

RESEARCH ARTICLE

# Yield response of barley to the application of mineral fertilizers containing major nutrients on Cambisols and Vertisols in Ethiopia<sup>†</sup>

Beza Shewangizaw<sup>1,\*</sup>, Gebreyes Gurumu<sup>2</sup>, Getachew Agegnehu<sup>3,4</sup>, Mulugeta Eshetu<sup>5</sup>, Shawl Assefa<sup>1</sup>, Fisseha Hadgu<sup>6</sup>, Jemal Seid<sup>2</sup>, Degefie Tibebe<sup>7</sup>, Gudeta W. Sileshi<sup>8,9</sup> and Lulseged Tamene<sup>10</sup>

<sup>1</sup>Amhara Regional Agricultural Research Institute, Debre Birhan Agricultural Research Center, P. O. Box 112, Debre Birhan, Ethiopia, <sup>2</sup>Ethiopian Institute of Agricultural Research, P. O. Box 2003, Addis Ababa, Ethiopia, <sup>3</sup>Ethiopian Institute of Agricultural Research, Holeta Agricultural Research Center, P. O. Box 31, Holeta, Ethiopia, <sup>4</sup>International Crop Research for the Semi-Arid Tropics, P. O. Box 5689, Addis Ababa, Ethiopia, <sup>5</sup>Oromia Agricultural Research Institute, Sinana Agricultural Research Centre, Sinana, Ethiopia, <sup>6</sup>Tigray Agricultural Research Institute, Mekelle Soil Research Center, Mekelle, Ethiopia, <sup>7</sup>Water and Land Resources Center, Addis Ababa University, Addis Ababa, Ethiopia, <sup>8</sup>Department of Plant Biology and Biodiversity Management, Addis Ababa University, Addis Ababa, Ethiopia, <sup>9</sup>School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Pietermaritzburg, South Africa and <sup>10</sup>International Center for Tropical Agriculture, P. O. Box 1569, Addis Ababa, Ethiopia

\*Corresponding author. Email: bezashewangezaw@gmail.com

(Received 02 June 2021; revised 03 August 2021; accepted 20 September 2021)

## Abstract

Increasing barley production in the face of declining soil fertility on smallholder farms is a critical challenge in Ethiopia. The objectives of this study were to (1) determine the optimum rates of nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) fertilizers under a balanced fertilization of other macro- and micronutrients (zinc and boron) and (2) quantify the agronomic efficiency of N and P on Cambisols and Vertisols. The trials were conducted for three consecutive years (2014–2016) on farmers' fields on 83 sites under rain-fed conditions. On each farm, six rates of N, P, K, and S with a balanced application of the other nutrients were laid out separately in a randomized block design with three replicates. Balanced fertilization resulted in yield increments of 26–59% on Cambisols and 18–74% on Vertisols, as compared with the control (0 N). Application of P increased grain yield from 11% to 30% and from 7% to 14% due to the interaction of P by soil type as compared with the control. The application of K and S, however, had no significant effect on barley yields on either soil type. The highest agronomic efficiency of N (AEN) was obtained from 46 kg N ha<sup>-1</sup>, with AEN increasing by 117% on Cambisols and 33% on Vertisols, as compared with the highest N rate of 230 kg N ha<sup>-1</sup>. The maximum agronomic efficiency of P (AEP) was recorded with 10 kg P ha<sup>-1</sup> on Vertisols, with AEP increasing by 73% on Cambisols and 452% on Vertisols, as compared with the application of 50 kg P ha<sup>-1</sup>. With balanced application of other nutrients, use of 230 kg N and 20 kg P ha<sup>-1</sup> was recommended for tepid sub-moist mid-highlands and Vertisols. For tepid sub-humid mid-highlands, application of 46 kg N and 20 kg P ha<sup>-1</sup> with balanced application of other nutrients was recommended. For Cambisols, application of 230 kg N and 40 kg P ha<sup>-1</sup> was recommended with balanced application of the other nutrients. Similarly, application of 230 kg N, 40 kg P, and 10 kg S ha<sup>-1</sup> was tentatively recommended for cool sub-most mid highlands. However, response to K was inconsistent and therefore a firm recommendation could not be proposed for the study sites. Further research needs to be conducted on more soil types and locations.

<sup>†</sup>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.

© The Author(s), 2021. Published by Cambridge University Press. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

**Keywords:** Agro-ecology; Agronomic efficiency; Nutrients; Soil type; Balanced fertilization

## Introduction

Enhancing agricultural productivity in sub-Saharan African countries (SSA) including Ethiopia is a major approach to break the vicious cycle of rural poverty. In this regard, the Alliance for a Green Revolution in Africa has aimed to increase fertilizer use from the current 8 kg to 50 kg fertilizer nutrients ha<sup>-1</sup> (Vanlauwe *et al.*, 2011). The judicious use of external nutrient sources is now recognized as a prerequisite for sustainable intensification. Fertilizers constitute an integral part of the crop production technologies, and their proper management is important for maximizing yields (Stewart *et al.*, 2005), optimum water utilization, and minimum effects on environment (Goulding *et al.*, 2008).

With increasing population pressure and limited possibilities of expanding arable land, application of mineral and organic fertilizers (among other things) contributes the highest share to increase productivity (Amede *et al.*, 2001; Vanlauwe *et al.*, 2010). Nevertheless, soil nutrient balance studies in Africa show evidence of widespread nutrient mining as compared with amendments. One result is a negative nutrient balance (Henao and Baanante, 1999; Sanchez, 2002; van Beek *et al.*, 2016), which leads to severe nutrient deficiencies across ecological zones and consequently declining crop productivity (van Beek *et al.*, 2011; Zeleke *et al.*, 2010). Nutrient mining of 130 kg N, 5 kg P, and 25 kg K ha<sup>-1</sup> year<sup>-1</sup> has been reported in the East African highlands, including Ethiopia (Smaling *et al.*, 1997). Nutrient losses are only partially compensated by natural and synthetic inputs; thus, the nutrient balance for all of SSA has been negative (i.e. -26 kg N, -3 kg P, and -19 kg K ha<sup>-1</sup> year<sup>-1</sup>) (Drechsel *et al.*, 2001). In Ethiopia, the losses were even larger than the average of in SSA: 122 kg N, 13 kg P, and 82 kg K ha<sup>-1</sup> year<sup>-1</sup> (Hailelassie *et al.*, 2005). The negative nutrient balances were mainly attributed to continuous cropping (Agegnehu *et al.*, 2014; Agegnehu *et al.*, 2008), application of suboptimal levels of mineral fertilizers, depletion of soil organic matter, and high proportions of cereals in the cropping system (Zeleke *et al.*, 2010; Agegnehu *et al.*, 2014; Agegnehu *et al.*, 2008). This is believed to disrupt the balance between providing a sufficient amount of the required nutrient and its associated impact on soil quality (van Beek *et al.*, 2016).

Fertilizer recommendation in Ethiopia was mainly based on a single blanket recommendation for most crops (64 kg N ha<sup>-1</sup> and 20 kg P ha<sup>-1</sup>) as urea and di-ammonium phosphate (DAP). This blanket recommendation often fails to take into consideration differences in resource endowment (soil type, labor capacity, and climate risk) or make allowances for dramatic changes in input/output price ratio, thereby deterring farmers from fertilizer application (Zeleke *et al.*, 2010; van Beek *et al.*, 2011). The nutrients in the blanket recommendation are not well balanced agronomically, and the continued use of this recommendation will gradually exhaust other soil nutrient reserves and create nutrient imbalances (Zeleke *et al.*, 2010). Therefore, neither yields nor profits can be sustained using unbalanced application of fertilizers, as the practice results in accelerating deficiencies of other soil nutrients. According to recent analysis, N, P, S, boron (B), and zinc (Zn) deficiencies are widespread in Ethiopian soils, while K, copper (Cu), molybdenum (Mo), manganese (Mn), and iron (Fe) are also reported as deficient (Dibabe *et al.*, 2007). This is particularly apparent in soils and/or areas where agricultural crop productions make use of only N and P fertilizers on a continuous basis. There is also growing evidence of K deficiency in Ethiopia even in soils with optimum amount of exchangeable K (Laekemariam *et al.*, 2018). This is associated with imbalances in Ca, Mg, and K in the soil, a problem known as induced deficiency.

