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Targeting nutrient sources and forms to identify yield-limiting nutrients for wheat under contrasting rainfall regimes and landscape positions in mixed-farming systems

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ABSTRACT

Wheat yield gap in Ethiopia is high due to low nutrient availability, soil heterogeneity, undulating landscape, and climate. A study was conducted to identify yield-limiting nutrients for wheat yield under varying landscape positions and rainfall regimes. The treatments included all nutrients in blended (All-Blend), compound (All-Comp), and individual (All-Ind) forms containing N, P, K, S, Zn, and B, while K, S, Zn, and B omitted treatments were (All-Blend)-K, (All-Blend)-S, (All-Blend)-Zn, and (All-Blend)-B. Besides, NP only, 50 and 150% of the rate of all nutrients in the blended form (All-Blend), and a control without any nutrients were included. Results showed that the highest yield was obtained from the application of 150% of All-Blend across landscape positions and rainfall regimes, with grain yield improvement of 109.5% (2.54 t ha^{-1}) by applying 150% of All-Blend under the foot slope position and high rainfall regime compared to the control and yield improvement of 72.5% under the low rainfall regime. With the control treatment grain yield was lower by 27–70% across landscape positions and rainfall regimes. The grain yield penalties due to K, S, Zn, and B omission were 0.54–9% over landscape positions and rainfall regimes compared to applying All-Blend, implying that the omission of K, S, Zn, and B were not yield-limiting nutrients for wheat production in the study areas. Thus, it will be crucial to consider landscape strata and rainfall regimes to optimize NP rates. Further study is also suggested as nutrient applications in blended, compound, or individual forms are inadequate to conclude.

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Introduction

Soil degradation and nutrient depletion are the major biophysical root causes of unsustainable crop production, declining per-capita food production, and natural resource conservation in

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sub-Saharan Africa (SSA) in particular (Agegnehu and Amede 2017; Haileslassie et al. 2005; Sanchez 2002; Sanchez et al. 1997; Zelleke et al. 2010) and globally in general (Lal 2007). Over several years, small-scale farmers have removed large quantities of nutrients from their soils without using adequate amounts of inorganic and organic fertilizers to replenish the soil. This has resulted in a very high average annual depletion rate of 22 kg of N, 2.5 kg of P, and 15 kg of K ha^{-1} of cultivated land over the last 30 years in 37 African countries (Sanchez et al. 1997). On the other hand, increasing crop production and productivity is critically important to bridge the existing and ever-increasing food demands as the population pressure increases over time (Dercon and Hill 2009).

Wheat (*Triticum aestivum* L.) is one of the most important crops contributing to global food security, providing ~20% of calories and protein in the human diet (Gilland 2002; Reynolds et al. 2012). Despite a continued increase in global wheat production over recent decades (FAO 2022), the rate of yield improvement has stagnated or declined in certain wheat-producing areas of the world (Ray et al. 2012) and projected yield gains fall below the predicted future grain demand (Crespo-Herrera et al. 2018). Global wheat yield gap analyses examine the difference between the potential yield (yield of well-adapted wheat cultivars grown with sufficient water and nutrients and without abiotic and biotic stress) and the average actual yield reported by farmers under conventional management practices (Getnet et al. 2022; Gobbett et al. 2017; Guarin et al. 2022). Research has shown that current wheat yield could be increased by up to 50% under favorable crop-growing conditions (Long, Marshall-Colon, and Zhu 2015; Reynolds et al. 2012). In Ethiopia, wheat is the third major cereal crop after teff and maize (CSA 2021) which is cultivated mainly as a monocrop or rotated as wheat-teff-food legumes (Ferede et al. 2020). The crop shows an increasing trend in area coverage and production, with about 1.90 million ha and 5.78 million tons produced in the main crop season, respectively (CSA 2021). The crop shares about 14.6% of the total cultivated area coverage and contributes about 16.9% to crop production. However, despite the considerable potential to increase wheat production, its yield is about 3.1 t ha^{-1}. This is mainly attributed to the deterioration of soil fertility and poor agronomic practices (Dercon and Hill 2009; Zelleke et al. 2010).

