitable in Bako and Jimma, whereas PK was not. None of the fertilizer treatments were profitable in CRV. Soils in Bako and Jimma supplied more N and K but less P than the soils in CRV. The PUE at maximum accumulation, median and maximum dilution of N were 27, 54 and 80 kg grain kg^{-1} N, while for P, the values were estimated to be 194, 350 and 505 kg grain kg^{-1} P, and for K they were 16, 52 and 87 kg grain kg^{-1} K. The estimated average N, P and K recovery fractions were 0.29, 0.05 and 0.06, respectively, in Bako, 0.22, 0.10 and 0.15 in CRV, and 0.38, 0.10 and 0.01 in Jimma. While these average parameter values are relevant, in particular agronomic use efficiencies and recovery fractions showed large variability and, moreover, averages were lower than what is deemed feasible with good agronomy. We discuss the variability in the derived parameters, the relation with yield levels, soil nutrient supply and rainfall, and conclude that caution is needed when deriving fertilizer recommendations from parameters obtained in on-farm experiments. Using single estimated average values is not sufficient: variability in these parameters and sub-optimum values need to be explained first, and derived insight should be used when developing site-specific fertilizer recommendations.

1. Introduction

Maize is an important staple food crop in Ethiopia, as in many other countries in Africa, and its projected demand for food and feed is increasing due to the steady rise of human population and dietary change (van Ittersum et al., 2016). Despite favourable climates and the existence of diverse genotypes for most agro-ecologies, the current national average maize yield of 3.4 t/ha (Cochrane and Bekele, 2018; CSA, 2016) is far below the potential yield (Yp = 15.8 t/ha) and the water-limited potential yield (Yw = 12.5 t/ha) (www.yieldgap.org) due mostly to low and variable soil fertility. The low natural soil fertility conditions have declined due to continuous mining of nutrients with

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addition of only small amounts of fertilizers leading to negative nutrient balances in many cropping fields (Sanchez, 2002; Smaling and Janssen, 1993; Stoorvogel et al., 1993). Consequently, there are high maize yield gaps (Yg) in Ethiopia (www.yieldgap.org). The yield gap (Yg) is the difference between potential yield and actual yield (Ya) achieved by farmers (van Ittersum et al., 2013). The potential yield is the yield of an adapted crop cultivar when water and nutrients are non-limiting and yield reducing (weeds, pests and diseases) factors are effectively controlled (van Ittersum et al., 2013; van Ittersum and Rabbinge., 1997). It can be designated as Yp for fully irrigated crops where the yield is determined only by growth defining factors such as crop phenology, temperature and solar radiation or as the water-limited potential yield (Yw) for rain-fed crops in which water is a yield-limiting factor. The yield gap (Yg) in this paper refers to the difference between Yw and Ya.

Crop yield depends on the availability of resources, resource capture and utilization efficiencies, which vary across regions, farms and fields. Nutrient use efficiency is explained in terms of (1) capture efficiency and (2) utilization efficiency. The former indicates the ratio of crop nutrient uptake (kg/ha) to the available nutrients (kg/ha), whereas the latter refers to the conversion of captured nutrients into grain yield (Chikowo et al., 2014; Tittonell et al., 2008). The capture efficiency is similar to the nutrient recovery fraction, but the latter specifically refers to applied nutrients. The term 'nutrient recovery fraction' is defined as the amount of nutrient recovered per unit of applied nutrient (Chikowo et al., 2010; Witt et al., 1999; Janssen, 1998). Utilization efficiency is also called internal use efficiency (Witt et al., 1999) or physiological use efficiency (PUE; Janssen, 2011), and is expressed as a ratio of kg grain produced per kg of nutrient taken up by a crop (Baligar and Fageria, 2015; Tittonell et al., 2008). Often a high proportion of applied nutrients is not captured by crops. Leaching, run-off, volatilization, and fixation by clay particles are important processes, which cause low nutrient recovery fractions (Baligar and Bennett, 1986). However, recovery fraction of nutrients can be improved through best fertilizer management practices (Dobermann et al., 2002; Witt and Dobermann, 2002) such as the 4R nutrient stewardship (i.e. application of the right source and amount of fertilizer at the right time and in the right place) (Roberts, 2007).

Mineral fertilizers play an indispensable role in improving soil fertility and maize productivity in Ethiopia (Abate et al., 2015). Blanket regional fertilizer recommendations are used in all maize-growing regions. Such recommendations, however, do not capture the soil fertility heterogeneity observed within regions, and between farms and fields (Vanlauwe et al., 2014; Zingore et al., 2007a). The blanket recommendations do not take into account differences in nutrients supplied from the soil and nutrient recovery fractions nor different potential yields in different agro-ecologies, which all cause yield responses to fertilizer applications to be highly variable across fields. From production, economic and environmental perspectives, site-specific fertilizer recommendations are most preferred. A generic model such as QUantitative Evaluation of Fertility of Tropical Soils (QUEFTS) (Janssen et al., 1990) can be used to develop site-specific fertilizer recommendations based on information of the indigenous soil nutrient supply, recovery fractions and physiological use efficiencies of nutrients (Smaling and Jenssen, 1993). However, quantitative data of these input parameters in Ethiopian maize based farming systems are scarce. These parameters can be derived from so-called nutrient omission trials (NOTs). The NOTs are trials in which at least one nutrient (of interest) is omitted but other nutrients are applied in ample amount so that the limiting effect of the nutrient of interest is clearly visible.

With the overall aim to underpin site-specific fertilizer recommendations for maize in Ethiopia, the objectives of this paper are (1) to understand yield response to fertilizer and profitability of maize to fertilizer use and assess the potential role of NPK fertilizer use in maize yield gap reduction in Bako, CRV and Jimma regions, (2) to assess indigenous soil nutrient supply and compare different methods of its assessment, and (3) to determine recovery fraction of applied nutrients and physiological use efficiencies of maize. In addition, we (4) explain and discuss the variability in these parameters, as well as implications for site-specific fertilizer recommendations.

2. Materials and methods

2.1. Characteristics of the study regions

The study was conducted in Bako, Central Rift Valley (CRV) and Jimma regions in Ethiopia in the main crop growing seasons of 2015 and 2016. Study sites were chosen to cover a variety of agro-ecologies (Fig. 1, see also Table 2), typical for major rain-fed maize growing areas. Bako is characterized by a warm and humid climate, and undulating topography. The region has high potential yields of maize (Yw = 14.7 t/ha), and other cereals and pulses (www.yieldgap.org). The on-farm nutrient omission trials (described below) were conducted at an altitude ranging from 1623 to 1864 meter above sea level (masl). The trials were situated in an area with coordinates ranging from 9°1′58.00′′ N and 37°0′34′′ E to 9°10′51′′ N and 37°1′35′′ E. The maize growing period in this region is from May to November. Cumulative rainfall during the trials is indicated in Fig. 1. The CRV is characterized by moisture deficit conditions and low Yw (6.2 t/ha). This region is known for its undulating topography with elevation ranging from 1500 to 1700 masl (Kassie et al., 2014; Awan et al., 2011). The trials in CRV were established in an area with coordinates ranging from 7°9′59′′ N and 38°15′0′′ E to 8°30′0′′ N and 39°24′59′′ E. This region has a bimodal rainfall pattern and receives 175−358 mm rainfall in the short rainy season (March to May) and 420−680 mm during the main rainy season (June to September). The maize growing calendar in CRV is usually from June to November, with occasional early sowing in May. Jimma is characterized by a mid-altitude sub-humid agro-ecology and the rainfall pattern is mono-modal. The trials in Jimma were established in coordinates ranging from 7°38′41′′ N and 37°14′55′′ E to 7°51′10′′ N and 37°13′31′′ E, whereas the altitude ranges from 1698 to 1872 masl. The annual rainfall in this region ranges from 1243−1876 mm with an average value of 1596 mm. Similar to Bako region, Jimma is a high potential region for maize (Yw = 15.7 t/ha) and the maize growing period in the region is from mid-May to end of November.

