Identifying limiting nutrient(s) for better bread wheat and teff productivity in acidic soils, West Amhara, Ethiopia

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Abstract

Food crop productivity is still low due to the decline of soil fertility in Ethiopia in general and western Amhara in particular. This is mainly associated with deficiencies of macronutrients N, P, K, and S as well as micronutrients. Satisfying nutrient deficiencies with the addition of synthetic fertilizer is one of the major options to boost crop productivity. However, the responses to fertilizer application are varied across geographical locations and environments. As a result, fertilizer use efficiencies and economic profitability are different across different environments. Thus, fine-tuning the use of nutrients through the right fertilizer source is needed to solve soil fertility problems. Therefore, this study was initiated to investigate the need for applying selected nutrients on teff and wheat in acidic soils of North West Amhara. This study was conducted in 74

experiment employed an omission trial design. The omitted nutrients were sulfur (S), Zinc (Zn), and boron (B). Potassium (K) was added rather than omitted that consisting of N, P, S, Zn, B, and K (All). Nitrogen and Phosphorus (NP) treatment was included as a positive control. Additional two treatments: 50% and 150% of the ALL+K were also included. High-yielding bread wheat (Ogalcho) and teff variety (Quncho) were used for the study. The outcome of the experiment shows that the application of different nutrient types with different rates has a significant role in grain and biomass yield of teff and bread wheat across landscape positions with and without lime application in acidic soils of the East Gojjam zone. Teff yield was not obtained without fertilizer application in the study area whereas the lowest yield of bread wheat was also obtained without fertilizer application (no input) treatment. The application of all nutrient types (NPKSZnB) has no significant yield advantage compared to NP fertilizer alone. This implies that N and P are the most yield-limiting nutrients in producing teff and bread wheat whereas KSZnB nutrients are not yield-limiting. However, this should be supported with grain quality analysis. Therefore, refining the rate of NP in acidic soils is important for the economical use of inorganic inputs. Finally, the use of blended fertilizer without empirical evidence for test crops is not recommended to smallholder farmers in the study area.

Keywords: Acidity, Deficiency, Fertilizer, Landscape, Omission.

Introduction

Achieving food security through increased productivity of food crops is the main problem in Ethiopia. Crop productivity is not improved due to the decline of soil fertility (Hirpa et al., 2012; Kebede, 2017; Tadele et al., 2018). To enhance crop yield, adding synthetic fertilizer is one of the major components. Thus, the national annual fertilizer use raised by about 30 % from 1994 to 2005, and 63 % from 2005 to 2010 (Birhan et al., 2017; Tefera et al., 2012). Recently the use of synthetic fertilizers for crop production was increased drastically even though the expected crop yield is not achieved.

Many studies in the last decades indicate that crop production constraints are mainly deficiencies of macronutrients N, and P, to some extent K and S (Ayalew, 2011; Aleminew and Legas 2015; Argaw, and Tsigie 2015; Tamene et al., 2017). The addition of sulfur is also recommended in lowland parts of the country (Habtegebrial, and Singh 2009; Habtegebrial, 2013). Contrary to these reports, other studies show that the deficiency of K is not a major problem for most agricultural soils in Ethiopia (Tadele et al., 2018; 2019). Recently, limitations of secondary nutrients and deficiencies of micronutrients are also obtaining attention (EthioSIS, 2016).

The responses to fertilizer application are varied across geographical locations (Tamene et al., 2017; Tadele et al., 2018) and environments. Site-specific fertilizer applications should consider landscape position in farms with undulating topographic features (Amede et al., 2020). The response of fertilizers is ranged from low too high for any nutrient combination. Moreover, the responses can be happened due to management factors and biophysical attributes. As a result, fertilizer use efficiencies and economic profitability are different. Thus, optimizing the use of nutrients through the right fertilizer source, rate placement, and time of application during crop growing season is critical to solve soil fertility problems (Ferguson, 2006; Ahmad et al., 2018; Barłóg et al., 2022) and economic use of fertilizers.

Fertilizer rates are better recommended based on the available nutrient in the soil and the crops' requirement for that nutrient (Scherer, 2001). The demand for the plant should be addressed through the supply of required plant nutrients in adequate amounts. However, this is not done in previous soil management efforts to halt soil fertility declines in Ethiopia. This is due to a lack of site-specific fertilizer use and the right fertilizer combination. On the other hand, there is a yield gap between teff and wheat production in Ethiopia due to sub sufficient fertilizer use (Tadesse *et al.,* 2000; Zeleke *et al.,* 2010; Mann, and Warner 2015; Birhan *et al.,* 2017). The yield gaps in these crops suggest that there is potential for increasing production through the lime application, selection of acid-tolerant crop varieties, increased use of fertilizers amount, and identification of the right nutrient types for each location and crop type, particularly in acidic areas.

In designing site-specific fertilizer recommendations, an understanding of the effects of each nutrient/fertilizer application on crop yield is required. Moreover, increasing crop production with the use of synthetic fertilizer must be profitable to smallholder farmers to promote sustainably (Tamene *et al.*, 2017). Inefficient use of chemical fertilizer might cost the farmer and pollute the environment (Vanlauwe *et al.*, 2011). In addition, the high variability between and within farms calls for site-specific recommendations that will reduce wastage and reap maximum benefits from fertilizer use. Therefore, fine-tuning fertilizer recommendations is required via selecting the right nutrient types in acidic soils for wheat and teff crops. Hence, the objective of this study was to identify the major yield-limiting nutrients for wheat and teff production in acidic-prone areas of North West Amhara, Ethiopia.

Materials and Methods

Location and description of the area

On-farm plant nutrient omission experiments were conducted in acid-prone areas of the Northern highlands of Ethiopia (Gozamen and Machakel districts), within the geographical coordinates of 10°00’N - 10°40’N latitudes and 37°20’E - 37°50’E longitude (Figure 1). Gozamen district is found at a distance of about 305 and 251 km from Addis Ababa (the capital city of Ethiopia) and Bahir Dar (the capital city of Amhara regional state), respectively. Whereas Machakel district is located 330 km on the road from Addis Ababa to East Gojjam, and 235 km east of Bahir Dar. The elevation of the Gozamen and Mackakel districts ranges from 1200 to 3510 and 1200 to 3200 m.a.s.l., respectively.

