On-farm nutrient omission research as a basis for developing site-specific nutrient management practices in the maize belts of west Amhara

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Abstract

The potential yields of improved maize varieties could not be fully realized mainly due to inappropriate soil nutrient management in most parts of the country. The site-specific recommendation is not often used to cover diverse agro-ecologies disregarding the variability in the cropping system, soil fertility, and other factors. This has highly hampered maize productivity resulting in an overall low average national maize grain yield. In view of this, a study was conducted for three consecutive rainy seasons in the maize belt areas of the northwestern parts of the Amhara National Regional State to obtain the maximum achievable yield potentials of maize, to determine the most yield-limiting nutrients, and to create a strong database of maize responses to applied nutrients so that decision support tools could be assessed for the study area. The yield-limiting potential of nitrogen, phosphorus, and potassium was intensively evaluated by omitting each of the three nutrients. Sulfur and Zn nutrients, as well as lime and compost, were added to improve the efficiency of NPK on the yield of maize. Two high-yielding hybrid maize varieties (BH-540 and BH-660) were used for the study. BH-540 was used for the Mecha district while BH-660 was used for the south Achefer, Jabitahnan, Burrie, and Womberma districts. The finding of the research showed us that yield was increased by more than 50% due to fertilizer applications. The achievable yield potential of maize for the study sites was more than 12 t ha^{-1} for both varieties. The most yield-limiting nutrient in the study sites was nitrogen followed by phosphorus. Potassium was not a yield-limiting nutrient for the study sites. Without nitrogen, the yield potential of both varieties was insignificant from the control (without nutrients). The result also showed very high variability with sites, indicating site-specific fertilizer consultation is important for the policymakers, farmers, and investors. Finally, intensive plant response to NPK database for maize was generated and could be used to devise site-specific decision support tools.

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

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 fertilizer source at the right rate, at the right time in the growing season, and in the right place is an essential basis for optimizing the use of nutrients (Chathurika, *et al.*, 2014; Ferguson *et al.*, 2002). The supply of required quantities of plant nutrients according to the demand of the plant in balanced quantities is not commonly practiced and it could be the main soil fertility constraint restricting crop growth in Ethiopia. It is also favorable

space and associated factors are not well quantified and reported in the farming systems of Ethiopia; and its implication on improving the productivity of targeted crop is immense. Supplementary approaches to the conventional field experimentations through decision support tools including crop response to nutrient modeling could help to generate the required information for immediate decision-makers, investors and farmers as well as for capturing existing potentials (MacCarthy *et al.*, 2018). However, to draw reliable conclusions on site-specific decision support tools a strong and well-organized database of 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 general lack of an organized database for the development crop and site-specific decision support tools.

Maize (*Zea mays*) is one of the major cereal crops with better achievable potentials to ensure food security of the nation and yet with less than 4 t ha^{-1} yield on national average (Abdulkadir *et al*., 2017; FAO, 2014). Under most agro-ecologies and soils of Ethiopia, the response of maize to nitrogen and phosphorus has been very high (Amare *et al*., 2018; Abdulkadir *et al*., 2017) and yet the achievable potential of maize yield is very high with a further increase of NP fertilizers in the maize belts of the country especially in the Northwestern parts. Intensive research and development work on soil fertility is highly needed to transform the current state of maize production to its achievable potential. The maximum attainable potentials of maize should be targeted and reduce the variations among smallholder maize producers. One of the perquisites to improve the productivity and production of maize is to bring on board an intensive database. The International Plant Nutrition Institute (IPNI) has been working with partners in sub-Saharan Africa to improve crop intensifications including maize. IPNI extended its project to maize belts of the Amhara National Regional State for three years (2016-2018) to generate intensive data on the response of maize to the applied nutrients focusing on NPK, to analyze achievable yield potential in the region, and generate a database that could help developing decision support tools.