Agriculture is facing a decline in crop responses to fertilizer applications in Ethiopia despite the consistent increase in the supply and use of N and P inorganic fertilizers since the 1990s (Dercon and Hill 2009). Matching fertilizer types to soil fertility issues depends on identifying limiting factors, characterizing sites, and developing appropriate recommendations. To identify nutrient management zones, the collection, and interpretation of spatial data, such as yield, elevation, soil nutrient maps, and farmers' soil fertility classification criteria, are required (Ameer et al. 2022; Desta et al. 2023). Understanding the variability in crop yield in the context of spatial variations in landscape positions and soil properties can help to apply fertilizers efficiently based on a site-specific approach (Amede et al. 2022; Ameer et al. 2022). Landscape-based soil, nutrient, and water management is a practical and effective method to characterize the soils into low, medium, and high nutrient status (Ameer et al. 2022; Desta et al. 2023). The description of soils based on their soil fertility status under different landscape positions could help handle them separately for the precise application of fertilizers and organic amendments (Amede et al. 2022). Crop yields vary greatly along landscape positions (Agegnehu et al. 2023; Amede et al. 2022). Higher bread wheat yield was obtained at the foot-slope compared to the hillslope positions, depending on location and input level (Amede et al. 2022; Desta et al. 2022). This is associated with the variability of soil physiochemical characteristics, such as soil organic carbon, clay content, and soil water content along the topo-sequence. Soil fertility variability also exists within a field along gradients and can be divided into sub-fields for site-specific nutrient management and recommendations. These sub-fields could be heterogeneous in soil fertility status and crop yield. Dividing a big field into subfields with similar attributes may help implement a uniform fertilizer rate application (Ameer et al. 2022).

Climate change, rainfall variability, and soil determine the food security situation of a given area. Rainfall variability is a critical factor dictating crop production and productivity in Ethiopia. Understanding the annual, seasonal, monthly, and weekly rainfall variability is crucial for improved agricultural production and productivity in rainfed agriculture (Bedane et al. 2022; Rao et al. 2011). The amount and distribution of water available to plants mainly depends on the onset of the rainy season, length, temporal distribution, and cessation, and may indirectly imply the climatic suitability of the crop and the chances of its success or failure in a season (Ngetich et al. 2014). Hence, knowledge of the onset and cessation of rainfall, amount, distribution, and length of the crop growing period would protect farmers from crop damage due to climatic anomalies (Bedane et al. 2022; Ngetich et al. 2014). From the perspective of rainfall variability, agricultural crop production depends on soil moisture availability, rainfall amount, onset, cessation, and length of the growing period. Terminal moisture stress affects the productivity of crops, particularly in low to medium-rainfall areas of the country. Rainfall variability impacts the soil's water availability to crops, causing reduced crop yield. The sustainability of agricultural production systems depends on prior knowledge of weather conditions, climate change, rainfall variability, and soil properties (Cooper et al. 2008; Rurinda et al. 2013).

In Ethiopia, severe organic matter depletion, driven by competing uses for crop residues as livestock feed and manure as an energy source for cooking is a great challenge (Agegnehu and Amede 2017; Zelleke et al. 2010). Although organic residues are key inputs for soil fertility management, about 63, 20, 10, and 7% of cereal straws, are used for feed, fuel, construction, and bedding purposes, respectively (Tsigie, Agegnehu, and Tesfaye 2011). Yield benefits were more evident when fertilizer application was accompanied by crop rotation, green manuring, or crop residue management. For example, the integrated application of organic and inorganic fertilizers increased bread wheat yield by 50–100%, whereas crop rotation with legumes increased cereal grain yields by up to 200% (Agegnehu and Amede 2017). Inorganic fertilizer rates applied for the major crops are still generally considered agronomically suboptimal in Ethiopia, despite the consistent increase in the adoption of fertilizers. Site-specific fertilizer recommendations to increase the yield and quality of crops are insufficient to give policy recommendations because they only address the optimal nutrient needs for individual fields, not the broader issues of access to fertilizers, market dynamics, environmental issues, and the economic realities faced by farmers, which are all crucial factors in policy decisions related to fertilizer use (Richards et al. 2015; Sanches et al. 2021). To address the problem of blanket fertilizer recommendations, fertilizer trials were conducted over the last half-century at research stations and a few selected on-farm testing sites, with limited efforts to extrapolate the results to a broader range of environments. However, the results of the fertilizer trials were not adequate to address this issue as they were conducted mostly on suitable landscapes regardless of undulating and hilly landscape positions. Hence, one of the main reasons for conducting nutrient omission trials under different environments and landscapes was to examine and interpret crop yield variability as soil properties are dynamic and change rapidly. There is limited information on how landscape positions could be used for refining fertilizer recommendations (Amede et al. 2022). Generally, research information about the effects of landscape position variation in crop yield response to different nutrient forms and rates is inadequate in the Ethiopian context. Thus, a comprehensive nutrient omission field research was conducted to test the hypothesis that applying different nutrient sources and rates would improve soil properties and wheat yield under different landscape positions and rainfall regimes.

