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RESEARCH ARTICLE

Yield-limiting plant nutrients for maize production in northwest Ethiopia‡

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Summary

The potential yield of improved maize varieties usually cannot be fully realised mainly due to inappropriate soil nutrient management practices in most parts of Ethiopia. Site-specific fertiliser recommendations are rarely used in the farming systems of Ethiopia. There is also a lack of data to develop or validate decision support tools for targeting specific crop production. A study was conducted for three consecutive rainy seasons (2016–2018) in the maize belt of the north-western parts of the Amhara National Regional State of Ethiopia. The objectives were to obtain the maximum achievable yield potential of maize, determine the most yield-limiting nutrients and create a database of maize responses to applied nutrients so that decision support tools could be developed for the study areas. Treatments were individual nutrients (nitrogen (N), phosphorus (P) and potassium (K)) and combinations of the three. In some treatments, NPK was also combined with sulphur, zinc, lime and compost. Two hybrid maize varieties (BH-540 and BH-660) adaptable to the study areas were used. BH-540 was used for the Mecha district, while BH-660 was used for the south Achefer, Jabitahnan–Burrie–Womberma districts. Maize yield increased by more than 50% due to fertiliser applications compared to without fertiliser. The study showed that the possibility of increasing maize productivity to more than 12 t ha^{-1} for the study sites. The most yield-limiting nutrient in the study sites was N, followed by P; K was not a yield limiting. Without N the yield of both varieties was non-significant from the control (without added nutrients). Maize grain yield did not respond to application of lime, compost, zinc and sulphur. The result also showed very high variability across sites, indicating that it is important for policymakers, farmers and investors to consider site-specific fertiliser recommendations. Finally, a database containing intensive plant response to NPK for maize was generated and could be used as input in site-specific decision support tools development.

Keywords: Maize; Achievable yield potential; Yield-limiting nutrients; NPK; Nutrient omission

Introduction

Soil fertility is one of the factors that limit agricultural productivity in Ethiopia (Amare *et al.*, 2018; Hirpa *et al.*, 2012; Kebede and Ketema, 2017). Applying the right nutrient at the recommended rate, at the right time in the growing season and in the right place is essential for optimising the use

‡The original version of this article was published with incorrect funding information. A notice detailing this has been published and the errors rectified in the online PDF and HTML version.

of nutrients by crops (Chathurika *et al.*, 2014; Ferguson *et al.*, 2002). The supply of required quantities of nutrients recommended by research and extension is not commonly practised, and it could be the main soil fertility constraint restricting optimum crop performance in Ethiopia. Moreover, the variability of productivity and associated factors are not well quantified and reported in the farming systems of Ethiopia, and its implication for improving the productivity of targeted crops is immense. Supplementary approaches to the conventional field experimentations through the use of decision support tools could help generate the required information for immediate consideration by decision makers, investors, extension staff and farmers as well as for identifying existing crop production potential (MacCarthy *et al.*, 2018). However, to draw reliable conclusions using site-specific decision support tools, a strong and well-organised database of crop nutrient responses that have spatial and temporal dimensions is critically important (Edreira *et al.*, 2018; Hengl *et al.*, 2015; Hengl *et al.*, 2017; Kaizzi *et al.*, 2017). Under the current situation of Ethiopia, there is a lack of an organised database for the development of crop and site-specific decision support tools.

Maize (*Zea mays*) is one of the major cereal crops grown in Ethiopia with higher yield potentials, although the current national average yield of maize is less than 4 t ha^{-1} (Abate *et al.*, 2015; Abdulkadir *et al.*, 2017; FAO, 2014). Under most agro-ecologies and soils of Ethiopia, the response of maize to nitrogen (N) and phosphorus (P) is very high (Amare *et al.*, 2018; Abdulkadir *et al.*, 2017), and the achievable maize yield potential could be attained with a better crop management interventions including a further increase of NP fertilisers in the maize belts of the country, especially those in the north-west. Intensive research and development work on soil fertility management is highly needed to transform the current state of maize production to its achievable potential. The attainable maize yield at smallholder level shall be targeted. One of the strategies to improving the productivity and production of maize is to bring on board an intensive database so that decision support tools could be developed. The International Plant Nutrition Institute (IPNI) has been working with partners in sub-Saharan Africa to improve crop intensification including maize. IPNI extended its project to maize belts of the Amhara National Regional State for 3 years (2016–2018) to generate large data sets on the response of maize to the applied nutrients focusing on NPK (nitrogen, phosphorus and potassium). The objective was to analyse the most yield-limiting nutrient(s) to maize production for major maize-growing areas and generate a database of yield response to applied N, P and K that could help to develop and validate decision support tools that will enable researchers make area-specific nutrient management recommendations.

