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Diagnosing plant nutrient deficiencies for maize (*Zea mays*) yield under mixed farming systems of Northwest Ethiopia

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Abstract

A decline in soil fertility is the major factor for global food production. Determining the extent of plant nutrient deficiencies for a given crop, soil, and environment is key to nutrient management. Thus, this experiment was initiated to investigate the yield-limiting plant nutrients for maize productivity in North West Ethiopia. It was arranged in a randomized complete block design with three replications. The treatments were comprised of omitting N (All-N), P (All-P), K (All-K), S (All-S), B (All-B), and Zn (All-Zn) nutrients. Then, NPKSZnB (All), recommended NP (RNP), no fertilizer (NF), and recommended NP with S (RNP + Sx1) treatments were included. The application of different nutrient kinds significantly ($p \leq 0.001$) affected grain yield. The highest grain yield (7.1 t ha^{-1}) was achieved from the treatment that received N and P nutrients. While the omission of KSZnB nutrients had no discernible effect as compared to NP nutrients. The lowest grain yield (1.3 t ha^{-1}) was recorded from the no-fertilized treatment, followed by N omitted treatment (1.4 t ha^{-1}). Without N nutrient application, grain yield was decreased by 29–80%, while the absence of P decreased grain yield by 5–40%. Therefore, N, followed by P nutrients, is the most yield-limiting nutrient for maize productivity in Ethiopian soils. So, optimizing the rate of yield-limiting nutrients is required for judicious use of fertilizers and contributes to food systems. We suggest a timely assessment of the inherent nutrient-supplying capacity of soils for fertilizer addition to improve crop productivity and environmental sustainability.

Keywords Food systems, Omission, Nitrogen, Nutrients, Phosphorus, Productivity

1 Introduction

Agriculture contributes about 50% to the annual gross domestic product in Ethiopia [1]. The cereal production has reached about 81%, and 88% in areas and production, respectively [2]. The cereal crops, mainly teff, maize, and wheat, have used about 90% of the fertilizer inputs of the nation [3]. These fertilizer uses have shown a linear increase from below 37 K t in 1985 to over 134 t at the end of 1994. However, there is no proper



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proportion of the fertilizer types imported with the demand for nutrients in the crop production system. The steady increase and even decline in crop yields have been shown with the application of high doses of blended fertilizers from different types of nutrients. The declining returns of fertilizers could be due to the lack of the right nutrient proportion of required nutrients. The reports from other countries show that N is the leading nutrient in global agriculture, followed by P and K [4, 5].

There are different factors affecting the response of crops to fertilizers; these may include poor targeting of the right fertilizers in the right places [1]. The fertilizers that are used in Ethiopia and the ways of fertilization cannot be site and crop-specific. Thus, the strict applications of the 4Rs (right fertilizers, right methods, right time, and right rate) in the use of multi-nutrient fertilizers are the frontier to exploit the potential of fertilizers [6–9]. Attainable yield can be achieved through the application of the proper type of nutrients.

The EthioSIS project has mapped the soil nutrient status of agricultural lands in Ethiopia [10]. They identified many essential nutrients that are deficient and critically required by soils of the country, mainly in the cereal-based mixed farming system. The deficient nutrients include N, P, K, S, B, Zn, Fe, and Cu. In addition, yield improvement is reported through the addition of NPKSB with and without micronutrient fertilizer addition in some soils of Ethiopia [11, 12]. Nevertheless, other evidence showed that K, S, Zn, and B nutrients are not deficient in the farming system of the study area [13–15]. Still, there is no empirical evidence of N and P nutrient deficiency level of the test crop in the study area. Thus, yield response helps to assess the capacity of the soil to supply nutrients [16]. Because a significant portion of the applied fertilizers, roughly 40–70% of N, 80–90% of P, 50–70% of K, and over 95% of the micronutrient content are lost into the environment [17]. The application of proper nutrients in specific soils could reduce the risks and uncertainties associated with agricultural crop productivity [18]. Studies show that yield is affected jointly by nutrient rate, soil properties (mainly soil organic carbon and pH), climate, and topography rather than a single dominant factor. Climatic variables (rainfall, temperature, radiation) are among the key factors of fertilizer response for some nutrients [19, 20]. Thus, this experiment was initiated to investigate the need for applying selected plant nutrients to maize productivity in nitisols of North West Ethiopia.

2 Materials and methods

2.1 Study site characteristics

The study location is found between 10°30'30"–11°50'0" N and 36°40'0"–37°40'0" E geographical position (Fig. 1). The experiment sites were selected from the farmers' fields in seven districts, including Jabitahnan, Burie, Womberma, South Achefer, Mecha, and Bahir Dar Zuria. Six districts are part of the West Gojjam administration zone of the Amhara National Regional State, whereas one district [Ayehu Guagusa] is found in the Awi administration zone. These districts are the major maize-growing areas in the northwestern part of Ethiopia. Nitisols are the dominant soil type in the study areas. Nitisols are generally fertile and suitable for agriculture with pH values ranging from 4.8 to 6.7 and a high amount of Al^{3+} and H^+ . It exhibits low organic carbon and total nitrogen, but it has high levels of available phosphorus and exchangeable potassium [21, 22]. It also has a high CEC, which allows it to retain essential nutrients for plant growth [21].