Barley (*Hordeum vulgare* L.) is one of the main cereals cultivated in the highlands of Ethiopia. The crop is the fifth most important crop after teff (*Eragrostis tef*), maize, wheat, and sorghum. Although barley covers an area of 951 993 million ha, the national average yield remains low at 2.16 t ha<sup>-1</sup> (CSA, 2018). Barley is the major grain used for malting and brewing by subsistence

farmers in the highlands of Ethiopia (FAO, 2016; Agegnehu *et al.*, 2014). And though there is a considerable potential for increased barley production, numerous factors are considered yield limiting (Mulatu and Lakew, 2011). The productivity of barley in Ethiopia has remained very low (about 1.3 t ha<sup>-1</sup> compared with the world average of 2.4 t ha<sup>-1</sup>) (Mulatu and Grando, 2011). The most important abiotic stresses include low soil fertility, low soil pH, poor soil drainage, drought, and poor agronomic practices. Among these factors, low levels of fertilizer application, soil acidity (pH < 5.5), deficiency of nutrients, especially N and P, due to continuous cropping contribute to the low yields of cereals ((Mulatu and Lakew, 2011; Agegnehu *et al.*, 2011; Agegnehu *et al.*, 2014). Fertilizer use for barley production is the lowest among all the cereals, which is only 48.3% of the total area of land covered by barley (Mulatu and Lakew, 2011; Agegnehu *et al.*, 2011).

Efficient use of mineral fertilizer inputs is crucial for the overall nutrient balance in intensive cropping systems. The N and P use efficiencies of cereals need to be specifically improved by proper management of N and P fertilizers to reduce negative environmental effects while increasing crop yields (Lichtfouse *et al.*, 2009; Raun *et al.*, 2002). To overcome the constraint of low nutrient recovery and optimize fertilizer use, there is a need to develop appropriate fertilizer recommendations that are differentiated according to agro-ecological zones (AEZs) and soil type. This can ensure production can be intensified in a cost-effective and sustainable manner. The objectives of the present study were therefore to (1) determine soil and AEZs-specific response of barley to N, P, K, and S under balanced application of other nutrients; (2) quantify the agronomic optimum rate for N, P, K, and S fertilizer; and (3) evaluate agronomic efficiency (AE) of N, P, K, and S nutrients in the Ethiopian highlands.

## Materials and Methods

### Description of experimental sites

The experiments were conducted in the main cropping season from 2014 to 2016 in 83 farmers' field in the main barley-growing districts of Basona Werana district, Siemen Shewa Zone of the Amhara Regional State, Alaje district of southern Tigray Zone of Tigray Regional State, and Sinana district of Bale Zone of Oromia regional State (Figure 1; Supplementary Table S1). Specifically, the experiment was conducted in Goshebado and Gudoberet kebele of Basona Werana district for three years, Ayeba kebele of Alaje district for one year, and Salka and Ilusinbitu kebele of Sinana district for three years (Figure 1). The number of farmers field at each soil type and AEZs are presented in Supplementary Table S1.

Geographically, Basona Werana is located at 9°43'58" to 9°52'42" E and 39°25'28" to 39°40'08" N; Alaje at 12°52'25" to 12°52'47" E and 39°32'45" to 39°33'02" N; and Sinana at 7°04'17" to 7°15'16" E and 40°23" to 40°12'20" N. The altitude ranges from 2802 to 3043 masl for Basona Werana, 2729–2756 masl for Alaje, and 2368–2463 masl for Sinana sites. Agro-ecologically, Basona Werana is found in warm, sub-moist mid-highlands (SM3) and in cool sub-moist mid-highlands (SM4). Alaje lies in cool sub-moist mid-highlands (SM4) and Sinana is found in warm, sub-humid mid-highlands (SH3).

All the three districts are characterized by bimodal rainfall pattern receiving average annual rainfall of 1029 mm, 1131 mm, and 773 mm for Basona Werana, Sinana, and Alaje district, respectively (the highest rainfall occurs in June–September). The long-term annual average minimum temperatures for Basona Werana, Sinana, and Alaje are 13.7°C, 13.5°C, and 12.7°C, respectively. The average annual maximum air temperatures are 18°C, 16.4°C, and 17.2°C, respectively. The monthly average rainfall and temperature of all districts are presented in Figure 2. The soil types on the study sites are Cambisols and Vertisols, which cover 10.2% and 15.3% of the land area in Ethiopia (Abebe, 1998). Selected soil physico-chemical properties of each AEZ and soil types are presented in Table 1.

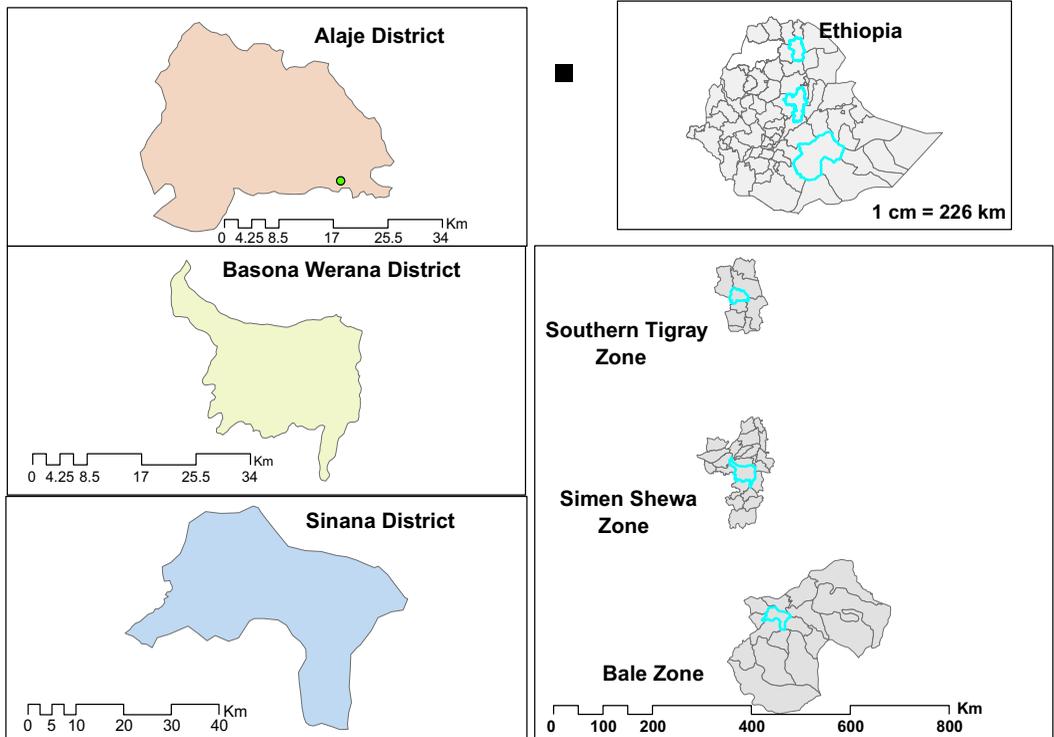


Figure 1. Study sites located in the three regions of the country.

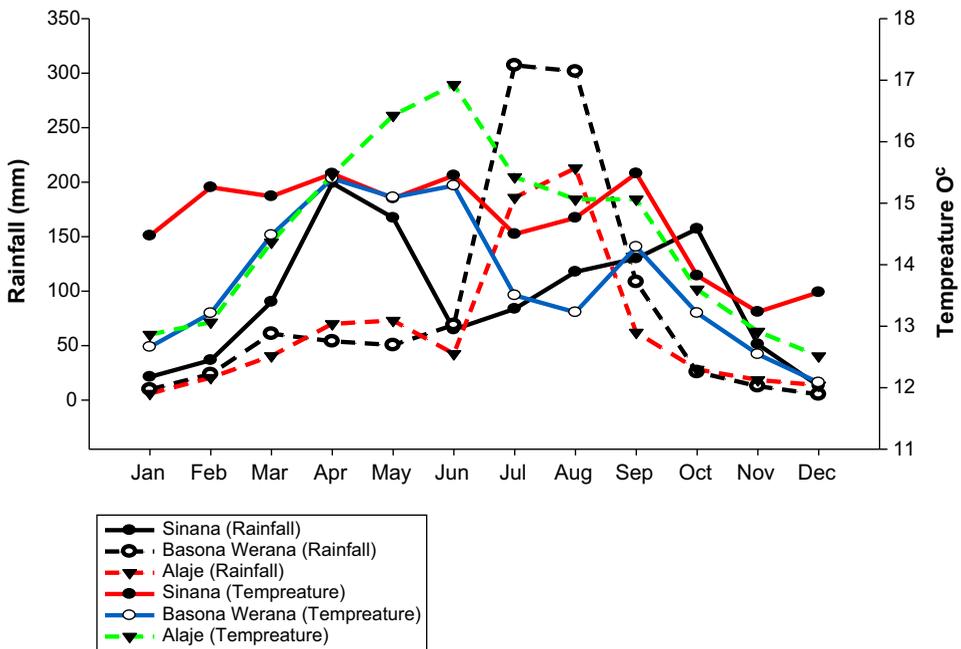


Figure 2. Monthly rainfall and temperature of the study area.