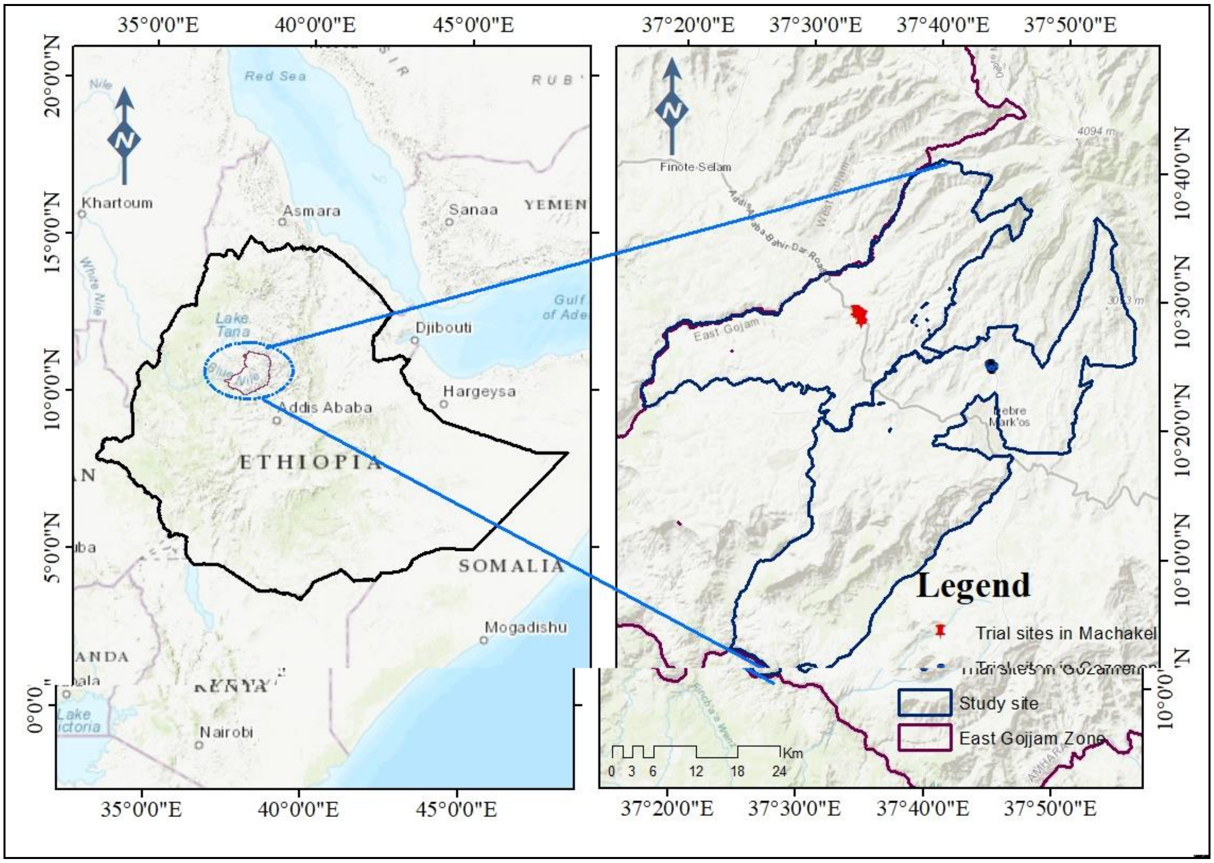

Figure 3. Location map trial sites in Gozamen and Mackale districts

In Both districts, the average annual rainfall ranges between 1300 mm and 1900 (EMA, 2020), with the highest amount of rainfall received in July and August. The maximum and the minimum annual average temperatures are 27 ^{o}C and 8 ^{o}C, respectively. Wheat (Triticum vulgare), tef, (Eragrostic tef), maize (Zea mays), barley (Hordeum vulgare), white lupine (Lupines albus), and food oat are the dominant cereal crops that are grown in both districts. Nitisols followed by vertisols are the most dominant agricultural soils in study districts.

This experiment was superimposed in previously lime-amended farmer fields in both districts. The lime was applied based on the blanket recommendation of 100 kg ha^{-1} by farmers with the help of development agents. For this experiment, lime-amended and not amended farmers' fields were selected and implemented side by side at all landscape positions for both test crops.

A total of 74 trial sites were used for this study. Out of these, 44 trial sites have been carried in Gozamen and 30 trial sites in Machakel districts that represent the acid soils of North West Amhara, Ethiopia (Table 1). About 38 sites were amended by lime whereas the remaining 36 sites were not amended by lime before experimentation. A total of 37 sites were used as common experimental sites for both teff and bread wheat in the study areas.

Table 19. Details of the number of sites in study districts

District	Landscape position	Test crop	Soil acidity management		Total number of sites [N]
			Lime amended	Not lime amended	
Gozamen	_	2	22	22	44
	Hill	Tef and Wheat	6	6	12
	Mid	Tef and Wheat	12	12	24
	Foot	Tef and Wheat	4	4	8
Machakel	_	2	16	14	30
	Hill	Tef and Wheat	6	4	10
	Mid	Tef and Wheat	6	6	12
	Foot	Tef and Wheat	4	4	8
Total [N]		2	38	36	74

Trial design

The core set of treatments was harmonized with the All-Ethiopian Coordinated Fertilizer Research (AECFR) Project. Recommended N and P rates for each location to teff and wheat were used as a positive control. The core treatment set was employed as an omission trial design (Table 2). The omitted nutrients were S, Zn, and B. “ALL” treatment consists of N, P, S, Zn, and B. K is an addition rather than omission treatment consisting of N, P, S, Zn, B, and K. In addition to the omission treatment and the K adding treatment, NP-only treatment is included such that the cumulative effect of S, Zn, and B omission were evaluated; this treatment then is effectively ALL- (S Zn B). Additional two treatments: 50% and 150% of the ALL+K were included. These treatments permit an evaluation of the fertilizer rate response according to landscape position and soil type. A non-fertilized control treatment was included in the core harmonized treatment set. Treatments were arranged in completely randomized designs by considering farmers as replicas in three landscape positions (foot, mid, and hill).

Table 20. Treatments were applied in the nutrient omission trials conducted in acidic soils of Gozamen and Machakel districts.

Treatments	Fertilizer rate (kg ha^{-1})											
	Bread wheat						Teff					
	N	P_2O_5	S	K_2O	Zn	B	N	P_2O_5	S	K_2O	Zn	B
NPSZnB	120	76	7		1	0.3	80	57	7		1	0.3
NPZnB	120	76			1	0.3	80	57			1	0.3
NPSB	120	76	7			0.3	80	57	7			0.3
NPSZn	120	76	7		1		80	57	7		1	
NPKSZnB	120	76	7	30	1	0.3	80	57	7	30	1	0.3
NP	120	76					80	57				
50%NPKSZnB	60	38	3.5	15	0.5	0.15	40	28.5	3.5	15	0.5	0.15
150%NPKSZnB	180	114	10.5	45	1.5	0.45	120	85.5	10.5	45	1.5	0.45

Fertilizer sources and test crop

Urea, triple super phosphate, potassium chloride, and borax are used as a source of fertilizer for nitrogen, phosphorus, potassium, and borax, respectively. Whereas zinc sulfate was used as a source for both S and Zn. The test crops used for this study were bread wheat (Ogalcho variety) and teff (Kuncho) at a seed rate of 150 and 10 kg ha^{-1}.

Experimental management

All trials were on farmers' fields, and soil and crop management practices were done following research recommendations. After preparing the trial sites, all the sites were planted by drill method at 20 cm spacing from 21 July 2020 to 31 July 2020. All fertilizers were applied by band application at plating except split urea for top dressing. The first split of nitrogen was applied one month after emergence. Weed management was started just after 2 weeks of seed emergence of the trials mainly for bread wheat (July 2020). Each site has been weeded twice. All experimental sites were harvested from 15 December 2020 to 06 January 2020. Then, the threshing is done after drying of harvested test crop.