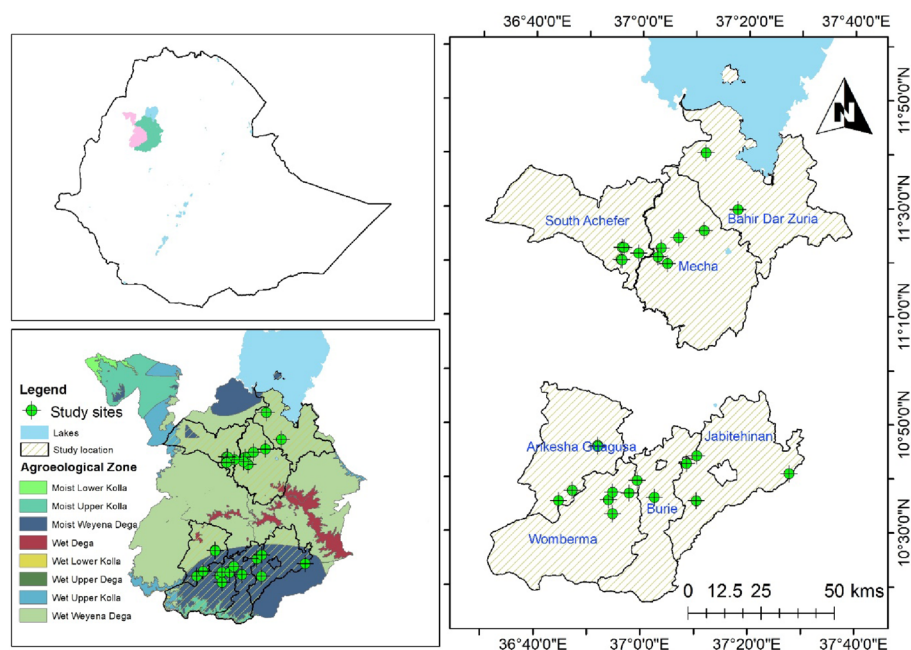


Fig. 1 Geographical location of study area

The exchangeable K and Zn contents of the soil range from medium to high in the study sites [10]. Whereas deficiency of B and low to medium contents of available sulfur are reported.

A cereal-based cropping system is the dominant type of cropping system in the study areas. Maize, teff, wheat, and finger millet are the major cereal crops grown in the study areas. Noug crop also produces oil sources for farmers. Moist weyna dega and Wet weyna dega are the major agro-ecological zone divisions of the study area (Fig. 1). Small-holder farmers are dominant and characterized by low-input, low-output, labor-intensive, and rain-dependent farming, with a fragmented system, which limits production capacity [23]. The major challenges, including limited access to fertilizers and irrigation, with market volatility, can hinder maize production in the study area [24, 25].

Unimodal rainfall pattern is dominant in the area. The minimum temperature ranges between 8 and 12 °C. Whereas the maximum temperature ranges from 24 to 27 °C. The area received 1786 mm of rainfall during the growing seasons (Fig. 2).

2.2 Research design

This experiment was conducted on a total of 27 sites across seven districts. The experiment was arranged in a completely randomized block design and replicated three times at each study site. The nutrient omission design consisted of ten treatments, including no fertilizer (NF), All (NPKSZnB), All-S (S omitted), All-K (K omitted), All-Zn (Zn omitted), All-B (B omitted), All-P (P omitted), All-N (N omitted), and recommended NP (KSZnB omitted). Another recommended NP treatment with the addition of S nutrient (RNP+S₁) was included. The recommended NP was denoted by RNP.

The rates for N and P nutrients were based on the previous recommendation for the maize crop in the districts. Thus, the rates of 138, 92, 60, 5, and 1 kg ha⁻¹ were used for N, P, K, Zn, and B, respectively, at all experimental sites. 10.5 and 30 kg ha⁻¹ rates were used for S and Sx1, respectively. The second rate of S (30 kg ha⁻¹) was used to