**Table 1.** Agro ecology (AEZ) and chemical properties of soils of Basona Werana, Sinana, and Alajie districts in Ethiopia in the 2014–2016 main cropping seasons

Site	Property	Quantity	
Basona Werana	AEZ	SM3 and SM4	
	Soil type	Cambisols	
	pH	6.8 ( $\pm 0.04$ )	Neutral <sup>a</sup>
	SOC (%)	3.7 ( $\pm 0.16$ )	High <sup>a</sup>
	N (%)	0.2 ( $\pm 0.013$ )	Moderate <sup>a</sup>
	P (mg/kg)	15.1 ( $\pm 2.1$ )	Medium <sup>b</sup>
	K (mg/kg)	764.5 ( $\pm 17.8$ )	Very high <sup>c</sup>
	Texture	Clay	
Sinana	AEZ	SH3	
	Soil type	Cambisols	
	pH	6.8 ( $\pm 0.04$ )	Neutral <sup>a</sup>
	SOC (%)	2.4 ( $\pm 0.13$ )	Moderate <sup>a</sup>
	N (%)	0.17 ( $\pm 0.012$ )	Moderate <sup>a</sup>
	P (mg/kg)	15.4 ( $\pm 1.9$ )	Medium <sup>b</sup>
	K (mg/kg)	356.6 ( $\pm 15.7$ )	Very high <sup>c</sup>
	Texture	Clay loam	
Alajie	AEZ	SM4	
	Soil type	Vertisols	
	pH	6.6 ( $\pm 0.04$ )	Slightly acidic <sup>a</sup>
	SOC (%)	1.7 ( $\pm 0.13$ )	Moderate <sup>a</sup>
	N (%)	0.18 ( $\pm 0.012$ )	Moderate <sup>a</sup>
	P (mg/kg)	17.5 ( $\pm 1.9$ )	Medium <sup>b</sup>
	K (mg/kg)	284 ( $\pm 15.6$ )	High <sup>c</sup>
	Texture	Clay	

AEZ = Agro-ecologica zones, SH3 = tepid sub-humid mid-highlands (Sinana district), SM3 = tepid sub-moist mid-highlands (Basona Werana districts, Gudoberet kebele), SM4 = cool sub-moist mid-highland (Goshebadu kebele of Basona Werana district and Alaje districts), <sup>a</sup>= Tekalign (1991), <sup>b</sup>= Cottenie (1980), Jones, J. Benton (2003), <sup>\*</sup>=Alajie district, <sup>\*\*</sup>= Basona Werana districts.

### Treatment and experimental design

The experiment included six rates of N (0, 46, 92, 138, 184, and 230 kg N ha<sup>-1</sup>), six rates of P (0, 10, 20, 30, 40, and 50 kg P ha<sup>-1</sup>), six rates of K (0, 18, 36, 54, 72, and 90 kg K ha<sup>-1</sup>), and six rates of S (0, 10, 20, 30, 40, and 50 kg S ha<sup>-1</sup>). The experiment was designed in such a way that dose–response to N, P, K, or S (individually) could be determined under balanced application of the other remaining macro- and micronutrients (Zn, B). The two micronutrients were selected based on the soil fertility map of those location were reported as deficient on those nutrients by ETHOSIS. For example, for determining response to N, all other nutrients were kept constant (30 kg P, 80 kg K<sub>2</sub>O, 30 kg S, 2 kg Zn, and 0.5 kg B ha<sup>-1</sup>), and N rate was varied as indicated above. Similarly, for determining response to P, the P rate was varied but with N, K, S, Zn, and B rates kept at 92 kg N, 80 kg K<sub>2</sub>O, 30 kg S, 2 kg Zn, and 0.5 kg B ha<sup>-1</sup>. When determining response to K, the K rates were varied as above but the N, S, Zn, and B rates were held constant at 92 kg N, 30 kg P, 30 kg S, 2 kg Zn, and 0.5 kg B ha<sup>-1</sup>. When determining response to S, the S rates were varied as above, but the N, P, K, Zn, and B rates were held constant at 92 kg N, 30 kg P, 80 kg K<sub>2</sub>O, 2 kg Zn, and 0.5 kg B ha<sup>-1</sup>. Treatment sequencing was randomized using randomized complete block design on a plot size of 3.6 x 3.4 m (12.24 m<sup>2</sup>) with three replicates for each factor. The spaces between treatments and blocks were 1 m and 1.5 m, respectively. Sowing was done in Basona Werana and Alaje from end of June to the first week of July, and in Sinana between the first and second week of August every year. Food barley varieties used were HB-1307, Shedo, and Arbu for sites in Basona Werana, Alaje, and Sinana, respectively. Phosphorus, potassium, and sulfur were applied as triple super phosphate, potassium chloride, and calcium sulfate at planting. The fertilizers were applied just on the side of the row with a depth of 3–5 cm. Nitrogen in the form of urea was applied half at planting and the other half

at tilling stage (~45 days after planting) with presence of small rainfall in the side of row. Boron as borax and zinc as zinc sulfate were applied as foliar. Other standard agronomic practices were applied as per the recommendations for the crop.

### **Sampling, data collection, and statistical analysis**

Harvesting was done from the first week of November to mid-November in Basona Werana and Alaje, whereas in Sinana harvesting was done in the first week of December. To measure total above-ground biomass and grain yields, the central 10 rows of each plot (2 x 3.4 m) were harvested at soil level, then grain yield and above-ground total biomass were recorded. After threshing, seeds were cleaned and weighed. Seed moisture content was measured using a gravimetric method. Total biomass (on dry matter basis) and grain yields (adjusted to a moisture content of 12.5%) were converted to kg ha<sup>-1</sup> before statistical analysis.

A linear mixed modelling framework was used to determine the variation in yield with the different levels of N, P, K, and S by soil type and agro-ecology combining study locations and years. The linear mixed modeling framework (in PROC MIXED of the SAS system) was chosen for the different levels of analyses because it allows modeling of hierarchical or clustered data arising from observational studies through inclusion of both fixed and random effects. The approach was also chosen to account for imbalance in terms of sample size and confounding of responses by uncontrolled variables. To account for imbalance in the sample sizes, the Kenward-Roger method was used for approximating the degrees of freedom. The fixed effects in the model were agro-ecology, soil type, nutrient rate, and their interactions, with location as the random effect. In mixed models, the random component specifies that the linear predictor contains a term that randomly varies with one or more ecological correlates of crop yield—for example, location. This helps to account for correlation (i.e., observations in the similar location are likely to be more related than observations in other locations, and that locations are nested within agro-ecology or soil types). The PROC MIXED procedure uses REML estimation method and the Prasad-Rao-Jeske-Kackar-Harville fixed effects method for estimating standard errors. The initial model was of the following form:

$$Y = \mu + AEZ + Soiltype + rate + AEZ * rate + Soiltype * rate + Location + \varepsilon \quad (1)$$

where  $\mu$  is the grand mean yield (kg ha<sup>-1</sup>), AEZ is agro-ecological zone, Soiltype is the soil type of the site according to the World Reference Base (WRB) classification and correlation system, rate is the t rate of application (kg ha<sup>-1</sup>) for the nutrient under study, location is the random component, and  $\varepsilon$  is the error term. In many cases, however, sample sizes were not adequate to accommodate a model with AEZ \* Soil type\*nutrient interactions and parameters were not correctly estimated.

Before settling on a given model, however, model fit was examined using Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) (Supplementary Table 2). As a rule of thumb, changes in BIC (differences between BICs of two models) of 2–6 provide weak evidence favoring the more complex model, while differences >10 provide very strong evidence favoring the more complex model. Accordingly, the model above was deemed satisfactory. In all cases, the intercept was used as the random effect where location is the subject, specifying that data from one location are more correlated than data from another location. Then, the intraclass correlation coefficient (ICC) was calculated as the ratio of the covariance estimate of the random intercept and the covariance estimate for the residual + intercept. The ICC indicates how much of the total variation in the outcome is accounted for by the location. The variations in yield with fixed effects were considered significant when  $p \leq 0.05$  (Supplementary Table 2). The Tukey-Cramer adjustment of P values was used for difference between least square means. Least square estimates and their 95% confidence intervals (CIs) were used for statistical inference. This is because the 95% CI functions as a very conservative test of hypothesis and it also attaches a measure of uncertainty to sample statistic (du Prel *et al.*, 2009). The means for two or more levels of a fixed effect were

significantly different from one another if their 95% CI were nonoverlapping. To achieve the second objectives of this study (i.e., to determine the optimum rate of the nutrient in question), nutrient response functions were compared and used as deemed appropriate. The first function chosen was the asymptotic function given as yield ( $Y$ ):  $Y = a - bc^N$ , where  $a$  is yield at the plateau (i.e. expected maximum),  $b$  is the amplitude (the gain in yield due to nutrient application),  $c$  is a curvature coefficient, and  $N$  is the nutrient rate applied. When the asymptotic function fails to converge, other similar models that well fit the data, such as polynomial function, were chosen to determine the optimum nutrient rate.