Data collection

Soil sampling

Before planting, one composite soil sample at 0-20 cm of depth was collected from each trial site to see the status of selected soil chemical properties. The composite samples were collected from

11 sites on lime-amended farmers and 12 not lime amended sites in Gozamen whereas 8 sites from each lime-amended and not amended farmer in Machakel district. Major soil parameters such as soil pH-H_2O, organic carbon (OC), available phosphorus (AP), exchangeable acidity, and total nitrogen (TN) analysis were conducted in Adet Agricultural Research Center's soil laboratory.

Biological data

Measurements such as plant height, spike/panicle length, number of kernels per spike for wheat, total aboveground biomass, and grain yield were done for each test crop and undertaken at the appropriate times. Plant height was measured from the soil surface to the tip of a spike (awns excluded) from 5 randomly selected plants from the net plot area at physiological maturity. Spike length/panicle length was measured at physiological maturity at the same time as plant height using 5 randomly selected plants for measuring plant heights. Spike/panicle length was measured from 5 plants starting at the base of the spike to the tip of the spike (excluding the awns) and averaged. The number of kernels per spike for wheat was determined from the five randomly sampled spikes mentioned above. Harvesting will be done from the middle rows of 3.2 m by 3 m area (9.6 m^2 net plot area), leaving the outside rows as a buffer to avoid border effects. Then, total biomass was determined from plants harvested from the net plot area after sun drying to a constant weight and converted to kg per hectare for statistical analysis. Grain yield was also determined after threshing the total biomass harvested from the net plot area and converted to kg ha^{-1} for statistical analysis. The grain yield was adjusted to 12.5% moisture content.

Soil analysis

All collected soil samples were air-dried and crushed to pass a 2-mm sieve. Analyses were performed on surface samples (0-20 cm) including pH, organic carbon (OC), total nitrogen (N), available phosphorus (P), sulfur (S), zinc (Zn), boron (B), and exchangeable aluminum (Al) following standard soil laboratory procedures.

Soil pH-H_2O was determined in soil-water suspensions of 1:2.5 ratios (Lean, 1982). Available phosphorus was also done following the Olsen method (Olsen, and Sommers, 1982) while total nitrogen was done using the Kjeldahl method (Bremner, and Mulvaney, 1982). The wet oxidation method was used to determine soil organic carbon (Walkley and Black, 1934). Cation exchange capacity was also determined by ammonium acetate extraction procedures (Houba *et al.*, 1986).

Data Analysis

For all the sites, yield and yield-related data were arranged in excel and subjected to analysis of variance using R software. Analyses of variance were performed for yield data for each landscape and all sites combined. A test of significance for the treatment by-site interaction of the combined analysis was performed as outlined by Cochran and Cox, (1992) for situations with heterogeneous variance among sites. Mean separation was carried out by DMRT at a 5% level of significance when ANOVA is significant.

Results and Discussion

Soil physical and chemical properties of the study sites

In Machakel district, the soil pH (H_2O) of the experimental sites (without lime amendment) ranged between 5.4 and 5.8 across three landscape positions (Table 1) and rated strongly to moderately acidic soils (Tadesse et al., 1991), whereas experimental sites that are previously lime amended were found between 5.3 and 6.0 (Table 2) with a similar range of soil acidity. The variation of soil organic carbon between limed and un-limed soils was low in all experimental sites except at site 3 in both conditions (Table 3).

Table 21. Soil characteristics of experimental sites at planting time in Gozamen and Machakel district

District	Lime status of trial sites	Landscape position	Statistical description	Soil parameters				
				Soil pH	Ex. Acidity [meq /100g soil]	P (Olsen) [mg kg^{-1}]	SOC [%]	CEC [$cmol_c$ kg^{-1}]
Gozamen	without lime amendment	Foot [2]	Range	4.8-5.4	0.4-3.4	4.5-14.5	1.5-1.7	25.0-29.0
			Mean	5.1	2.2	8.8	1.6	27.3
		Hill [3]	Range	4.9-6.4	0.2-0.8	4.4-20.0	1.4-2.1	27.0-38.0
			Mean	5.4	2.0	11.4	1.8	31.7
		Mid [6]	Range	5.0-5.4	0.2-2.4	8.8-17	1.0-1.9	28.0-35.0
			Mean	5.2	0.8	12.7	1.6	32.0
	Previously lime amended	Foot [2]	Range	5.1-5.5	0.2-1.38	7.7-10.7	1.5-1.9	28.9-37.6
			Mean	5.3	0.9	9.2	1.6	35.3
		Hill [3]	Range	5.1-6.0	0.1-3.5	5.1-20.8	1.1-1.8	28.8-31.7
			Mean	5.5	1.8	12.9	1.5	30.3
		Mid [6]	Range	5.0-6.1	0.1-2.6	10.8-19.3	1.4-2.2	25.6-35.5
			Mean	5.4	1.1	14.3	1.7	33.0
Machakel	without lime amendment	Foot [2]	Range	5.5-5.8	0.2-0.8	10.8-13.2	1.2-1.3	30.0-32.0
			Mean	5.7	0.5	12.0	1.2	30.8
		Hill [2]	Range	5.4-5.5	0.7-1.2	7.3-9.0	1.1-2.3	34.2-34.7
			Mean	5.4	0.9	8.1	1.4	34.5
		Mid [3]	Range	5.4-5.6	0.4-1.5	5.8-7.4	1.2-1.31	22.7-29.8
			Mean	5.5	1.0	6.6	1.3	26.3
	Previously lime amended	Foot [2]	Range	5.3-5.4	0.6-1.3	7.2-10.7	1.1-1.3	29.3-31.2
			Mean	5.3	0.9	7.5	1.2	30.3
		Hill [3]	Range	5.1-5.6	0.3-2.1	3.2-6.1	1.3-2.7	26.3-27.9
			Mean	5.3	1.2	4.4	2.2	27.0
		Mid [3]	Range	5.3-6.0	0.1-1.6	4.7-24.1	1.4-1.7	22.3-31.1
			Mean	5.7	0.7	11.9	1.5	27.5

CEC: cation exchange capacity, P: available phosphorus, SOC: soil organic carbon, Numbers in parenthesis indicates the number of observations in each landscape.

The highest soil organic carbon content of 2.7 and 2.3 % was recorded from hill landscapes in lime-amended and non-amended sites, respectively (Table 1), while the lowest soil organic carbon content of 1.1 was obtained from foot landscapes in lime-amended soils. This result is in agreement with many previous studies that reported that cropland had low soil organic carbon due to frequent tillage and removal of residue (Nega and Heluf, 2009; Tamene et al., 2017). The soil pH (H_2O) of the experimental sites (without lime amendment) was found between 4.8 (foot) and 6.4 (hill) in Gozamen district (Table 3) and ranked very strongly to slightly acidic (Tadesse et al., 1991). Whereas experimental sites that are previously lime amended were found between

5.0 and 6.0 (Table 3) with a strong to slightly acidic range of soil acidity. Some sites at hill and mid have an exchangeable acidity value of 2.1 and 1.6 (meq /100g soil), particularly in Gozamen district. These values were found higher exchangeable acidity that is above a critical level. The mean value of available phosphorus ranged between 6.6 to 12.9 mg kg^{-1} which is ranked low to medium (Tadesse et al., 1991).