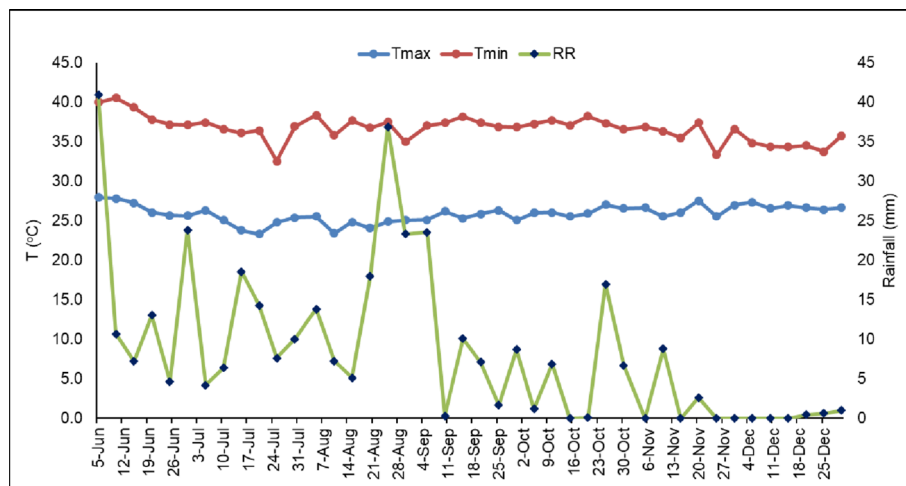


Fig. 2 Growing season mean rainfall and temperature amount and distribution.(Source: nearby metrological station)

exhaustively see the effects of S on maize yield in the farming system of Ethiopia. Unfertilized and RNP treatments were used as negative and positive controls for this study.

The mineral fertilizers were applied under the treatments with their respective sources of fertilizers. The sources of N, P, K, S, Zn, and B were obtained from fertilizers such as urea (46-0-0), triple super phosphate (0-46-0), potassium chloride (0-0-60), magnesium sulfate (28% SO_3^-), EDTA Zn (12% Zn), and borax (11% B), respectively.

Recently, the released early maturing maize variety (BH-546) was used in the Mecha and Bahir Dar Zuria districts, whereas the late-maturing maize variety (BH 661) was also used for the remaining districts. The maize varieties BH 546 (released in 2013) and BH 661 (released in 2011) were generated through a collaborative effort by the Ethiopian Institute of Agricultural Research (EIAR) and the International Maize and Wheat Improvement Center (CIMMYT) at Bako Agricultural Research Center. The maize varieties used in this study were commercially cultivated in Amhara Seed Enterprise, a public seed provider authorized to distribute certified seeds in Ethiopia under controlled conditions. No specific permissions were required for cultivated varieties, and seed collection complied with institutional guidelines.

2.3 Trial management

The soil and crop management practices were done following research recommendations. After preparing the fields, all the sites were planted from 5 June to 30 June 2021. An average maize plant stands of 44,444 per hectare was reached by sowing two seeds in each hole at intervals of 0.3 and 0.75 m between seeds and rows, respectively, which were then thinned to one plant per hill. All fertilizers were applied by band application at planting except N. Three equally split applications of N were done: at planting, 35 days following emergence, and 65 days afterward. Weed management started just 2 weeks after the emergence of the maize seeds. Each site has been weeded three times. All experimental sites were harvested from 15 November 2021 to 30 November 2021.

2.4 Data collections

Before planting, one composite soil sample of 0–20 cm was collected from each trial site to determine the indigenous soil nutrient supply. Major soil properties such as soil pH-H₂O, organic carbon (OC), available phosphorus (AP), and total nitrogen (TN) analysis were conducted in Adet Agricultural Research Center's soil laboratory.

Maize was harvested from a net plot of 9 m² (40 plants), that is, constituting the 4 middle rows in each plot, leaving 0.75 m on each side of the row from a whole plot area of 14.75 m². All plants in the net plots were harvested, and the total fresh weights of ears and stover were measured in the field using a digital balance and then converted into kg per hectare. Grain yield: all cobs were taken for drying. It was dried by air to constant weight and converted to kg ha⁻¹. The grain yield was expressed on dry weight by adjusting to 12.5% moisture content.

2.5 Soil analysis

All collected samples were air-dried and crushed to pass a 2-mm sieve. Analyses were performed on surface samples, including pH, organic C, total N (N), available P (P), and cation exchange capacity following standard soil laboratory procedures. Soil pH-H₂O was determined in soil-water suspensions of 1:2.5 ratios [26]. Available P was also done following the Olsen method [27], while total N was done using the Kjeldahl method [28]. The wet oxidation method was used to determine soil organic carbon [29]. Cation exchange capacity was also determined by ammonium acetate extraction procedures [30].

2.6 Data analysis

A fixed model for the response of dependent variables to treatments was conducted at the site level, and a mixed model for the response of dependent variables to treatments, sites, and replications was performed at the district level using R software [31]. Thus, 810 datasets from 27 experimental sites were analysed. The mixed model was displayed as follows:

$$y_{ijkl} = \mu + Nt_i + Rep_k + (1|Location)_l + \epsilon \quad (1)$$

Where μ is the grand mean yield (kg ha⁻¹), Nt_i is the applied nutrient types (kg ha⁻¹) in the study, location is the random component, and ϵ is the error term in the mixed model effects. Based on Akaike's Information Criteria (AIC) and Bayesian Information Criteria (BIC), the above model was applied for data analysis.