AE, defined as grain yield per unit of N and P applied, was computed as

$$AE \text{ (kg kg}^{-1}\text{)} = \frac{GY_f - GY_u}{Na} \quad (4)$$

where  $GY_f$  is the grain yield of the fertilized plot (kg),  $GY_u$  is the grain yield of the unfertilized plot (kg) for each replicate, and  $Na$  is the quantity of N applied as N fertilizer (kg).

Rainwater productivity (RWP), defined as grain yield per unit of crop growth period rainfall (RF), was computed as

$$RWP \text{ (kg mm}^{-1}\text{)} = \frac{GY}{RF} \quad (5)$$

where RF = Rainfall amount (mm) and GY = grain yield (kg)

Means of treatments for N, P, K, and S were presented using upper and lower CI.

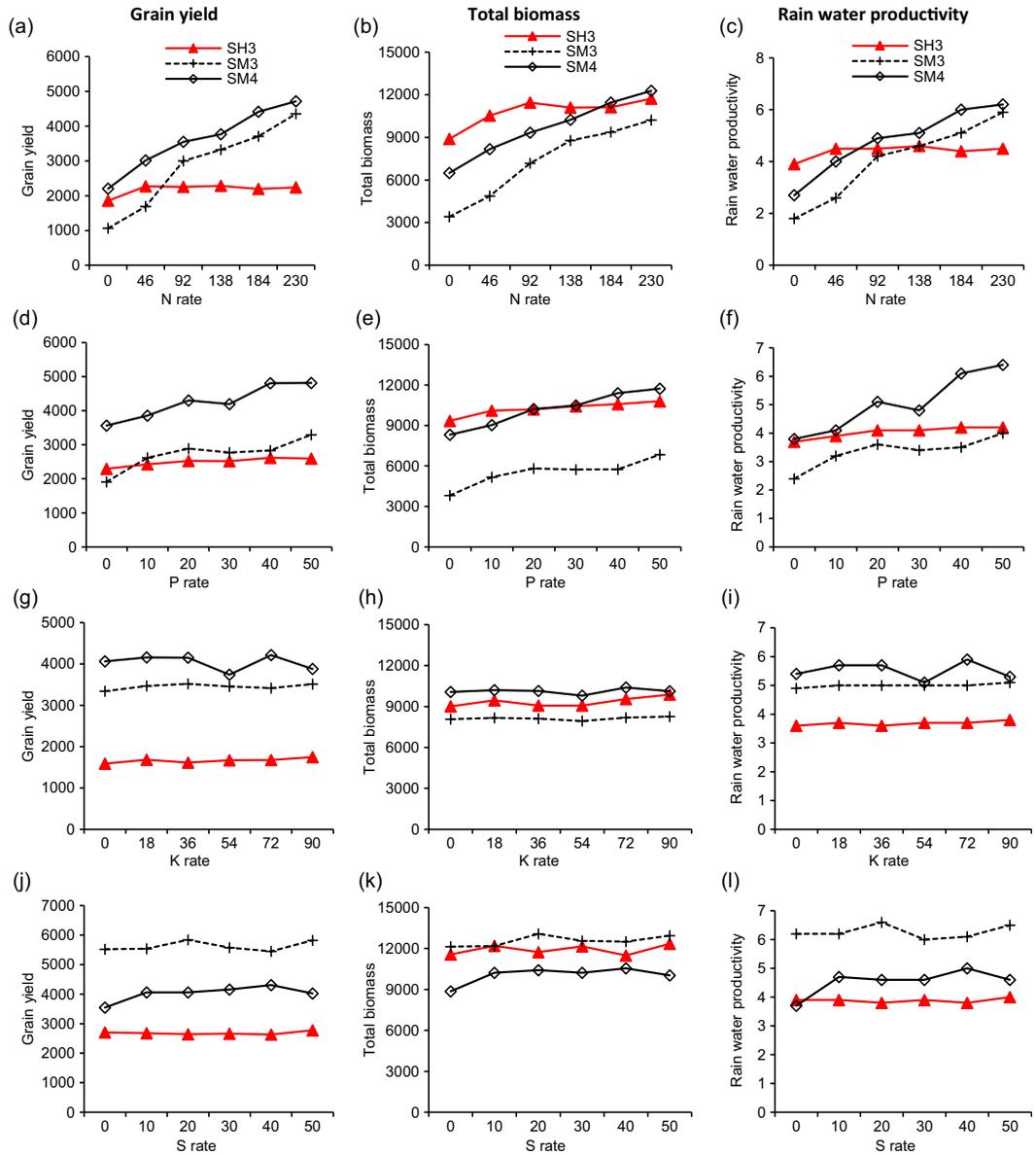
## Results

### ***Yield response to applied N and P***

Response to N and P did not significantly vary with the main effects of AEZ or soil type. Response to N and P rates significantly varied with and the interaction effect of nutrient rates and AEZ (Supplementary Table 2). The intraclass correlation (ICC) indicated that 65.1, 52.6, 56.3, and 56.4% of the variation in response to N, P, K, and S rates are accounted for by location (Supplementary Table 3).

Grain yield and total biomass significantly ( $p \leq 0.01$ ) responded to N application rates relative to the control without N application. Grain yield also varied significantly ( $p \leq 0.01$ ) among P rates but not for total biomass. The highest responses were recorded in the higher N and P rates as compared with the lower N and P rates. The interaction between N rate and AEZ (agro-ecological zone) is highly significant ( $p \leq 0.01$ ) affecting both barley grain yield and biomass.

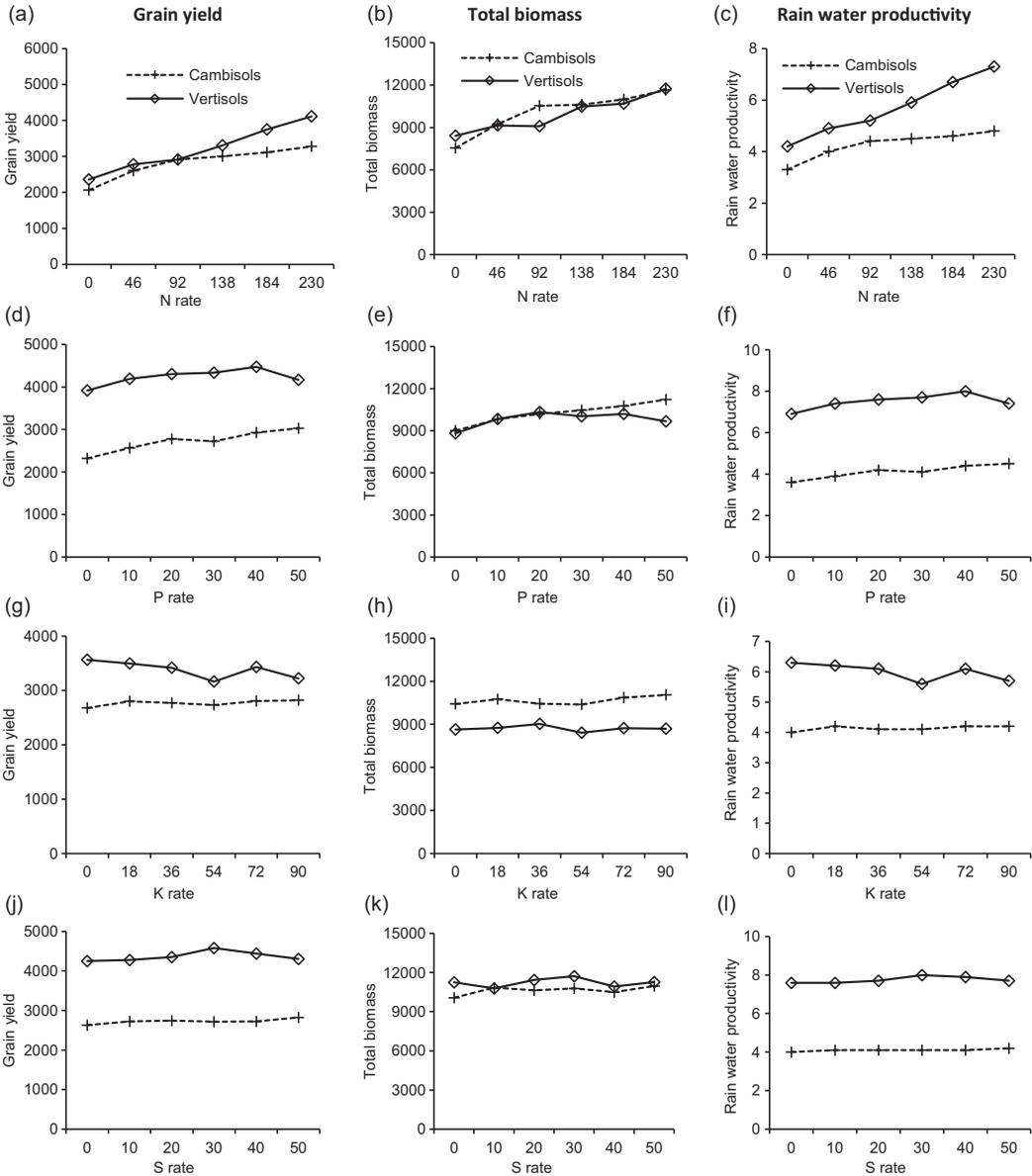
Nitrogen rate by AEZ interaction increased grain yield from ~59% (625 kg ha<sup>-1</sup>) to 309% (3293 kg ha<sup>-1</sup>) in warm sub-moist mid-highlands (SM3), from 37% (811 kg ha<sup>-1</sup>) to 114% (2516 kg ha<sup>-1</sup>) in cool, sub-moist mid-highland (SM4), and from 18% (338 kg ha<sup>-1</sup>) to 23% (426 kg ha<sup>-1</sup>) in warm, sub-humid mid-highlands (SH3) as compared with the control. The highest yield increment was recorded in SM3 and SM4 AEZs. Similarly, N rate by soil type interaction resulted in consistent yield increments of ~26% (544 kg ha<sup>-1</sup>)–59% (1213 kg ha<sup>-1</sup>) on Cambisols and 18% (416 kg ha<sup>-1</sup>)–74% (1750 kg ha<sup>-1</sup>) on Vertisols, as compared with the control. The N response curves reveal that the asymptote is reached around 200 kg N ha<sup>-1</sup> on Cambisols, while on Vertisols the asymptote could not be determined as yields were still increasing even at 230 kg N ha<sup>-1</sup> (Figure 5). Grain yield steadily increased with the increase in N rate across AEZs, although the yield response to N was significantly greater at SM3 and SM4 than SH3 (i.e., in Basona Werana and Alaje districts than in Sinana district). The trend in grain yield increase was inconsistent with the increase in N rates at SH3, where the yield was higher at 138 kg N ha<sup>-1</sup> (2281 kg ha<sup>-1</sup>). However, the yield obtained at this rate was found to be comparable with the yield observed at the rate of 46 kg N ha<sup>-1</sup> (2268 kg ha<sup>-1</sup>), indicating that the lowest rate (46 kg N ha<sup>-1</sup>) could be sufficient for barley production at SH3. This might be probably due to the