This research, therefore, aimed to offer practical, profitable, scale-appropriate nutrient management recommendations for productive farming systems. This includes developing and transferring soil fertility management practices that improve nutrient use efficiency with the 4Rs of nutrient stewardship (right source, right time, right rate, right place), including the right management. Therefore, the objectives of this study were to (1) investigate the influence of landscape variability on wheat yield response to different nutrient sources; (2) evaluate the main and interaction effects of nutrient sources, landscape position, and production potential in terms of rainfall status (high *vs.* low potential areas) on wheat yield; and (3) identify variations in soil nutrient status and yield-limiting nutrients (N, P, K, S, Zn, and B) for wheat production.

Materials and methods

Description of the study sites

Comprehensive on-farm nutrient omission research was conducted under field conditions in the 2020 and 2022 cropping seasons in major bread wheat-growing regional states (Amhara, Oromia, and Central Ethiopia) of Ethiopia (Figure 1). The selection of trial sites was made based on the rainfall regime, which indicates crop production potential at different agroecological zones. Representative bread wheat-producing districts selected for conducting the field trials were Gozamen, Machakel, Burie, Debre Elias, and Wemberma from the Amhara region; Ambo, Bora, Dugda, and Welmera from the Oromia region; and Anlemo, Doyogena, Lemo, and Soro from the Central Ethiopia Regional State (Figure 1). The trial sites were distributed in the high-rainfall and low-to-medium rainfall regime areas representing the major wheat-growing agroecologies in the Ethiopian farming systems. Accordingly, except for Dugda, Anlemo, and Soro districts which fall under low-to-medium rainfall and low potential wheat-growing areas, the remaining districts are grouped under the high rainfall regime. The annual rainfall, minimum and maximum temperatures, soil types, and agroecological zones of the research sites are presented in Table 1.

The average annual rainfall ranged from 832 to 1680 mm while the maximum and minimum temperatures of the entire wheat-growing sites were between 21–29 and 8.5–13.1 °C, respectively. Tepid moist mid-highlands (M3), tepid humid mid-highlands (H3), warm sub-moist lowlands (SM2); warm sub-humid lowlands (SH2), and tepid sub-humid mid highlands (SH3) are the predominant agroecological zones. Regarding soil taxonomy, Vertisols, Cambisols, Nitisols,