A test of significance for the treatments was conducted for significant ANOVA results as outlined by Cox [32] for situations with heterogeneous variance among treatments. Forest plot analysis was done to compare the positive control with other treatments over 27 experimental sites, which helps to extract the effect of site heterogeneity [33]. Graphs were also generated using R programming software.

3 Results

3.1 Soil chemical properties

The soil chemical properties before planting from the specific experimental sites within a district exhibited wide variability, with mean soil pH (H₂O) ranging from 4.9 to 6.0 [34]. The available P was found between 2.9 and 19.0 mg kg⁻¹, whereas the cation

Locations	Selected soil properties				
	pH (H ₂ O)	P (mg kg ⁻¹)	CEC (Meq/100 g s)	OC (%)	TN (%)
Ayehu Guagusa	5.4 [5.1–5.8]	8.0 [7.1–9.7]	34.7 [28.2–42.8]	2.6 [2.2–3.2]	0.16 [0.1–0.2]
Burie	5.2 [5.2–5.3]	6.6 [6.0–7.1.0.1]	29.4 [27.5–31.9]	2.6 [2.2–2.8]	0.13 [0.1–0.2]
Jabitehnan	5.2 [4.8–5.8]	7.9 [5.1–14.0]	28.1 [20.7–38.6]	2.0 [1.9–2.2]	0.13 [0.1–0.2]
Mecha	5.1 [4.9–5.3]	7.8 [2.9–19.0]	28.2 [25.0–31.6.0.6]	1.8 [1.8–1.9]	0.14 [0.1–0.18]
South Achefer	5.4 [4.9–6.0.9.0]	4.7 [3.9–5.7]	30.3 [23.2–36.9]	2.3 [1.8–2.6]	0.15 [0.1–0.16]
Womberma	5.6 [4.7–5.6]	7.8 [3.8–11.0]	30.2 [26.6–34.1]	2.6 [2.1–3.1]	0.18 [0.18–0.2]
Critical value	5.5	10	-	2	0.2
Rating	Strong to moderately acidic	Low to high	Medium to very high	Low to medium	Medium to high
References	[34]	[34]	FAO (2006)	[34]	[34]

Figure 2 consists of two panels. Panel (a) is a lower triangular heatmap showing the Spearman's rank correlation coefficients between the variables: C_L, C_D, S_C, C_WP, G_y, B_y, and Int. The diagonal elements are 1.00. The off-diagonal elements are: C_L-C_D: 0.53 (p=0.000); C_L-S_C: 0.39 (p=0.000); C_L-C_WP: 0.58 (p=0.000); C_L-G_y: 0.62 (p=0.000); C_L-B_y: 0.64 (p=0.000); C_L-Int: -0.11 (p=0.001); C_D-S_C: 0.12 (p=0.000); C_D-C_WP: 0.62 (p=0.000); C_D-G_y: 0.57 (p=0.000); C_D-B_y: 0.36 (p=0.005); C_D-Int: 0.03 (p=0.322); S_C-C_WP: 0.19 (p=0.000); S_C-G_y: 0.41 (p=0.000); S_C-B_y: 0.03 (p=0.605); S_C-Int: -0.02 (p=0.659); C_WP-G_y: 0.84 (p=0.000); C_WP-B_y: 0.62 (p=0.000); C_WP-Int: -0.01 (p=0.659); G_y-B_y: 0.64 (p=0.000); G_y-Int: 0.03 (p=0.420); B_y-Int: -0.37 (p=0.000). Panel (b) is a scatter plot of 'All' (y-axis, 2.5 to 10.0) versus 'NP' (x-axis, 2 to 10). It shows a positive correlation with a regression line and a shaded confidence interval. The statistics $R = 0.7$ and $p = 5.3e-13$ are displayed in the top right.

exchange capacity ranged from 26.6 to 33.9 Meq/100 g soil, and the soil organic carbon from 1.8 to 3.1% (Table 1). The highest P content (19 mg kg⁻¹) was observed in Mecha at one site, which is found in the Koga irrigation command area. The average total N content of experimental sites was also observed between 0.13 and 0.18% across districts. The organic carbon content of the soil was found between 1.8 and 3.2% in the soils of the study area [34].