Materials and Methods

The study sites

The trial sites covered the major maize production districts (Jabitahnan–Burrie–Womberma, south Achefer and Mecha) in the Amhara region, located in the north-western highlands of Ethiopia (Figure 1) – an area usually referred to as the ‘food basket’ of Ethiopia. Selected fields represent the main soil types occurring in the area, commonly used cropping systems and farm management practices and a range of socioeconomic conditions (low to high resource endowment). The soil type of these districts is predominantly characterised by Nitisols. The general feature of the agricultural landscape where maize is the dominant crop is flat, which is good for future expansion and application of mechanised agricultural technologies. All districts have a uni-modal type of rainfall which extends from April to October; the main rainy months are June–August, and a mixed type of farming system (crop and livestock production) is practised. Generally, this region is rich in water sources. Mecha district receives about 1600 mm annual rainfall on average with a temperature range of 16–20 °C. The altitude of major maize-growing areas of the district ranges

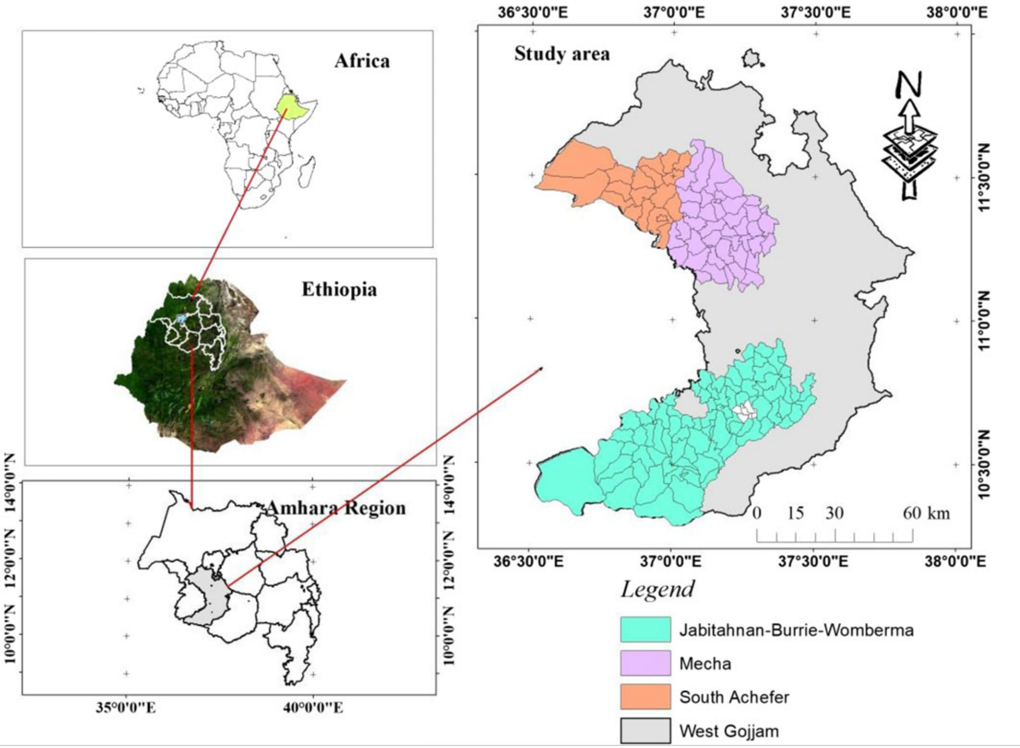

Figure 1. Map of the study areas.

from 1900 to 2200 m asl. Maize and finger millet are the dominant cereal crops grown in the Mecha district, and late-maturing maize varieties with days to maturity greater than 165 days are not commonly grown in the district unlike to the other districts of the study sites. Therefore, variety BH-540 with maturity days of 140 was used for this district.