**Figure 3.** Barley grain yield, biomass and rain water productivity with N, P, K and S rates in three agroecological zones (SH3, SM3 and SM4).

relative high soil content of this AEZ compared with other AEZs (Table 1). Implying that additional yield with increasing N rate will be low. In contrast, marked yield increments were observed with the increase in N rates at SM3 and SM4, signifying actual and potential yield differences among AEZs. The trend in overall total biomass was very similar to the trend in the grain yield.

With balanced application of the other nutrients, P fertilizer substantially improved barley grain yield relative to the control without P application. When compared with the control (without P), application of P increased grain yield by 37% (703 kg ha<sup>-1</sup>) – 72% (1377 kg ha<sup>-1</sup>) in SM3, 8% (291 kg ha<sup>-1</sup>) – 35% (1259 kg ha<sup>-1</sup>) in SM4, and 6% (128 kg ha<sup>-1</sup>) – 14% (324 kg ha<sup>-1</sup>) in SH3. The highest yield increment was recorded in SM4 at the rate 50 kg P ha<sup>-1</sup> (Figure 3:



**Figure 4.** Barley grain yield, biomass and rain water productivity with N, P, K and S rates on two soil types (Cambisols and Vertisols). For details are in Supplementary Table S5 and S6.

Supplementary Table S5). Similarly, application of P resulted in consistent yield increments of 11% (244 kg ha<sup>-1</sup>)–30% (701 kg ha<sup>-1</sup>) on Cambisols and 7% (278 kg ha<sup>-1</sup>)–14% (556 kg ha<sup>-1</sup>) on Vertisols, compared to the control without P (Figure 4: Supplementary Table S6). Although higher yields were achieved on Vertisols than on Cambisols, yield increase due to P application rates was greater on Cambisols than on Vertisols. The P response curves did not reveal the maximum response on Cambisols; it was still increasing even up to 115 kg P ha<sup>-1</sup>, while an asymptotic response reached on Vertisols around 40 kg P ha<sup>-1</sup>. On Vertisols, there was consistently increasing trends in barley yield up until the P rate of 40 kg P ha<sup>-1</sup>. A decreasing trend was observed only at 50 kg P ha<sup>-1</sup>.

### **Yield response to applied K and S**

Balanced application of different rates of K did not significantly increase grain yield and total biomass of barley on different soil types and AEZs (Supplementary Table 2). This result agrees with other previous studies. For example, Yitaferu *et al.* (2010) found that maize grain yield did not significantly respond to application of K fertilizer in Ethiopia. Similarly, Tariq and Shah (2002) also reported that application of K did not significantly affect wheat yield, as the experimental soil already had sufficient K for plant growth and some K<sup>+</sup> might be released from non-exchangeable sources. There were no clear trends in yield due to application of different rate of K rates on both soil types (Figure 4; Supplementary Table S6). The trend in grain yield with K levels was also not consistent on different AEZs. Numerically, potassium rate by AEZ and soil type interaction consistently increased grain yield from ~2 to 5% in warm sub-moist mid-highlands (SM3) and Vertisols, respectively. As K rates increased, yields surprisingly decreased on Vertisols and higher grain yields were recorded in the control (0 K application) than at the highest K rate (90 kg K ha<sup>-1</sup>) (Figure 4; Supplementary Table S6). Similarly, the yield response to K application rates was inconsistent across AEZs; yield increments, even with higher K rates, were negligible. The low response of barley to K application might be attributed to the presence of this nutrient in sufficient amount for crop production in the study areas (Figure 3). The result of this study corresponds with the EthioSIS soil map, where the level of K is sufficient in most Ethiopian soils to meet crop requirements (EthioSIS, 2021).

Similarly, in spite of numerical variations among treatments, increasing rates of S did not result in significant increases in grain yield and total biomass of barley on the soils under study. The trend in both grain yield and total biomass was inconsistent with S rates. Grain yield significantly ( $p < 0.01$ ) differed among AEZs in response to different S rates; however, yield increments ranged from 14% (511 kg ha<sup>-1</sup>) to 21% (761 kg ha<sup>-1</sup>) in SM4 compared with the control. However, the yield increase was negligible in SH3 and SM3 (Figure 3; Supplementary Table S5). Similarly, yield increments due to S rates over two soil types were inconsistent and very low, where the highest yield increment of 8% was recorded at 50 kg S ha<sup>-1</sup> on Cambisols and 8% at 30 kg S ha<sup>-1</sup> on Vertisols. Although crop S requirement is low compared with other macronutrients, numerically yield variations were observed among different S rates, particularly at SM4, which represents Basona Werana and Alaje districts. On this agro-ecological zone, increasing the rate of sulfur from nil to 10 kg S ha<sup>-1</sup> appeared to have elevated the yield to a significant level. However, beyond this level, no significant increments in yield occurred at all for all agro-ecological zones and sulfur rates. Therefore, considering the economic feasibility of the S rates, the first two rates (10 and 20 kg S ha<sup>-1</sup>) may have yield advantages if applied on SM4AEZs.