The correlation analysis showed 36 significant associations between all traits measured under the nutrient omission study from 810 observations (Fig. 3). Grain yield with crop parameters such as ear length ($r=0.64^{***}$), ear diameter ($r=0.36^{***}$), plant height ($r=0.69^{***}$), and biomass ($r=0.64^{***}$) was displayed in Fig. 2. All correlation analysis results showed highly significant ($p<0.001$) and positive associations between yield and yield component parameters. Highly significant ($p<0.001$), and a weak positive correlation was also observed between plant height and ear diameter, with a correlation coefficient value of 0.12, whereas a strong positive correlation was recorded between grain yield and cob weight per plant ($r=0.84^{***}$). This indicates that cob weight per plant is the most important yield parameter for the fertilizer study. The maize grain yield from the application of All nutrients and NP had a highly significant correlation with an r value of 0.7 ($p<0.000$).

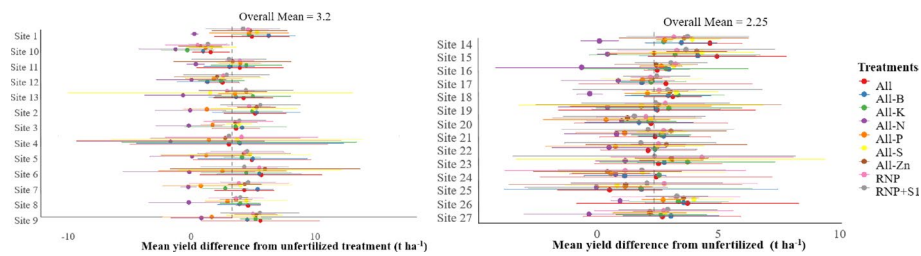


Fig. 4 Forest plot of grain yield mean difference (t ha^{-1}) from unfertilized treatment with 95% confidence intervals by site and omitted nutrient types

Table 2 Analysis of variance for nutrient omitted on maize grain yield

Locations		Bahir Dar Zuria	Mecha	South Achefer	Ayehu Guagusa	Womberma	Burie	Jabitehnan
Treatment	Degree of freedom	9	9	9	9	9	9	9
	Significance level at $\alpha = 5\%$	***	***	***	***	***	***	***
	CV (%)	15.2	18.2	18.1	19.9	24.2	16.9	25.2

***: significant at 1%, CV: coefficient of variation

3.3 Response of maize yield to nutrient types at variable sites

The grain yield variability was noticed over all experimental sites. Figure 4 displayed the mean grain yield difference of treatments from the unfertilized treatment (negative control) with 95% confidence interval across 27 experimental sites. Lower mean grain yield difference ranging from -1.76 (-9.38 – 5.86) to 1.06 (-1.07 – 2.28) metric t ha^{-1} were obtained from N omitted treatment in the experimental sites. The maximum grain yield difference ($6.17 \pm [4.01$ – $8.33]$ t ha^{-1}) was recorded from All-B nutrient application at trial site 1. The mean grain yield differences between 0.45 (-2.17 – 3.06) and 5.4 (3.99 – 6.89) metric t ha^{-1} were attained from recommended NP treatment. From 0.42 (-1.76 – 2.60) to 5.56 (0.64 – 10.50) metric t ha^{-1} mean grain yield difference was recorded from the application of all six nutrients. The mean grain yield difference ranging from 1.27 (-0.29 – 2.83) to 5.50 (2.27 – 8.72) metric t ha^{-1} was obtained from the application of S with recommended N and P.

Table 2 displays the influence of omitted nutrients on maize grain yield. The combined grain yield was highly significant ($p \leq 0.001$) and varied with the application of nutrient types compared with unfertilized and All-N treatments in all study districts. The application of six plant nutrients (All) provided a higher grain yield (7.1 metric t ha^{-1}) in the South Achefer district (Fig. 5). Similarly, 4.6 and 5.0 metric t ha^{-1} of grain yields were obtained from the K omitted (All-K) treatments in Jabitehnan and Womberma districts. In the Mecha district, 7.0 metric t ha^{-1} grain yield was recorded from both S and B omitted treatments, whereas 5.4 metric t ha^{-1} grain yield was gained from All-S treatment in the Burie district. The lowest grain yield (0.9 – 3.9 metric t ha^{-1}) was obtained from no fertilizer treatment across all districts. Moreover, All-N treatment also exhibited lower yields ranging from 1.1 to 3.3 metric t ha^{-1} over study locations.