2.2. Nutrient omission trials (NOTs)

Farmers willing to host the NOTs were randomly selected from the three regions. In 2015, 23, 35 and 24 farmers hosted the trials in Bako, CRV and Jimma, respectively. In 2016, 14, 31 and 20 farmers hosted the trials in the respective regions. In Bako, CRV and Jimma respectively, 17, 100 and 25 % of the trials were repeated in the same fields in both

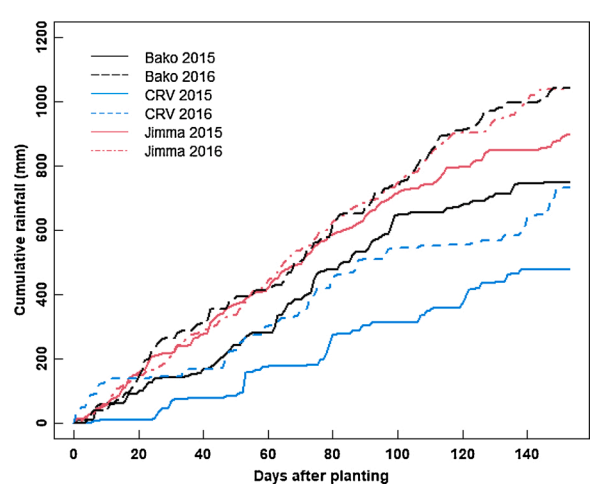

Fig. 1. Cumulative rainfall (mm) in nutrient omission trials (NOTs) regions during the maize growing periods of 2015 and 2016.

seasons. The trials were replicated across farms. In Jimma and Bako, BH-660 and BH-661 hybrid maize varieties (both with 160 days to maturity) were used in 2015 and 2016, respectively, whereas BH-540 hybrid maize (with 140 days to maturity) was used in CRV in both seasons. A plot of 8 × 8 m was used for a treatment. Seeds were planted with 0.75 m between rows by 0.25 m within rows to achieve a plant density of 53,000 plants/ha (see Rurinda et al., 2020). The trials comprised six treatments: (i) a control (no fertilizer applied), (ii) PK (N omitted from NPK), (iii) NK (P omitted from NPK), (iv) NP (K omitted from NPK), (v) NPK and (vi) NPKSM (secondary and micronutrients added to NPK) (Table 1).

The sources of N and P were urea and tri-superphosphate (TSP), respectively, whereas the source of K was K_2SO_4. Sulphur was supplied from sulphates of Ca, Mg and Zn. The sources of Ca, Mg and Zn were hydrated forms of $CaSO_4$, $MgSO_4$, and $ZnSO_4$ respectively, while for B it was borax. Nitrogen fertilizer was applied in three splits with 1/3rd at planting, 21 days after emergency (DAE) and 35 DAE, whereas P, K and SM were applied at planting. Soil samples were collected from 0−0.20 m depth in each trial field before establishing the trial in 2015 and were analysed at the International Institute for Tropical Agriculture (IITA) in Ibadan, Nigeria, for major diagnostic soil characteristics (Table 2).

Soil organic carbon was analyzed using Walkley and Black chromic acid wet chemical oxidation and the spectro-photometric method (Heanes, 1984) and total nitrogen was determined using a micro-Kjeldahl digestion method (Bremner, 1996). Soil pH was measured from 1:1 soil:water ratio using a glass electrode pH meter, whereas particle size distribution was measured with the hydrometer method. Available phosphorus and exchangeable K were measured with the Mehlich 3 extraction procedure (Mehlich, 1984).

Grain yield and straw dry matter were measured at physiological maturity of the crop. From the 8 × 8 m gross plot size, a net plot of 4.5 × 4 m was harvested. Cobs were separated from the stalks mechanically and total cob weight (kg/plot) was recorded. From the cobs, five representative cobs were selected, weighed, shelled and the grain was weighed with a sensitive balance. Shelling factor was determined from the ratio of grain weight to cob weight. The product of total cob weight (kg cobs/net plot) and the shelling factor (kg grain/kg cobs) is the maize grain yield. Moisture content of the grain was measured with a grain moisture meter and the grain yield was corrected to 15.5 % moisture content on weight basis. Finally, plot-level yields were converted to per hectare yields. From the harvested stalks, three representative stalks were selected, chopped with a machete and weighed to obtain fresh weight of the stover. Then, these fresh biomass samples were oven dried at 70 °C to a constant weight and based on these samples stover yield was expressed in kg dry matter (DM)/ha. For the 2015 season for CRV and Jimma, total nitrogen in grain and stover was determined using a micro-Kjeldahl digestion method (Bremner, 1996), whereas P and K were analysed by digestion with 1:3 nitric acid (HNO_3) and their concentrations were measured with Inductively Coupled Plasma optical emission spectroscopy.

2.3. Yield, agronomic efficiency and yield gaps

Differences in yields among fertilizer treatments were tested with ANOVA using the aov () function of R (https://cran.r-project.org). The honestly significant difference test (HSD.test) function of the agricolae package (de Mendiburu, 2017) was used to show significant differences between treatments, using the 0.05 probability level as critical value. Agronomic efficiencies (AE; see Eq. 1) of N, P and K were determined following Dobermann et al. (2002) with Eq. 1:

$$AE_i\left(\frac{\text{kg grain}}{\text{kg nutrient}}\right) = \frac{\text{Grain yield}\left(\frac{kg}{ha}\right)_F - \text{Grain yield}\left(\frac{kg}{ha}\right)_{io}}{\text{Nutrient applied}\left(\frac{kg}{ha}\right)} \quad (1)$$

where i refers to N, P or K; F is fully fertilized treatment (NPK or NPKSM); and io is the nutrient i omitted treatment. Yields and AEN were also related to rainfall using regression analysis. For yield, the best fit was obtained with a broken stick regression using the segmented() function in R, whereas for AEN the relation with rainfall was obtained using linear regression with the lm() function.

To quantify the role of fertilizer use in reducing maize yield gaps (Yg), yields of the control and NPK treatments from NOTs were compared with water-limited potential yields (Yw, based on 2005–2011) according to the Global Yield Gap Atlas (GYGA; www.yieldgap.org) in each region and average actual yields (Ya) of farmers for 2015–2016 from the Central Statistical Agency report (CSA, 2015; 2016). Yield variability was assessed within and between regions and seasons. To assess the variability, the coefficient of variation was computed for each treatment in each region.

2.4. Profitability of fertilizer application

The profitability of fertilizer use was assessed for every field by using fertilizer amount, cost of fertilizers, maize grain yield and market price of maize grain in that season. The purchasing price of the fertilizers (from farmers' cooperatives in each region) was used to calculate the total cost of applied fertilizer. Maize prices (ETB/kg of grain) for the three study regions were obtained from farm surveys of the projects 'Taking Maize Agronomy to Scale in Africa (TAMASA)', and the 'Integrated assessment of the determinants of the MAize yield gap in sub-Saharan Africa: towards farm INnovation and Enabling policies (IMAGINE)'. For each treatment except the control, the monetary value of maize yield (extra compared to the control yield) was computed. The ratio of monetary value of extra maize yield to the fertilizer costs (Eq. 2) is the marginal rate of return (MRR) and was then used for judging whether using a given type and amount of fertilizer is profitable in maize production.

$$MRR_{Fi} = \left(\frac{\text{Yield}_{Fi} - \text{Yield}_{ctrl}\left(\frac{kg}{ha}\right)*\text{Maize Price}\left(\frac{ETB}{kg}\right)}{\sum\left(F_i\left(\frac{kg}{ha}\right)*C_{Fi}\left(\frac{ETB}{kg}\right)\right)}\right) \quad (2)$$

Here, MRR is the marginal rate of return, fertilizer profitability; F_i refers to the fertilizer used in the respective treatment (for example in NP treatment, i stands for N or P); ctrl is control; and C_{Fi} refers to the cost of the fertilizer. ETB stands for Ethiopian Birr. If the ratio is greater than 1, the fertilizer use was profitable and if the ratio is less than or equal to 1, it was not profitable to use that fertilizer at the specified rate.

2.5. Indigenous soil nutrient supply

In this study, N deposition from the atmosphere was assumed to be negligible. Nitrogen (and P and K) supply was therefore the sum of soil supplied N (P and K) and fertilizer supplied N (P and K). The soil supply is the indigenous nutrient supply of soils and was estimated by three different methods, explained in the subsequent sections.

Table 1
Amount of each nutrient used in treatments of nutrient omission trials (NOTs) conducted in Bako, Central Rift Valley and Jimma in Ethiopia.

	Nutrient application rates (kg/ha)			
Treatments	N	P	K	SM (secondary and micro nutrients)
Control	0	0	0	0
PK	0	40	40	0
NK	120	0	40	0
NP	120	40	0	0
NPK	120	40	40	0
NPKSM	120	40	40	S = 20,Ca = 10,Mg = 10,Zn = 5,B = 5

Table 2
Range (mean in brackets) of diagnostic soil properties for the nutrient omission trials (NOTs) fields in 2015 in the study regions.

