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Improving fertilizer response of crop yield through liming and targeting to landscape positions in tropical agricultural soils

Getachew Agegnehu [a,*], Tilahun Amede [b], Gizaw Desta [a], Teklu Erkossa [c], Gizachew Legesse [a], Tadesse Gashaw [d], Andre Van Rooyen [a], Rebbie Harawa [e], Tulu Degefu [a], Kindu Mekonnen [f], Steffen Schulz [c]

[a] *International Crops Research Institute for Semiarid Tropics (ICRISAT), Addis Ababa, Ethiopia*
[b] *Alliance for Green Revolution in Africa (AGRA), Addis Ababa, Ethiopia*
[c] *Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ-Ethiopia), Addis Ababa, Ethiopia*
[d] *Cranfield University, Cranefield, United Kingdom*
[e] *International Crops Research Institute for Semiarid Tropics (ICRISAT), Nairobi, Kenya*
[f] *International Livestock Research Institute (ILRI), Addis Ababa, Ethiopia*

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ABSTRACT

Nutrient management research was conducted across locations to investigate the influence of landscape position (hill, mid-, and foot slope) in teff (*Eragrostis tef*) and wheat (*Triticum aestivum*) yield response to fertilizer application and liming in the 2018 and 2019 cropping seasons. The treatments included 1) NPS fertilizer as a control treatment (42 N + 10P + 4.2S kg ha^{-1} for teff and 65 N + 20P + 8.5S kg ha^{-1} for wheat); 2) NPS and potassium (73 N + 17P + 7.2S + 24 K kg ha^{-1} for teff and 103 N + 30P + 12.7S + 24 K kg ha^{-1} for wheat) and 3) NPSK and zinc (73 N + 17P + 7.2S + 24K + 5.3Zn kg ha^{-1} for teff and 103 N + 30P + 12.7S + 24K + 5,3Zn kg ha^{-1} for wheat) in acid soils with and without liming. Results showed that the highest teff and wheat grain yields of 1512 and 4252 kg ha^{-1} were obtained at the foot slope position, with the respective yield increments of 71% and 57% over the hillslope position. Yield response to fertilizer application significantly decreased with increasing slope owing to the decrease in soil organic carbon and soil water content and the increase in soil acidity. The application of lime with NPSK and NPSKZn fertilizer increased teff and wheat yields by 43–54% and 32–35%, respectively compared to the application of NPS fertilizer without liming where yield increments were associated with the application of N and P nutrients. Orthogonal contrasts revealed that landscape position, fertilizer application, and their interaction effects were significant on teff and wheat yields. Soil properties including soil pH, organic carbon, total N, and soil water content were increased down the slope, which might be attributed to sedimentation down the slope. However, available P is yet very low both in acidic and non-acidic soils. We conclude that crop response to applied nutrients could be enhanced by targeting nutrient management practices to agricultural landscape features and addressing other yield-limiting factors such as soil acidity and nutrient availability by conducting further research.

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[*] Corresponding author.
E-mail address: Getachew.Agegnehu@icrisat.org (G. Agegnehu).

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1. Introduction

Soil nutrient depletion and low nutrient use efficiency are critical challenges for improving agricultural productivity in undulating agricultural landscapes of Ethiopian highlands. Soil properties vary spatially within a field or a larger area due to inherent soil-forming factors and anthropogenic activities such as soil management practices, liming, fertilization, and cropping system practices [1,2]. Understanding soil properties across landscape positions and agroecological zones is key in guiding nutrient management to improve soil health and enhance productivity. Topography is strongly linked to soil fertility gradients and nutrient availability at the local scale [3]. Topographical variables, such as elevation and slope can affect soil properties [4]. For example, soils in valleys tend to be wetter and more fertile than those near ridgetops [5,6]. Therefore, steeper sites have a higher nutrient output and generally have fewer available nutrients in the soil than flatter sites [3,7].

The level of crop yield is low in most parts of sub-Saharan Africa (SSA), and nutrient balances are negative. Stoorvogel et al. [8] estimated the average nutrient loss for arable lands in SSA was 22 kg N, 2.5 kg P, and 15 kg of K ha^{-1} yr^{-1}, and negative balances for N, P, and K of 41, 6, and 26 kg ha^{-1} y^{-1}, respectively in Ethiopia. In contrast, Haileslassie et al. [9] estimated nutrient losses of 122 kg N, 13 kg P, and 82 kg K ha^{-1} y^{-1}, respectively in the central highlands of Ethiopia. The major causes of soil fertility decline include nutrient removal through entire crop harvests, uncontrolled soil erosion, low soil organic matter and inherent soil fertility, limited application of appropriate types and rates of fertilizers, and inappropriate land management practices [1,10,11]. In addition, P fixation and aluminum toxicity are two major constraints for most Ethiopian agricultural soils with pH values less than 5.5 [12]. Recent research findings indicated that the decline in soil fertility and nutrient availability is starker on steep slopes than on gentle slope agricultural lands because of severe topsoil erosion and nutrient removal [7,11,13]. So, the loss of topsoil and its serious impact on crop growth and yields are more pronounced on soils with steep slopes.

In East African regions, agricultural landscapes involving high-elevation hillslopes, mid-slopes, foot slopes, and plateaus, which occur within short distances, require various levels of inputs and different agronomic management [7]. Studies in Vietnam [6,14], Malawi [15], central highlands of Ethiopia [16], northern Ethiopia [7], and southern Ethiopia [13,17,18] have demonstrated soil nutrient variabilities across landscape positions. Landscape variability also creates soil fertility variability between farms and within farms in soil nutrient status [5,14,17], soil organic matter content [19], soil water holding capacity [20], and agronomic management requirements of crops [21]. The variability is increased further by soil erosion [22], which commonly degrades the hillslopes and mid-slopes and deposits them on the foot slopes [5,17]. Generally, soils are more gravelly and thinner with rock outcrops close to hilltops and get more fertile towards the mid-slope and while the foot slope and the valleys are often characterized by fertile alluvial deposits.

High yield gaps in SSA are partly due to the failure in appreciating the variability of crop response to external inputs across farms and landscapes [7,23]. The research to understand soil variability and its potential effect on crop yield based on topography-related patterns has continued for over a century, but soils with undulating landscapes or poorly developed profiles were treated as exceptions to the more common, generalized trends of normal soils [24]. In recent years, variability in crop yields within and between farms [2,25,26] and landscape positions [7] have attracted research attention in SSA. In other cases, three different crop response categories to fertilizer application have been identified, namely responsive, fertile non-responsive, and degraded non-responsive to indicate yield variability in small-scale farms [21,25,26]. Previous studies have shown that higher rates of fertilizer application have not led to higher crop yields in both fertile and degraded non-responsive soils [20,21,26–28]. Studies show that marginal soils produce lower yields compared to moderately fertile soils, even with the application of higher rates of fertilizers [1,27]. However, there is a limited understanding of why there was a positive response in some farms while there was a limited crop response in others within the same locality [5]. Even in some cases the positive crop response and economic incentives for farmers to higher rates of mineral fertilizer application were rare [29]. The mixed crop response to the application of fertilizers could be partly due to the variability of farms and landscape positions and the failure in identifying the right type and amount of nutrients required for a specific landscape niche [30].

Teff *(Eragrostis tef)* and wheat (*Triticum aestivum* L.) are among the major cereal crops in Ethiopia that are mainly cultivated as mono-crops or rotated as teff-wheat-food legumes and wheat-teff-food legumes [31]. The two crops show an increasing trend in area coverage, with about 3.10 and 1.79 million ha, respectively [32]. However, despite the considerable potential to increase their production, their yield remains low (1.85 for teff and 2.97 t ha^{-1} for wheat). This was attributed mainly to the prevailing poor soil fertility and crop management practices [10,33].

Fertilizer trials were conducted on research stations and a few selected testing sites, with limited effort to extrapolate the results to a wider range of environments. This could be one of the reasons for the yield variation in crops in the different areas as soil properties are variable and change rapidly. Thus, the crop yield gaps could be related to inadequate replenishment and improper management of soil nutrients [10]. There is limited information on how landscape positions could be used for refining fertilizer recommendations. In this study, we used teff and wheat as test crops to understand the factors affecting the crop response to fertilizers in the undulating setting of soils of the Ethiopian highlands across the catena. Generally, research information about the effects of landscape position variation in crop yield response to fertilizer application and liming in the Ethiopian context is inadequate. Accordingly, a nutrient management trial was conducted to test the hypothesis that the application of fertilizer and lime would improve soil properties and yield of teff and wheat under different landscape positions and agroecological zones. This study was, therefore, initiated to 1) investigate the influence of landscape variation in crop yield response to fertilizer application and liming; 2) evaluate the main and interaction effect of fertilizer and lime on crop yield and soil properties in acid soils of Ethiopian highlands; and 3) identify variations in soil nutrient status and yield-limiting nutrients (N, P, K, S, and Zn) across landscape positions and their adequacy for teff and wheat production.