Teff grain and biomass yield response to nutrients

For all the sites and landscape positions, application of all nutrient types (N, P, K, S, Zn, and B) was not resulted from significant teff yield increments ($p > 0.05$) as compared to NP nutrient alone at Machakel district (Table 4 and 5). Only increasing the rate of all nutrients by 150% gave a higher biological yield over NP alone. Nevertheless, we are not sure whether the higher yield of 150% in all nutrients comes from the increase of NP nutrients only or due to other nutrients as the experiment did not have a treatment with NP with a 150% increment. Even though the trial was designed with one no fertilizer treatment, teff yield was not recorded at all in acidic soils. This shows that without fertilizer application, it is difficult to produce teff under the current farming system in the study area. In the nutrient omission trials, teff grain yields ranged between 447.9 and 1260.4 kg ha^{-1} in Machakel district (Table 4). The trend of biomass yield was similar to grain yield to nutrient types and amounts. From this result, K, S, Zn, and B are not yield-limiting for teff in the study area.

Table 22. Teff grain and biomass yield without lime amended farm sites of three landscapes in Machakel district

	Landscape					
	Foot [2]		Mid [3]		Hill [2]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
NPSZnB	692.7	3020.8	508.3 bc	4437.5 bc	781.3 c	3052.1 bc
NPZnB	666.7	2656.3	556.3 bc	4608.3 bc	760.4 c	2555.6 cd
NPSB	447.9	2265.6	636.3 b	3875.0 bc	847.2 bc	2979.2 bc
NPSZn	661.5	2838.5	595.8 b	3316.7 c	687.5 c	2336.8 de
NPKSZnB	666.7	3046.9	704.2 ab	4941.7 ab	989.6 b	3402.8 b
NP	682.3	2500.0	641.7 b	5175.0 ab	736.1 c	2725.7 cd
50%NPKSZnB	401.0	1250.0	327.1 c	3643.8 bc	642.4 c	1961.8 e
150%NPKSZnB	937.5	4302.1	895.8 a	6330.4 a	1260.4 a	4836.8 a
CV (%)	15.1	16.9	29.3	26.2	13.1	10.5
P level (0.05)	ns	ns	**	***	***	***

*CV: coefficient of variation, ***: significant at 1 %. Numbers in parentheses indicate the number of observations in each landscape.*

Table 23. Teff grain and biomass yield at previously lime-amended farm sites of three landscape positions in Machakel district

	Landscape					
	Foot [2]		Mid [3]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
NPSZnB	942.7	3614.6	377.1 c	1404.2 c	491.7 bc	1633.3 bc
NPZnB	1005.2	2958.3	514.6 bc	1722.9 bc	670.8 ab	2247.9 b
NPSB	802.1	2765.6	427.1 c	1697.9 bc	504.2 bc	1702.1 bc
NPSZn	776.0	2947.9	495.8 bc	1627.1 bc	466.7 bc	1575.0 bc
NPKSZnB	963.5	3218.8	664.6 ab	2227.1 b	633.3 ab	2079.2 b
NP	859.4	2880.2	489.6 bc	1795.8 bc	485.4 bc	1727.1 bc
50%NPKSZnB	505.2	1520.8	308.3 c	1102.1 c	306.3 c	1045.8 c
150%NPKSZnB	1119.8	5479.2	852.1 a	3162.5 a	818.8 a	3243.8 a
CV	12.9	17.1	28.7	27.7	31	27.4
P level (0.05)	ns	ns	***	***	**	***

*CV: coefficient of variation, ***: significant at 0.1 %, **: significant at 1 %, ns: non-significant. Numbers in parentheses indicate the number of observations in each landscape.*

The productivity of tef in the acidic highlands areas was very low and it was not possible to harvest yield from those plots without fertilizer. The analysis of variance indicated that there is no significant teff grain and biomass yield difference due to nutrient types and amounts at different landscapes and liming conditions except the mid-landscape position in Gozamen district (Tables 6 and 7). For both lime-amended and not amended sites, a relatively better yield was obtained from NP and 150% NPKSZnB treatments (Tables 6 and 7).

Table 24. Teff grain and biomass yield without lime amended farm sites of three landscapes in Gozamen district

	Landscape					
	Foot [2]		Mid [5]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
NPSZnB	764.3	2791.7 bc	926.3	3386.9	871.9	3482.6
NPZnB	699.2	2932.3 b	1043.9	3809.5	993.1	4388.9
NPSB	584.6	2237.0 bc	831.1	2614.6	902.8	3347.2
NPSZn	563.8	2554.7 bc	1035.7	3651.8	984.4	3510.4
NPKSZnB	658.9	3099.0 b	1157.7	3474.0	923.6	3833.3
NP	713.5	2744.8 bc	1037.2	3522.3	944.4	3506.9
50%NPKSZnB	505.2	1700.5 c	873.3	2841.1	819.4	3454.9
150%NPKSZnB	1056.0	5471.4 a	1026.8	4075.9	861.9	3295.1
CV (%)	34.2	25	33	29.1	15.2	21.9
P level (0.05)	ns	***	ns	ns	ns	ns

*CV: coefficient of variation, ns: non-significant, ***: significant at 1 %. Numbers in parentheses indicate the number of observations in each landscape.*

Table 25. Teff grain and biomass yield at previously lime-amended farm sites of three landscape positions in Gozamen district

	Landscape					
	Foot [2]		Mid [6]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
NPSZnB	868.5	4420.6	910.3 bc	3094.3 bc	739.6	3289.9
NPZnB	914.1	4078.1	935.8 abc	3256.9 bc	965.3	4130.2
NPSB	1001.3	4404.9	859.4 bc	3024.3 bc	849.0	3529.5
NPSZn	885.4	4242.2	957.8 ab	3686.9 bc	788.2	3187.5
NPKSZnB	1128.9	4386.7	828.1 bc	2931.1 bc	925.3	3673.6
NP	791.7	4658.9	979.2 ab	3464.1 bc	854.2	3262.2
50%NPKSZnB	688.8	2819.4	703.7 c	2478.6 c	675.3	2342.0
150%NPKSZnB	1096.4	4153.6	1151.6 a	4861.7 a	849.0	3588.5
CV (%)	27.8	30.02	25.1	31.3	21.8	31.1
p (0.05)	ns	ns	*	**	ns	ns

*CV: coefficient of variation, ns: non-significant, *: significant at 5 %. Numbers in parentheses indicate the number of observations in each landscape.*

Response of teff to omitted nutrients

There was no significant difference across trial sites in teff yield resulting from the omission of a macronutrient from the K and S treatment and micronutrients from Zn and B treatments (Figure. 2). The omitted treatment did not show a significant yield difference in both previously lime amended and not amended trial sites. The omission of sulfur (All-S) led to a reduction in yield compared to the NPKSZnB treatment in mid and hill landscape positions in previously lime-amended sites, but this reduction was not significantly varied with All (below 100 kg ha^{-1}) in Machakel districts. The omission of K, Zn, and B nutrients did not show a statistically significant teff grain yield compared to the combined application of NPKSZNB (ALL) and recommended NP nutrients. This result was consistent with earlier research showing that adding K, S, Zn, and B did not substantially boost crop yield in the majority of Ethiopia's teff-growing regions (Tadele et al., 2018, 2019).