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

fields represent the main soil types occurring in the area, commonly used cropping systems and farm management practices, and a range of socio-economic conditions (low to high resource endowment). The soil of these districts is dominantly characterized by Nitisols. The general feature of the agricultural landscape where maize takes the larger area coverage is flat, which is good for future expansion and intervention of mechanized agricultural technologies. All districts have a uni-modal type of rainfall which extends from April to October. The main rainy months are June, July, and August. A mixed type of farming system (crop production and livestock raising) is practiced. 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^{o}C. The altitudinal range of major maize growing areas of the district ranges from 1900-2200 masl. Maize and finger millet is the dominant cereal crops grown in the Mecha district. Early maturing maize varieties are commonly grown in the district compared to other districts of the study sites. Following the Koga irrigation scheme, crop diversity steadily increased. The district is also known for high production and coverage of eucalyptus. Compared to Mecha, South Achefer receives a higher amount of rainfall with an extended growing period; helping to grow high-yielding late maturing maize varieties. The annual rainfall of Jabitahnan-Burrie-Womberma districts reaches about 1600 mm, with mean minimum and maximum temperatures of 12 and 29^{O}C, respectively. The major maize-growing areas of this district are in the mid-altitude of 1700 to 2200 masl. Crop diversity in Jabitahnan-Burrie-Womberma districts is better than Mecha and South Achefer. The major crops grown in this part of the study are maize, wheat, tef, finger millet, pulses, and pepper; maize is the dominant crop. Perennial crops like coffee and fruits are also commonly grown. Because of extended amounts of rainfall, high-yielding and late maturing maize varieties are commonly grown in the district.