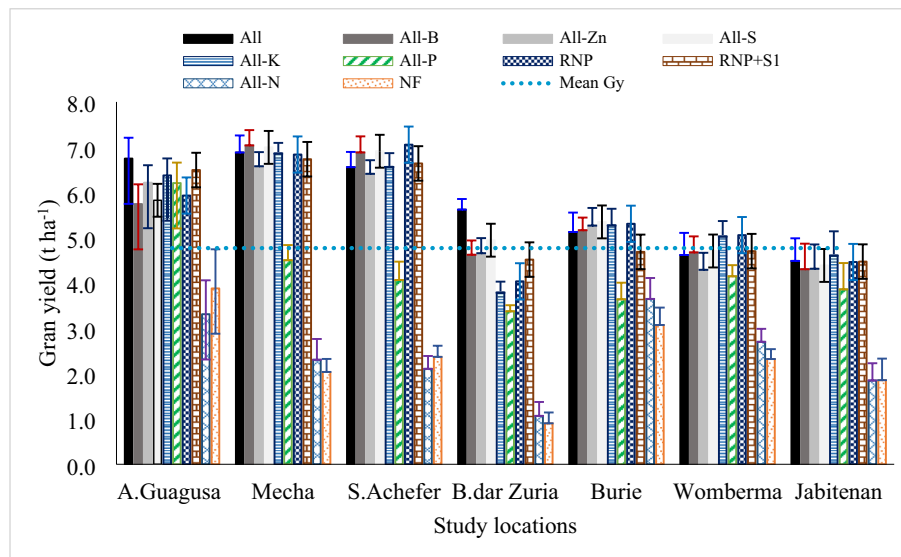


Fig. 5 Maize yield (t ha^{-1}) response to nutrient types in the study locations of North West Amhara. The bars show the standard error of the mean, the horizontal dot line show the overall mean grain yield (metric t ha^{-1})

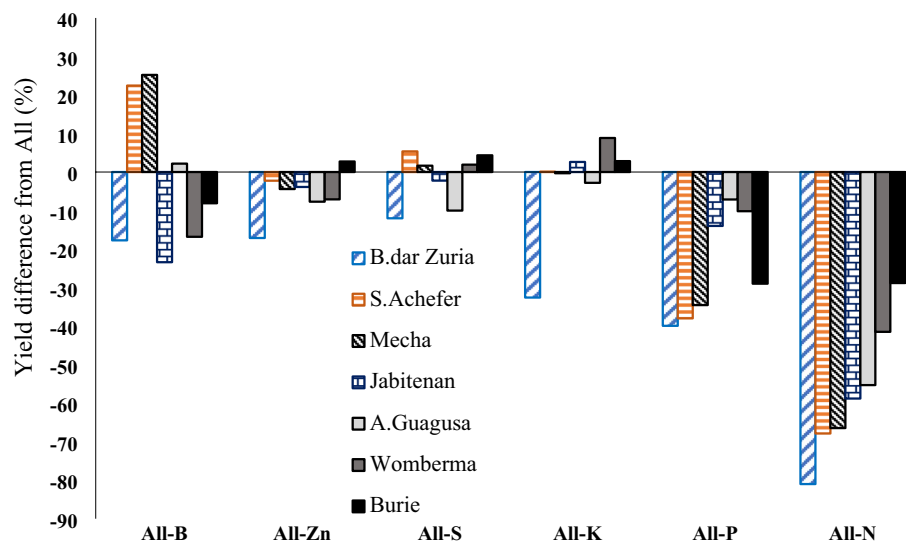


Fig. 6 Grain yield (%) contribution of each omitted nutrient types across study locations

3.4 Role of nutrients in biological grain yield and association with yield component parameters

The contribution of N and P fertilizers was clearly quantified in maize growing soils of the study locations. Ranging from 29 to 80% of maize grain yield was declined due to the omission of N nutrient application in the maize growing belts of the study area (Fig. 6). The highest grain yield reduction from the application of All-N was observed in the Bahir Dar Zuria district. Similarly, without P nutrient, grain yield with a range of 5–40% was reduced across study sites. The lowest grain yield from the application of All-P was noticed in the Womberma district. The absence of K decline yield by 32% only in the Bahir Dar district. The omission of S, K, Zn, and boron did not show a similar trend in yield contribution across study locations. In South Achefer and Mecha districts,

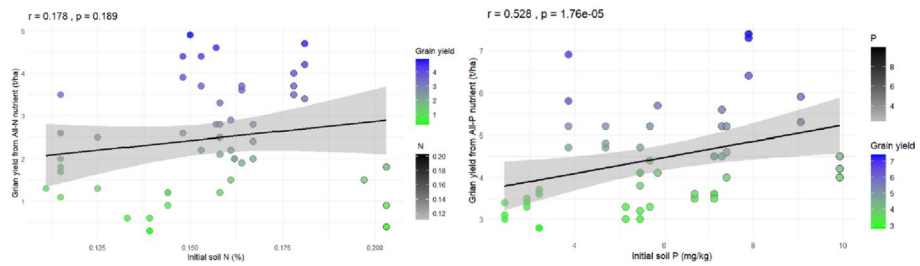


Fig. 7 Correlation of grain yield response from N and P omitted treatments with initial soil N and P