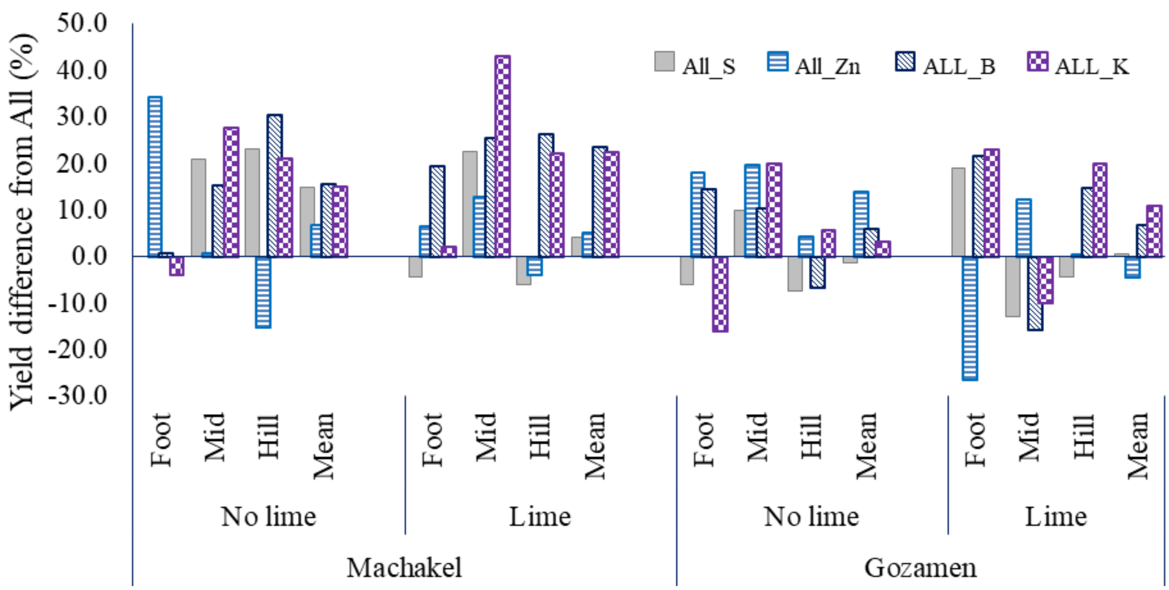

Figure 4. Effect of omission of S, K, Zn, and B on tef yield difference (5) relative to NPKSZnB in Machakel district trial sites. Error bars are confidence intervals.

Similarly, the omission of S led to a non-significant reduction in yield compared to the NPKSZnB treatment in foot and mid-landscape positions in both study districts, it was relatively low (below 200 kg ha^{-1}) in Gozamen districts (Figure 3). It had a similar trend in K omitted treatment that shows a no significant decline of yield in foot and mid landscape in previously lime amended and not amended trial sites, respectively. The omission of born had resulted from a decline of teff grain yield in mid-landscape sites in both without lime application and lime amended sites in the Gozamen district. This decrease was not statistically significant ($p < 0.05$). This result is supported by Tadele et al. (2018, 2019) who indicate that the addition of KSZnB with NP did not boost yield compared to NP alone. The finding agreed with Rawal et al. (2018) who reported that nitrogen and phosphorous are found to be the most limiting nutrient for wheat production in all sites.

Response of bread wheat to applied nutrients

The statistical analysis of bread wheat grain and biomass yield in Machakel district showed that there was a significant difference among nutrient types and rate as compared to control (no fertilizer) except biomass yield at hill landscape position (Tables 8 and 9). Higher rate and all nutrients received treatment gave maximum yield but no significant (p>0.05) as compared to NP fertilizer. This finding was similar to the finding of teff in the same district. Bread wheat grain yields ranged between 145.8 and 2678.6 kg ha^{-1} in Machakel district (Table 8) whereas it ranged from 300.7 to 3942.5 kg ha^{-1} in Gozamen district (Table 10).

Table 26. Bread wheat grain and biomass yield from without lime amended farm sites of three landscapes in Machakel district

	Landscape					
	Foot [2]		Mid [3]		Hill [3]	
Nutrient type	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
Control	145.8	484.4	255.8 ^{d}	1554.2 ^{d}	261.0 ^{d}	819.4
NPSZnB	2106.7	4739.6	1863.5 ^{b}	4437.5 ^{bc}	1268.6 ^{bc}	3641.7
NPZnB	2025.6	4614.6	2075.8 ^{b}	4608.3 ^{bc}	1484.4 ^{bc}	4023.4
NPSB	2187.5	4885.4	1782.3 ^{b}	3875.0 ^{bc}	1313.5 ^{bc}	3630.2
NPSZn	2123.4	4687.5	2139.9 ^{b}	3316.7 ^{c}	1301.6 ^{bc}	3893.0
NPKSZnB	2110.4	5057.3	1941.2 ^{b}	4941.7 ^{ab}	1692.9 ^{b}	4592.2
NP	2069.4	4531.3	1868.7 ^{b}	5175.0 ^{ab}	1369.9 ^{bc}	4083.3
50%NPKSZnB	1180.8	2541.7	1327.0 ^{c}	3643.8 ^{bc}	996.9 ^{c}	3653.6
150%NPKSZnB	2678.9	6500.0	2641.6 ^{a}	6330.4 ^{a}	2261.9 ^{a}	3942.7
CV (%)	13.2	17.3	15.7	26.2	24.3	35.1
P level (0.05)	*	*	***	***	***	ns

*CV: coefficient of variation, ns: non-significant, *: significant at 5 %.***: significant at 0.1 %. Numbers in parentheses indicate the number of observations in each landscape.*

Table 27. Bread wheat grain and biomass yield at previously lime-amended farm sites of three landscape positions in Machakel district