2. Materials and methods

2.1. Description of the study sites

Landscape-based fertilizer trials were conducted over years and locations to determine the response of wheat and teff to different nutrient sources. Over 209 and 155 on-farm fertilizer trials were conducted on teff and wheat, respectively in Gozamin, Machakel, and West Belesa districts of Amhara, Ambo and Sokoru districts of Oromia, and Alaje and Raya Azebo districts of Tigray regions during the 2018 and 20219 main cropping seasons (Fig. 1). The trial sites were selected based on rainfall status or agroecological zones, the extent of soil acidity, and landscape positions which are key indicators of crop production potential in different agroecological zones of the country. The trials were jointly implemented by ICRISAT and regional agricultural research institutes, with sites representing a wide diversity of soil types and landscape positions.

The geographical locations and agroecological zones of all the study sites are summarized in Table 1. Agroecologically, Ambo, Gozamin, and Machakel are found in Tepid moist mid-highlands (M3), Sokoru in Tepid sub-humid mid-highlands (SH3), West Belesa in cool sub-moist mid-highlands (SM4), and Raya Azebo is situated in Warm sub-moist lowlands (SM2). The selected sites are characterized by monomodal and bimodal rainfall patterns with varying rainfall amounts, intensity, and duration. Gozamin, Machakel, Ambo, and Sokoru districts have monomodal rainfall patterns with relatively moderate to high rainfall regimes while West Belesa and Raya Azebo districts have bimodal rainfall patterns with low rainfall regimes. The highest rainfall usually occurs from June to September. The average annual rainfall and maximum and minimum air temperatures of selected study sites in each district are indicated in Table 1. The monthly average rainfall and temperature of all districts are presented in Fig. 2. The dominant soil types on the study sites are Vertisols, Nitisols, and Cambisols, with respective coverage of 10.2%, 11.8%, and 15.3% of the land area in Ethiopia [34]. These soils vary in terms of drainage and nutrient status, and most are deficient in N and P [35]. Selected soil physicochemical properties of each soil type are presented in Table 1.

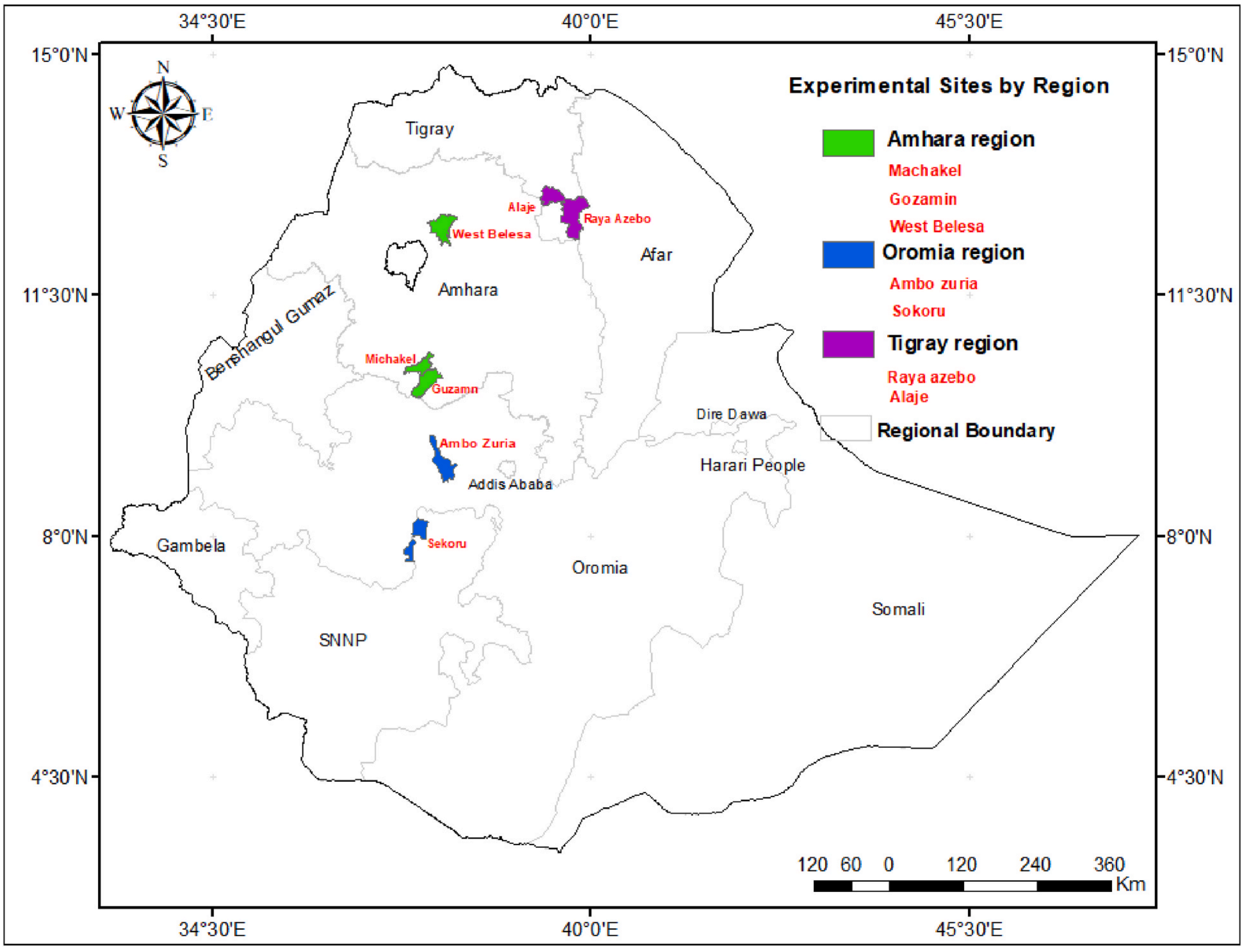

Fig. 1. Geographical locations of experimental sites.

Table 1
Weather, agroecological and soil characteristics of the experimental sites.

Property	Gozamin	Machakel	Ambo	Sokoru	Alaje	West Belesa	Raya Azebo
Latitude	9°43′58″-9°52′42″N	10°28′23.01096″-10°29′4.36495″N	9°0′ 3.996″-9°8′8.988″N	7°44′39.984″-7°45′58.2984″N	12°52′25″-12°52′47″ N	12° 25′ 58.8″-12° 27′ 7.2″N	12°46′54.264″-12°49′1.848″N
Longitude	39°25′28″-39°40′08″E	37°33′20.17141″ 37°33′50.00929″E	37°9′32.004″-37°19′5.016″E	37°20′11.76″- 37° 21′ 48.6″E	39°32′45″-39°33′02″ E	37° 36′ 0” −37° 46′ 44.4″E	39°37′38.172″-39°38′34.62″E
Altitude	2802–3043	2729–2756	1299–3368	1060–2258	1555–3945	1860–1920	2368–2463
Rainfall	1334	1432	1258	1344	632	680	658
Max. temp	24.8	25.3	30	29.9	27.8	34.1	34.1
Min. temp	10.8	11	13.8	13.5	11.6	13.1	16.1
AEZ	M3	M3	M3	SH3	SM4	SM3	SM2
Soil type	Nitisol	Nitisol	Vertisol	Nitisol	Cambisol	Cambisol	Vertisol
Soil pH	5.22	5.26	6.38	5.23	6.60		7.95
Soil OC (%)	1.34	1.05	0.89	0.86	1.70		0.94
Total N (%)	0.15	0.15	0.14	0.11	0.18		0.07
P (mg kg^{-1})	2.20	1.65	2.55	0.10	17.5		5.49
S (mg kg^{-1})	9.70	11.6	1.35	0.28	–		1.81
Zn (mg kg^{-1})	0.80	0.38	0.59	0.05	–		0.30
B (mg kg^{-1})	0.27	0.26	0.32	0.04	–		0.11
CEC (cmol kg^{-1})	14.7	15.5	–	–	–		51.4

‡AEZ: Agroecological zone; M3: Tepid moist mid-highlands; SH3: Tepid sub-humid mid-highlands; SM3: Tepid sub-moist mid highlands; SM4: Cool sub-moist mid-highlands; SM2: Warm sub-moist lowlands.