### **Agronomic efficiency of N and P**

Nitrogen and P use efficiencies of cereals need to be improved by proper management of N and P fertilizers, while maintaining or, optimally, increasing crop yields. AEN (Agronomic efficiency of N) varied significantly ( $p \leq 0.01$ ) with N and P rates applied on both soil types (Figure 3). The mean AEN ranged from 5.5 to 11.8 kg grain kg<sup>-1</sup> N applied on Cambisols and 2.1–9.7 kg grain kg<sup>-1</sup> N applied on Vertisols. Similarly, AEP (agronomic efficiency of P) ranged from 13.2 to 24.2 kg grain kg<sup>-1</sup> P applied on Cambisols and 5–27.6 kg grain kg<sup>-1</sup> P applied on Vertisols (Figure 3). Our results on N and P use efficiency of barley were consistent with the findings of previous studies (Raun *et al.*, 2002; Ruisi *et al.*, 2015; Agegnehu *et al.*, 2016). Earlier findings indicate that mean AEN of 22–29 kg kg<sup>-1</sup> was obtained for barley grown in organic and inorganic amended Cambisols (Shejbalová *et al.*, 2014) and 6.2–26 on Nitisols (Agegnehu *et al.*, 2016). Similar studies on wheat reported mean AEN of 2–18 kg kg<sup>-1</sup> N applied (Guarda *et al.*, 2004) and AEN of 12.6–29 kg kg<sup>-1</sup> N applied on Nitisols (Tarekegne and Tanner, 2001). The highest AEN was obtained from the lowest application rate of 46 kg N ha<sup>-1</sup> on both soil

types, with the increments over the highest N rate (230 kg N ha<sup>-1</sup>) being ~117% and 33% on Cambisols and Vertisols, respectively. Similarly, the maximum AEP was obtained from the lowest application rate of 10 kg P ha<sup>-1</sup> on both soil types, with increments over the highest P rate (50 kg P ha<sup>-1</sup>) being ~73% and 452% on Cambisols and Vertisols, respectively. Similarly, Jama *et al.* (2017) reported that AEN was higher with 50% of the recommended N rate as compared with 100% of the recommended N rate. AEN and AEP followed an inverse relationship with N and P application rates, suggesting that as their rates of application increased, nutrient use efficiency decreased. Overall, the lowest AEN and AEP values were recorded at the highest N and P rates (230 kg N ha<sup>-1</sup> and 50 kg P ha<sup>-1</sup>), and the maximum values were recorded at the lower rates (46 kg N ha<sup>-1</sup> and 10 kg P ha<sup>-1</sup>) (Figure 3). This is because at low levels of N and P nutrient supply, rates of increase in yield and N and P uptake are large because N and P is the primary factor limiting crop growth and final yield. As the N and P supply increases, incremental yield gains become smaller. This is because maximum potential yield is determined by other factors than N and P nutrients.

### **Rainwater productivity**

In rain-fed agricultural systems, rainfall use efficiency can be increased by crop genetics and agronomic practices including fertilization (Turner and Asseng, 2005). Therefore, there is a need to consider crop production not solely in terms of production per unit of area but per unit of water (Molden *et al.*, 2003). RWP (Rainwater productivity) expresses the amount of yield produced per unit of rainwater during the crop growth period. RWP significantly ( $p < 0.05$ ) differed among N, P, and S rates and interaction of N rates by AEZ. RWP also significantly ( $p < 0.01$ ) varied among soil types and N and P rates. RWP due to changes in N rate ranged 3.9–4.6 kg mm<sup>-1</sup> in SH3, 1.8–5.9 kg mm<sup>-1</sup> in SM3, and 2.7–6.2 kg mm<sup>-1</sup> for SM4. Regardless of AEZs and soil types, the highest RWP was recorded from the highest N rate and it consistently increase with increasing N rate (Figure 3). This could be probably N application resulted in more prolific and deeper root to efficiently utilize the soil moisture which ultimately increased yield (Shepherd *et al.*, 1987). In relation to P rates, RWP ranged 2.4–6.4 kg mm<sup>-1</sup> across AEZ and 3.6–8 kg mm<sup>-1</sup> under the two soil types. In all AEZs, the highest and lowest RWP were recorded from the highest (50 kg P ha<sup>-1</sup>) and lowest (0 kg P ha<sup>-1</sup>) P rate. The percentage increase in RWP were found to be 13.5% (0.5 kg mm<sup>-1</sup>), 66.7% (1.6 kg mm<sup>-1</sup>), and 68.4% (2.6 kg mm<sup>-1</sup>) on SH3, SM3, and SM4, respectively (Figure 3; Supplementary Table S5). The same trend also observed on different soil types. The percentage increase in RWP on Cambisols and Vertisols was found to be 25% (0.9 kg mm<sup>-1</sup>) and 7.2% (0.5 kg mm<sup>-1</sup>), respectively. The RWP obtained for the soil types was greater than the WRP achieved for AEZs, implying that efficiency of P was more affected by soil types than agro-ecology.

## **Discussion**

### **Barley yield response to applied N and P**

Soil texture is one of the inherent soil properties less affected by management and which determines nutrient status, organic matter content, air circulation and water holding capacity of a given soil. The soil textures of the experimental sites varied from clay to clay loam soils. The pH of the soils of all experimental locations in all AEZ ranged from slightly acidic to neutral. In terms of the content of soil organic matter, SH3 and Vertisols are in the high range, whereas all others are in the medium range. In terms of the content of available P and N, soils in all locations are in the medium range. Likewise, the exchangeable K of the soils of all locations is in the very high range (Tekalign, 1991; Cottenie, 1980; Jones and Benton, 2003).

Grain and biomass yield steadily increased with the increase in nitrogen rate across AEZs and soil types. The overall grain and biomass yield trends were very similar to the trends of the total biomass in that the treatments without N had the lowest grain and biomass yields. Indicating that N is the most limiting element after water for crop production. Other studies have also shown that application of nitrogen markedly increased grain yields of both food barley (Agegnehu *et al.* 2016; Beatty *et al.* 2010) and malting barley (Agegnehu *et al.* 2014). The non-linear regression analysis using asymptotic model over two soil types clearly showed that yield steadily increased with the increase in N rate on Cambisols, implying that some additional rates will be required to meet the response curve (Figure 3). In contrast, since the convergence criterion was not met using non-linear regression model for Vertisols, the polynomial regression analysis indicated that grain yield increased with the increase in N rate (Figure 3). Across AEZs, barley yields were considerably lower in SH3 than SM3 and SM4 (i.e., in Sinana than Basonaworana and Embaalaje) for all nutrient studies, in which the highest yields for all nutrients were recorded at SM4. These differences could be attributed to differences in management practices, soil nutrient status, barley varieties used for the study, and climatic condition such as rainfall and temperature.

Grain and biomass yield also progressively increased with the increase in phosphorus rate across AEZs and soil types up to application of P at the rate of 20 ha<sup>-1</sup>. The steady increase in yield with the increase in P rates without reaching a plateau on Cambisols (Figure 5) implies that higher P rates will be needed to attain the maximum yield. The overall grain and biomass yield trends were very similar to the trends of the total biomass in that the treatments without P had the lowest grain and biomass yields. Although higher yields were achieved on Vertisols than on Cambisols, yield increase due to P application rates was greater on Cambisols than on Vertisols. The steady increase in yield with the increase in P rates on Cambisols implies that higher P rates will be needed to attain the maximum yield. Vertisols has more puffer power that leads to rapid replenishment of P taken up by plant roots from the soil solution, thereby enabling plants to take up P at higher rates and grow better. The Cambisols, despite having numerically higher available P content than Vertisols, it has a low buffer power and would replenish P taken up by plant roots from the soil solution at a slower rate. The organic carbon content of Vertisols is high whereas that of Cambisols is medium according to the rating of Tekalign (1991) (Table 1). Organic carbon is the other source of available P, which will put the barley plants growing on Vertisols in a better position to take up more P and hence better yield. The nonlinear regression analysis over two soil types clearly showed that yield steadily increased with the increase in P rate for Cambisols, implying that more rates will be needed to attain the response curve. However, the same model for Vertisols revealed that grain yield showed a gradual decreasing trend just after 10 kg P ha<sup>-1</sup> with the increase in P rate (Figure 3).

## Conclusions

Blanket recommendation of fertilizers often fails to take into consideration differences in soil types and AEZs. The nutrients in the blanket recommendation are not well balanced agronomically, and the continued use of this recommendation will gradually exhaust other soil nutrient reserves and create nutrient imbalances. The current study was carried out to determine soil and AEZs specific response of barley to N, P, K, and S under balanced application of other nutrients on major barley growing areas of Ethiopia for three years. In this regard, it is the first study that reports yield responses of barley to N, P, K, and S under balanced application of the other nutrients in different soil types and AEZs in Ethiopia. The results emphasize the benefits of balanced application of N, P, K, and S fertilizers for improving barley yield. The highest agronomic efficiency of N and P was obtained using 46 kg N ha<sup>-1</sup> and 10 kg P ha<sup>-1</sup>. With balanced application of other nutrients, use of 230 kg N and 20 kg P ha<sup>-1</sup> was recommended for tepid sub-moist mid-highlands and Vertisols. For tepid sub-humid mid-highlands, application of 46 kg N and 20 kg P ha<sup>-1</sup> with balanced