Region	Soil type	pH	OC* (g/kg)	Total N (g/kg)	Available P (mg/kg)	Exchangeable K (cmol (+)/kg)
Bako n = 23	Clay	4.5–6.1 (5.4)	17.1–30.6 (25.3)	1.3–3.3 (2.5)	1.8–10.2 (3.6)	0.2–2.8 (1.2)
CRV n = 35	Sandy loam	6.7–7.9 (7.2)	4.3–10.6 (6.6)	0.3–1.3 (0.6)	6.9–29.7 (15.7)	0.1–1.5 (0.5)
Jimma n = 24	Clay	4.6–5.9 (5.1)	11.8–26.5 (19.2)	1.2–3.0 (2.1)	3.5–21.5 (8.2)	0.4–1.4 (1.0)

* OC refers to organic carbon.

2.5.1. Analysis of soil properties

In this method, the results from the analysis of soil samples of 2015 were used. The relations of diagnostic soil properties and nutrient supply as described in the first step of QUEFTS (Janssen et al., 1990; Tittonell et al., 2008; Sattari et al., 2014) were used to estimate indigenous nutrient supply from soil (Eq. 3,4 and 5). These soil properties are organic carbon, pH, total N, available P and exchangeable K.

$$SN = fN \times 6.8 \times OC \tag{3}$$

$$SP = fP \times 0.35 \times OC + 0.5 \times \text{extractable P} \tag{4}$$

$$SK = \frac{fK \times 400 \times \text{exchangable K}}{2 + (0.9 \times OC)} \tag{5}$$

where SN, SP and SK refer to the indigenous supply of N, P and K, respectively, from soil mineralization and expressed in kg/ha; OC is organic carbon content of the soil expressed in g/kg of soil; K and P are expressed in cmol/kg and mg/kg, respectively. Mineralization of N, dissolution of P and exchangeability of K from soils depend on pH of the soil and hence pH correction factors were used in Eq. 6–8 (Sattari et al., 2014); the fN, fP, and fK are pH (H_2O) correction factors for N, P and K, respectively.

$$fN = 0.25 \times (pH - 3) \tag{6}$$

$$fP = 1 - 0.5 \times (pH - 6.7)^2 \tag{7}$$

$$fK = (6.1 \times pH)^{-1.2} \tag{8}$$

2.5.2. Plant tissue analysis

Nutrient uptake in the PK, NK and NP treatments depends on the N, P and K supply from the soils. Under sufficient supply of P and K but under N omission, the N uptake by maize is assumed to be the indigenous N supply of the soil (Witt et al., 1999). Likewise, P and K soil supply were estimated from the treatments in which these nutrients were omitted. To estimate N, P and K supply in these treatments, nutrient concentrations in grain and straw were analysed for CRV and Jimma as explained in Section 2.2. For Bako this method was not implemented.

2.5.3. Yield response and PUE

A similar reasoning was applied as in the previous method, i.e. yields of PK, NK and NP treatments depend on the N, P and K supply from the soils. When yields in the nutrient omission treatments are divided by their physiological use efficiencies (PUE; see Section 2.7), nutrient uptake from the indigenous soil supply can be estimated. PUEs were estimated based on plant tissue analysis, so that the second and the third method are related. For Bako, where plant tissue analysis was not performed, the PUE of Jimma was used, at treatment level (see section 2.7. for a justification).

2.6. Nutrient uptake and recovery fractions

The N, P and K uptake of maize under NPK fertilizer use were estimated from yields multiplied by plant nutrient contents. To account for the uptake from fertilizer, the nutrient supplied from soil (using the methods described in Section 2.5.2 and 2.5.3 for comparison) was subtracted from the total uptake. Then, the ratio of this uptake to the amount of the nutrient applied was the recovery fraction of that nutrient (Eq. 9).

$$RF_i = \left[\frac{\left(Y_{FF}\left(\frac{kg}{ha}\right) \times [i]_{FF}\left(\frac{kg}{kg}\right) \right) - \left(Y_{io}\left(\frac{kg}{ha}\right) \times [i]_{io}\left(\frac{kg}{kg}\right) \right)}{i_{amount}\left(\frac{kg}{ha}\right)} \right] \tag{9}$$

where RF is recovery fraction; i refers to N, P or K nutrients, Y_{FF} yield of the crop under full fertilization with NPK, $[i]_{FF}$ is the concentration of nutrient i in aboveground biomass under full fertilization and Y_{io} refers to the yield of the crop under omission of nutrient i and $[i]_{io}$ is the concentration of nutrient i in above ground biomass under omitted nutrient i.

2.7. Physiological use efficiencies

Physiological use efficiencies of N, P and K were estimated from the ratios of yield to the aboveground N, P and K uptake by maize. Maximum and minimum N, P and K physiological use efficiencies are equivalent to maximum dilution (d) and accumulation (a) of the nutrients in the crop, respectively (Witt et al., 1999). Eq. 10 and 11 were used to estimate these:

$$YiD = di \times (Ui - ri) \tag{10}$$

$$YiA = ai \times (Ui - ri) \tag{11}$$

where i refers to N, P or K nutrient; YiD refers to grain yield at diluted concentration of nutrient i and Y_iA is a grain yield at accumulated concentration of nutrient i; di refers to the slope of the boundary lines of yield versus nutrient i uptake at diluted nutrient i concentration in above ground biomass and ai refers to the slope of the boundary lines of yield versus nutrient i uptake at accumulated nutrient i concentration in above ground biomass of the crop. Ui is uptake of nutrient i whereas ri is the minimum uptake of nutrient i required to produce any measurable grain. The minimum uptake (ri) of N, P and K are 5, 0.4 and 2 kg/ha for N, P and K, respectively (Janssen et al., 1990). To estimate the slopes, the upper 2.5 % and the lower 2.5 % of the yield to uptake ratios were considered as outliers and they were not included in the analysis. As uptake was not determined by tissue analysis in Bako, PUE for this region was not computed. However, because the same maize variety and fertilizer rate were used in Bako and Jimma, we assumed that PUE of Jimma and Bako are similar. As a result, PUE of Jimma was also used for nutrient recommendation in Bako.

2.8. Estimation of nutrient requirements for defined target yields

To estimate nutrient requirements, the steps in Fig. 2 were followed. In this exercise, 50 % and 70 % of Yw were set as target yields of maize in each region, and combined with median physiological use efficiency to obtain nutrient uptake. Soil supplied N, P and K were estimated by the yield response method in Bako and by the plant tissue analysis method in CRV and Jimma. We captured the variability in soil supply by categorizing the data into 25th percentile (poor soils), average and 75th percentile (good soils). To compute the final fertilizer requirement, we divided the uptake from fertilizers by the recovery fraction. For N, we compared outcomes obtained with the average recovery fraction from the NOTs with outcomes obtained with standard values assuming good

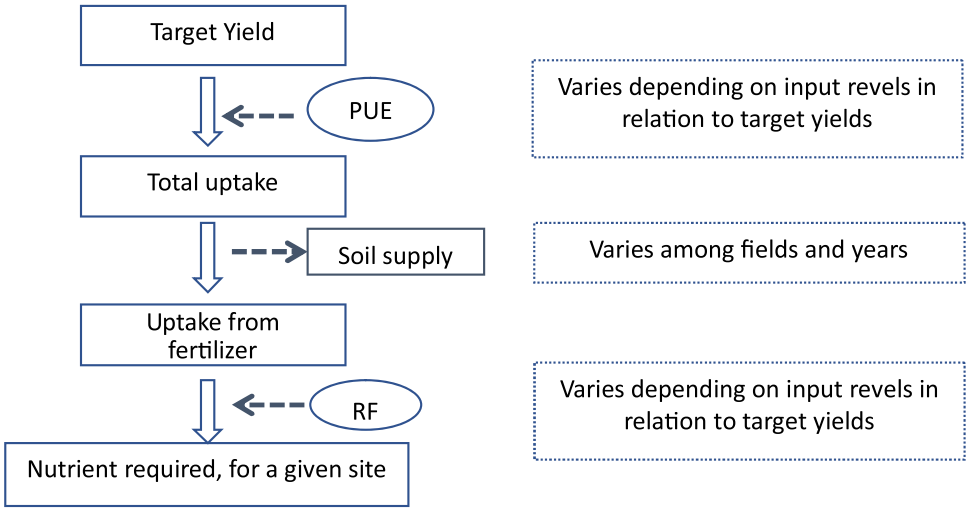

Fig. 2. Steps of site-specific estimation of required fertilizer application rate to fulfill the nutrient requirement for a target yield. PUE and RF refer to physiological use efficiency and recovery fractions, respectively.

agronomy (ten Berge et al., 2019). For P, we used the average recovery fraction obtained from the NOTs. As K was not limiting, average recovery fractions were very low and not used, and only the standard value of 0.5 (Janssen et al., 1990) was employed to assess the minimum required K application rate.