2.2. *Treatments and experimental design*

The effects of different fertilizer treatments targeting various nutrient sources and rates under limed and non-limed conditions on wheat and teff yield were evaluated on over 364 sites in different landscape positions of three regions from the 2018–2019 cropping seasons. According to Amede et al. [7], the landscapes were divided into foot slope, mid-slope, and hillslope positions following topo-sequential variations with slope ranges of 0–5, 5–15, and >15%, respectively. The experiment tested zinc-based fertilizer (NPSK and basal Zn) in comparison with the recommended NPS fertilizer rate. The fertilizer treatments for teff included (a) optimal rates of 73, 17, 7.2, and 24, 5.3 kg ha^{-1} N, P, S, K, and Zn, respectively, with NPS as a compound fertilizer and K applied as KCl and Zn as $ZnSO_4$; (b) 73, 17, 7.2 and 24 kg ha^{-1} N, P, S, and K kg ha^{-1}; and (c) farmer's rates of 43, 10 and 4.2 kg ha^{-1} N, P, and S as NPS compound fertilizer. Similarly, the treatments for wheat comprised (a) optimal rates of 103, 30, 12.7, 24, 5.3 kg ha^{-1} N, P, S, K, and Zn, respectively; (b) 73, 17, 7.2, and 24 kg ha^{-1} N, P, S, and K kg ha^{-1}, with NPS as a compound fertilizer and K as KCl; and (c) farmer's rates of 43, 10 and 4.2 kg ha^{-1} N, P, and S as NPS compound fertilizer under limed and non-limed conditions where soils are acidic. Variable rates of N and P were applied for teff and wheat in comparison to the recommended blanket extension NPS rates.

The blanket extension recommended fertilizer rate, practiced by farmers, was considered as the first control treatment, which was applied as a single rate of nutrients for a specified crop type across a given district regardless of soil fertility status and landscape position. The second treatment was planned based on the decision guide that ICRISAT has developed using the findings of previous extensive fertilizer trials [7]. It mainly included NPS with rates that differed by crop and landscape position and K fertilizer at a rate of 24 kg ha^{-1}. The micronutrient Zn was selected based on the soil fertility map of those locations which were reported as deficient in this nutrient by the ETHOSIS soil map [36]. The third treatment comprised similar rates of NPS and K as the second treatment plus zinc sulfate fertilizer at the rate of 25 kg ha^{-1}. The sources of nitrogen were NPS and urea fertilizers and NPS fertilizer for phosphorus.

Treatment sequencing was randomized using a split-plot design with liming as main plots and fertilizer treatments as sub-plots on a plot size of 3.6 × 3.4 m (12.24 m^2) with three replicates for each factor. The spaces between treatments and blocks were 1 m and 1.5 m, respectively. In this experiment, wheat and teff were used as test crops. Wheat was planted from the end of June to the first week of July in all districts, while teff was sown in Raya Azebo between the second and fourth week of July every year and in Gozamin, Machakel, Ambo, and Sokoru between the third week of July and second week of August. Wheat varieties used were *Denda'a* in Ambo, Gozamin, and Machakel, and *Kingbird* in Alaje, while teff varieties used were *var. Kuncho* in Ambo, Gozamin, and Machakel districts and *cv. Bunign* in Raya Azebo district. Phosphorus and K were applied as NPS and KCl just on the side of the row at a depth of 3–5 cm at planting. Nitrogen in the form of urea was applied half at planting and the other half at the full tillering stage of both crops. Lime was applied in acidic soil areas as calcium carbonate at least a week before planting and incorporated into the soil. Lime rate (LR) was calculated according to Agegnehu et al. [37] based on the exchangeable acidity of the soil as:

$$LR, CaCO_3(kg/ha) = \frac{cmolEA/kg\ soil \times 0.15m \times 10^4 m^2 \times B.D(mg/m^3) \times 100}{2000} \qquad (1)$$

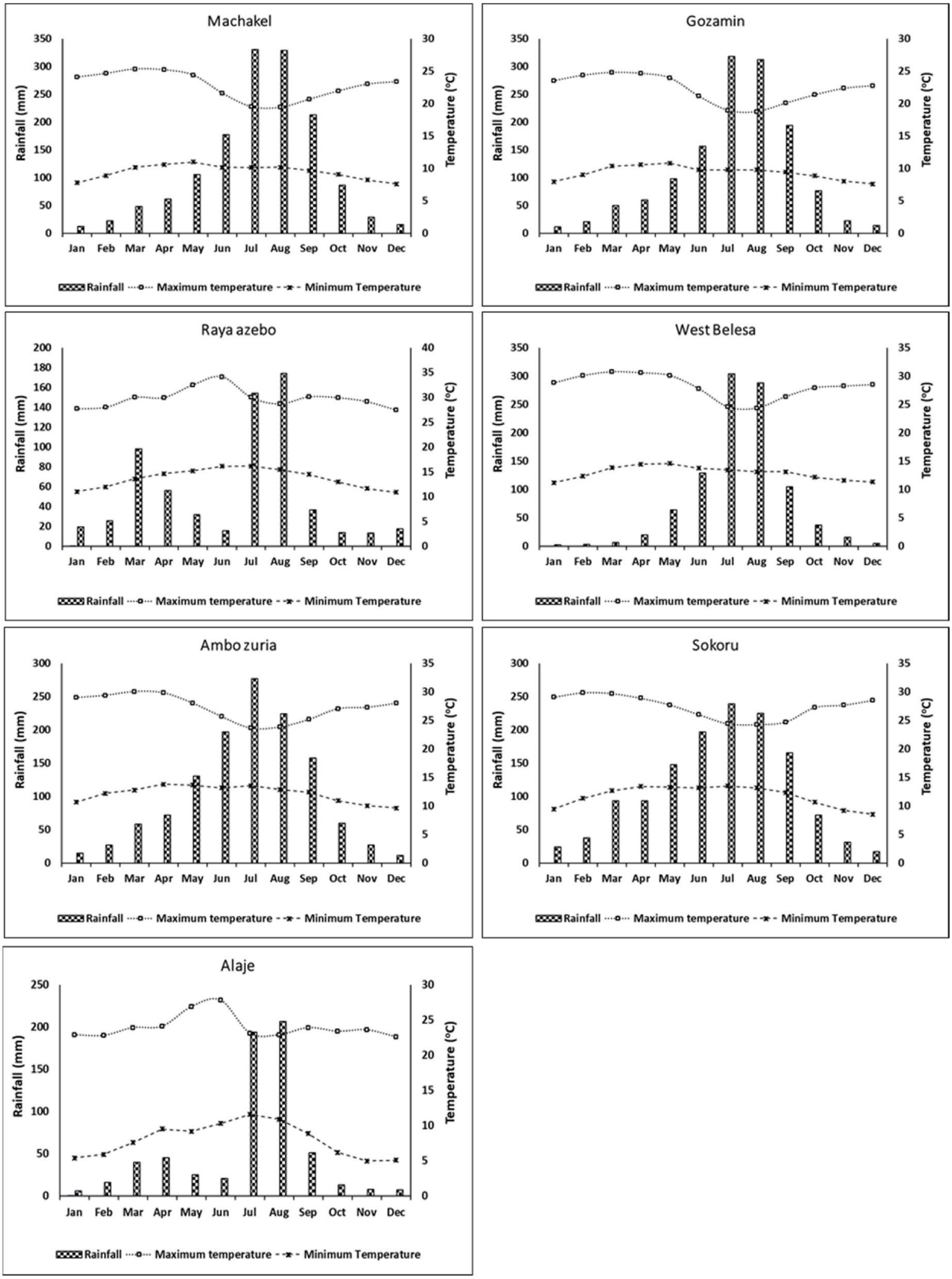

Fig. 2. Long term average rainfall and temperatures of experimental sites.

2.3. Sampling and measurements

Harvesting was done from the first week of November to the first week of January depending on the temperature and altitude of each trial location. To measure the total aboveground biomass and grain yields of both crops, the central 10 rows of each plot (2 m × 3.4 m) were harvested at the soil level. Samples of the sun-dried aboveground total biomass of the two crops were measured. After threshing, grains of wheat and teff were cleaned and weighed. Grain moisture content was measured using a gravimetric method. The total biomass (dry matter basis) and grain yields (adjusted to a moisture content of 12.5%) of the two crops, which were recorded on a plot pilot basis, were converted to kg ha^{-1} for statistical analysis.

Soil samples were collected from different landscape positions before planting and after harvesting under limed and non-limed conditions for analysis of selected soil chemical properties. Soil pH was analyzed using a ratio of 2.5 ml water to 1 g soil [38]; soil OC content using Walkley and Black [39] method; total N content using the Kjeldahl method [40]; available P using Bray method [41]; cation exchange capacity (CEC) using ammonium acetate (NH4OAc) extraction method [42]; sulfur (S) using $CaCl_2$ extraction method, Mehlich-3. Soil zinc (Zn) and boron (B) concentrations were analyzed using DTPA (diethylenetriaminepentaacetic acid) micronutrient extraction method, Mehlich-3. The portable soil moisture meter (TDR 300) was used to measure volumetric soil water content, using 20 cm rod depth to verify the variability of water content along with landscape positions (hillslope, mid-slope, and foot slope position). The measurement of soil water content was made during the booting and grain-filling stages of the two crops and the average of the two values was taken for statistical analysis.