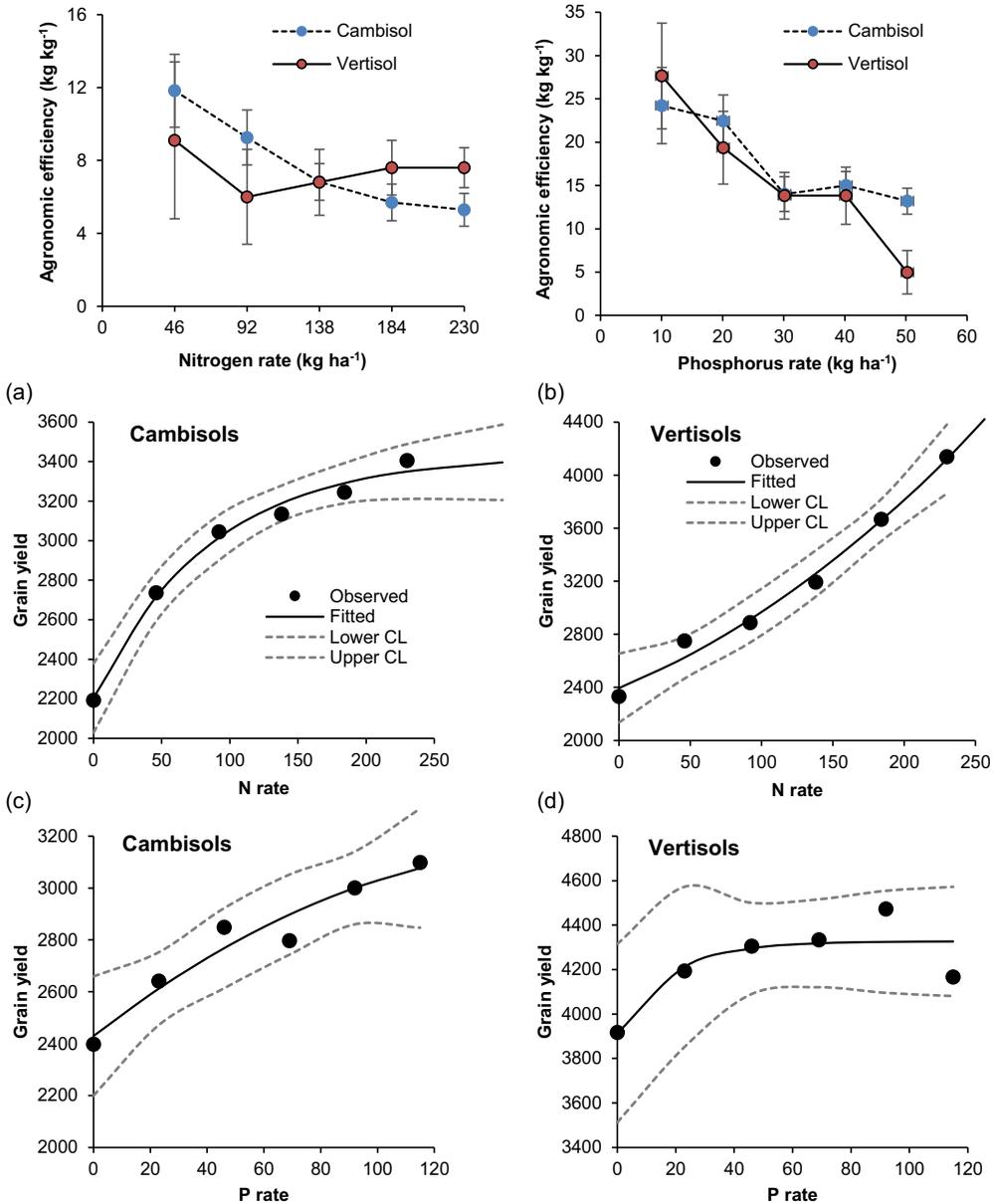


Figure 5. Agronomic efficiency of N and P, nitrogen response curve, and phosphorus response curves for barley grain yield. Error bars represent  $\pm 1$  SE.

application of other nutrients was recommended. For Cambisols, application of 230 kg N and 40 kg P ha<sup>-1</sup> was recommended with balanced application of the other nutrients. Similarly, application of 230 kg N, 40 kg P, and 10 kg S was tentatively recommended for cool sub-most mid highlands agro-ecology. However, response to K was inconsistent and therefore a firm recommendation could not be proposed for the study sites. Further research needs to be conducted on more soil types and locations.

**Supplementary material.** To view supplementary material for this article, please visit <https://doi.org/10.1017/S0014479721000223>

**Acknowledgements.** The authors thank the Ethiopian Institute of Agricultural Research, Oromia, Amhara, and Tigray research institutes for funding this research and generating data. We greatly appreciate the International Center for Tropical Agriculture and Deutsche Gesellschaft für Internationale Zusammenarbeit for organising the data and facilitating and financing the preparation of this manuscript.

**Funding Support.** This work was supported, in whole or in part, by the Bill & Melinda Gates Foundation [INV-005460]. Under the grant conditions of the Foundation, a Creative Commons Attribution 4.0 Generic License has already been assigned to the Author Accepted Manuscript version that might arise from this submission.

**Conflicts of Interest.** None.

## References

- Abebe M. (1998). *Nature and management of Ethiopian soils*. Alamaya University of Agriculture, Alemaya, Ethiopia.
- Agegnehu G., Ghizaw A. and Sinebo W. (2008). Yield potential and land-use efficiency of wheat and faba bean mixed intercropping. *Agronomy for Sustainable Development* **28**, 257–263. DOI: [10.1051/agro:2008012](https://doi.org/10.1051/agro:2008012)
- Agegnehu G., Lakew B. and Nelson P.N. (2014). Cropping sequence and nitrogen fertilizer effects on the productivity and quality of malting barley and soil fertility in the Ethiopian highlands. *Archives of Agronomy and Soil Science* **60**, 1261–1275. DOI: [10.1080/03650340.2014.881474](https://doi.org/10.1080/03650340.2014.881474)
- Agegnehu G., Liben M., Molla A., Feyissa A., Bekele A. and Getaneh F. (2011). Research achievements in soil fertility management in relation to barley in Ethiopia. In B. Mulatu and S. Grando (Eds), *Barley Research and Development in Ethiopia*. Addis Ababa, Ethiopia: ICARDA, pp. 137–153.
- Agegnehu G., Nelson P.N. and Bird M.I. (2016). The effects of biochar, compost and their mixture and nitrogen fertilizer on yield and nitrogen use efficiency of barley grown on a Nitisol in the highlands of Ethiopia. *Science of the Total Environment* **569–570**, 869–879. DOI: [10.1016/j.scitotenv.2016.05.033](https://doi.org/10.1016/j.scitotenv.2016.05.033)
- Amede T., Belachew T. and Geta E. (2001). *Reversing the degradation of arable land in the Ethiopian highlands*. Managing Africa's Soils No. 23, 1–23. Addis Ababa, Ethiopia.
- Beatty P.H., Anbessa Y., Juskiw P., Carroll R.T., Wang J. and Good A.G. (2010). Nitrogen use efficiencies of spring barley grown under varying nitrogen conditions in the field and growth chamber. *Annals of Botany* **105**, 1171–1182. DOI: [10.1093/aob/mcq025](https://doi.org/10.1093/aob/mcq025)
- Cottene A. (1980). Soil and plant testing as a basis of fertilizer recommendations. FAO soil bulletin 38/2. Food and Agriculture Organization of the United Nations, Rome.
- CSA (2018). *Report on area and production of major crops*. Agricultural Sample Survey 2017/18, Central Statistical Agency (CSA). Vol.1. Addis Ababa, Ethiopia.
- Dibabe A., Bekele T. and Assen Y. (2007). The status of micronutrients in Nitisols, Vertisols, Cambisols and Fluvisols in major Maize, Wheat, Teff and Citrus growing areas of Ethiopia. In: *Proceedings of the Workshop on Status of Micronutrients*, 77–96. Addis Ababa, Ethiopia.
- Drechsel P., Kunze D. and De Vries F.P. (2001). Soil nutrient depletion and population growth in sub-Saharan Africa: a Malthusian nexus? *Population and Environment* **22**, 411–423. DOI: [10.1023/A:1006701806772](https://doi.org/10.1023/A:1006701806772)
- du Prel J.B., Hommel G., Röhring B. and Blettner M. (2009). Confidence interval or p-value?: part 4 of a series on evaluation of scientific publications. *Deutsches Ärzteblatt International* **106**, 100–105. DOI: [10.3238/arztebl.2009.0100](https://doi.org/10.3238/arztebl.2009.0100)
- EthioSIS (Ethiopian Soil Information System). (2021). <http://www.ata.gov.et/highlighted-deliverables/ethiopian-soil-information-system-ethiosis/>. Accessed 30 July 2021.
- FAO (2016). FAO Stat 2016. Rome, Italy: Food and Agriculture Organization of the United Nations (FAO).
- Goulding K., Jarvis S. and Whitmore A. (2008). Optimizing nutrient management for farm systems. *Philosophical Transactions of the Royal Society of London B: Biological Sciences* **363**, 667–680. DOI: [10.1098/rstb.2007.2177](https://doi.org/10.1098/rstb.2007.2177)
- Guarda G., Padovan S. and Delogu G. (2004). Grain yield, nitrogen-use efficiency and baking quality of old and modern Italian bread-wheat cultivars grown at different nitrogen levels. *European Journal of Agronomy* **21**, 181–192. DOI: [10.1016/j.eja.2003.08.001](https://doi.org/10.1016/j.eja.2003.08.001)
- Haillassie A., Priess J., Veldkamp E., Teketay D. and Lesschen J.P. (2005). Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agriculture, Ecosystems and Environment* **108**, 1–16. DOI: [10.1016/j.agee.2004.12.010](https://doi.org/10.1016/j.agee.2004.12.010)
- Henao J. and Baanante C.A. (1999). *Estimating rates of nutrient depletion in soils of agricultural lands of Africa*. International Fertilizer Development Center (IFDC): Citeseer, Alabama, USA. [www.ifdc.org](http://www.ifdc.org)
- Jama B., Kimani D., Harawa R., Mavuthu A.K. and Sileshi G.W. (2017). Maize yield response, nitrogen use efficiency and financial returns to fertilizer on smallholder farms in southern Africa. *Food Security* **9**, 577–593. DOI: [10.1007/s12571-017-0674-2](https://doi.org/10.1007/s12571-017-0674-2)
- Jones J. Benton Jr. (2003). *Laboratory Guide for Conducting Soil Tests and Plant Analysis*. Boca Raton, FL: CRC Press.