Compared with Mecha, south Achefer receives a higher amount of rainfall with an extended growing period, helping to grow high-yielding late-maturing maize varieties (greater than 165 maturity days). Therefore, variety BH-660 with maturity days of greater than 165 days was used for this district and Jabitahnan–Burrie–Womberma districts. The annual rainfall of Jabitahnan–Burrie–Womberma districts is about 1600 mm, with mean minimum and maximum temperatures of 12 and 29 °C, respectively. The major maize-growing area of this district is in the mid-altitude of 1700–2200 m asl. Crop diversity in Jabitahnan–Burrie–Womberma districts is better than in Mecha and south Achefer. The major crops grown comprise maize, wheat, teff, finger millet, pulses and pepper; maize is the dominant crop. Perennial crops like coffee and fruits are also commonly grown. Because of the high amounts of rainfall, high-yielding and late-maturing maize varieties are commonly grown in the districts.

Experimental setup

The nutrient omission trial was established on 30 sites per year with 11 non-replicated treatments per site during the first 2 years. In the third year, the trial was established on 15 sites with treatments replicated three times at each site. All the trials were carried out on farmers' field. The

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Table 1. Descriptions of the treatments

Treatment	Description and justifications of the treatments
Control	Soil supplies for NPK could be evaluated
N	Provided sufficient N only, other nutrients from indigenous soil supply
P	Provided sufficient P only, other nutrients from indigenous soil supply
K	Provided sufficient K only, other nutrients from indigenous soil supply
PK	N omitted with sufficient P and K amounts applied
NK	P omitted with sufficient N and K amounts applied
NP	K omitted with sufficient N and P amounts applied
NPK	Provided sufficient NPK input
NPKSZn	Provided sufficient NPK plus sufficient sulphur and zinc to assess the contribution of secondary and micronutrients on maize productivity
NPK + Compost	Provided sufficient NPK input plus compost to assess the contribution of compost to maize productivity through its multiple effects, including regulation of nutrient supply and water and air circulation
NPK + Lime	Provided sufficient NPK input plus lime to correct acidity and regulate nutrient

Table 2. Nutrient application rates (kg ha^{-1})

Treatments	N	P_2O_5	P	K_2O	K	S	Zn	$ZnSO_4$
1. Control	0	0	0	0	0	0	0	0
2. N	150	0	0	0	0	0	0	0
3. P	0	125	55	0	0	0	0	0
4. K	0	0	0	72	58	0	0	0
5. PK	0	125	55	72	58	0	0	0
6. NK	150	0	0	72	58	0	0	0
7. NP	150	125	55	0	0	0	0	0
8. NPK	150	125	55	72	58	0	0	0
9. NPKSZn	150	125	55	72	58	20	5	25
10. NPK + Compost	150	125	55	72	58	0	0	0
11. NPK + Lime	150	125	55	72	58	0	0	0

research consisted of nitrogen, phosphorus and potassium (NPK) stand-alone plots, NPK omission plots, control plots, NPK plus secondary and micronutrients, NPK plus compost and NPK plus lime treatments (Tables 1 and 2).