2.4. Statistical analysis

A linear mixed model framework was used to determine the variation in yield and some yield components of the two crops with the different fertilizer treatments by landscape position, and liming combining study locations and years. The linear mixed modeling framework (in PROC MIXED of the SAS system) was employed for the different levels of analyses since it allows the modeling of hierarchical or clustered data arising from observational studies through the inclusion of both fixed effects. We preferred the approach to account for the imbalance in terms of sample size and confounding of responses by uncontrolled variables. To justify the imbalance in the sample sizes, the Kenward-Roger method was used for approximating the degrees of freedom. The fixed effects in the model were landscape position, liming, fertilizer 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 a similar location are likely to be more related than observations in other locations, and that locations are nested within soil types). The PROC MIXED procedure uses the REML estimation method and the Prasad-Rao-Jeske-Kackar-Harville fixed effects method for estimating standard errors. The following model was used to conduct the statistical analysis using the SAS-STAT (version 9.3) Statistical Software [43]:

$$Y = \mu + LS + L + F + LS * F + LS * L + L * F + Loc + \varepsilon \tag{2}$$

where Y is the measured value, μ is the grand mean yield (kg ha^{-1}), LS is the landscape position of the site, L is the lime applied according to the exchangeable acidity of the site, F is the fertilizer treatment based on the source and rate of application (kg ha^{-1}) for the nutrients understudy, location (Loc) is the random component, and ε is the error term. Means for the main effects were compared by using the MEANS statement with the least significant difference (LSD) test at $p \leq 0.05$. Means for the interactions were compared using the PDIFF STDERR option in the LSMEANS statement of the GLM procedure of SAS, using error terms for separating LSMEANS for the interactions.

Table 2
Analysis of variance for teff and wheat yield and other agronomic traits tested at three fertilizer and two liming treatments under landscape positions.

Source	Teff			
	Grain yield	Total biomass	Straw yield	Harvest index
Landscape	*	*	*	***
Lime	***	***	**	**
Fertilizer	***	***	***	**
Landscape*fertilizer	**	**	*	NS
Liming* fertilizer	*	*	NS	NS
Error mean square	121117	3648757	2514620	30.2
CV (%)	29.1	26.5	25.6	27.3
Source	**Wheat**			
Landscape	***	***	***	***
Lime	***	***	NS	***
Fertilizer	**	*	*	NS
Landscape* fertilizer	*	**	*	NS
Liming* fertilizer	*	**	*	*
Error mean square	639022	2150824	88319	23.4
CV (%)	22.6	19.8	21.7	11.2

*, **, *** Significance levels at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively; NS: Not significant.

φ CV: Coefficient of variation.

3. Results

3.1. Crop response to fertilizer and liming as affected by landscape position

The highest rainfall amount during the cropping seasons across locations was recorded in July and August, followed by the amount in June and September. Raya Azebo and Alaje districts had relatively lower rainfall especially in September and October, compared to the other locations (Fig. 2). Overall, the rainfall amount and distribution in the highland trial locations were higher compared to the low and midland areas, implying a favorable moisture regime for the growth and yields of crops. However, Gozamin and Machakel districts which received high rainfall in the main cropping seasons were not as productive as other study districts due to soil acidity and poor nutrient availability to the crops, even with optimal fertilizer application rates.

The response of teff and wheat to fertilizer and lime application was investigated under different landscape positions in the 2018 and 2019 cropping seasons in different districts of Amhara, Oromia, and Tigray regions. Results showed that yield and some yield components of teff and wheat significantly ($p < 0.05$, $p < 0.01$, and $p < 0.001$) differed between landscape positions, lime, and fertilizer treatments (Table 2). Liming improved grain yields of teff and wheat, with teff and wheat grain yield increments of 46 and 35%, respectively compared to the yields from non-limed conditions (Table 3). Despite numerical variations, significant differences were not observed between the NPSK and NPSKZn fertilizer treatments for all agronomic parameters of teff and wheat. A higher harvest index was recorded with the application of NPSK and NPSKZn than with NPS fertilizer. Significantly higher grain and total biomass yield of teff and wheat were recorded at the foot slope position than at the mid-and hillslope positions, with the respective grain yield increments of 5 and 20% and 10 and 34% across locations. Landscape by fertilizer, and lime by fertilizer interactions significantly ($p < 0.05$ and $p < 0.01$) influenced grain yield, total biomass, and straw yields of teff and wheat (Table 2).

Liming by fertilizer and landscape position by mineral fertilizer interactions significantly ($p < 0.05$ and $p < 0.01$) influenced total biomass, grain, and straw yields of teff and wheat over locations. Lime by fertilizer interaction resulted in the highest teff and wheat grain yields of 1582 and 3777 kg ha^{-1}, respectively (Fig. 3). Application of NPSK and NPSKZn with lime increased teff yield by 43 and 54% and wheat yield by 28 and 32%, respectively at the foot slope position relative to the yields achieved from the application of NPS at the hillslope position (Fig. 3). Likewise, marked variations were observed in yields of teff and wheat due to landscape by fertilizer interaction with the highest grain yields of 1514 and 4252 kg ha^{-1} for teff and wheat, respectively (Fig. 4). Application of NPSK and NPSKZn under foot slope position increased teff yield by 55 and 71% and wheat yield by 47 and 57%, respectively compared to the yields achieved from the application of NPS under hillslope position (Fig. 4).

Orthogonal contrast, the powerful option for the analysis of variance procedures, computes any linear contrast for any main or interaction effect. Linear contrasts are linear combinations of the means for any main or interaction effect, and they are valuable for examining the structure of the data after the overall F test indicates that the effect of interaction is significant. To specify the general contrast, first, the main and interaction effects were selected to construct the contrasts. Partitioning of the treatments into single degrees of freedom orthogonal contrasts revealed that grain and straw yields, total biomass, and harvest index of teff and wheat significantly differed due to the application of inorganic fertilizer at different landscape positions (Table 4). The first contrast (landscape - LS response) had a significant ($p < 0.05$, $p < 0.01$, and $p < 0.001$) effect on grain and straw yield, total biomass, and HI of teff and wheat (Table 4). Nevertheless, the second contrast between the foot slope and mid-slope position (LS1 vs. LS2) had no significant effect on the yield of teff and wheat, except for the HI of wheat. The results showed the third contrast (inorganic fertilizer – IF response) had a significant ($p < 0.05$, $p < 0.01$, and $p < 0.001$) effect on grain yield and total biomass of teff and wheat, but not on the HI of teff and straw yield and HI of wheat. However, yield and yield components of teff and wheat did not significantly vary due to the

Table 3
Yield and some yield components of teff and wheat as affected by landscape position, liming and fertilizer application in 2018 and 2019 cropping seasons.

Factor	Teff				Wheat			
	Grain yield	Total biomass	Straw yield	Harvest index	Grain yield	Total biomass	Straw yield	Harvest index
	(kg ha^{-1})			(%)	(kg ha^{-1})			(%)
Landscape								
Foot slope	1320a	6595a	5285a	22.5a	3970a	8134a	4328a	48.2a
Mid-slope	1267a	6551a	5274a	21.4a	3605b	7932a	4164a	44.4b
Hillslope	1104b	5934b	4912b	19.1b	2972c	6691b	3719b	43.2b
LSD (0.05)	130.6	512	302.1	1.7	238.2	544.5	385.6	2.3
Liming								
Limed	1487a	6067a	4580a	24.5a	3808a	8084a	4276a	47.1a
Unlimed	1021b	5181b	4060b	22.5b	2830b	6854b	3924b	42.7b
LSD (0.05)	281.2	587.9	325.5	0.97	384.3	571	230.5	3.2
Fertilizer								
NPSKZn	1341a	6800a	5458a	21.9a	3751a	8065a	4314a	45.5
NPSK	1269a	6487a	5217a	21.6 ab	3535 ab	7587a	4052a	45.4
NPS	998b	5795b	4797b	19.6b	3261b	7105b	3844b	44.9
LSD (0.05)	157.1	615.9	497.5	2.1	365.4	835.1	391.1	3.5

†Within a column means followed with different letters are significantly different at $p < 0.05$.
¶LSD: Least significant difference.