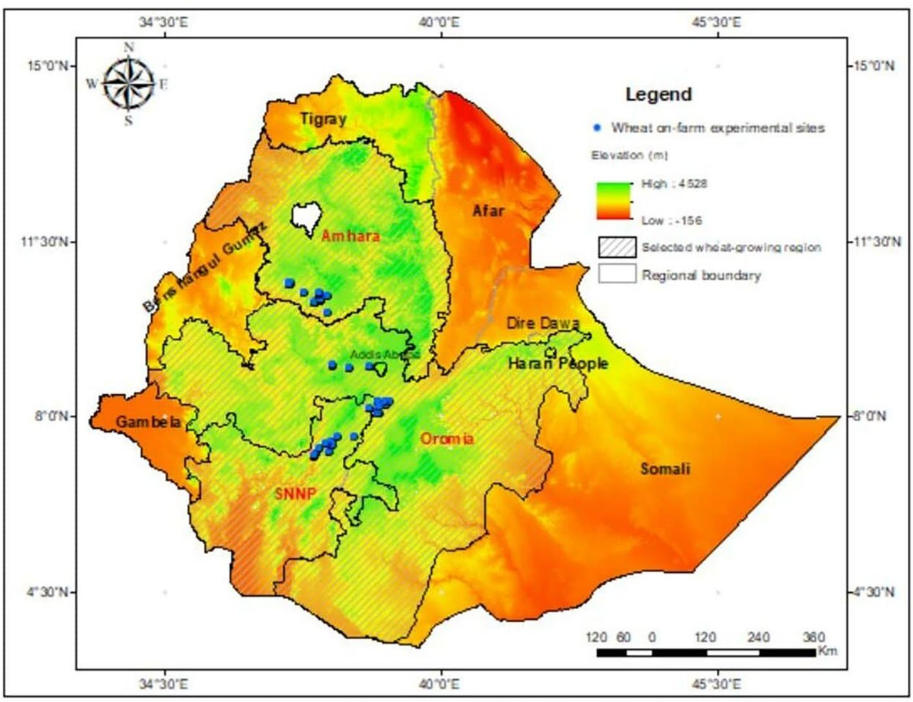

Figure 1. Distribution of study sites across the Amhara, Oromia, and SNNP regions.

Table 1. Characteristics of the study sites in the Amhara, Oromia, and SNNP regions.

Region	Location (district)	Rainfall (mm)*	Minimum temperature (°C)*	Maximum temperature (°C)*	Soil type (WRB 2022)	Agroecological zone (Hurni 1998)
Amhara	Burie	1645–1680 (1660.7)	10.8–11 (10.9)	24–25 (24.5)	Nitisols	M3
	Debre Elias	1389–1445 (1399.5)	10.3–10.5 (10.4)	23–24 (23.5)	Nitisols	M3
	Gozamen	1269–1363 (1349.7)	9.7–10.5 (10.1)	23–25 (23.5)	Nitisols	M3
	Machakel	1440–1487 (1452.3)	10.2–10.7 (10.4)	23–25 (23.5)	Nitisols	M3
	Wemberma	1672–1673 (1672.5)	10.0–10.9 (10.6)	23–24 (23.8)	Nitisols	M3
Oromia	Ambo	906–1113 (1008)	10.2–11.1 (10.4)	23–24 (23.6)	Nitisols and Vertisols	M3
	Bora	832–1026 (897.2)	10.0–10.2 (10)	25–29 (27)	Andosols and Cambisols	SM2
	Dugda	885–920 (914.2)	9.9–11.0 (10.3)	26–27 (26.5)	Andosols and Cambisols	SH3
	Welmera	1053–1097 (1060.3)	8.9–9.3 (9.3)	21–22 (21.5)	Nitisols	H3 and SH3
Central Ethiopia	Anlemo	939–1217 (1128.5)	9.4–11.5 (9.8)	22–26 (23.1)	Cambisols, Luvisols, Nitisols	SH3
	Doyogena	1114–1306 (1261.2)	8.5–13.0 (11.4)	21–26 (24.6)	Vertisols, Luvisols	SH3 and SH2
	Lemo	1141–1322 (1237.2)	9.5–13.0 (11.7)	24–27 (25.9)	Vertisols, Cambisols, Acrisols	SH3
	Soro	1081–1134 (1107.5)	10.4–10.7 (10.5)	24–25 (24.5)	Nitisols, Vertisols	SH3

M3: tepid moist mid highlands; H3: tepid humid mid highlands; SM2: warm sub-moist lowlands; SH2: warm sub-humid lowlands; SH3: tepid sub-humid mid highlands.
*Values in brackets are average values.

Andosols, Luvisols, and Acrisols are the dominant soil types that were covered to implement the field trials.