The rates of nutrients were: 150 kg N h^{-1}, 125 kg P_2O_5 ha^{-1} (55 kg P ha^{-1}), 72 kg K_2O ha^{-1} (58 K ha^{-1}), 20 kg ha^{-1} S and 5 kg ha^{-1} Zn. The rate of lime was calculated based on the lime requirements developed for wheat (Agumas *et al.*, 2016) and applied in rows at sowing. The sources of nutrients were NPS (for nitrogen, phosphorus and sulphur), urea (for nitrogen), triple superphosphate (for phosphorus), muriate of potash (for potassium) and $ZnSO_4$ (as sources of S and Zn); 1 t ha^{-1} of compost was applied at sowing in rows in plots receiving this treatment uniformly for all locations. The pH, available phosphorus, cation exchange capacity, soil organic carbon (SOC) and total nitrogen (TN) content of the compost were 6.9, 7.48 ppm, 65.3, 4.6 and 1.3%, respectively. Nitrogen was applied in three equal splits as follows: 50 kg ha^{-1} at planting, 50 kg ha^{-1} top-dressed at about 35 days after emergence and 50 kg ha^{-1} at about 60 days after emergence. All other nutrients were applied at the time of planting. Plot sizes were 3 × 4.5 m, and the distance between plots and replications was 1 m. The distance between rows and plants was 0.75 m and 0.3 m, respectively. Two commonly grown maize varieties: BH-540 for the Mecha district and BH-660 for the south Achefer and Jabitahnan–Burrie–Womberma districts were used. Sowing date varied from end of May to first week of June that depends on the start of the rainy season. Weed was managed manually and uniformly for all treatments. Grain yield data were

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collected at maturity and the moisture content of the grain was measured and finally the yield data were adjusted to 12.5% moisture content.

Soil sampling, preparations and analysis

One composite soil sample was collected at depths of 0–20 cm before sowing from each site. Samples were air-dried and then ground using a pestle and mortar to pass through a 2-mm sieve. Soil pH was determined in a 1:2.5 soil-to-water suspension following the procedure outlined by Sertsu and Bekele (2000). SOC content was determined by wet digestion method using the Walkley and Black procedure (Nelson and Sommers, 1982). TN was determined according to Sertsu and Bekele (2000). The available P was determined following the Olsen procedure (Olsen and Sommers, 1982). The exchangeable K was measured by flame photometer after extraction of the samples with 1N ammonium acetate at pH-7 following the procedures described by Sertsu and Bekele (2000).

Data analysis

The effect of independent variables (treatments) on the dependent variable (maize yield) was statistically tested. Analysis of variance (ANOVA) was carried out to assess the difference between treatments using Statistical Analysis System (SAS) 9.2 software (SAS, 2003). Upon the existence of significant difference for ANOVA ($p < 0.05$), further analysis of mean separation was carried out using Duncan's multiple range test.

Results

Results of soil analysis for the study sites

The results of soil analysis collected before planting are summarised below. The pH of the soil ranged from 4.6 to 5.5, with mean values of 5 for all the study sites of the Mecha district. In south Achefer, it ranged from 4.6 to 5.2, with a mean value of 4.9, whereas for Jabitahnan–Burrie–Womberma districts the average value was 5.2 with a low level of exchangeable acidity (less than 2 cmol kg^{-1} of soil). Mean values of the SOC content were 2, 2.01 and 1.75% for Mecha, south Achefer and Jabitahnan–Burrie–Womberma districts, respectively. However, there were some sites with SOC values below 1.5%. The mean values of TN content were 0.17, 0.14 and 0.21% for Mecha, south Achefer and Jabitahnan–Burrie–Womberma districts, respectively. The mean values of available P for Mecha, south Achefer and Jabitahnan–Burrie–Womberma districts were 7.4, 3.6 and 7.6 ppm, respectively. The mean values of exchangeable K were 0.6, 0.61 and 0.75 cmol kg^{-1} of soil for Mecha, south Achefer and Jabitahnan–Burrie–Womberma districts, respectively.

Yield response

The findings of the research showed similar trends of yield responses across the study sites and years. Although the trends of response were similar, there were large differences between sites with the same treatments that could be associated with the history of individual farms. The productivity of maize without fertiliser was very low compared with the fertilised ones (about less than 50%) with the exception of a few cases. The findings of our research showed that achievable grain yields were more than three times those of the 3 t ha^{-1} of the national average with 11.6 and 11.7 t ha^{-1} with NP and NPK treatments, respectively, in the 2016 cropping season at Mecha district. Similarly, 9 and 10.6 t ha^{-1} were recorded with NP and NPK treatments, respectively, in the 2017 cropping season at a site called Ambomesk of Mecha district (data are not shown as only the mean values of all sites in the districts presented in Table 3), with no significant difference between the two treatments. At Jabitahnan–Burrie–Womberma, the highest grain yield recorded