3. Results

3.1. Yield response to nutrients

Data presented in Fig. 3 shows the variability in yield responses to different nutrients across fields, seasons and sites. Yields were higher with NPK than PK fertilizer in both seasons in all three regions (Fig. 3a, e, i; Fig. 4). In Bako, 83 and 95 % of the fields fertilized with NPK resulted in higher yield than fields fertilized with PK in 2015 and 2016, respectively; for CRV these percentages were 85 and 94 %, and for Jimma 100 and 95 %. Compared with the yield for the NK treatment, the yield increased with the application of NPK fertilizer in CRV and Jimma in both seasons, but in Bako the yields between these two treatments were similar (Fig. 3b, f, j). In both seasons in CRV, yield of NPK was greater than yield of NK treatment in 71 % of the fields. In Jimma, the yield of NPK fertilizer was higher than yields of NK in 79 and 70 % of the

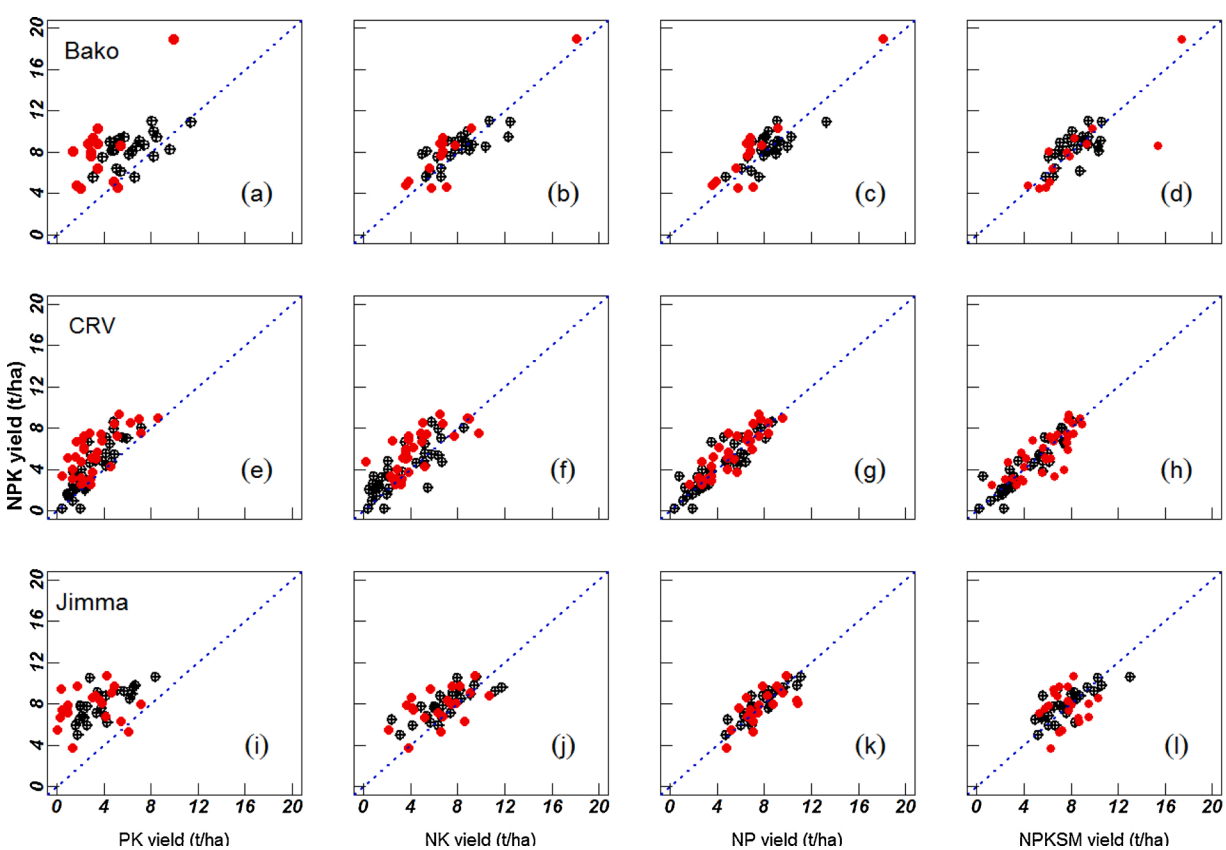

Fig. 3. Scatterplots of maize yield under NPK versus PK (a, e, i), NK (b, f, j), NP (c, g, k) and NPKSM (d, h, l) in Bako, CRV and Jimma, respectively. The black and red dots refer to yields of 2015 and 2016, respectively. The dotted line represents the 1:1 line.

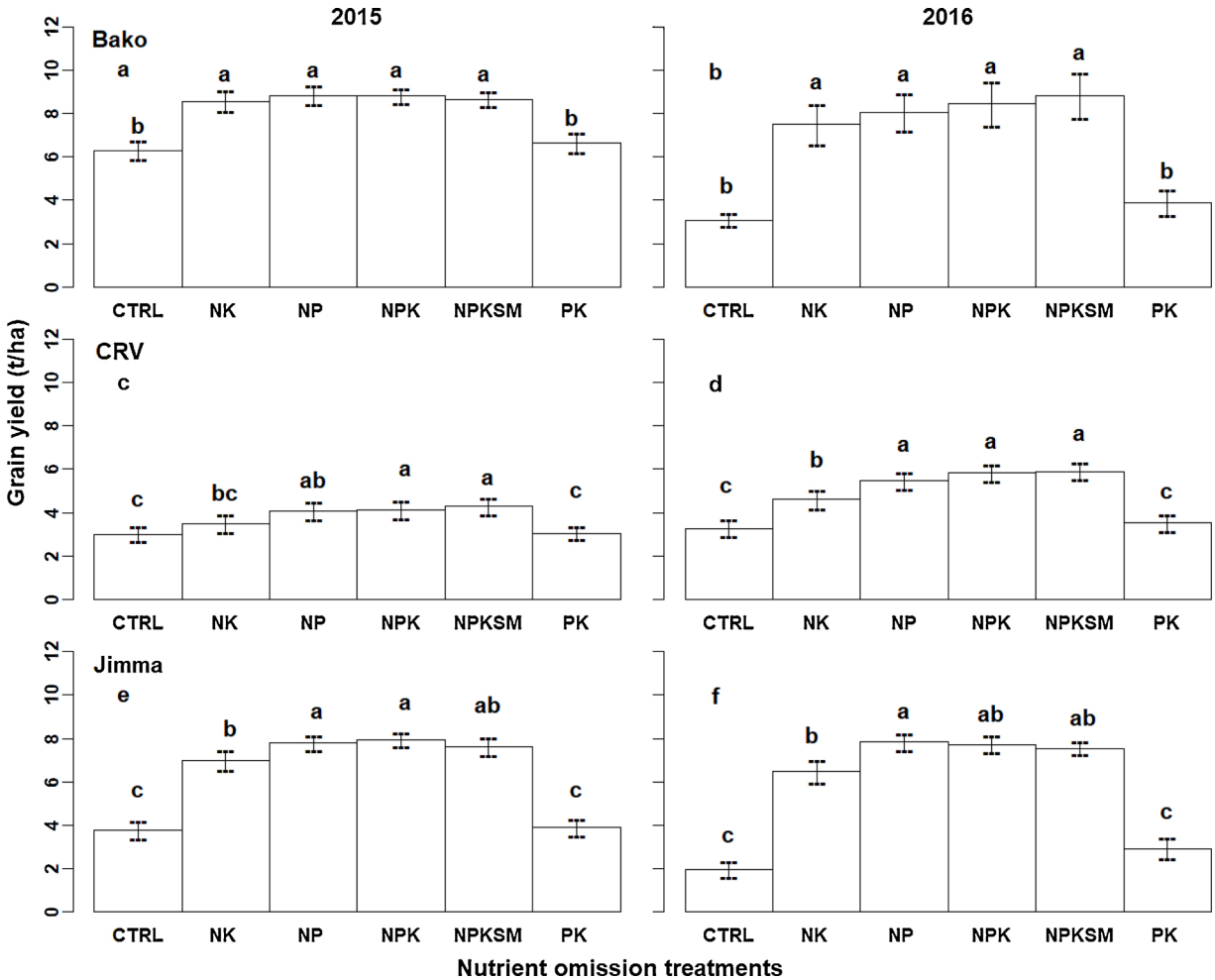

Fig. 4. Maize grain yield at 15.5 % moisture level in nutrient omission trials in Bako, CRV and Jimma. The minimum values of honestly significance difference (HSD) of Bako in 2015 and 2016 were 1.71 t/ha and 2.03 t/ha, whereas these values were 0.60 t/ha and 0.67 t/ha for CRV in the same seasons. The HSD values of Jimma in 2015 and 2016 were 0.77 t/ha and 1.29 t/ha. Yields with the same letter within a season-region combination are not significantly different from each other at 0.05 probability level. CTRL refers to control treatment whereas n stands for the number of fields. Error bars indicate standard error of the means at 95 % confidence level.

fields in 2015 and 2016, respectively. Maize grain yields for the NPK and NP treatments (Fig. 3c, g, k), and for the NPK and NPKSM treatments (Fig. 3d, h, l) were distributed around the 1:1 line in both seasons in all three regions suggesting that overall maize did not respond to K and secondary and micronutrients.