	Landscape					
	Foot [2]		Mid [3]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
Control	72.9	218.8	343.4 [d]	819.4	333.7 [b]	819.4
NPSZnB	1278.0	3036.5	2317.3 [b]	3641.7	1864.4 [a]	3641.7
NPZnB	1488.2	3395.8	2459.9 [ab]	4023.4	2025.1 [a]	4023.4
NPSB	1520.3	3474.0	2319.6 [b]	3630.2	1828.4 [a]	3630.2
NPSZn	1596.9	1958.3	2456.1 [ab]	3893.0	1810.0 [a]	3893.0
NPKSZnB	1750.7	3963.5	2495.5 [ab]	4592.2	2030.3 [a]	4592.2
NP	1636.6	3682.3	2394.8 [b]	4083.3	1964.4 [a]	4083.3
50%NPKSZnB	1073.2	2484.4	1696.3 [c]	3653.6	1377.9 [a]	3653.6
150%NPKSZnB	2653.6	6000.0	2955.5 [a]	3942.7	1942.1 [a]	3942.7
CV (%)	14.1	16.7	17.1	35.1	26.9	35.1
P level (0.05)	*	*	***	ns	***	ns

*CV: coefficient of variation, ns: non-significant, *: significant at 5 %. ***: significant at 0.1 %. Numbers in parentheses indicate the number of observations in each landscape.*

There were grain and biomass yield differences among the experimental sites to bread wheat. The statistical analysis result at Gozamen district showed that there was a significant difference ($p<0.01$) in grain and biomass yield when all other treatments were compared to the control treatment (Tables 10 and 11). Generally, a higher and more significant yield was recorded when 150% NPKSZnB was applied. However, the relatively equal biological yield of bread wheat was obtained from the NP compared to the NPKSZnB fertilizer type with equal rates. So, the application of NP fertilizer alone has a yield advantage for smallholder farmers in highlands areas. Phosphorus and nitrogen are critical nutrients to improve bread wheat production (Kolawole et al., 2018). The omission of potassium, sulfur, zinc, or boron did not affect the yields of bread wheat. This result is supported by Nziguheba et al. (2009) who indicate that K and B omission are not reduced cereal crop yield.

Table 28. Bread wheat grain and biomass yield without lime amended farm sites of three landscapes in Gozamen district

	Landscape					
	Foot [2]		Mid [6]		Hill [3]	
Nutrient type	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
Control	220.9 c	861.1 c	265.0 e	551.2 c	329.2 c	819.4
NPSZnB	1814.2 ab	4825.5 ab	2510.8 cd	5886.2 a	1338.0 b	3641.7
NPZnB	1937.3 ab	4656.3 ab	3441.2 ab	6773.1 a	1787.9 ab	4023.4
NPSB	1464.9 b	4875.0 ab	2825.5 bc	5720.2 a	2033.1 ab	3630.2
NPSZn	1821.0 ab	5112.0 ab	3468.4 ab	6601.3 a	1991.9 ab	3893.0
NPKSZnB	2325.0 ab	5838.5 a	3020.8 abc	6561.0 a	2223.7 a	4592.2
NP	2238.3 ab	5697.9 a	2914.8 bc	6639.9 a	1740.0 ab	4083.3
50%NPKSZnB	1630.1 ab	3697.9 b	2025.4 d	4113.1 b	1807.6 ab	3653.6
150%NPKSZnB	2535.6 a	6455.7 a	3618.4 a	7103.4 a	2067.7 ab	3942.7
CV	34.1	23.7	21.2	20.2	28.4	35.1
P level (0.05)	**	***	***	***	**	ns

*CV: coefficient of variation, ns: non-significant, ***: significant at 1 %, **: significant at 5 %. Numbers in parentheses indicate the number of observations in each landscape.*

Table 29. Bread wheat grain and biomass yield at previously lime-amended farm sites of three landscape positions in Gozamen district

	Landscape					
	Foot [2]		Mid [6]		Hill [3]	
Nutrient types	Grain yield	Biomass	Grain yield	Biomass	Grain yield	Biomass
Control	300.7 b	916.7 b	419.5 d	1218.8 d	566.6 b	1222.2 b
NPSZnB	2112.9 a	5099.0 a	3126.6 b	7283.6 b	2536.7 a	5644.1 a
NPZnB	2437.2 a	6059.9 a	3081.3 b	7030.7 b	2965.2 a	6982.6 a
NPSB	2364.8 a	5904.9 a	2924.8 b	6877.3 b	2295.9 a	5191.0 a
NPSZn	2418.4 a	5346.4 a	2945.4 b	6588.0 b	2704.5 a	5704.9 a
NPKSZnB	2066.8 a	6615.9 a	3270.2 b	7071.8 b	2570.3 a	5362.8 a
NP	2697.1 a	5113.3 a	3226.7 b	7134.3 b	2703.5 a	6053.8 a
50%NPKSZnB	1772.7 a	4147.2 a	2409.3 c	4871.5 c	2352.8 a	5215.3 a
150%NPKSZnB	2615.1 a	6163.8 a	3942.5 a	8383.1 a	2535.7 a	5474.0 a
CV(%)	26.3	28.8	17.1	15.9	18.0	19.2
P level (0.05)	***	***	***	***	***	***

*CV: coefficient of variation, ***: significant at 0.1 %. Numbers in parentheses indicate the number of observations in each landscape.*

Response of bread wheat to omitted nutrients

There was variability between sites from the omission of a macronutrient from the K and S treatment and micronutrients from Zn and B in bread wheat yield in study areas (Figure 3). The omitted treatments did not show significant yield differences in both previously lime-amended and not amended trial sites. The omissions of zinc (All-Zn) and boron (All-B) led to a non-significant reduction of yield compared to the NPKSZnB treatment in previously lime-amended sites. This result is harmonized with Tadele et al. (2018, 2019) which indicates that the addition of K is not increased crop yield significantly in most bread wheat growing areas of Ethiopia. In the Machakel district, the omission of Zn in sites of hill landscapes exhibited a negative Zn index (Figure 4). This finding, however, does contradict that of Kihara et al. (2022), who stated that micronutrients are required to increase wheat output.