Treatments and experimental design

The response of bread wheat to different nutrient forms and rates was evaluated under three landscape positions and two rainfall regimes. At each landscape position, two to four trial sites with two replications per site, were selected based on the availability of suitable land for the trial. The response of bread wheat to Nitrogen (N) and phosphorus (P), sulfur (S), potassium (K), zinc (Zn), and boron (B) was assessed as outlined in Table 2. The experiment included eleven treatments: (1) all nutrients (N, P, K, S, Zn, and B) in blended form (All-Blend); (2) all nutrients (N, P, K, S, Zn, and B) in compound form (All-Comp); (3) all nutrients (N, P, K, S, Zn, and B) in individual forms (All-Ind); (4) 150% All-Blend containing 150% of the rate of each nutrient in blended form; (5) 50% of All-Blend containing 50% of the rate of each nutrient in the blended form; (6) (All-Blend)-K containing N, P, S, Zn, and B in blended form without K; (7) (All-Blend)-S containing N, P, K, Zn, and B in blended form without S; (8) (All-Blend)-Zn containing N, P, K, S, and B in blended form without Zn; (9) (All-Blend)-B containing N, P, K, S, and Zn in blended form without B; (10) NP containing the recommended rate of N and P nutrients only; and (11) the control without any nutrient.

Fertilizer blending was carried out using the International Fertilizer Development Center (IFDC) guidelines using a small cement mixer at Debre Zeit Agricultural Research Center, Ethiopia. Blends were weighed for individual plots. The formulations of S, Zn, and B-containing fertilizers for the study sites were prepared according to the recommendations of the Ethiopian Soil Information System (EthioSIS) (EthioSIS 2015). The fertilizer forms were all granular as N: DAP or NPS (19-38-0 + 7S) fulfilled by urea balance; P: DAP or NPS; K: KCl; S: $MgSO_4$; Zn: Zn sulfate monohydrate; and B: Borax Decahydrate. Coated Zn and B onto granules of NPKS were

Table 2. Treatments and nutrient rates (kg ha^{-1}) under rainfall regimes.

	Rainfall regime											
	High						Low to medium					
Treatment	N	P_2O_5	K_2O	S	B	Zn	N	P_2O_5	K_2O	S	B	Zn
All-Blend	120	76.0	60	14.8	0.50	1.50	75.0	38	60	7.4	0.250	0.750
All-Comp	120	76.0	60	14.8	0.50	1.50	75.0	38	60	7.4	0.250	0.750
All-Ind	120	76.0	60	14.8	0.50	1.50	75.0	38	60	7.4	0.250	0.750
150%All-Blend	180	114.0	90	22.2	0.75	2.25	112.5	57	90	11.1	0.375	1.125
(All-Blend)-K	120	76.0	–	14.8	0.50	1.50	75.0	38	–	7.4	0.250	0.750
(All-Blend)-S	120	76.0	60	–	0.50	1.50	75.0	38	60	–	0.250	0.750
(All-Blend)-Zn	120	76.0	60	14.8	0.50	–	75.0	38	60	7.4	0.250	–
(All-Blend)-B	120	76.0	60	14.8	–	1.50	75.0	38	60	7.4	–	0.750
NP-only	120	76.0	–	–	–	–	75.0	38	–	–	–	–
50% All-Blend	60	38.0	30	7.4	0.25	0.75	37.5	19	30	3.7	0.125	0.375
Control	–	–	–	–	–	–	–	–	–	–	–	–

Nutrient sources: Diammonium phosphate (DAP, 46-18-0), NPS (19-38-0 + 7S), and Urea (46-0-0); N: urea; P: DAP or NPS; K: KCl; S: NPS, Zn: zinc sulfate monohydrate; B; solubor.

Note: All-Blend: N, P, K, S, B, and Zn nutrients in blended form; All-Comp: N, P, K, S, B, and Zn in the compound form; All-Ind: N, P, K, S, B, and Zn applied individually; NP: nitrogen and phosphorus.

used to ensure even distribution. All nutrients and fertilizers were applied at planting except N, which was applied in two equal splits, i.e. half at planting, and the rest half 30–40 days after planting. Muriate of potash was also top-dressed at 30–90 kg K_2O ha^{-1} when the second 50% of N was applied to wheat plants. Nutrient rates used for the fertilizer treatments were according to research recommendations for the different crops and rainfall regimes. Land preparation and other crop management practices were done according to the requirements of the test crop.