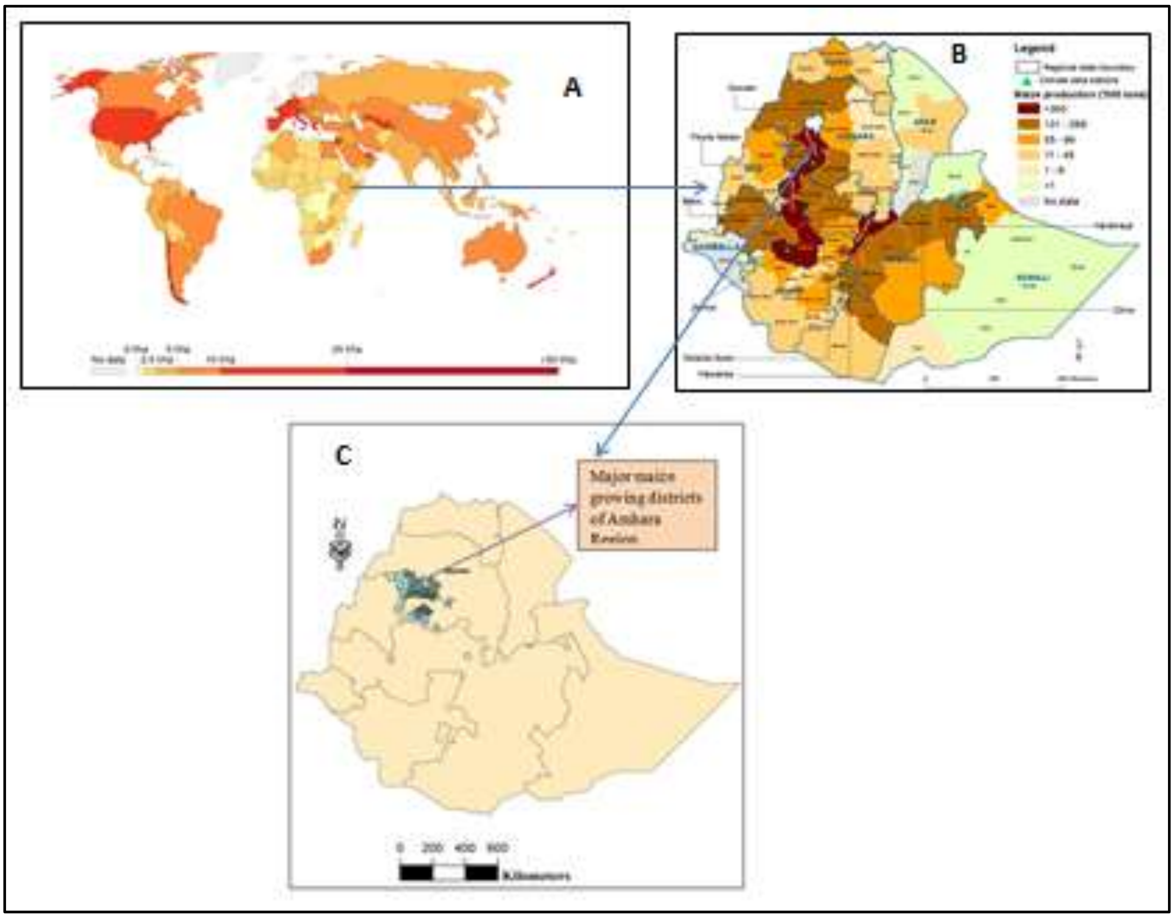

Figure 1. A: Maize productivity at global level and Ethiopian position (https://ourworldindata.org/grapher/maize-yields), **B**: Maize production and productivity in Ethiopia (Abate *et al.*, 2015), and **C**: Major maize growing districts of the Amhara National Regional State (Mecha, south Achefer, Jabitahnan, Burrie, and Womberma) where the research was conducted.

Experimental setup

The nutrient omission trial was established on 30 sites per year with 11 non replicated treatments per site during the first two years. In the third year, it was established on 15 sites with treatments replicated thrice at each site. The research consisted of NPK stand-alone plots, NPK omission plots, control plots, NPK plus secondary and micronutrients, NPK plus compost, and NPK plus lime treatments (Table 1 and 2).

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 regulates nutrient

Table 2. Nutrient application rates

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

The rate of Nutrients (NPK) was applied at rates required to achieve the expected attainable yield without nutrient limitation in each location. The rate of lime was calculated based on the lime requirements developed for wheat (Agumas *et al.*, 2016.) and applied in rows at planting. The sources of nutrients were: NPS, Urea, TSP, MOP, and $ZnSO_4$. One t ha^{-1} of compost was applied at planting in rows. 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 while all other nutrients were applied as basal at the time of planting. Plot sizes were 3 m by 4.5 m and the distance between plots and replications was 1 m while the distance between rows and plants was 0.75 m and 0.3 m; respectively.

Soil sampling, preparations, and analysis

Composite soil samples were collected at depths of 0-20 cm before planting for each site. Samples were air-dried; ground using 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). Soil organic carbon content was determined by the wet digestion method using the Walkley and Black procedure (Nelson and Sommers, 1982). The available phosphorus was determined following the Olsen procedure (Olsen and Sommer, 1982). The exchangeable potassium 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. Upon the existence of significant difference for ANOVA, ($p < 0.05$), further analysis of

were also employed to evaluate responses.

Results and discussion

Results of soil analysis for the study sites

The results of soil analysis collected before planting are summarized 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 while for Jabitahnan-Burrie-Womberma district the average value was 5.2 but with a low level of exchangeable acidity (less than 2 -

Mean values of the soil organic carbon (SOC) contents 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 average values of available P for Mecha, south Achefer, and Jabitahnan-Burrie-Womberma were 7.4 ppm, 3.6 ppm, and 7.6 ppm; respectively. The mean value of exchangeable potassium was 0.6, 0.61, and 0.75 cmol kg^{-1} of soil for Mecha, South Achefer, and Jabitahinan-Burrie-Womberma districts; respectively.

The pH of the soil for all the sites was acidic (FAO, 1984) but with a low level of exchangeable acidity (less than 2 - implying maize yield maximization could be achieved by fertilizer applications and 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 the SOC for sustainable yield production, to improve crop responses and recovery of applied fertilizers as the critical value is 2% (Loveland and Webb, 2003; Murphy, 2014). Because of the low levels of SOC, the high productivity of maize for the study sites could not be expected without synthetic fertilizers application (NP). Therefore, sustainable maize production could be achieved through integrated

10.8 t ha^{-1} of yield was recorded from NPK application for the year 2016 at Tyatya *Kebele* of Burrie district (only the mean values of all sites in the districts presented in Table 3). The maximum mean grain yield of maize ($^{-}$) in south Achefer with NP fertilizer was recorded in 2018 cropping seasons compared to the control (2.5 t ha^{-1}) (only the mean values of all sites in the districts presented in Table 3).