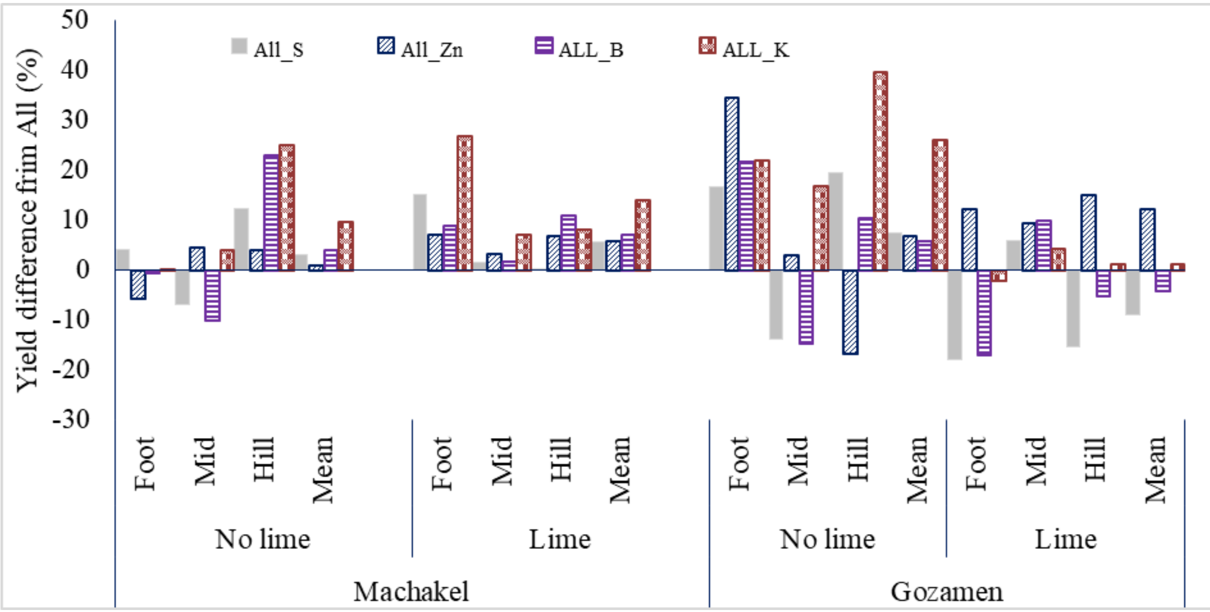

Figure 5. Effect of omission of S, K, Zn, and B on bread wheat yield (%) compared to NPKSZnB in Machekel and Gozamen districts. Error bars are confidence intervals. Note: All = NPKSZnB applied

Response of teff and bread wheat to lime amendment

The result indicated that previously lime amendment plus nutrient type and rate have a relatively higher yield of tef and bread wheat across all landscape positions except with deviation at the hill (teff) in Machakel and Gozamen districts and foot (bread wheat) in Machakel district (Figure 4 and 5). This might be associated with blanket rate lime application during 2019/20. The fertilizer application was varied across landscapes. Because when the slope is increased, there is a decrease in crop yield (Amede et al., 2020). It might be related to the decline of soil fertility. The highest mean grain yield of tef 872, and 994 kg ha^{-1} were recorded in lime amended at foot, and without lime amended at mid landscape positions (Figure 4), while the bread wheat yield 2846 and 2160 kg ha^{-1} were observed from lime amended at mid landscape position, respectively (Figure 5).

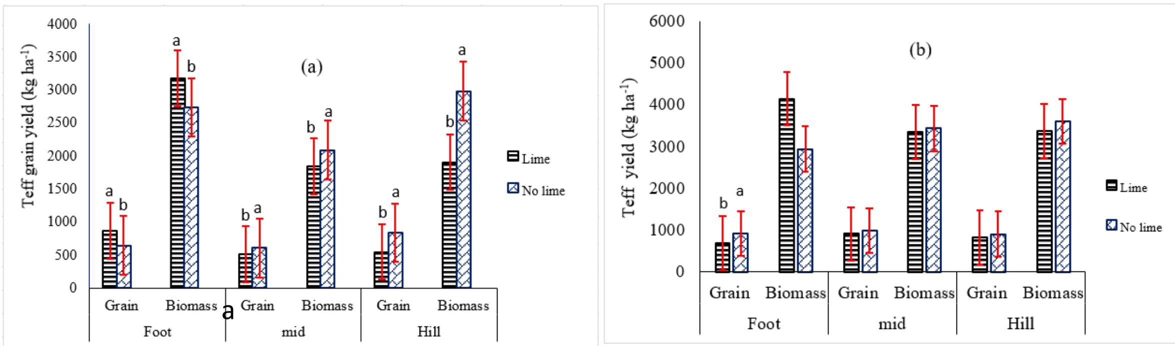

Figure 6. Effect of lime amendment and landscape on teff grain yield and biomass in Machake (a) and Gozamen (b) districts. Short lines at the top of each bar represent the standard error of lime amendment, lowercase letters indicate significant differences (p<0.05) among lime amendments.

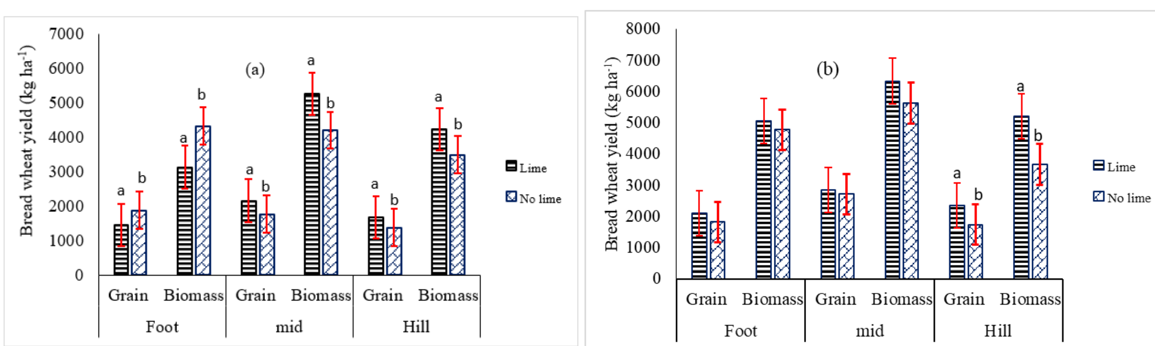

Figure 7. Effect of lime amendment and landscape on bread wheat grain yield and biomass in Machake (a) and Gozamen (b) districts. Short lines at the top of each bar represent the standard error of lime amendment, lowercase letters indicate significant differences (p<0.05) among lime amendments.

Teff and bread wheat response to the nutrient type and rate across three landscapes and lime amendment

The combined analysis of variance revealed that the mean tef yield was highly significantly different among nutrient types (p < 0.001) whereas there was no significant variation in tef yield due to the interaction effect of nutrient types, lime amendment, and landscape position in the study districts (Table 12). The grain yield of tef was significantly varied with lime amendment ($p < 0.01$) and landscape positions ($p < 0.05$) in Machakel district (Table 12).

Table 30. Analysis of variance for different factors to teff in acidic soils of East Gojjam zone districts

	Gozamen		Machakel	
Factors	Grain yield	Biomass	Grain yield	Biomass
Nutrient types	0.09^{ns}	0.003**	1.6^{-11}***	2.2^{-16}***
Landscape	0.03*	0.7^{ns}	0.0001***	5.5^{-10}***
Amendment	0.9^{ns}	0.2^{ns}	0.003**	9.2^{-5}***
Nutrient types *Landscape	1.0^{ns}	0.9^{ns}	1.0^{ns}	0.4^{ns}
Nutrient types *Amendment	1.0^{ns}	0.9^{ns}	1.0^{ns}	0.9^{ns}
Landscape * Amendment	0.02*	0.007**	1.9^{-5}***	2.2^{-5}***
Nutrient types *Landscape*Amendment	1.0^{ns}	1.0^{ns}	1.0^{ns}	0.9^{ns}

****: significant at 0.1%, **: significant at 1 %, *: significant at 5 %, ns: non-significant.*

Likewise, teff, the result for bread wheat at Gozamen and Machakel districts on acidic soils indicates that there was a highly significant ($p<0.001$) yield difference among nutrient type and the rate at three landscapes with lime amendment (Table 13). Maximum and significant biological grain and biomass yield were recorded when 150% NPKSZnB was applied in both districts. A highly significant yield of bread wheat was obtained due to the application of nutrients compared to no input at all (control). However, there was no significant difference among nutrient types (between NP and NPKSZnB) in both districts.