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Table 3. The effect of nutrients on grain yields (t ha^{-1}) of maize across locations over the season affected

Treatments	Mecha			Jabitahnan–Burrie–Womberma			South Achefer	
	2016	2017	2018	2016	2017	2018	2017	2018
Control	3.98^{e}	3.99^{c}	2.68^{c}	3.72^{de}	2.43^{c}	1.50^{c}	2.47^{f}	2.08^{d}
N	6.57^{bc}	5.97^{b}	4.61^{b}	5.17^{cd}	7.20^{a}	4.85^{ab}	3.94^{ef}	3.77^{c}
P	4.85^{de}	4.28^{c}	3.75^{bc}	3.38^{e}	3.40^{c}	2.01^{c}	3.47^{ef}	2.73^{d}
K	4.82^{de}	4.42^{c}	2.61^{bc}	3.74^{de}	2.01^{c}	1.77^{c}	3.01^{f}	2.11^{d}
PK	5.53^{cd}	4.35^{c}	3.45^{bc}	4.37^{de}	3.11^{c}	1.81^{c}	3.23^{ef}	2.14^{d}
NK	7.44^{ab}	6.01^{b}	6.13^{a}	6.28^{bc}	5.45^{b}	3.70^{b}	4.81^{bde}	3.44^{c}
NP	7.69^{ab}	7.53^{a}	6.90^{a}	7.66^{a}	7.75^{a}	5.54^{a}	5.61^{abcd}	6.51^{b}
NPK	8.44^{a}	8.07^{a}	7.30^{a}	6.96^{ab}	7.11^{a}	4.92^{a}	6.41^{abc}	6.86^{b}
NPKSZn	8.45^{a}	8.09^{a}	7.29^{a}	7.71^{a}	7.21^{a}	5.62^{a}	6.43^{ab}	7.78^{a}
NPK + VC	7.74^{ab}	7.18^{ab}	7.16^{a}	7.94^{a}	7.75^{a}	5.94^{a}	6.79^{a}	6.97^{a}
NPK + Lime	7.52^{ab}	7.79^{a}	7.18^{a}	7.65^{a}	7.72^{a}	5.34^{a}	6.47^{ab}	6.52^{b}
Prob.	**	**	**	**	**	**	**	**
CV(%)	21.0	20.7	35.7	31.3	19.1	32.5	27.1	24.5

**Significant at $p < 0.01$ and the same letters in the same column are non-significant.

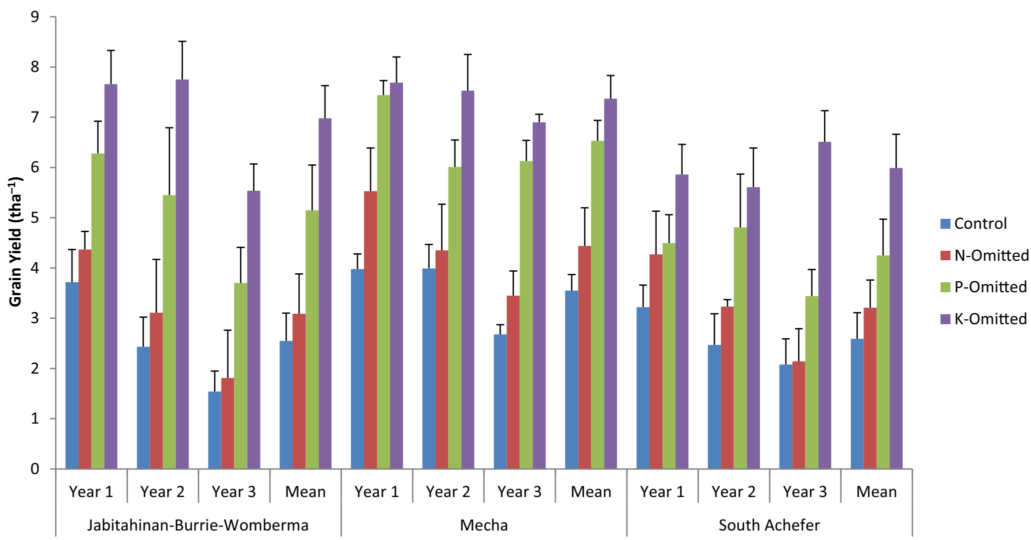

Figure 2. The effect of omitting each nutrient (NPK) on the yield of maize for all the study sites across the years with the standard errors.