In all cropping seasons and regions, except in 2015 in CRV (Fig. 4c), maize yields obtained with NK, NP, NPK and NPKSM fertilizers were significantly higher than the control yields (Fig. 4a, b, d-f). NP, NPK and NPKSM treatments resulted in the best yields and did not differ significantly in any of the regions and years. Compared to these best-performing treatments, NK resulted in poorer yields only in some cases in CRV (2016) and Jimma (both years). The lower yields produced with PK did not significantly differ from the control yields (Fig. 4a–f). This implies that N was the most limiting nutrient for maize production in all three regions in both seasons, and P was the second limiting nutrient in CRV and Jimma. Overall, K and SM were not yield limiting nutrients in the study regions (Fig. 4a–f). The control yields varied with location and season. In Bako, the yield of the control treatment varied widely from 2.9 t/ha in 2016 to 5.8 t/ha in 2015, while in the CRV this difference was small (i.e. from 2.8 t/ha in 2015 to 3.2 t/ha in 2016). In Jimma, the control yield ranged from 1.9 t/ha in 2016 to 3.6 t/ha in 2015. Maize grown with PK, NK, NP, NPK and NPKSM fertilizers in Bako resulted in 5, 34, 38, 39 and 36 % yield advantages, respectively, over the control in 2015, whereas in 2016, the yield gains were 24, 141, 159, 169 and 182 % in the same order. In CRV, the yield increments for these treatments were mostly smaller, i.e. 1, 18, 36, 36 and 39 %, respectively, in 2015 and 21, 57, 86, 100 and 104 % in 2016. In Jimma, 3, 86, 108, 111 and 106 % yield improvements were achieved over the control in 2015, and the yield increments in 2016 were 47, 226, 305, 289 and 278 % from PK, NK, NP NPK and NPKSM fertilizer application, respectively.

We estimated that NPK fertilized maize yield increased linearly with rainfall up to 830 mm (Fig. 5) after which additional rainfall did not contribute to yield. In the 479−830 mm rainfall range, an increase in 1 mm of rainfall resulted in 10 kg/ha additional yield (Fig. 5). In Bako and Jimma, grain yield of NPK fertilized maize did not vary with rainfall during the growth period suggesting that the rainfall in these regions is not limiting maize production. However, in CRV, which is often characterized by low seasonal rainfall, a significant yield difference between 2016 and 2015 was observed. Compared to the yield achieved in the lower rainfall season in 2015, 40 % more yield was achieved in 2016. On the other hand, control yields in CRV were similar in both years, while control yields in Bako and Jimma were lower in the wetter year 2016 than in 2015 (Fig. 4).

Coefficients of variation of yields were generally high and up to ca. 92 % under PK fertilizer use in 2015 (Fig. 6). In all region-year combinations, variability of the NP and NPK yields were lowest or tended to be lower.

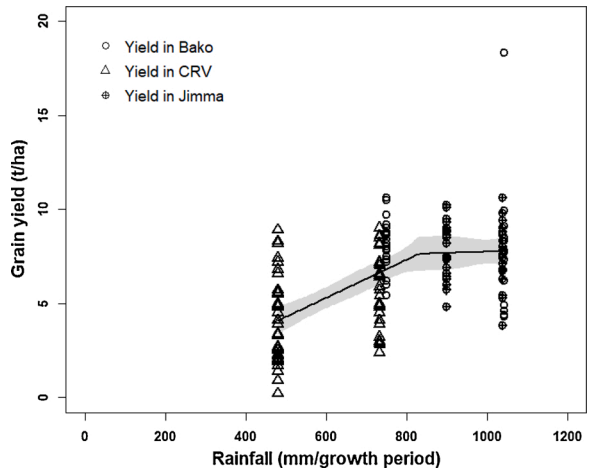

Fig. 5. Maize yield as influenced by rainfall in Ethiopia. For each region-year combination all yields from the NPK treatments are plotted (see cumulative rainfall in Fig. 1). The shaded region refers to the standard error at 95 % confidence interval.

3.2. Agronomic efficiencies

Agronomic efficiencies (kg grain kg^{-1} applied nutrients) of N (AEN) in Bako and Jimma were higher than in CRV in both seasons (Table 3). The average AEN obtained across the study sites ranged from 8.4–38.4 kg grain kg^{-1} N, with the highest values recorded in Jimma and Bako in 2016, followed by Bako in 2015 and the lowest in CRV in 2015. The average AEP ranged from 8.3–30.4 kg grain kg^{-1} P, with highest values also observed in Jimma in the 2016 season followed by CRV in the same season, and lowest in Bako in 2015. The AEN was less variable across fields than the AEP and AEK in both cropping seasons (Table 3).

Average agronomic efficiency of N increased with rainfall amount (Fig.7). As can also be observed from Fig. 4, three different but complementary reasons can be given for this: 1) AEN was higher in higher rainfall regions in Bako and Jimma compared to CRV, 2) in Bako and Jimma control yields were lower in a wetter year, while NPK yields remained similar, and 3) in CRV control yields were the same in both years, but NPK yields were higher in a wetter year.

3.3. Profitability of fertilizer use

In Bako and Jimma, fertilizer use was profitable on average, in particular NP (Fig. 8). In CRV, however, average profit was negative for all fertilizers. The use of NP fertilizer was profitable on 84, 44 and 100 % of the fields in Bako, CRV and Jimma, respectively. Application of PK was profitable in only 14 % of the fields in Bako, in only 1.5 % of the fields in CRV and in 21 % of the fields in Jimma (Fig. 8) indicating that using PK was not profitable in most cases.

3.4. Actual and potential maize yield

With the use of NPK fertilizers at rates of respectively, 120, 40 and 40 kg/ha, a yield level at (Jimma) or above (Bako and CRV) 50 % of Yw was achieved (Table 4). Actual yields were ranging from 2.6 t/ha in CRV to 3.9 t/ha in Bako and Jimma (CSA, 2015; 2016) under farmers' fertilizer use, which is lower than the rates used in the fertilized treatments of the NOTs. While the yield gap between the NOT control and Yw was estimated to be 70, 50 and 82 % in Bako, CRV and Jimma, respectively, NPK application with the used rates can reduce these gaps to 44, 21 and 50 % (Table 4).

3.5. Indigenous nutrient supply of soils

The N, P and K supply from the soil varied with the approach used to estimate this supply (i.e. soil measurement, plant tissue analysis and yield response). For N, the three methods estimated similar amounts, whereas this was not the case for P and K (Table 5). For P, the soil analysis method estimated a smaller amount compared to the yield response method in Bako and both other methods in Jimma. In the CRV the tissue analysis estimated the smallest amount of P. For K, the soil analysis method differed considerably from the other methods but in inconsistent ways across the regions. The soil supply of N, P and K in Bako and Jimma was generally much higher than in CRV (Table 5), except for P supply estimated by soil analysis. Based on soil analysis, the lower 25th percentile fields supplied less than 86, 37, 61 kg/ha N in Bako, CRV and Jimma, whereas the upper 25th percentile of the fields supplied at least 113, 49 and 83 kg/ha in the respective regions. Based on plant tissue analysis, in CRV the 25 % least fertile fields supplied less than 35, 4 and 77 kg/ha N, P and K, whereas in Jimma, this was less than 48, 15 and 140 kg/ha N, P and K (Table 5). The relationship between the relative yield response to NPK fertilizer and indigenous soil N supply (as

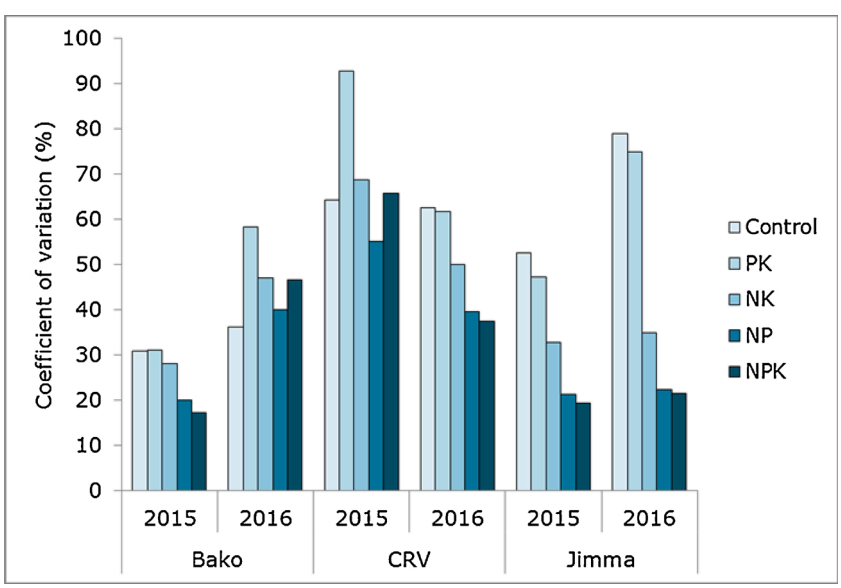

Fig. 6. Coefficient of variation of maize yield for different fertilizer treatments across regions in Ethiopia in 2015 and 2016.