Table 31. Analysis of variance of bread wheat yield and biomass response across landscapes and lime amendment in acidic soils of study districts

	Gozmen		Machakel	
Factors	Grain yield	Biomass	Grain yield	Biomass
Nutrient types	2.2^{-16}***	2.2^{-16}***	2.2^{-16}***	2.2^{-16}***
Landscape	3.3^{-14}***	4.3^{-13}***	3.4^{-8}***	1.4^{-6}***
Amendment	0.002**	4.5^{-6}***	0.0003***	0.0005***
Nutrient types *Landscape	0.7^{ns}	0.8^{ns}	0.9^{ns}	1.0^{ns}
Nutrient types *Amendment	0.7^{ns}	0.04*	0.9^{ns}	0.8^{ns}
Landscape * Amendment	0.047*	1.0ns	0.0002***	0.0001***
Nutrient types *Landscape*Amendment	0.9^{ns}		0.9^{ns}	0.8^{ns}

****: significant at 0.1 %, **: significant at 1 %, *: significant at 5 %, ns: non-significant, CV: coefficient of variation, amendment: lime management*

The maximum grain (1026 and 942 kg ha-1) and biomass (4246 and 3703 kg ha^{-1}) yields were recorded from 150% NPKSZnB treatment (Table 14). In Gozamen district, there was a non-significant grain yield between NP, NPKSZnB, and 150% NPKSZnB. This is supported by

Alemayehu et al. (2022) who stated yield of tef is not maximized due to the application of KSZnB nutrients. However, the result disagreed with Gessesew et al. (2022) who described that applying higher rates of NPSZnB nutrients enhances crop yield. how

Table 32. Combined tef and biomass yield response to nutrient types and rate across landscapes and lime amendment in acidic soils of East Gojjam zone districts

	Gozamen		Machakel	
Factors	Grain yield	Biomass	Grain yield	Biomass
Nutrient types				
NPSZnB	868.1[ab]	3357.5 [bc]	568.2 [c]	1252.4 [d]
NPZnB	935.2[a]	3652.6[ab]	651.5 [bc]	2129.3 [bc]
NPSB	838.4[ab]	3090.6 [bc]	585.4 [c]	2178.0 [bc]
NPSZn	896.6 [ab]	3535.0 [ab]	578.6 [c]	2120.1 [bc]
NPKSZnB	941.8 [a]	3438.7 [b]	738.2 [b]	2058.2 [c]
NP	916.3[ab]	3606.4 [ab]	608.0 [bc]	2557.8 [b]
50%NPKSZnB	736.0[b]	2636.2 [c]	384.0 [d]	2170.0 [bc]
150%NPKSZnB	1026.1[a]	4245.8 [a]	942.2 [a]	3703.1 [a]
Landscape				
Foot	807.5 [b]	3543.5	758.1 [a]	2954.1 [a]
Mid	949.5 [a]	3488.5	562.2 [c]	1967.0 [c]
Hill	869.3 [ab]	3385.6	656.3 [b]	2309.7 [b]
Amendment				
Lime	901.3	3553.5	588.3 [b]	2091.0 [b]
No lime	888.7	3326.0	684.4 [a]	2487.2 [a]
CV(%)	38.3	40.4	34.4	29.2

****: significant at 0.1%, **: significant at 1 %, ns: non-significant, CV: coefficient of variation.*

A higher yield of bread wheat was obtained from the mid-landscape position. Yield variability has occurred across landscape positions within farmers’ fields with a range of 588 and 901 kg ha^{-1} (Table 15). This finding was contrary to Amede et al. (2020) who stated higher yield is recorded in foot landscapes due to relatively improved soil fertility at the lower slopes.

Table 33. Overall bread wheat yield and biomass response to nutrient types and rate across landscapes and lime amendment in acidic soils of East Gojjam zone districts

	Gozmen		Machakel	
Factors	Grain yield	Biomass	Grain yield	Biomass
Nutrient types				
Control	351.8 [d]	941.9 [c]	267.5 [d]	1067.5 [f]
NPSZnB	2399.5 [bc]	5740.4 [a]	1805.8 [b]	4351.6 [cd]
NPZnB	2753.7 [ab]	6148.2 [a]	1968.9 [b]	4492.9 [cd]
NPSB	2465.8 [bc]	5650.0 [a]	1818.1 [b]	4193.6 [cd]
NPSZn	2704.1 [ab]	5807.1 [a]	1915.8 [b]	3806.9 [de]
NPKSZnB	2733.9 [ab]	6059.3 [a]	2021.7 [b]	5274.3 [b]
NP	2758.9 [ab]	6316.2 [a]	1891.7 [b]	4706.2 [bc]
50%NPKSZnB	2167.5 [c]	4548.1 [b]	1318.2 [c]	3294.4 [e]
150%NPKSZnB	2999.5 [a]	6457.0 [a]	2486.3 [a]	6387.0 [a]
Landscape				
Foot	1958.6 [b]	4922.0 [b]	1663.3 [b]	3713.4 [b]
Mid	2789.2 [a]	6028.2 [b]	1963.0 [a]	4733.3 [a]
Hill	2010.4 [b]	4336.3 [c]	1535.4 [b]	3868.1 [b]
Amendment				
Lime	2568.7 [a]	5808.3 [a]	1844.6 [a]	4475.8 [a]
No lime	2220.0 [b]	4883.4 [b]	1626.5 [b]	3933.0 [b]
CV(%)	32.9	27.7	28.8	30.6

****: significant at 1 %, **: significant at 5 %, ns: non-significant, CV: coefficient of variation, treatment: nutrient type and rate, amendment: lime management*

Conclusions and Recommendations

The application of different nutrient types has a significant grain and biomass yield of teff and bread wheat across landscape positions with and without lime application in acidic soils of the East Gojjam zone. Teff yield cannot obtain without fertilizer application in the study area. Similarly, the lowest yield of bread wheat was obtained without fertilizer application (no input). There was yield variability among trial sites and applied nutrients in the study area. The application of all nutrient types (NPKSZnB) has no significant yield advantage compared to NP fertilizer alone. This implies that N and P are the most yield-limiting nutrients compared to other applied nutrients in the acidic soils of Machakel and Gozamen districts whereas the application of KSZnB nutrients was not yield-limiting. Therefore, refining the rate of NP in acidic soils is important for the sustainable use of inorganic fertilizer. The application of sulfur fertilizer with NP needs further study. Future research is looked-for to finetune crop response to micronutrient element's limitations for grain yield with the support of grain quality analysis to meet the demand for food nutrition.

Acknowledgments

The experiment was done with the financial support from International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and International Fertilizer Development Center (IFDC). We thank ICRISAT and IFDC for facilitating and funding the project. The authors are also grateful to farmers for allowing us their farms for experimentation.

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