Without nitrogen (omitting nitrogen), the use of phosphorus was not significantly different from the one without nutrient (control) as shown in Figure 3. With nitrogen alone, the yield was better than using phosphorus alone or phosphorus in combination with potassium (Table 3). But when nitrogen was combined with phosphorus, the yield surpassed the one with nitrogen alone and statistically non-significant 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 mono-cropping and less emphasis on soil health restoration, the sustainability of crop production might be broken into difficult situations. Our findings of highest yield records from Mecha and south Achefer districts were maize grown after lupine (*Lupinus albus*) or noug (*Guizotia abyssinica*); indicates the importance of rotation compared to the mono-cropping system or cereal after cereal rotation system.

The result was clearly separated into two groups for the majority of the sites: Treatment 1-6 in one group and treatment 7-11 in the second group (refer to Table 2 for the treatments). Therefore, the significant difference for most of the sites was between these groups while there was no significant difference between treatments above 6; indicating maximum yield potential of maize could be realized by NP fertilizers without any further cost to potassium, lime, and organic matter. The yield-limiting nutrients (NPK) were elaborated by separating the NPK treatment and the control from the rest of the treatments for all sites across the years by omitting each of the nutrients as shown in Figure 2. The yield of maize was slightly higher than the control when N was omitted and the trend was similar for all sites and years. The yield penalty for N omission accounts was higher than the yield penalty by phosphorus. The interaction effect of N and P boosted the productivity of maize as shown even with the omission of potassium (Figure 3).

The productivity of maize without fertilizer was very low compared to the fertilized ones (about less than 50%) with the exception of a few cases. This finding indicated that optimum maize production could be simply achieved by NP nutrient optimization as already analyzed by Abate *et al*. (2015). The findings of our research showed that more than three times achievable grain yield (Figure 2 and Figure 3) compared to the 3t ha^{-1} of the national average (Abate *et al*., 2015) with NP nutrients alone.

In general, the yield found all over the sites across the seasons was above the national average estimated by FAO (2014) (2.5 to 5 t ha^{-1}) and 3 t ha^{-1} (Abate *et al*., 2015), indicating the existence of large potential to boost the productivity of maize even with modern old varieties though nutrient optimization. The yield attained with our research could be the highest in the sub-Saharan countries except for South Africa (Abate *et al*., 2015; FAO, 2014; Gudeta *et al*., 2009; Gudeta *et al*., 2010).

As described above in the analysis of soils for the study sites, there was a significant difference ($p< 0.01$) among and between treatments. Without nitrogen (omitting nitrogen), the use of phosphorus was not significantly different from the one without nutrient (control) and hence the addition of a nutrient without nitrogen leads to economical risk for the farmers and the nation as stated by Gudeta *et al.*, (2010). With nitrogen alone, the yield was better than using phosphorus alone or phosphorus in combination with potassium. But when nitrogen was combined with phosphorus, the yield surpassed the one with nitrogen alone and statistically non-significant with treatment combinations of NPK as well as NPK plus other soil amendments (lime and vermicompost). This indicates that K is not limiting maize yield in the study areas while N and P is the yield-limiting nutrients.