Table 3
Mean agronomic efficiency of nitrogen (AEN), phosphorus (AEP) and potassium (AEK) in Bako, CRV and Jimma regions in 2015 and 2016, with standard deviation in brackets.

Region	AEN			AEP			AEK		
	2015	2016	Average	2015	2016	Average	2015	2016	Average
Bako	16.1b (13.9)	35.4a (21.2)	25.6	8.3 (34.5)	20.7 (32.4)	14.5	1.3 (29.5)	8.2 (32.3)	4.7
CRV	8.40c (10.1)	18.2b (13.3)	13.3	14.9 (34.3)	28.7 (38.3)	21.8	1.4 (26.4)	7.3 (24.7)	4.4
Jimma	32.6a (11.2)	38.4a (20.6)	35.5	23.4 (33.9)	30.1 (47.4)	26.7	3.8 (18.6)	−2.8 (31.9)	0.5

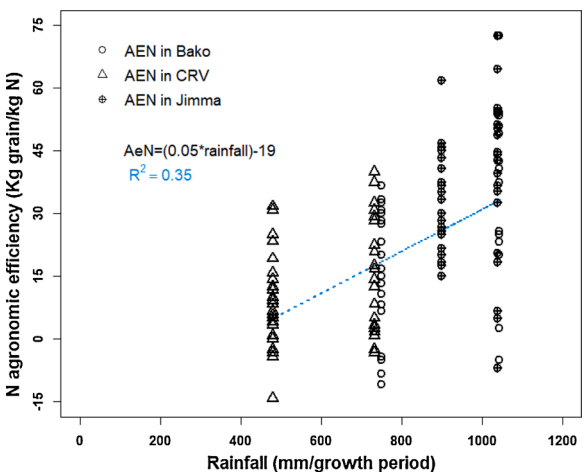

Fig. 7. Agronomic efficiency of N of maize grown with NPK fertilizer as affected by seasonal rainfall in Ethiopia.

measured from soil samples) was non-significant for all three regions (not shown).

3.6. Recovery fraction

The nutrient recovery fractions varied across regions, seasons and fields within regions (Table 6). Higher N recovery fractions were observed in Bako and Jimma than in CRV. In Bako and CRV, a higher mean value of N recovery was observed in 2016 (0.40 in Bako and 0.29 in CRV) than in 2015 (0.18 in Bako and 0.13 in CRV). The differences in N recovery fractions between regions and years are likely related to differences in rainfall, as explained in Section 3.2. Average K recovery was low, as K was not limiting.

3.7. Physiological use efficiencies

Minimum and maximum physiological use efficiencies of N, P and K were, respectively, aN = 27 kg grain kg^{-1} N, dN = 80 kg grain kg^{-1} N, aP = 194 kg grain kg^{-1} P, dP = 505 kg grain kg^{-1} P, and aK = 16 kg grain kg^{-1} K, dK = 87 kg grain kg^{-1} K. The median physiological use efficiencies of N, P and K were 54, 350 and 52 kg grain kg^{-1} of the respective nutrient uptakes. Theoretically, the borderlines do not need to pass through the origin, as a certain quantity of nutrients (r) is taken up by a crop even if no measurable grain is produced. These are rN = 5, rP = 0.4 and rK = 2 kg/ha (Janssen et al., 1990) for N, P and K, respectively (Fig. 9). The physiological use efficiency of N is close to the reported accumulation and dilution values by Janssen et al. (1990) (aN = 32 kg grain kg^{-1} N, dN = 73 kg grain kg^{-1} N), whereas the P and K use efficiencies obtained were lower (Fig. 9). The analysis also showed that the physiological use efficiencies of N, P and K were lower in CRV than in Jimma, probably because of stronger water-limitation in CRV.

4. Discussion

4.1. Maize responses to fertilizers

Maize yields did not significantly increase due to PK fertilizers in any of the three regions and two cropping seasons, while maize yields did respond to NK and in particular to NP fertilizers in all regions and seasons. Maize yields were higher with NPK than with PK in 83–100 % of the fields, indicating a clear N response (at 120 kg N/ha). In CRV and Jimma, maize yields were higher with NPK than with NK in more than 70 % of the fields in both seasons, pointing at a P effect (at 40 kg P/ha), but in Bako this was not the case. Fertilizers including K and microntrients did not result in signficant yield advantages. Overall, this study confirmed that N and P are the major nutrients limiting maize production in Ethiopia as also reported for other countries in Africa (Rurinda et al., 2020) suggesting that African governments should support farmers to have access to NP fertilizers.

In Bako and Jimma, the high yielding regions, fertilizers (particularly NP fertilizers) were profitable on average, while in CRV, the low yielding region, none of the fertilizers were profitable on average. In general we also found stronger fertilizer effects in the wetter season, in 2016. Using household survey data and frontier analysis, Van Dijk et al. (2020) suggested an economic optimum N level between 137–262 kg N/ha across regions in Ethiopia, which is higher than the amount of N applied in the NOTs (120 kg N/ha). For this optimum to be reached, however, all best available agronomic practices should be adopted. Assefa et al. (unpublished), using a different set of household survey data suggested an average economic optimum of 145 kg N/ha, but similar to our results, showed that this largely varied among fields.

We found that recovery rates were generally low as also reported for other countries in Africa (Kurwakumire et al., 2014; Rurinda et al., 2020). For N, average recovery fractions were at best 0.40, but could be as low as 0.14. Even in the high-yielding region Bako, N recovery was only 0.18 on average in 2015. In 2016 in Bako and in both seasons in Jimma the recovery was much higher than in CRV. Just as in Bako, N recoveries in CRV were higher in the wetter year 2016 than in 2015, while in Jimma the difference between both years in terms of both rainfall and recovery was relatively small. This suggests some positive relationship between recovery and yield potential. In addition, high N applications should be accompanied by good agronomy to make use of N availability. The P recovery fraction observed in Jimma was similar to commonly reported values for maize in tropical regions, i.e. 0.10 (Janssen et al., 1990), but lower in Bako and CRV. Recovery of K in this study was generally low in comparison with reported values (Janssen et al., 1990).

Our estimations of PUE for N and P were within the ranges found in literature, while these for K were somewhat lower than those found in the literature (Table 7). As N was the limiting factor, at yield levels up to 50 % of Yw, PUE of N was close to the maximum.

4.2. Towards fertilizer recommendations

At the onset of our experiments we assumed that fertilizer recommendations could be based on soil nutrient supply, recovery fraction and physiological use efficiency derived from on-farm experiments. Yet, our results point at the need to nuance this for the following reasons. First,