was 10.3 t ha^{-1} using only NP, whereas 10.8 t ha^{-1} of yield was recorded from NPK application in 2016 at a site called Tyatya (only the mean values of all sites in the districts presented in Table 3). The maximum mean grain yield of maize (8.3 t ha^{-1}) in south Achefer with NP fertiliser was recorded in the 2018 cropping seasons compared with the control of 2.5 t ha^{-1} (only the mean values of all sites in the districts presented in Table 3).

Without N (i.e. omitting nitrogen), the use of P was not significantly different from the one without nutrient (control) (Figure 2). With N alone, the yield was better than using P alone or P in combination with K (Table 3). But when N was combined with P, the yield surpassed the one with N alone and was statistically insignificant with treatment combinations of NPK as well as NPK plus other soil amendments (lime and vermicompost). As the farming system of the maize belt in the region is dominated by cereal monocropping and less emphasis on soil health restoration, the sustainability of crop production might be broken into difficult situations. Our findings of highest

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yield records from Mecha and south Achefer districts where maize was grown after lupine (*Lupinus albus*) or noug (*Guizotia abyssinica*) indicate the importance of rotation compared with the monocropping system or the cereal-after-cereal rotation systems. This rotation is not exercised in the Jabitahnan–Burrie–Womberma parts of the study site.

The result was clearly separated in two groups for most of the sites: treatment 1–6 in one group and treatment 7–11 in the second group (see Table 2 for the treatments). Therefore, the significant difference for most of the sites was between these groups, whereas there was no significant difference between treatments above 6. This indicates that a maximum yield of maize can be obtained by NP fertilisers alone. The yield of maize was slightly higher than the control when N was omitted; the trend was similar for all sites and years. The yield penalty for N omission accounts was higher than the yield penalty for P omission. The interaction effect of N and P boosted the productivity of maize as shown, even with the omission of K (Figure 2).

Discussion

Results of soil analysis for the study sites

The pH of the soil for all the sites was acidic (FAO, 1984) and with a low level of exchangeable acidity (less than 2 cmol kg^{-1} of soil), implying that maize yield could be maximised by fertiliser applications. Hence, acidity could not be considered as a yield-limiting factor, at least for the present situation. The SOC contents of the study sites need further attention to improve crop responses and recovery of applied fertilisers as the critical value is 2% (Loveland and Webb, 2003; Murphy, 2014) for general crop production and within the range of 1.9 to 2.2% for maize (Musinguzi *et al.,* 2016). Because of low levels of SOC, a high productivity of maize for the study sites could not be expected without the application of synthetic fertilisers (NP). According to Munialo *et al.* (2020), the critical values of soil TN are above 0.2% indicating soils of the study sites are poor in nitrogen and this nutrient limits the productivity of crops including maize. The average values of available P for all the study sites were below the critical levels for optimum crop yield, which ranges from 10.9 ppm to 21 ppm as revised by Bai *et al.* (2013). Previously, 20 ppm of Olsen-P was considered as a threshold for optimum crop production in China (Li *et al.*, 2011), where the most recent data showed high variability of optimum ranges of Olsen-P between locations (Wu *et al.*, 2020). For maize, the critical values of available P (Olsen-P) reported are a mean of 15 ppm, with 13.1 ppm for the desert soils of China (Wang *et al.*, 2016). Recently, 14.2 ppm was reported as a general critical value of Olsen-P for maize production in China (Wu *et al.*, 2018). All these findings indicate that our study sites have a high potential to increase the productivity of maize by applying P fertilisers without affecting the environment, as the threshold value of Olsen-P is 40 ppm (Zhong *et al.*, 2004, cited by Bai *et al.*, 2013) that cause environmental pollution. The values of exchangeable K were far above the threshold values of soil exchangeable potassium for the growth of crops (Barbagelata, 2006; IPI, 2016), indicating that K application could not significantly improve maize production and productivity for the study sites. Adeoye and Agboola (1985) in Nigeria reported a critical level of exchangeable K that ranges from 0.6 to 0.8 cmol kg^{-1} of soil for maize, whereas Farina *et al.* (1992) in South Africa reported 0.32 cmol L^{-1} for the production of maize-critical exchangeable K. The inherent potential of the soil is sufficient to supply the required quantities of K to produce maize in the study site for at least the present situation. The finding of this soil analysis for K clearly showed that omitting K fertiliser did not affect the maize yield (see Figure 2).