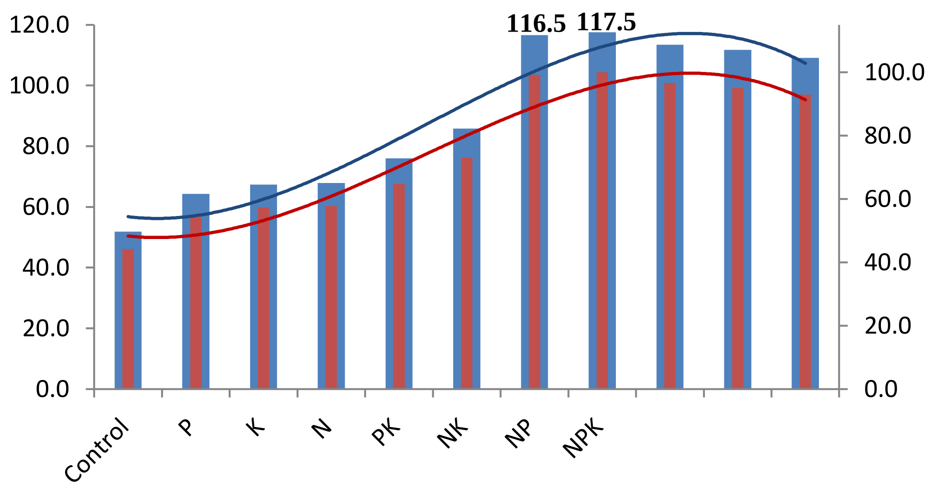

Figure 1. Achievable yield potentials and relative yield of maize (variety, BH 540) at Mecha district of Mekeni-Warka site (single site) in 2016 cropping season.

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

	Mecha	Jabitahinan-Burrie-Womberma	South Achefer

The contribution of soil organic matter to improve the efficiency of the nutrient the NPK nutrients was not significant albeit the low levels of the SOC matter all over the study areas; might be because its amount was lower or its effect might not be visible in the short term. Otherwise, the contribution of organic fertilizers to sustainable maize production in sub-Saharan African was recognized and reported (Gudeta, *et al*., 2009, Gudeta, *et al*., 2010). Abate *et al*. (2015) reported a drastic reduction in the use of organic fertilizer sources for the majority of maize-producing areas in the country in general and in the Amhara Regional State in particular. This could be due to its less competent effect compared to the synthetic fertilizers, despite high mobilizations and campaigns towards organic fertilizer, especially for compost. Our result to soil analysis and the yield responses (Table 3) supported each other indicating nitrogen and phosphorus are still the most yield-limiting nutrients and it was again in line with the findings of Amare *et al*. (2018).

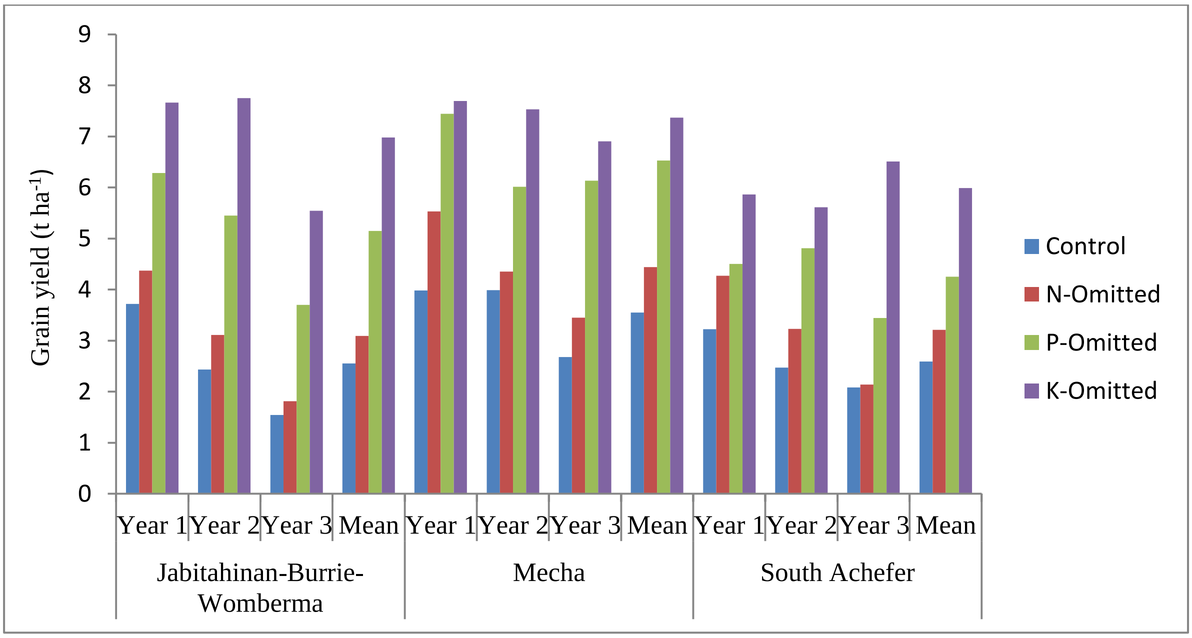

Figure 3. The effect of omitting each nutrient (NPK) on the yield of maize for all the study sites across the years.