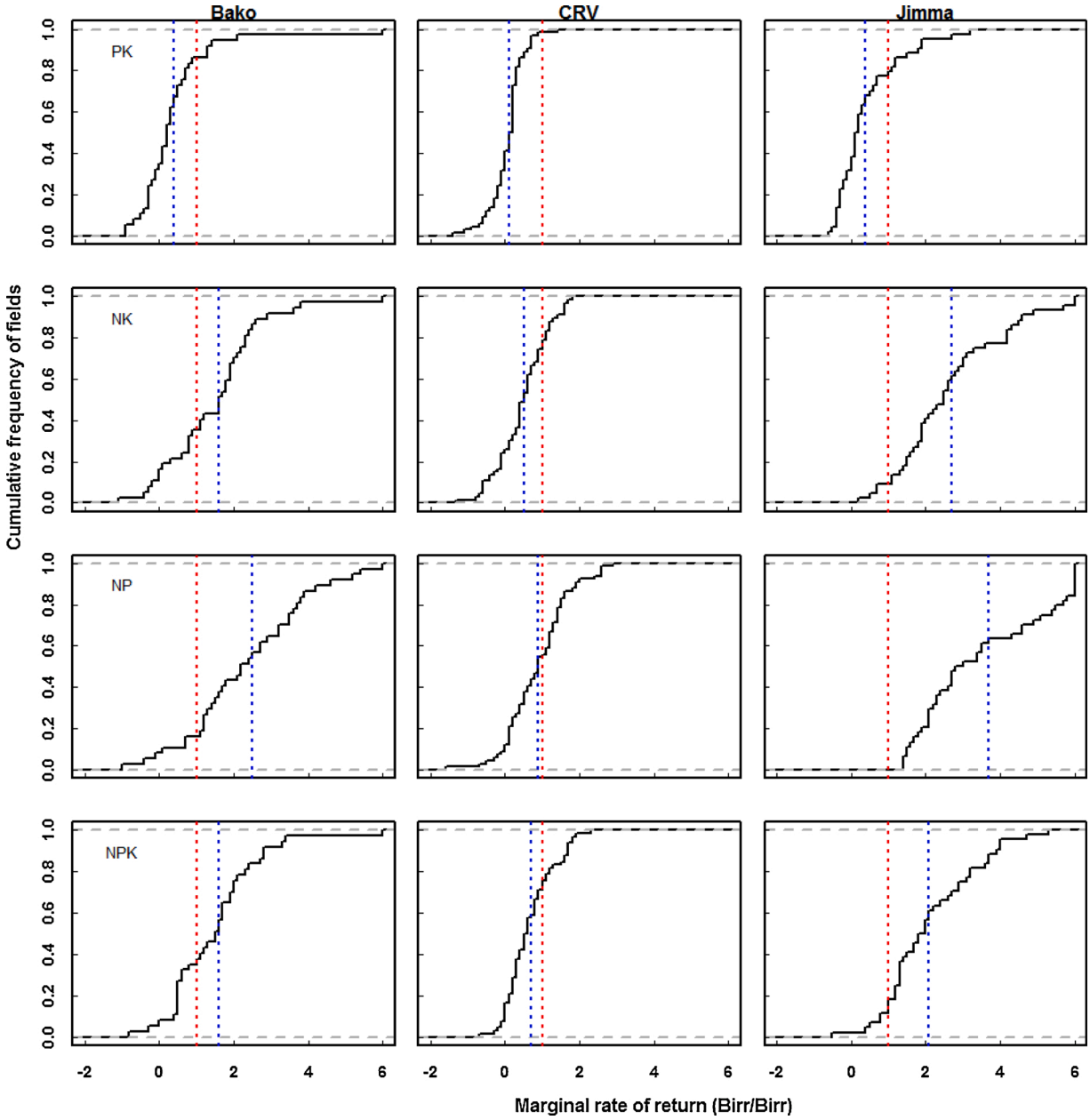

Fig. 8. Cumulative frequency of profitability of fertilizer application, based on the NOTs data from 2015 and 2016 combined. Values greater than 1 represent profitability, whereas values lower than 1 are not. The red dotted lines were drawn at abscissa = 1 and indicate the boundary between profitable and non-profitable fields, whereas the blue dotted lines show the average marginal rate of return (the ratio between the extra (compared to the control) monetary value of maize and the fertilizer costs).

Table 4
Comparisons of maize yields in the NOTs in Bako, Central Rift Valley and Jimma (averages of 2015 and 2016), with actual (CSA, 2015; 2016) and water-limited (Yw) potential yields (GYGA; www.yieldgap.org).

Regions	Actual yield (t/ha)	GYGA		NOT		% of Yw		
		Potential yield (Yw) (t/ha)	50 % of Yw (t/ha)	Control yield (t/ha)	NPK yield (t/ha)	Actual yield	Control yield	NPK yield
Bako	3.9	14.9	7.5	4.5	8.3	26	30	56
CRV	2.6	6.2	3.1	3.1	4.9	42	50	79
Jimma	3.9	15.7	7.9	2.9	7.9	25	18	50

different ways of measuring indigenous soil nutrient supply resulted in different estimates, and there was no correlation between maize yield response and the indigenous soil nutrient supply as measured from the soil samples. This corroborates the conclusion of Schut and Giller (2020), who showed that errors due to soil sampling and analysis methods result in inaccurate estimates of soil nutrient supply, and therefore site-specific fertilizer recommendations based on single soil samples remain elusive. Second, the relatively low recovery rates for nitrogen point at other growth factors than nitrogen which are limiting or reducing production, for instance plant population, weed, pest and

Table 5
Mean (standard deviation in brackets), 25th and 75th percentile of indigenous soil supply (kg/ha) of nitrogen, phosphorus and potassium as estimated by three methods in Bako, CRV and Jimma in Ethiopia (2015).

Region	Parameter	N supply			P supply			K supply		
		Soil analysis	Tissue analysis	Yield response	Soil analysis	Tissue analysis	Yield response	Soil analysis	Tissue analysis	Yield response
Bako	25th perc	86	–	76	6.5	–	25	99	–	83
	Mean	101(22)	–	97 (32)	8 (3)	–	28 (6)	140 (62)	–	104 (42)
	75th perc	113	–	122	9.7	–	34	178	–	106
CRV	25th perc	36	35	44	11	4.0	12	12	77	29
	Mean	44(11)	51 (13)	51 (9)	16 (6)	6.0 (3)	17 (5)	19(12)	117 (50)	53(32)
	75th perc	49	65	55	20	8.0	24	20	133	77
Jimma	25th perc	61	48	47	7.0	15	26	147	140	91
	Mean	73 (17)	72 (35)	83 (42)	9.0 (3)	22	33 (13)	169(46)	219 (99)	107 (28)
	75th perc	83	82	111	11	27	39	200	300	118

Table 6
Maximum, mean and standard deviation (in parentheses) of nutrient recovery fractions across regions in 2015 and 2016 under NPK fertilizer use.

Region	Nutrients	2015		2016		Average across cropping seasons	
		Max	Mean (SD)	Max	Mean (SD)	Max	Mean
Bako	N	0.42	0.18 (0.16)	0.83	0.40 (0.24)	0.62	0.29
	P	0.20	0.04 (0.10)	0.16	0.05 (0.08)	0.18	0.05
	K	0.38	0.01 (0.24)	0.52	0.10 (0.26)	0.45	0.06
CRV	N	0.50	0.14 (0.16)	0.63	0.30 (0.21)	0.56	0.22
	P	0.24	0.07 (0.10)	0.32	0.10 (0.11)	0.28	0.85
	K	0.68	0.14 (0.40)	0.98	0.15 (0.37)	0.83	0.15
Jimma	N	0.56	0.37 (0.13)	0.83	0.40 (0.28)	0.69	0.38
	P	0.26	0.10 (0.09)	0.28	0.10 (0.12)	0.27	0.10
	K	0.36	0.03 (0.15)	0.40	−0.02 (0.26)	0.38	0.01

disease pressure. Although the experiments were supposed to be set-up with 'best management practices', some of these factors may have played a role in sub-optimal growth and recovery of nutrients, and perhaps also the exploitation of soil nutrient supply. If that is the case, we argue that it is not appropriate to base fertilizer recommendations on the measured recovery rates, as this inherently implies inefficient use of fertilizers and losses to the environment.

To illustrate the influence of soil supply, recovery fraction and target yield, we compare the required nutrient application rates for different assumptions on the former factors in the three study sites (Table 8). With average N recovery fraction derived from the NOTs, the required N

Table 7
Physiological use efficiencies of maize at maximum dilution (kg grain kg^{-1} nutrient uptake) and accumulation (kg grain kg^{-1} nutrient uptake) of N, P and K of maize in different studies at 15.5 % moisture level.

Authors	Country	N		P		K	
		*d*N	*a*N	*d*P	*a*P	*d*K	*a*K
This study	Ethiopia, CRV and Jimma	80	27	505	194	87	16
Sattari et al., 2014	Kenya	62	27	562	187	100	25
Setiyono et al., 2010	USA/Nebraska	83	40	726	225	125	29
Liu et al., 2006	China	65	21	391	128	92	20
Smaling and Janssen, 1993	Kenya	83	31	624	166	125	31
Janssen et al., 1990	Kenya	73	32	625	208	125	31