Yield response

The productivity of maize without fertiliser was very low compared with the fertilised ones (about less than 50%), except for a few cases. This finding indicated that optimum maize production

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could be simply achieved by NP nutrient optimisation, as already reported by Abate *et al.* (2015). The findings of our research showed that achievable grain yield was more than three times compared with the 3 t ha^{-1} of the national average (Abate *et al.*, 2015) with NP nutrients alone. In general, the yield found across all the sites was above the national average estimated by FAO (2014) (2.5–5 t ha^{-1}) and Abate *et al.* (2015) (3 t ha^{-1}), indicating the existence of large potential to boost the productivity of maize by nutrient optimisation. The yield attained in our research could be one of the highest yields in the sub-Saharan countries (Abate *et al.*, 2015; FAO, 2014; Gudeta *et al.*, 2009; Gudeta *et al.*, 2010).

There was a significant yield difference ($p < 0.01$) between treatments. Without N (i.e. omitting nitrogen), the use of P was not significantly different from the one without applied nutrients (control), and hence the addition of any nutrient without N is not economical for both the farmers and the country (see Gudeta *et al.*, 2010). With N alone, the yield was better than using P alone or P in combination with K. But when N was combined with P, the yield surpassed that with N alone and was statistically non-significant from treatment combinations of NPK as well as NPK plus other soil amendments (lime and vermicompost). This indicates that, unlike N and P, K is not limiting maize yield in the study areas.

The contribution of compost to improve the response of maize to nutrients NPK was not significant, albeit the low levels of the SOC matter all over the study areas. This might be because its amount was lower or its effect might not be visible in the short term. Otherwise, the contribution of organic fertilisers to sustainable maize production in sub-Saharan African was recognised and reported (Gudeta *et al.*, 2009; Gudeta *et al.*, 2010). Abate *et al.* (2015) reported a drastic reduction in the use of organic fertiliser sources for most maize-producing areas in the country in general and in the Amhara Regional State in particular. Our results on soil analysis and the yield responses (Table 3) supported each other, indicating that N and P are still the most yield-limiting nutrients that are in line with the findings of Amare *et al.* (2018).

Conclusions

The research was conducted on farmers' fields for three consecutive years in the maize-growing belts of the Amhara Regional State. From the research, a large database for maize yield response to NPK nutrients was generated. The findings of the study showed that a maize yield of more than 10 t ha^{-1} could be achieved with optimum nutrient management, even when using the old varieties (BH-660 and BH540), that was more than thrice the national as well as the regional average yields. Our findings indicated maize productivity could be increased through N and P nutrient management. Despite similar trends over the years and across the sites, there was high variability between fields with short distances. The only variable that may have caused the variability could be the differences in the management (rotation, for example) of different farmer fields. Therefore, sustainable intensification of maize production should also consider improving existing farm management practices. The yield-limiting nutrients to produce maize for the major maize-producing areas of the region were first, N, followed by P. Hence, intensive research and development focus should be for only NP nutrients to attain optimum maize yield for the study areas. Our research was based on application rates of 150 kg N ha^{-1} and 125 kg P_2O_2 ha^{-1}. Further research on the optimum rates of N and P nutrients to meet the biological and economic optimum is recommended.

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Conflict of Interest. The authors declare no conflict of interest.

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