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 strong database for maize yield related to NPK nutrients was generated. The findings of the research showed that the yield of maize could be achieved more than 10 t ha^{-1} with nutrient management even using the old improved varieties (BH-66o and BH540) that were more than three times the national as well as the regional average yield. Our finding indicated maize productivity could be increased through NP 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 caused the variability could be the history of the farm management (rotation etc.). Therefore, sustainable intensification of maize production should also take into account improving existing farm management practices (rotation, fertilizer application, disease and pest management, etc.). The yield-limiting nutrients for the production of maize for the major maize-producing areas of the region were in the order of nitrogen than phosphorus. 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 150 kg N ha^{-1} and 125 kg P_2O_2 ha^{-1}. Further research work on the appropriate rates of nitrogen and phosphorus nutrients to meet the biological and economic optimum is critically important.

Amare T., Bazie Z., Alemu E., Wubet A., Agumas B., Muche M., Feyisa T. and Fentie D. (2018). Crops response to balanced nutrient application in northwestern Ethiopia. Blue Nile Journal of Agricultural Research: 1 (1), 1-14.

Bai Z., Li H., Yang X., Zhou B., Shi X., Wang B., Li D., Shen J., Chen Q., Qin W., Oenema O. and Zhang F. (2013). The critical soil P levels for crop yield, soil fertility and environmental safety in different soil types. Plant Soil: 372, 27-37. Doi: 10.1007/s11104-013-1696-y.

Barbagelata P.A. (2006). Evaluation of potassium soil tests and methods for mapping soil fertility properties in Iowa corn and soybean fields. Retrospective Theses and Dissertations, Iowa State University. https://lib.dr.iastate.edu/rtd/1797

Chathurika J.A.S., Indraratne S.P. and Dandeniya W.S. (2014). Site specific fertilizer recommendations for maize (*Zea mays L.*) grown in reddish brown earth and reddish brown Latasolic Soils. Tropical Agricultural Research: 25 (3), 287-297.

Edreira J.I.R., Cassman K.G., Hochman Z., van Ittersum, M.K., van Busse L., Claessens L., and Grassini P. (2018). Beyond the plot: technology extrapolation domains for scaling out agronomic science. Environ. Research Letters: 13 (5).

Farina M.P.W., Channon P., Thibaud G.R. and Phipson J.D. (1992). Soil and plant potassium optima for maize on a kaolinitic clay soil. South African Journal of Plant and Soil: 9 (4), 193-200. Doi: 10.1080/02571862.1992.10634628

FAO. (2014). Average maize yields. The United Nations Food and Agricultural Organization, Rome, Italy. Accessed on: 07/05/2019.

FAO. (1984). FAO Fertilizer and plant nutrition bulletin 9. Food and Agricultural Organization of the United Nations, Rome, Italy.

Ferguson R.B., Hergret G.W., Schepers J.S., Gotway C.A., Cahoon J.E. and Peterson T.A. (2002). Site specific nitrogen management for irrigated maize: Yield and Soil Residual Nitrate effects. Soil Science Society of America Journal: 66, 544-553.

Gudeta S., Akinnifesi F.K., Ajayi O.C., Place F. (2009). Evidence for impact of green fertilizers on maize production in sub-Saharan Africa: a meta-analysis. ICRAF Occasional Paper No. 10. Nairobi: World Agroforestry Centre.

Variation in maize yield gaps with plant nutrient inputs, soil type and climate across sub-Saharan Africa. Field Crops Research: 116, 1-13.

Hengl T., Heuvelink G.B., Kempen B., Leenaars J.G., Walsh, M.G., Shepherd K.D., Sila A., MacMillan R.A., Mendes de Jesus J., Tamene L., Tondoh J.E. (2015). Mapping soil properties of Africa at 250 m resolution: random forests significantly improve current predictions. PLoS ONE: 10(6), e0125814. Doi: 10.1371/journal.pone.0125814.