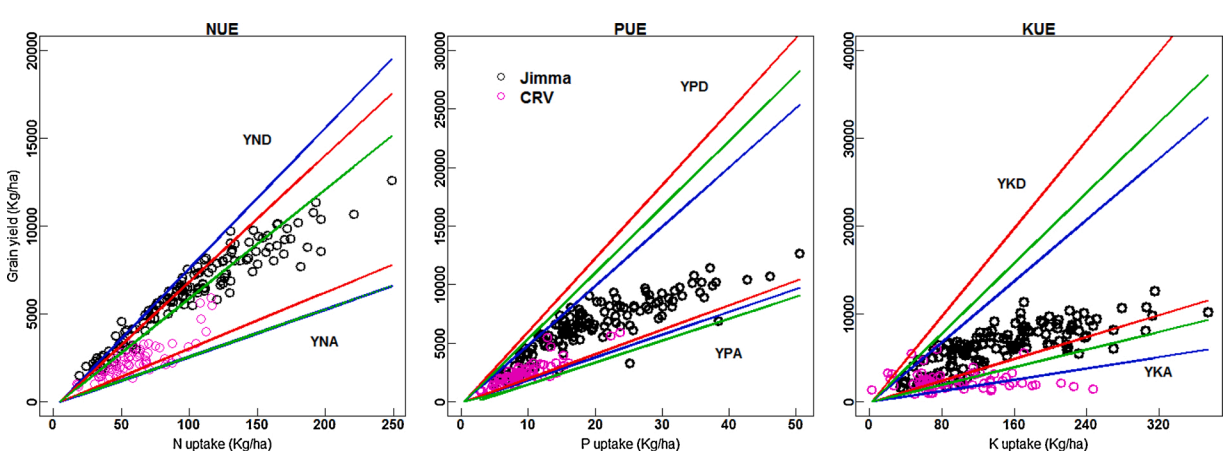

Fig. 9. Relations of maize grain yield and nutrient accumulation in above ground plant dry matter at maturity. The border lines indicate maximum dilution: $Y_iD = di$ (Ui-ri) where i is N, P or K and accumulation $Y_iA = ai$(Ui-ri) of the nutrients. Maximum dilution and accumulation represent maximum and minimum physiological use efficiencies. The blue boundary lines were estimated from NOTs data, the red by Janssen et al. (1990) and the green by Sattari et al. (2014).

Table 8
Nutrients required to achieve the target yields in Bako, CRV and Jimma in Ethiopia for different soil nutrient supplies and nutrient recovery fractions.

Region	Nutrients	Uptake at target yield (kg/ha)		Soil supply (kg/ha)		Required uptake from fertilizer (kg/ha)		Required nutrients in fertilizer (kg/ha) after adjusting for			
								average recovery fraction		optimal recovery fraction	
		50 % of Yw	70 % of Yw	Category	Values	50 % of Yw	70 % of Yw	50 % of Yw	70 % of Yw	50 % of Yw	70 % of Yw
				25th perc	76	63	117	217	403	126	234
	N	139	193	Average	97	42	96	144	331	84	192
				75th perc	122	17	71	58	245	34	142
				25th perc	25	0	4.7	0	94	–	–
Bako	P	22	30	Average	28	0	1.7	0	34	–	–
				75th perc	34	0	0	0	0	–	–
				25th perc	99	47	101	–	–	94	202
	K	146	200	Average	140	6	60	–	–	12	120
				75th perc	179	0	21	–	–	0	42
				25th perc	35	22	45	102	206	56	113
	N	57	80	Average	51	6	29	29	134	16	73
				75th perc	65	0	15	0	70	0	38
				25th perc	4	4.8	7.7	48	77	–	–
CRV	P	9	12	Average	6	2.8	5.7	28	57	–	–
				75th perc	8	0.8	3.7	8	37	–	–
				25th perc	77	0	1.8	–	–	0	3.6
	K	60	79	Average	117	0	0	–	–	0	0
				75th perc	133	0	0	–	–	0	0
				25th perc	48	98	156	258	409	196	311
	N	146	204	Average	72	74	132	194	346	148	263
				75th perc	82	64	122	168	320	128	243
				25th perc	15	8	16.4	80	164	–	–
Jimma	P	23	31	Average	22	1	9.4	10	94	–	–
				75th perc	27	0	0	0	0	–	–
				25th perc	140	12	64	–	–	24	128
	K	152	204	Average	219	0	0	–	–	0	0
				75th perc	300	0	0	–	–	0	0

inputs to reach 50 % of Yw with average soil supply ranged from 29 kg N/ha in CRV to 194 kg N/ha in Jimma (Table 8). For 70 % of Yw, the N requirements increased to more than 300 kg/ha on the average soils of Jimma and Bako, and about 130 kg/ha on the average soils of CRV. However, the NOTs suggested that 120 kg N/ha was on average sufficient to reach 50 % of Yw (Table 4). Two main reasons can be given for the higher recommendations: 1) in some years and locations, the recovery fraction was very low because control yields were already high, and other agronomic practices were likely not sufficient to further increase NPK yields, and 2) as N was limited, N was diluted in the crop and the PUE at 50 % of Yw was much higher than the median value (Fig. 9). Therefore, we argue that the average measured recovery fractions for N are not a good basis for nutrient recommendations, and we propose to use a medium standard value of 0.5 for Bako and Jimma and a poor-medium value of 0.4 for CRV (Ten Berge et al., 2019). When using these adapted parameter values, N recommendations to reach 50 % of Yw decrease to 16, 84 and 148 kg N/ha on average soils in CRV, Bako and Jimma, respectively (Table 8). Household survey data suggest that on average higher application rates are needed (Van Dijk et al., 2020; Assefa et al. (unpublished), but as the NOTs showed, high recoveries are possible when accompanied with good agronomy (see also Vanlauwe et al., 2014). In wetter conditions, N recommendations could increase to the higher end of the range, because higher rainfall resulted in lower soil N supply in Bako and Jimma (potentially due to leaching), and higher achievable yields in CRV.

For P, there were less uncertainties, and as the obtained recovery fraction from the NOTs was within the expected range, no differentiation between average and optimal recovery was made in Table 8. No P applications were needed in Bako to obtain 50 % of Yw, whereas the required P application ranged from 8 to 48 kg/ha in CRV and from 0 to 80 kg/ha in Jimma for good and poor soil conditions, respectively (Table 8). To achieve 70 % of Yw, P is needed on the average soils in all locations, but the most fertile fields in Bako and Jimma can reach this level without P application.

As also observed by Kihara et al. (2016), soil K supply is generally sufficient to achieve actual yields, and in CRV virtually no applications are needed irrespective of target yield and observed soil supply (Table 8). As K was not limiting, soil K supply estimates could not be derived from the NOTs, so we used the estimates based on the soil sample analysis for the calculations. The results suggest that 50 % of Yw can be reached without additional K application, except in Bako and on the poor soils in Jimma. Furthermore, our estimates suggest that substantial K application is required in Bako to reach 70 % of Yw (Table 8).

It is generally proposed to use median PUE values as these will be achieved with balanced nutrition (Janssen et al., 1990). Our results, however, showed that substantially lower or higher values may be found in practice (Fig. 9), depending on nutrient limitation (Janssen, 1998). Using the higher PUE values that were measured would reduce the recommended rates, but as this would violate the principle of balanced nutrition, such estimates were not included in Table 8.

5. Conclusion

The aim of this study was to parameterize an analytical approach for site specific fertilizer recommendation for maize. In the analytical approach, nutrient requirements of maize for achieving a given yield target were estimated based on physiological nutrient use efficiency, soil nutrient supply and recovery fractions of nutrients from fertilizer in each region. These parameters were estimated in three different agro-ecological regions in Ethiopia, using NOTs, and we analysed how parameters varied depending on environmental and agronomic conditions. Based on our analysis, higher fertilizer rates were recommended for maize grown in the high yielding regions Bako and Jimma than in the lower yielding region CRV. Within each region, fertilizer recommendations varied strongly due to the variation in soil fertility among fields. By using NPK fertilizer at the rate of the NOTs (120:40:40 kg N:P:K per ha), yields of 50 % of Yw were achieved in all three regions. Our results show that with current maize and fertilizer prices, it is not profitable to use K, secondary and micronutrient fertilizers in the study regions, while N and P at the tested levels were profitable for Bako and Jimma, but not

for CRV due to climatic constraints. This work shows that while developing site-specific fertilizer recommendations is needed to minimize financial risk for farmers and avoid environmental emissions, it is challenged by uncertainty in the key parameters (soil nutrient supply, nutrient recovery rate and physiological use efficiency) that are derived from on-farm trials. Soil nutrient supply could not be accurately measured from soil analysis; nutrient recovery rates depend on agro-ecological conditions, application rates and management; and physiological use efficiency rates depend on the relative abundance of other nutrients. Therefore, explaining the variability and sub-optimum values of these parameters needs to precede the development of site-specific fertilizer recommendations.

CRediT authorship contribution statement

Workneh Bekere Kenea: Conceptualization, Methodology, Formal analysis, Visualization, Writing - original draft. **Pytrik Reidsma:** Conceptualization, Formal analysis, Writing - review & editing. **Katrien Descheemaeker:** Conceptualization, Writing - review & editing. **Jairos Rurinda:** Investigation, Resources, Writing - review & editing. **Tesfaye Balemi:** Investigation, Resources, Writing - review & editing. **Martin K. van Ittersum:** Conceptualization, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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