The treatments were arranged in a randomized complete block design with two to three replications within a farmer site per landscape position on a plot size of 12 m^2 (3 m by 4 m). The spacings between blocks and plots were 0.75 and 0.5 m, respectively. The space between the experimental plots and borders on all 4 sides was 1 m. Improved varieties of bread wheat seeds suitable for each area were planted manually in a row at the seed rate of 125–150 kg ha^{-1}, with 20 cm spacing between rows. Wheat var. *TAY* and *Dandaa* were used in high and medium rainfall areas as they are late-maturing varieties and var. *Kekeba* was planted in the low-rainfall areas of Bora and Dugda Districts. All nutrients except nitrogen were applied during planting in different forms. However, nitrogen in the form of urea was applied in two splits, that is, half at planting and the other half as top-dressing at the tillering stage, just after weeding and with adequate moisture in the soil. Land preparation and other crop management practices were uniformly applied following the recommendations for the wheat crop.

Data collection

Representative soil samples were collected from the hillslope, mid-slope, and foot slope landscape positions before planting at two depths (0–20 and 20–60 cm) in 2020 and 2022. Five soil samples per site were collected systematically to make one composite sample. The collected soil samples were air-dried and milled to pass through a 2-mm sieve and sent to the laboratory of the International Fertilizer Development Center (IFDC) in the USA for the analysis of soil pH, total carbon (TC), total nitrogen (TN), available phosphorus (P), sulfur (S), exchangeable aluminum (Al), zinc (Zn), and boron (B). Soil pH (water) was measured following the standard operating procedure for soil pH determination (FAO 2021). The TC and TN were analyzed by dry combustion method according to Provin (2014). Mehlich 3 is most commonly used for the determination of macronutrients such as phosphorous (P), calcium (Ca), potassium (K), and magnesium (Mg) and micronutrients including copper (Cu), Zn, B, manganese (Mn), and iron (Fe). Accordingly, available P, S, Zn, and B were analyzed following the procedure of Mehlich 3 (Harova and Spejra

2014; Ziadi and Tran 2007). The percent volumetric soil moisture content at 20 cm soil depth was also measured using the portable soil moisture meter (TDR-300) with a 20 cm rod to validate the variability of soil moisture content along the three landscape positions (hillslope, mid-slope, and foot slope). The soil water content was measured during the booting and grain-filling stages of the wheat crop, and the mean values of the two measurements were used for statistical analysis.

Growth and yield of wheat were collected as the major agronomic parameters. The whole plot of 12 m^2 was harvested manually at physiological maturity to measure the total aboveground wheat biomass and grain yield. Grain yield was measured with a sensitive balance of ± 0.01 kg and adjusted to a moisture content of 12.5%. The total wheat biomass and grain yield recorded on a plot basis were converted to t ha^{-1} for statistical analysis.

Statistical analysis

The normality and homogeneity of the measured data were checked before an analysis of variance. The agronomic data were subjected to statistical analysis following a proc mixed model using the SAS statistical package Version 9.3 (SAS Institute Inc 2011) as follows:

$$Y = \mu + \mathrm{RF} + \mathrm{LS} + \mathrm{NF} + \mathrm{Loc} + \mathrm{ST} + \mathrm{AEZ} + \mathrm{RF} * \mathrm{NF} + \mathrm{LS} * \mathrm{NF} + \mathrm{RF} * \mathrm{LS} * \mathrm{NF} + \varepsilon$$

where Y is the measured parameter, μ is the grand mean, RF is the rainfall regime, LS is the landscape position, NF is a nutrient form, and ST is the soil type of the trial sites according to the World Reference Base (WRB 2022), AEZ is the agro-ecological zone, Loc is the sites where the field trials were conducted and ε is the error term. RF, LS, and NF were considered fixed factors, while Loc, ST, and AEZ were considered random factors. Means for the main effects of location and landscape position on soil chemical properties were compared by using the MEANS statement with the least significant difference (LSD) test at $p \leq 0.05$.