Shangguan W., Wright M.N., Geng X., Bauer-Marschallinger B., Guevara M.A., Vargas R., MacMillan R.A., Batjes N.H., Leenaars J.G.B., Ribeiro E., Wheeler I., Mantel S., Kempen B. (2017). SoilGrids250m: Global gridded soil information based on machine learning. PLoS ONE: 12(2), 1-40. Doi: 10.1371/journal.pone.0169748.

Hirpa A., Meuwissen M.P.M, Van der Lans I.A., Lommen W.J.M., Oude L.A.G.J.M., Tsegaye A. and Struik P.C.
attributes in Ethiopia: A conjoint analysis. Agronomy Journal, 104:1413-1424.

IPI (International Potash Institute). (2016). Technical manual on potash fertilizer: Use for soil fertility experts and development agents. Doi: 10.3235/978-3-905887-22-8

Kaizzi K.C., Mohammed M.B., Nouri M. (2017). Fertilizer use optimization: Principles and approach. Vol 17, CAB International, Nairobi, Kenya, 9-19.

Kebede D. and Ketema M. (2017). Why do smallholder farmers apply inorganic fertilizers below the recommended rates? Empirical evidence from potato production in eastern Ethiopia. Adv. Crop Sci Tech: 5 (2).

Li H., Huang G., Meng Q., Ma L., Yuan L., Wang F., Zhang W., Cui Z., Shen J., Chen X., Jiang R., Zhang F. (2011). Integrated soil and plant phosphorus management for crop and environment in China. A review. Plant Soil: 349, 157-167.

Loveland P and Webb J. (2003). Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil and Tillage Research: 70, 1-18.

MacCarthy D.S., Masikati J.K.P., Adiku S.G.K. (2018). Decision support tools for site-specific fertilizer recommendations and agricultural planning in selected countries in sub-Sahara Africa. Nutrient Cycling in Agro-ecosystems: 110 (3), 343-359.

Murphy B.W. (2014). Soil organic matter and soil function- review of the literature and underlying data. Department of the Environment, Canberra, Australia.

Nelson D.W. and Sommers L.E. (1982). Total carbon, organic carbon and organic matter. In A.L. Page, R.H. Miller, and D.R. Keeney (Ed.), Methods of soil analysis. Part 2: Chemical and microbiological properties. Wisconsin: Madison.

Olsen S.R. and Sommers L.E. (1982). Phosphorus. In: A.L. Page, R.H. Miller, and D.R. Keeney (Ed.), Method of soil analysis. Part 2: Chemical and microbiological properties, 403-430. Wisconsin: Madison.

Sertsu S. and Bekele T. (2000). Procedures for soil and plant analysis. Technical paper no. 74. National Soil Research Centre, Ethiopian Agricultural Research Organization, Addis Ababa, Ethiopia.

Tang X, Li JM, Ma YB, Hao X, Li XY (2008). Phosphorus efficiency in long-term (15 years) wheat-maize cropping systems with various soil and climate conditions. Field Crops Res 108:231 237 doi:10.1016/j.fcr.2008.05.007

Wang B., Liu H., Hao XY., Wang XH., Sun JS. Li JM. and Ma YB. (2016). Agronomic threshold of soil available phosphorus in grey desert soils in Xinjiang, China. Earth and Environmental Science: 41, 012010. Doi: 10.1088/1755-1315/41/1/012010

Wu Q., Zhang S., Ren Y., Zhan X., Xu M. and Feng G. (2018). Soil phosphorus management based on the agronomic critical value of Olsen P, Communications in Soil Science and Plant Analysis. Doi: 10.1080/00103624.2018.1448410

Wu Q.H., Zhang S.X., Feng G., Zhu P., Huang S.M., Wang B.R., Xu M.G. (2020). Determining the optimum range of soil Olsen P for high P use

832-843. Doi:10.1016/S1002-0160(20)60040-6.

Zhong, X. Y., X. R. Zhao, H. J. Bao, H. H. Li, and Q. M. Lin. (2004). The evaluation of phosphorus leaching risk of 23 Chinese soils. I. Leaching criterion. Acta Ecological Sinica 24:2275 80.