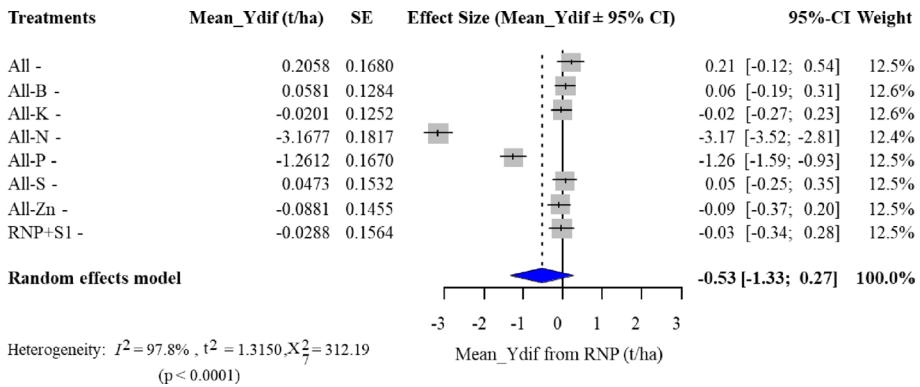


Fig. 8 Forest plot of mean grain yield difference (Mean_Ydif) from recommended NP under different treatments. Horizontal bars represent 95% confidence limits of means estimated using linear mixed effects models. The balk vertical lines represent Mean_ydif=0. When the 95% CL encompasses the balk line, the response in the treatment is not significantly different from the response in the recommended NP. The balk dot vertical lines with blue diamond represent the overall treatment effect with 95% confidence limits

omission of B increased yield by more than 20% compared to all added nutrients in the farming system. Whereas it declined by more than 15% in other study locations.

The correlation of grain yield obtained from All-N and initial N was weak ($r=0.178$) and not statistically significant (0.189). The grain yield obtained from All-P was moderately correlated with initial soil P, showing p-values of <0.000 and $r=0.528$ (Fig. 7).

The overall variability of soil for nutrient application was exhibited by Tau and I^2 . There was a highly significant ($p<0.0001$) variation between treatments (Fig. 8). The high value of τ^2 (1.32) indicates there were significant differences among treatments. The highest I^2 (312.19) shows heterogeneity of experimental sites, in which treatments respond differently across sites. As the forest plot graph clearly indicates, a significantly lower mean yield difference (-3.17 ± 0.18) metric $t\ ha^{-1}$ was obtained from the application of All-N nutrient, followed by the application All-P nutrient with a mean yield difference of (-1.26 ± 0.17) metric $t\ ha^{-1}$. The omission of K, S, Zn, and B did not significantly reduce maize yield. The overall effect with a value of -0.5 metric $t\ ha^{-1}$ was below zero. This indicates RNP is a better treatment for maize productivity compared to others in maize growing belts of the study area.

4 Discussion

4.1 Experimental sites soil characteristics

The variability of selected soil properties across multi-location experimental sites is associated with the intrinsic nature of soils and management. Relatively strongly acidic soils are observed in Womberma, Jabitehnan, Mecha, and South Achefer districts. The

study area exhibited a range of low to medium in organic carbon content as per the criteria developed by Taddese et al. [34]. All experimental sites, except the Engutie trial site in the Mecha district, had a mean available P far below the critical value. The higher soil P in the soil might be associated with the frequent application of phosphate fertilizers in the double cropping seasons at the Koga irrigation site in Mecha district. The total N content varied from site-to-site experimental locations. The total N of study soils ranged from medium to high based on Taddese et al. [34] ratings. This is associated with low soil pH, which directly affects the uptake of nutrients in the soil as a result of interlinked factors.

4.2 Response of grain yield to nutrients

The overall response of maize yields to NPKSZnB (All) application varied across sites. The variation of nutrient responses from site to site indicates the need for site-specific nutrient management for crops. The variability in crop responses to nutrients supplied is a reflection of the intrinsic heterogeneity of soils among farmer fields, which is mostly brought on by soil management in the belt region of Ethiopia's Amhara Region (19). Similar results were reported by Aliyu et al. [35], Kihara et al. [36] maize yield is varied due to native soil variability in Nigeria and sub-Saharan Africa. This is due to spatial variability in the soil's nutrient-supplying capacity throughout the farmer's field, so it is vital to assess both soil and environment for effective nutrient use to boost maize productivity.

More than double the yield was observed from the application of N and P compared to the unfertilized treatment in the study area soils. N omission substantially reduced grain yield across all the studied districts owing to low N soil content. There is severe N nutrient depletion in Ethiopian highland soils [37–39]. Our finding shows that N is the most limiting nutrient to maize yield in the study areas. This tells the larger requirement for N fertilizer in the study area soils, which are deficient in N [13, 19, 40]. This result shows that the addition of limiting nutrients as fertilizer is mandatory to improve crop production [13, 38, 41, 42, 43].