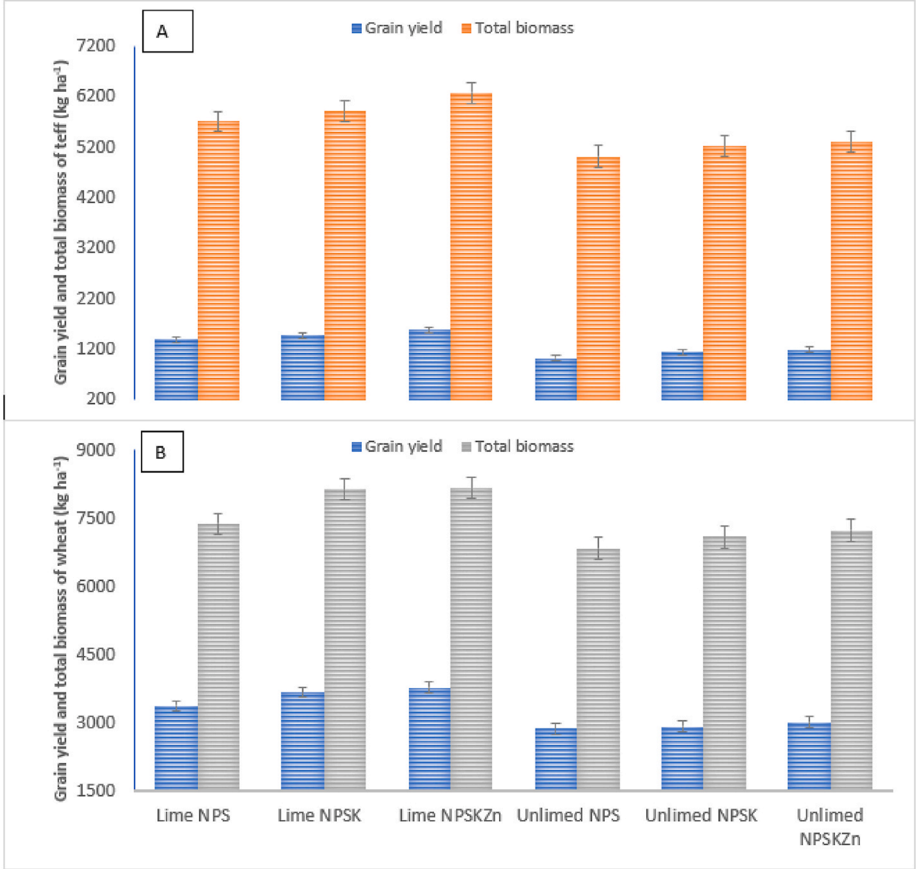

Fig. 3. Liming by fertilizer application interaction effect on grain yield and total biomass of teff (A) and wheat (B) in 2018 and 2019 cropping seasons across locations. Error bars represent ±1SE.

fourth contrast (IF2 vs. IF3), i.e., between NPSK and NPSKZn treatments (Table 4).

The landscape by fertilizer interaction (LS × F) had also differential effects on the yield and yield components of the two crops. The fifth contrast (LS × IF) significantly ($p < 0.05$, $p < 0.01$, and $p < 0.001$) affected grain yield and total biomass of teff and wheat, but not HI of teff and straw yield and HI of wheat (Table 4). The sixth contrast, LS × (IF2 vs. IF3), had no statistically significant effect on yield and yield components of teff and wheat. Similarly, yield and yield components of teff did not significantly respond to the seventh ((LS1 vs. LS2) × IF) and eighth (LS1 vs. LS2) × (IF2 vs. IF3) contrasts, but grain yield and HI of wheat responded significantly ($p < 0.01$) to these contrasts (Table 4). Generally, orthogonal contrast is the advanced form of analysis of variance that helps determine the presence of significant differences between treatments that is not likely by the normal analysis of variance.

3.2. Soil chemical properties as influenced by liming under different landscape positions

Landscape and liming had a significant influence on selected post-harvest soil chemical properties in wheat and teff experimental fields. Soil nutrient status differed substantially between landscape positions and liming treatments. Soil pH, organic carbon (OC), total N, and available P were increased down the slope and limed condition on the cultivated land-use types of the area, in keeping with the differences in pre-trial soil analysis results as well as yield and yield components of teff and wheat between sites. According to Hazelton and Murphy [44], the soil pH was strongly acidic (5.3–5.6) at all sites except at Ambo which is moderately acidic (Table 5). The soils of the study areas are generally poor in soil OC content (0.83–1.55%), with the lowest being at the hillslope position. Soil total N ranged between 0.10 and 0.18%, i.e., low to medium concentration. The critical levels of soil OC and total N are 2% and 0.15%, respectively, below which a potentially serious decline in soil quality will occur and affect agricultural productivity. Statistically significant differences were observed for SOC, total N, and CEC only among landscape positions in West Belesa, but not for other soil chemical properties (Table 5). Soil OC and total N contents were very low in this drought-prone district.

Lime-amended plots were significantly ($p < 0.05$) higher in soil OC content, total N, available P, S, Zn, B, and CEC than the control plots without lime, accompanied by higher yields of crops (Table 5). For instance, the maximum soil OC contents of 1.55, 1.84, 1.42, and 1.16% were recorded at Gozamin, Machakel, Sokoru, and Ambo, respectively at foot slope positions. Almost all sites affected by soil acidity had high soil exchangeable Al (8–19 cmol(+)/kg) but lower in lime-amended than unamended soils. Bray available soil P

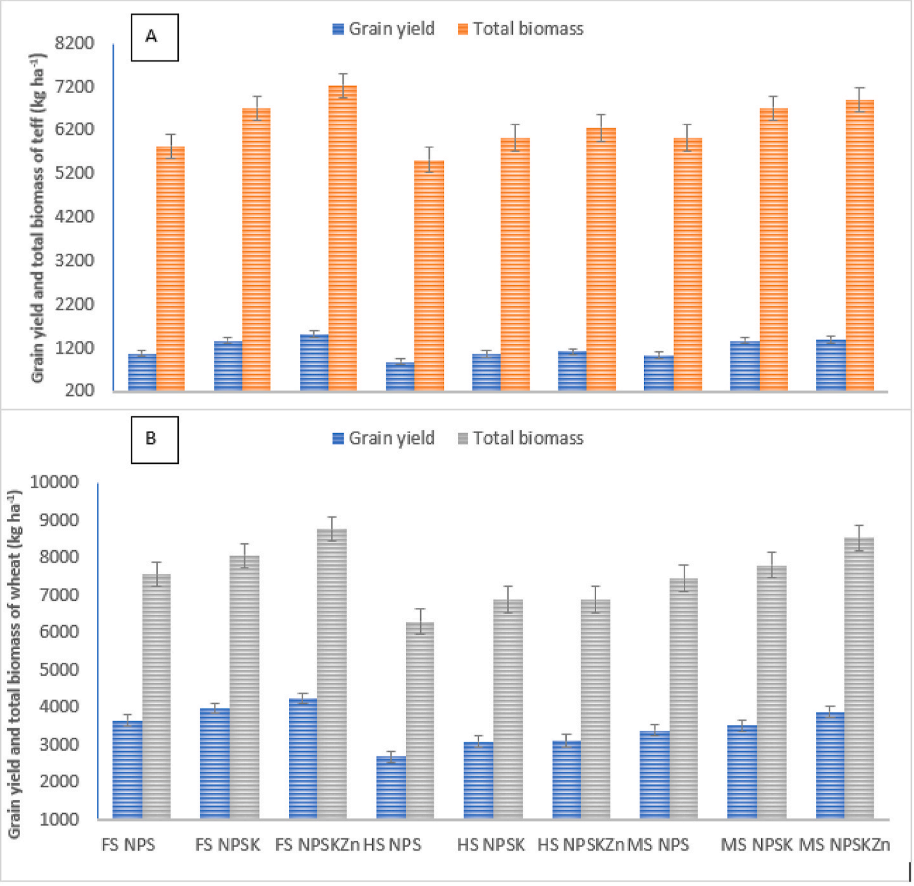

Fig. 4. Grain yield and total biomass of teff (A) and wheat (B) as influenced by landscape position by fertilizer application interaction in 2018 and 2019 cropping seasons over locations. FS, HS, and MS represent foot, hill, and mid-slope positions. Error bars represent ±1SE.

content was drastically low (0.05–4.15 mg kg^{-1}) across the trial sites due to acidity and inherently poor soil fertility. Relatively higher soil P values were recorded under foot slope position and limed condition than under mid-and hillslope position and non-limed condition, with a very negligible value of 0.05 mg P kg^{-1}. Despite an ideal soil pH in moisture deficit trial locations for P availability, Olsen soil P content was also low (Table 5). Soil sulfur ($CaCl_2$–S) concentration ranged between 9.6 and 20.1 mg kg^{-1} in Gozamin and Machakel and between 0.27 and 3.93 mg kg^{-1} in Sokoru and Ambo districts under different landscape positions. Thus, based on the sufficiency range of S [45], the soil S concentrations were adequate to high in Gozamin and Machakel districts but very low in Sokoru and Ambo districts (Table 5). The application of lime resulted in significantly higher concentrations of soil S compared to non-limed conditions, though its concentration was yet very low in Sokoru and Ambo districts.

Although micronutrients are required in small quantities, the absence of any of these crucial elements can have critical effects on the growth and yields of crops. Soil zinc and boron concentrations were low in most trial sites (Table 5), where a zinc soil test above 1.5 mg kg^{-1} using the DTPA extraction method is sufficient for most crops, while soil B test values below 0.50 mg kg^{-1} are low [45]. Soil Zn concentrations ranged between 0.38 and 1.81 mg kg^{-1} in Gozamin and Machakel districts and 0.04–0.51 mg kg^{-1} in Sokoru and Ambo districts under different landscape positions, with the highest values being at the foot slope and the lowest at the hillslope position. Despite insufficient soil concentrations of Zn and B in most sites, the application of lime significantly improved both Zn and B in acidic soils (Table 5).