- Laekemariam F., Kibret K. and Shiferaw H.** (2018). Potassium(K)-to-magnesium (Mg) ratio, its spatial variability and implications to potential Mg-Induced K deficiency in Nitisols of Southern Ethiopia. *Agriculture & Food Security* 7(13). DOI: [10.1186/s40066-018-0165-5](https://doi.org/10.1186/s40066-018-0165-5)
- Lichtfouse E., Navarrete M., Debaeke P., Souchère V., Alberola C. and Ménéssieu J.** (2009). Agronomy for sustainable agriculture: a review. In Lichtfouse E., Navarrete M., Debaeke P., Véronique S. and Alberola C. (eds), *Sustainable agriculture*. Dordrecht: Springer Netherlands, pp. 1–7. DOI: [10.1007/978-90-481-2666-8\\_1](https://doi.org/10.1007/978-90-481-2666-8_1)
- Molden D., Murray-Rust H., Sakthivadivel R. and Makin I.** (2003). A water-productivity framework for understanding and action. In: *Paper presented at the Water productivity in agriculture: Limits and opportunities for improvement*, (Eds J. W. Kijne, R. Barker, and D. J. Molden). CABI publishing, Wallingford, UK. ISBN: 978-0-85199-669-1
- Mulatu B., Grando S.** (eds). (2011). *Barley Research and Development in Ethiopia: Proceedings of the 2nd National Barley Research and Development Review Workshop*. Holetta, Ethiopia. ICARDA, Aleppo, Syria: xiv–391.
- Mulatu B. and Lakew B.** (2011). Barley research and development in Ethiopia—an overview. In Mulatu B. and Grando S. (eds), *Barley Research and Development in Ethiopia*. Addis Ababa, Ethiopia: ICARDA, pp. 1–8, Aleppo, Syria. ISBN 92-9127-249-3.
- Raun W.R., Solie J.B., Johnson G.V., Stone M.L., Mullen R.W., Freeman K.W., Thomason W.E. and Lukina E.V.** (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. *Agronomy Journal* 94, 815–820. DOI: [10.2134/agronj2002.8150](https://doi.org/10.2134/agronj2002.8150)
- Ruisi P., Frangipane B., Amato G., Frenda A.S., Plaia A., Giambalvo D. and Saia S.** (2015). Nitrogen uptake and nitrogen fertilizer recovery in old and modern wheat genotypes grown in the presence or absence of interspecific competition. *Frontiers in Plant Science* 6, 185. DOI: [10.3389/fpls.2015.00185](https://doi.org/10.3389/fpls.2015.00185)
- Sanchez P.A.** (2002). Soil fertility and hunger in Africa. *Science* 295, 2019–2020. DOI: [10.1126/science.1065256](https://doi.org/10.1126/science.1065256)
- Shejbalová Š., Černý J., Vašák F., Kulhánek M. and Balík J.** (2014). Nitrogen efficiency of spring barley in long-term experiment. *Plant, Soil and Environment* 60, 291–296. DOI: [10.17221/916/2013-PSE](https://doi.org/10.17221/916/2013-PSE)
- Shepherd K., Cooper P., Allan A., Drennan D. and Keatinge J.** (1987). Growth, water use and yield of barley in Mediterranean-type environments. *The Journal of Agricultural Science* 108, 365–378. DOI: [10.1017/S0021859600079399](https://doi.org/10.1017/S0021859600079399)
- Smaling E., Nandwa S.M. and Jansen B.H.** (1997). Soil fertility in Africa is at stake. In R.J. Buresh, P.A. Sanchez and C. Frank (eds), *SSSA Special Publications*. Madison, WI, USA, pp. 47–61. DOI: [10.2136/sssaspecpub51.c2](https://doi.org/10.2136/sssaspecpub51.c2)
- Stewart W.M., Dibb D.W., Johnston A.E. and Smyth T.J.** (2005). The contribution of commercial fertilizer nutrients to Food Production. *Agronomy Journal* 97, 1–6. DOI: [10.2134/agronj2005.0001](https://doi.org/10.2134/agronj2005.0001)
- Tarekegne A. and Tanner D.R.** (2001). Effects of Fertilizer application on N and P uptake, recovery and use efficiency of bread wheat grown on two soil types in central Ethiopia. *Ethiopian Journal of Natural Resources* 3, 219–244.
- Tariq M. and Shah M.** (2002). Response of wheat to applied soil potassium. *Asian Journal of Plant Sciences* 1, 470–471.
- Tekalign Tadese.** (1991). Soil, plant, water, fertilizer, animal manure and compost analysis. Working Document NO. 13. International Livestock Research Center for Africa, Addis Ababa.
- Turner NC and Asseng S.** (2005). Productivity, sustainability, and rainfall-use efficiency in Australian rainfed Mediterranean agricultural systems. *Australian Journal of Agricultural Research* 56, 1123–1136. DOI: [10.1071/AR05076](https://doi.org/10.1071/AR05076)
- van Beek C., Agegnehu G., Debele T., Terano Y., Heesmans H. and Elias E.** (2011). Evaluation of nutrient management strategies at farm level in Ethiopia for improved food production. In: *Wageningen Conference on applied soil science*, Wageningen, The Netherlands 18–22 September, 2011, 62. Wageningen University.
- van Beek C., Elias E., Yihenew G., Heesmans H., Tsegaye A., Feyisa H., Tolla M., Melmuye M., Gebremeskel Y. and Mengist S.** (2016). Soil nutrient balances under diverse agro-ecological settings in Ethiopia. *Nutrient Cycling in Agroecosystems* 106, 257–274. DOI: [10.1007/s10705-016-9803-0](https://doi.org/10.1007/s10705-016-9803-0)
- Vanlauwe B., Bationo A., Chianu J., Giller K.E., Merckx R., Mokwunye U., Ohiokpehai O., Pypers P., Tabo R. and Shepherd K.D.** (2010). Integrated soil fertility management: operational definition and consequences for implementation and dissemination. *Outlook on Agriculture* 39, 17–24. DOI: [10.5367/000000010791169998](https://doi.org/10.5367/000000010791169998)
- Vanlauwe B., Kihara J., Chivenge P., Pypers P., Coe R. and Six J.** (2011). Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant and Soil* 339, 35–50. DOI: [10.1007/s11104-010-0462-7](https://doi.org/10.1007/s11104-010-0462-7)
- Yitaferu B., Tesema T. and Ayalew Z.** (eds). (2010). *Proceedings of the 3rd Annual Regional Conference on Completed Research Activities on Soil and Water Management, Forestry, and Agricultural Mechanization*, 1–4 September 2008, Amhara Region Agricultural Research Institute (ARARI), Bahir Dar, Ethiopia.
- Zeleke G., Agegnehu G., Abera D. and Rashid S.** (2010). *Fertilizer and soil fertility potential in Ethiopia: Constraints and opportunities for enhancing the system*. Working Paper, International Food Policy Research Institute (IFPRI), 1–42. Washington DC, USA. [www.ifpri.org](http://www.ifpri.org)

**Cite this article:** Shewangizaw B, Gurumu G, Agegnehu G, Eshetu M, Assefa S, Hadgu F, Seid J, Tibebe D, Sileshi GW, and Tamene L. Yield response of barley to the application of mineral fertilizers containing major nutrients on Cambisols and Vertisols in Ethiopia. *Experimental Agriculture*. <https://doi.org/10.1017/S0014479721000223>