The response to addition of P nutrient varied, with higher response observed in Mecha, South Achefer, and Burie districts with a wide range of soil P deficiency. Previous findings also indicate that the response to crop yield varied from site to site [13]. Next to N, the absence of P is also limiting the maize yield in soils of maize-growing belts. P is the limiting nutrient to maize yield [44, 45]. Low response to addition of N and P nutrients associated with low uptakes and availability to the plant under lower soil pH as indicated in our soil tests. So, right type and amount of said nutrients have not been acquired by the crop [46, 47]. Preceding studies also indicate that N and P are widely deficient nutrient types in Ethiopian soils [13]. The present result agrees with many research findings that show that without N and P, a severe yield reduction is observed in the study area as well as in many parts of the country [13, 14]. And yet, slight grain yield increment was recorded to P fertilization in soils of Ayehu Guagusa, Womberma, and Jabitehnan districts. Similarly, findings show that low P response is observed in some soils of the Amhara region [48]. Thus, N and P are key nutrient types to boost crop productivity.

The analysis of variance shows non-significant grain yield differences among potassium, S, Zn, and B omitted treatments across all trial sites. The lack of response to potassium and S nutrients suggests that KS nutrients are not a significant limiting nutrient in most of the soils in the study areas. This tells that the inherent K and Sulfur-supplying

capacity of the soils are relatively high in the Northwest Amhara region [13, 48]. Yet, the need to supply these nutrients is suggested by other findings in Ethiopia [49, 50], and other countries [35, 51].

The omission of Zn and B nutrients was shown inconsistently. No significant yield response in all studied districts. Either addition or omission of these nutrients leads to an increase in the grain yield of maize in some trial sites. Similar soil test reports have shown variabilities from site to site under different agroecologies, climates and farm management histories [10]. This might have been associated with soil variability across trial sites. Our finding indicates that the use of these micronutrients has not brought a substantial yield increase [13, 19]. In contradiction to our result Lelago et al. [52], and EthioSIS [10] reported that Zn and B nutrients are deficient in Ethiopian soils, which must be added as mineral fertilizer.

Boron fertilization did not increase yields in any of the 15 sites, but increased uptake in 11 sites. Yields were reduced through B fertilization in five sites, likely because B application induced toxicity [53].

The addition of S with recommended N and P gave almost equal or non-significant grain yield compared with recommended N and P nutrients in all districts of Northwest Amhara, Ethiopia. Generally, recommended NP and NP plus S treatments show almost equal grain yield of maize in all study areas. So, the application of S might not be profitable in the farming system. Our result is contradict with the findings of EthioSIS [10] and Chala et al. [54], who reported that S is deficient in the soils of Ethiopia. The addition of All nutrients and NP had similar trends across all trial sites. This tells us that only N and P fertilizers addition were responsible in enhancing productivity of maize in the study area. Low N and P availability within the soil is linked with many factors, mainly soil acidity and erosion [55, 56]. Lower soil pH exacerbated nutrient deficiencies. Other added nutrients are not limiting due to their adequate supply by inherent soil. Contrary to our findings, Hailu et al. [57], the application of All nutrients is recommended in vertisols of the central highlands of Ethiopia. Moreover, the additions of S and micronutrients are suggested to enhance production in sub-Saharan Africa [58].

5 Conclusion and recommendations

This study articulates yield-limiting factors, mainly nutrients in the farming system. The major variation in yield is due to site soil heterogeneity and environmental variability. The response of nutrients to yield significantly varied among soils at various sites and agroecologies. Maize yield declined sharply when N was omitted, with P omission causing the next greatest reduction in yield. The result revealed that the soil of the study sites was deficient in N and P, due to low uptake and availability in moderately to strongly acidic soils. The addition of K, S, Zn, and B nutrients did not significantly increase yield in all experimental sites, and therefore, they are not limiting to improving yield targets. Overall, N and P are largely required to boost the yield of maize in cereal based mixed farming systems of Ethiopia. This implies that the yield gap of maize should be minimized by addressing the demand for N and P fertilizers for food systems. Soil test based addition of K, S, and micronutrient fertilizers, which are not currently limiting maize productivity, is suggested for smallholder farmers in the region, as well as in Ethiopia. Further assessments are requisite to see the status and requirement of K, S, Zn, and B in vegetable crops and other parts of the country.

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Author contributions

Tadele Amare, Tesfaye Feyisa, Anteneh Abewa: Conceptualization of the proposal; Zerfu Bazie performed the experiment, data collection, and analyses, drafted the manuscript; Erkihun Alemu, Bitewulign Kerebh, Abere Tenagne, Zelalem Addis, Beamlaku Alemayehu, Desalegn Getaneh, Atakltie Abebe, Dres Tewabe, Alebachew Enyew performed the experiment and data collection; Abraham Awoke, Zmie Ambaw: soil data collection and analyses. All authors have read and agreed to the published version of the manuscript.

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Data availability

Datasets generated or analyses during the current study will be given upon request to the corresponding author.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

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Sources of the plants used in this study

Not applicable.

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Competing interests

The authors declare no competing interests.

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