3.3. Soil water content as affected by landscape position

Soil water content during the growing stage of the crops is important owing to their great implication on crop performance and response to fertilizers. Results showed that clear variations were observed in soil water content over the landscape positions, where soil water content increased from the hillslope to the foot slope position (Fig. 5). The highest volumetric soil water content of 37% was measured at the foot slope position, followed by the soil water content of 35% at the mid-slope position, while the lowest volumetric soil water content of 10% at the hillslope position. Landscape position also had a significant influence on soil water contents of teff and wheat experimental fields. For instance, the volumetric soil water content of 32% was measured at the foot slope position for teff and 30% under the same landscape position for wheat fields. The lowest soil water contents of 22% and 18% were at hillslope positions for

Table 4
Variance ratios and probabilities of variance ratios of single degrees of freedom orthogonal contrasts of fertilizer by landscape position interaction effect on yield and some yield components of teff and wheat.

		Teff				Wheat			
Contrasts		GY$^{\delta}$	BY	STY	HI	GY	BY	STY	HI
Contrast 1	LS$^{\varphi}$-response								
	Variance ratio	4.51	1.92	1.53	5.98	21.54	11.18	3.44	3.38
	F-probability	0.0013	0.0503	0.3051	0.0001	0.0000	0.0000	0.0089	0.0099
Contrast 2	LS1vsLS2								
	Variance ratio	0.82	1.24	1.25	0.13	3.55	0.91	1.04	4.25
	F-probability	0.4126	0.2167	0.2130	0.9698	0.0074	0.3631	0.2980	0.0022
Contrast 3	IF-Response								
	Variance ratio	5.69	11.57	11.48	0.61	2.35	2.41	1.55	0.56
	F-probability	0.0002	0.0000	0.0000	0.6581	0.0504	0.0163	0.1212	0.5792
Contrast 4	IF2vsIF								
	Variance ratio	1.04	1.49	0.55	0.21	1.39	1.34	1.04	0.10
	F-probability	0.2969	0.1364	0.6973	0.8375	0.1657	0.1802	0.3000	0.9218
Contrast 5	LS*IF								
	Variance ratio	6.62	13.54	13.47	0.61	2.38	2.45	1.63	0.42
	F-probability	0.0000	0.0000	0.0000	0.6553	0.0502	0.0148	0.1037	0.6757
Contrast 6	LS*(IF2vsIF3)								
	Variance ratio	1.07	1,41	1.38	0.35	1.32	1.39	1.15	0.25
	F-probability	0.2870	0.1597	0.1683	0.7284	0.1880	0.1648	0.2507	0.8051
Contrast 7	LS1vsLS2*(IF)								
	Variance ratio	0.17	0.38	0.39	0.73	3.55	0.91	1.04	4.25
	F-probability	0.9546	0.8213	0.8169	0.4643	0.0074	0.3631	0.2980	0.0022
Contrast 8	LS1vsLS2*(IF2vsIF3)								
	Variance ratio	1.09	1.40	0.47	0.11	3.13	0.92	0.89	3.57
	F-probability	0.2764	0.1617	0.7610	0.9785	0.0148	0.3582	0.3749	0.0071

‡GY: Grain yield; BY: Biomass yield; STY: Straw yield; HI: Harvest index. LS: landscape; LS1: Foot slope; LS2: Mid-slope; LS3: Hillslope; IF: Inorganic fertilizer.

teff and wheat fields, respectively (Fig. 5). Interestingly, soil water content difference was also observed between soil types, where higher soil water content was measured on Vertisols than on other soil types, indicating the higher water holding capacity of Vertisols (data not shown). Despite variations in water content among landscape positions, the lowest soil water contents were measured in drought-prone areas (Fig. 5). In the highland areas, the soil water content was relatively high which could be due to the cooler temperature and the availability of well-distributed rainfall in an adequate amount.

4. Discussion

4.1. Crop response to fertilizer application as influenced by landscape positions

Our results showed clear effects of fertilizer application and liming on the growth and yield of teff and wheat under different landscape positions. In Ethiopian highlands where demographic and economic pressures are high, soil fertility depletion is severe and applications of fertilizer and other agricultural inputs are very low [10,37]. The response of farmers to such pressures is to grow few and selected crops every year without amending soil acidity and improving the cropping system [12]. This strategy appears to be unsustainable because yields of crops usually decline under monocropping, acidic and nutrient-depleted soils [1,7]. Based on the results of this study (Table 3), grain yields of teff and wheat were not high even with the application of higher fertilizer rates possibly due to very low soil water holding capacity and nutrient deficiency associated with low soil OC and unavailability of nutrients to plants at the required level. A large area of agricultural land in Ethiopian highlands is affected by soil acidity and the productivity of these soils is low and is declining rapidly [12,46].

This study showed that clear differences were observed spatially in all measured parameters because of different topo-sequence positions. Crop yield improvements due to input application were more pronounced at the foot slope than at mid and hillslope positions, which may be due to higher nutrient and water availability at the foot slope position. The application of NPSK and NPSKZn fertilizer at the foot and mid-slope position resulted in teff and wheat yield increases of 1.57 and 1.71 times and 1.43 and 1.57 times, respectively compared to the yields achieved with NPS fertilizer at hillslope position (Fig. 4). Variability may occur within short distances in a landscape characterized by high elevation hillslopes, mid-slopes, and foot slopes. Such variations generally could lead to differences in soil fertility status [13,47], soil water-holding capacity [20], agronomic management requirements [21], and crop responses to the application of fertilizers [47]. Other studies showed that differences in topo-sequence position may lead to variation in soil properties and hydrological conditions [6,48] and hence crop yield. For instance, in tropical mountainous areas of northern Vietnam, intensive cultivation of upland crops exacerbated large nutrient losses through erosion in the upland areas [6], while in the bottom and valley areas, sediment deposition can enhance soil fertility depending on the quality of the sediments and influence the productivity of crops. Thus, site-specific nutrient management would optimize the utilization of resources, contribute to higher yield and lead to sustainable agricultural production.

Table 5
Soil chemical properties as influenced by landscape positions and liming in different districts.

Factor	pH:H$_2$0	Total N	SOC	Sulfur	Av. P	Zinc	Boron	CEC	Al
		%		mg kg^{-1}				cmol (+)/kg	
Landscape	Gozamin district								
Foot slope	5.57a$^{¥}$	0.18a	1.55a	20.1a	2.91	1.81a	0.42a	20.6a	1.64b
Mid-slope	5.30b	0.16b	1.53a	14.2b	2.47	0.99b	0.40a	18.3 ab	1.86a
Hillslope	5.28b	0.15b	1.34b	9.6c	2.20	0.78b	0.26b	15.1b	1.91a
LSD (0.05)	0.11	0.01	0.15	2.8	0.57	0.35	0.07	4.8	0.17
Liming									
Limed	5.50a	0.17	1.55a	17.2a	2.96a	1.39a	0.51a	20.3a	0.12b
Non-limed	5.27b	0.16	1.39b	12.0b	2.09b	0.99b	0.21b	16.2b	0.93a
LSD (0.05)	0.09	0.01	0.13	2.4	0.73	0.30	0.05	3.8	0.40
Landscape	**Machakel district**								
Foot slope	5.49a	0.22a	1.84a	17.4a	2.19a	0.61	0.31	20.8a	1.56b
Mid-slope	5.46a	0.16b	1.23b	14.7b	1.67b	0.52	0.28	19.5 ab	1.67b
Hillslope	5.34b	0.15b	1.04b	11.6c	1.64b	0.38	0.26	14.9b	1.85a
LSD (0.05)	0.10	0.03	0.30	2.2	0.37	0.26	0.07	5.7	0.11
Liming									
Limed	5.54a	0.19	1.61a	17.2a	2.42a	0.81a	0.47a	20.9a	0.18b
Non-limed	5.32b	0.16	1.14b	12.0b	1.23b	0.19b	0.10b	16.4b	0.84a
LSD‡ (0.05)	0.11	0.03	0.31	2.1	0.89	0.27	0.08	4.3	0.46
Landscape	**Sokoru district**								
Foot slope	5.60a	0.17a	1.42a	0.65a	0.20a	0.67a	0.11a	22.4	0.92b
Mid-slope	5.47b	0.16a	1.36a	0.30b	0.06b	0.42b	0.05b	21.2	1.01b
Hillslope	5.32c	0.10b	0.83b	0.27b	0.05b	0.05c	0.04b	18.7	2.86a
LSD (0.05)	0.11	0.02	0.15	0.23	0.05	0.23	0.02	4.8	0.85
Liming									
Limed	5.61a	0.15a	1.28a	0.57a	0.13a	0.48a	0.08a	21.9a	0.82b
Non-limed	5.30b	0.13b	1.13b	0.25b	0.07b	0.27b	0.05b	18.8b	1.72a
LSD (0.05)	0.10	0.01	0.12	0.20	0.04	0.19	0.02	2.7	0.27
Landscape	**Ambo district**								
Foot slope	6.45	0.18a	1.16a	3.93a	4.15a	0.68	0.44a	19.0a	0.73b
Mid-slope	6.45	0.15b	1.07a	3.09b	3.09b	0.63	0.35b	17.1 ab	0.86b
Hillslope	6.38	0.14b	0.85b	1.35c	2.55b	0.59	0.32b	12.9b	1.03a
LSD (0.05)	0.48	0.02	0.18	0.58	0.75	0.31	0.08	5.6	0.10
Landscape	**West Belesa**								
Foot slope	8.04	0.08a	1.13a	2.11	6.10	0.33	0.16	61.6a	–
Mid-slope	7.96	0.07a	0.98 ab	1.82	4.80	0.33	0.11	57.6a	–
Hillslope	7.88	0.05b	0.72b	1.49	5.60	0.26	0.07	45.1b	–
LSD (0.05)	0.49	0.02	0.3	0.75	1.75	0.09	0.15	11.5	

‡N: Nitrogen; Av. P: Available phosphorus; CEC: Cation exchange capacity; Al: Aluminum.
†Means followed with different letters in a column are significantly different at $p < 0.05$.
¶LSD: Least significant difference.

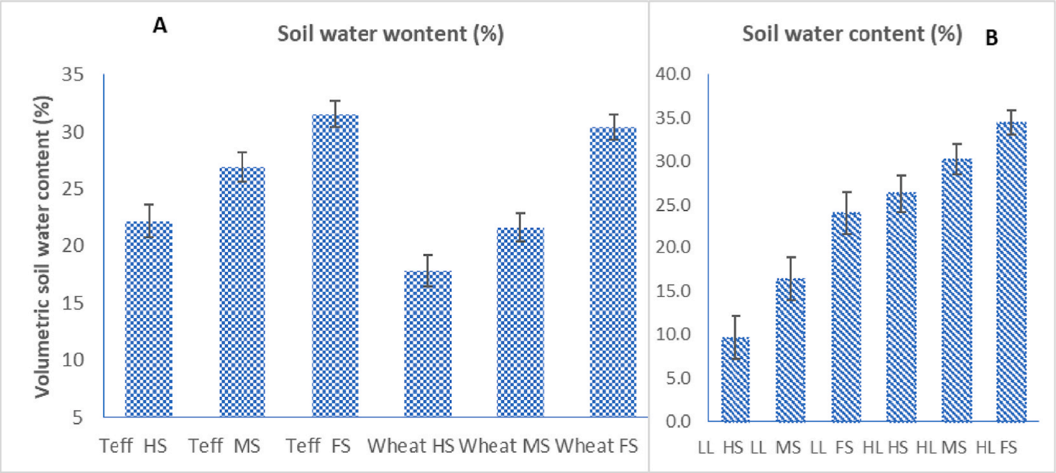

Fig. 5. Interaction effects of crop type by landscape position (A) and agroecology by landscape position (B) on percent volumetric soil water content. Error bars represent ±1SE. LL: Low land agroecology; HL: Highland agroecology.

4.2. Crop yield response to liming as affected by landscape positions

A large area of agricultural land in the highlands of Ethiopia is affected by soil acidity and the productivity of these soils is low and declining rapidly [12,46]. Liming resulted in significantly higher yields of teff and wheat at the foot slope than under non-limed conditions both at mid-and hillslope positions, with teff and wheat grain yield increments of 16–47% and 58–63% at the foot and mid-slope positions over the hillslope position across all locations, depending on the gradient of farms (data not shown). Liming increased yields of teff and wheat 1.46 and 1.35 times compared to the yields recorded from non-limed plots. The addition of lime with NPSK and NPSKZn fertilizer substantially improved grain yields of teff and wheat, with respective yield increments of 1.43–1.54 and 1.32–1.35 times (Table 3) compared to the application of NPS fertilizer under non-limed conditions, indicating a significant response to the application of lime and N and P rates. Yields of teff and wheat showed a strong positive relationship with lime application and soil pH level as both crops are sensitive to soil acidity, implying that an ideal soil pH is a prerequisite for attaining optimum yield of both crops, but with the application of other crop management practices. Previous studies indicated that the combined application of 1.65 t lime ha^{-1} and 30 kg P ha^{-1} resulted in 133% more barley grain yield than without the application of lime and P fertilizer [49] and faba bean seed yield increments of 45–81% with the addition of lime at the rate of 1–5 t ha^{-1} over the control without lime [12]. According to Li et al. (2019), averaged across different crop species, liming acid soils with different lime sources resulted in crop yield increments of 13.2–66.5%. Haile and Boke [50] also reported that the application of NPK + lime resulted in the highest potato tuber yield of 30.67 t ha^{-1} in southern Ethiopia with yield increments of 332 and 73% over NP and NPK fertilizer treatments alone, respectively. Similar trends were observed in grain yields and total biomass of both crops across landscape positions where the treatments without fertilizer application and liming acid soils had lower total biomass and grain yields, indicating that applying N and P fertilizer and lime in acid soils are the most limiting nutrients for crop production.

Yields were generally very low due to severe depletion of soil fertility and soil acidity, suggesting that unless such degraded soils were rehabilitated by improving the soil organic matter content and applying lime, there would be a total crop failure without fertilizer application and even with optimal fertilizer application, the expected yield would not be attained under the current farming system in the study areas (e.g., Gozamin, Machakel, and Sokoru districts). Studies indicate adverse effects of soil acidity such as loss of crop diversity, decline in yields of crops, lack of response to N and P fertilizers, and complete failure of crop yields [12,46]. For instance, yields of barley, wheat, and faba bean were extremely low, even under the application of the optimum rate of NPK fertilizer on acid soils of Bedi [51] and Chencha in central and southern Ethiopian highlands [50] due to severe soil acidity. Similarly, the application of NPK fertilizer with lime significantly resulted in higher potato tuber yield in Chencha district (20.5 t ha^{-1}) than in Hagereselam (13.8 t ha^{-1}), with 42%–279% higher yield in Chencha than in Hagereselam [50]. This signifies that lime application alone did not significantly improve potato tuber yield, where the soil fertility status in Chencha was better and more responsive to the soil fertility treatments than the soil in Hagereselam which was low in pH, nutrient content, and yield. Liming improves the yield of crops if acidic soil has essential nutrients rendered unavailable to crops due to low pH, but if the soils are already depleted of nutrients, crops respond to the lime application only [52].

Single degrees of orthogonal contrasts revealed that growth and yields of teff and wheat significantly varied due to fertilizer treatments and landscape positions. However, the second contrast between the foot and mid-slope position had a significant effect on grain yield and HI of wheat, but not on grain yield and other agronomic parameters recorded, indicating that the differential effect of landscape position on wheat yield was more pronounced than the effect on teff as the responsiveness of wheat to nutrients are higher across landscape position than teff (Table 4). Similarly, the means for the control treatment (NPS fertilizer) were significantly different from the means of the two treatments (NPSK and NPSKZn) across landscape positions, implying that the differences could be attributed to higher rates of N and P nutrients in NPSK and NPSKZn than the NPS treatment. However, the difference between NPSK and NPSKZn was not significant for the growth and yield parameters of the two crops as evidenced in the contrasts (Table 4), signifying that grain quality analysis is required whether the addition of Zn influenced the production of nutrient-dense teff and wheat grains. The contrast of the landscape position by fertilizer interaction significantly influenced grain yield and total biomass of both crops, suggesting that landscape-based nutrient application is important to increase fertilizer use efficiency and economic profitability of smallholder farmers. Overall, contrasts between the closest treatments were not significant for growth and yield parameters as proved by other statistical analyses. Desta et al. [46] also reported that contrast analysis showed significant differences among landscape positions for sorghum yield.

4.3. Crop yield as influenced by the interaction of fertilizer, liming, and landscape positions

Liming by fertilizer and landscape position by fertilizer interactions markedly increased grain yield and total biomass of teff and wheat in acidic soils. The synergistic effects of lime and fertilizer application produced an effect that is larger than the effects of each of them. It was found that the combined application of lime and fertilizer resulted in higher yields for both crops (Fig. 3), compared to the yields obtained from separate applications of each input. This indicates that the amendments produced by the lime on soil chemical properties in terms of rising soil pH and reducing exchangeable Al may have enhanced the efficiency of fertilizer and nutrient availability to plants and hence the growth and yields of both crops. Previous studies also indicated that the application of lime with fertilizer in acid soils resulted in yield increments of 34–252% in wheat, barley, and teff, 29–53% in beans [1], and 73–332% in potato in Ethiopia [50] and 111–182% in maize in Kenya [53]. This was accompanied by a corresponding increase in soil pH up to 1.9 units and a decrease in exchangeable acidity and Al up to 2.1 cmol kg^{-1} soil [12,49].

Landscape position by fertilizer application interaction was significant for grain yield and total biomass of wheat and teff. There was an inverse relationship between crop fertilizer response and slope gradient where a significant increase was observed in the response of crops to fertilizer applications with decreasing slope gradient (Fig. 4) due to the marked improvement in soil organic carbon, nutrient contents, and soil water content. Amede et al. [7] reported a decrease in a crop fertilizer response with an increasing slope due to a significant decrease in soil organic carbon, clay content, and soil water content. They further elucidated that the difference in the crop response between landscape positions was higher with higher nutrient application rates, but differences between landscape positions diminish at lower nutrient rates. Ullah et al. [54] also reported that the application of organic amendments such as biochar significantly decreased nutrient and pollutant leaching in soils and increased wheat yield. Hence, based on the results of the study landscape position could be considered a good indicator for targeting fertilizer recommendations in areas with undulating topographic features. Differences were observed between the two crops in response to fertilizer and lime application under different landscape positions, with greater wheat response to both inputs across the three landscape positions than teff.

4.4. Soil properties response to liming as influenced by landscape positions

Soil properties are very important in improving yield, water productivity, and nitrogen use efficiency [55]. Soil pH, organic carbon (OC), total N, available P, S, Zn, B, exchangeable Al, and CEC showed significant variation due to slope position differences and application of lime. It was found that the foot slope position followed by the mid-slope position had higher mean values of the parameters, while the hillslope position had the lowest mean value for all soil parameters recorded which is in line with the grain yield and total biomass of teff and wheat (Table 5). Similarly, Amare et al. [16] indicated that higher mean values of soil pH, OC, total N, available P, and exchangeable cations were recorded at the toe slope position followed by the crest slope position, while the lowest mean values of these parameters were recorded at the shoulder slope position. Previous studies also reported that lower landscape positions and forest land had higher mean values of soil OC, total N, available P, CEC, exchangeable cations, and available micronutrients, while lower mean values of these nutrients were recorded at upper landscape positions and intensively cultivated lands [13,18]. Other studies indicated that topography directly affects soil-forming processes through erosion and deposition, and thus variations were observed in soil texture, N, P, and K content along the topo-sequence [56–58].

Soil organic matter (OM) is a surrogate for soil carbon and is measured as an indication of overall soil health. When monitored for several years, it shows an indication of whether soil quality is improving or degrading. Soil OM is important to a wide variety of soil physicochemical and biological properties. As soil OM increases, so does CEC, soil total N content, and other soil properties such as water-holding capacity and microbiological activity [59,60]. In this study, however, the soil OC was markedly low across trial locations due to the complete removal of crop residues, soil erosion, and a cereal-dominated cropping system (Table 5). The low soil OC and total N contents, particularly in drought-prone districts such as West Belesa are indications of low total biomass production and the absence of retention of crop residues in the field. Hammad et al. [61] indicated that the addition of organic amendments markedly improved wheat yield response to inorganic fertilizer application, soil physicochemical properties, and soil moisture content in moisture deficit areas. Soil exchangeable Al was lower at the foot slope position than at the mid-and hillslope position, indicating inverse relationships with soil pH where the increase in exchangeable aluminum and acidity was accompanied by the decrease in soil pH. The extremely low soil available P could be due to the sorption of P by oxides and hydroxides of Al and Fe. Researchers also indicated that sorption of P was significantly correlated with exchangeable and extractable forms of Fe and A1 as well as pH and organic matter, but it was not related to the clay content of the soils and the role of A1 was more important than that of Fe [12,35].

The fertility status of the experimental soils was sub-optimal for teff and wheat production, with as low as initial soil pH, SOC, total N, and available P of 5.2, 0.86%, 0.07%, and 0.10 mg kg $^{-1}$, respectively. The influence of pH is known for macronutrient uptake and crop yields, but a greater investigation is needed to understand the role of pH on micronutrient availability, crop yield, and quality responses. According to the soil Zn and boron sufficiency range [45], the concentrations of Zn and B in the soil were low to medium, which ranged between 0.05 and 1.81 mg kg^{-1} and 0.04–0.51 mg kg^{-1}, respectively. The deficiency of zinc is common in plants growing in highly weathered acidic or calcareous soils [62]. The benefit of Zn fertilizer applications on grain quality improvements above their baseline levels will also be affected by several soil factors, including landscape variability and soil pH. A deficiency of boron may occur if its extractable concentration is less than 0.5 mg kg^{-1} in most crops. While low levels of boron may limit plant growth, high concentrations can be toxic. If the concentration of boron is greater than 2, it is excessive and boron toxicity may occur in sensitive crops [45]. For cereal crops, the most reliable indicator for boron toxicity is grain analysis. Soil nutrients were very low in most trial locations, particularly in acidic areas of the highlands of the country. This had a direct relationship with crop growth and yields, which were higher for limed than non-limed soils. In most cases, soils with a pH less than 5.5 are deficient in available P and exchangeable cations [52]. In such soils, P becomes unavailable to a crop and the P fertilizer rate becomes inadequate [12,52] unless liming materials are applied. Higher variability in grain yield of teff and wheat under limed than non-limed conditions may have been related to greater variability in the less fertile environment. Experimental plots treated with lime exhibited improvement in some soil chemical properties. Li et al. [63] reported that lime application significantly increased soil exchangeable Ca and Mg. Higher CECs were recorded at the foot slope position and lime-amended soil than at the hillslope position and non-limed soils. Soils with low CEC are often low in fertility and vulnerable to soil acidification. The buffering capacity of soil increases with the increase in CEC and SOC content. Recent studies showed that increased CEC improved soil fertility through greater nutrient availability as nutrients are retained in the soil against leaching [12,64].

The seasonal variability in rainfall amount and distribution poses a significant influence on the yield of crops in drought-prone areas of the country. For instance, the erratic rainfall in September and October during the grain filling of wheat in the Raya Azebo and Alaje districts impacted wheat yield. This might have exposed wheat to water deficit at the later growth stages of the crop as opposed to the high rainfall and Vertisol agricultural areas of the country where waterlogging might have affected the crops.

The aim of the measurement of soil water content was mainly to verify whether the soil water content of the trial crops varies across landscape positions. Clear variations were observed in soil water content along with the landscape positions where soil water content was the highest at the foot slope position and, agreeing with the results of other soil properties (Fig. 5). Soil water content was increased down the slope on the cultivated land-use types of the area. The highest mean volumetric soil water content of 37% was recorded at the foot slope position, followed by 35% at the mid-slope position, and the lowest soil water content of 10% was obtained from the hillslope position. Bufebo et al. [13] showed that the order of the bulk density across different landscape positions was 1.30 g cm^{-3} for the foot slope position, 1.34 g cm^{-3} for mid-landscape, and 1.44 g cm^{-3} for the upper landscape position, indicating that bulk density decreases towards down landscape position. Soil bulk density is inversely correlated with soil physicochemical properties such as soil water content and soil OC where higher values of these parameters were recorded from soils with lower bulk densities. However, soil water content is positively correlated with soil organic matter content, which is a key input for the retention of water and nutrients in the soil, consistent with the findings of other studies [59,65–67]. Opportunities to invest in soil fertility management practices in hillslope farms are very limited for farmers where crop response to fertilizer application and profitability are poor [7,68]. Fertilizer recommendations have been based on crop and soil types thus far, regardless of how agricultural landscape features, cropping systems, and other agronomic practices that are changing over time and space affect crop nutrient response and yield. Hence, targeting sources and amounts of plant nutrients based on landscape positions and other crop production factors will reduce input costs and improve farm profitability and environmental quality.

5. Conclusions

We found substantial differences in crop response to applications of fertilizers and lime along landscape positions. The implication of this research is that yield increased down the slope from the hillslope to the foot slope position, possibly due to better soil fertility and soil water content of the soil at the foot slope than at the hillslope position, and thus fertilizer recommendations and amelioration of soils should consider these contexts. Yield variations in teff and wheat between NPS and NPSK or NPSKZn could be associated with differences in the applied N and P rates rather than nutrient sources, implying that significant differences were not observed between NPSK and NPSKZn for yields of both crops due to the addition of Zn as the NP rates were similar. Hence, based on the response of teff and wheat, determining the best site-specific N and P rates will be vital to attain optimum economic crop yields for producers. Yields of teff and wheat were very low even with the optimal fertilizer application rates in acid soils, and hence the application of lime should be considered as an approach to optimize soil pH and nutrient availability for increased crop yield. On the other hand, as evidenced from the current and previous studies, liming alone will not be a sustainable solution for increased crop yield in nutrient-depleted soils unless combined with the applications of organic amendments and optimum rates of inorganic fertilizers to restore soil fertility and enhance fertilizer use efficiency. Overall, scaling landscape-based site-specific nutrient management with the integration of other agronomic advisory services, including soil, climate, and crop information will be vital to improve the prediction of site-specific fertilizer recommendations.

Author contribution statement

Getachew Agegnehu: Analyzed and interpreted the data; Wrote the paper.

Tilahun Amede: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Gizaw Desta: Teklu Erkossa: Andre Van Rooyen: Rebbie Harawa: Kindu Mekonnen: Steffen Schulz: Contributed reagents, materials, analysis tools or data.

Gizachew Legesse: Tadesse Gashaw: Tulu Degefu: Performed the experiments.

Data availability statement

The authors do not have permission to share data.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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