Before choosing a specific model, the fit of the models was assessed using Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC) (Zhang, Yang, and Ding 2023). The model was ultimately selected due to its lower AIC and BIC values compared to the other models because a lower AIC and BIC indicate a better fit for the model. As a general guideline, a difference in BIC of 2–6 suggests weak evidence, favoring the more complex model, while differences >10 provide strong evidence favoring the more complex model. Therefore, the selected model was deemed satisfactory. To assess the significance of the variations in yields with fixed effects, the intraclass correlation coefficient (ICC) was calculated by comparing the covariance estimate of the random intercept to the covariance estimate of the residual intercept. The ICC provides insights into how much the best-fitted model values the total variation in the outcome. Significance for the variations in yield with fixed effects was considered when $p \leq 0.05$.

The Tukey-Cramer method was used to adjust the *p*-values to compare least-square means. Statistical inference was based on least square estimates and their 95% confidence intervals (CIs). The 95% CI served as a cautious test for the hypothesis and provided a measure of uncertainty for sample statistics (Du Prel, Röhrig, and Blettner 2009). If the 95% CI of the means for two or more levels of a fixed effect did not overlap, it indicated that they were significantly different from one another. In addition, orthogonal contrast was performed using Scheffe's F test to determine the effect of nutrient forms and rates. Contrast analysis was performed between fertilizer treatments, including the comparisons of the NP-only treatment with nutrient-omitted treatments, landscape positions, and rainfall regimes. Cluster analysis was also performed to group and characterize a set of trial sites into similar clusters and understand their differential response to applications of different fertilizer treatments.

Results

Soil chemistry and water content over districts and landscape positions

The soil chemical analysis for the study sites before planting revealed that total soil carbon (TC), total nitrogen (TN), available phosphorus (P), available sulfur (S), and extractable zinc (Zn) generally decreased along down the topo-sequence, with lower nutrient concentrations observed on the hillslope compared to the foot slope and mid-slope positions. The ranges of the major soil chemical properties at district and landscape level were pH (5.1–6.5), TC (1.01–2.94%), TN (0.15–0.27%), C/N ratio (7.57–11.57), exchangeable aluminum (1.18–3.43 cmol(+) kg^{-1}), available P (3.17–60.16 mg kg^{-1}), available S (0.30–15.22 mg kg^{-1}), Zn (1.68–12.87 mg kg^{-1}), and B (0.01–1.24 mg kg^{-1}) (Table 3).

The contents of all nutrients increased from hillslope to lower gradients of foot slope positions, except for Mehlich exchangeable Aluminum (Al) along the topo-sequence where its relative content decreased from hillslope to foot slope position. For instance, soil pH was higher by 0.3 units at the foot slope than at the hillslope position over districts. Similarly, mean total C and N, available P, and extractable Zn were higher by 17.7, 29.4, 50.5%, and 67.1%, respectively, at the foot slope compared to the hillslope position. In contrast, soil Al concentration was lower by 0.32 cmol(+)/kg at the foot slope than at the hillslope position (Table 3). Higher soil TC and TN concentrations were recorded in Doyogena, Lemo, Anlemo, and Soro compared to other districts. The mean available soil P concentrations were in low to very low ranges across districts and landscape positions. Available sulfur was below the critical level in Lemo, Anlemo, and Bora districts, where a sulfur soil test above 5 mg kg^{-1} is adequate for most field crops (Horneck et al. 2011). Except in the Gozamen district, soil Zn was in the medium and high range. However, extractable B was deficient in most districts except in Anlemo and Doyogena where the soil boron concentrations are slightly higher than the critical level (Table 3). According to the soil analysis results, soil boron concentration tested below the sufficiency range in most districts. Soil test values of zinc and boron above 1.5 and 0.5 mg kg^{-1}, respectively, using the DTPA extraction method are adequate for most crops (Horneck et al. 2011), denoting the necessity of applying the recommended rate of boron as borax or other suitable forms of fertilizer to correct boron deficiency.

Table 3. Average selected soil chemical properties before planting across districts and landscape positions in wheat experimental sites.

		TC	TN		Al	Av. P	S	Zn	B
	pH	%		C: N	cmol(+)/kg	(mg kg^{-1})			
Location									
Ambo	6.4a	1.35ef	0.16 cd	7.57ef	2.52a	6.16c	3.63 cd	3.24 cd	0.01e
Doyogena	5.8b	2.94a	0.27a	11.57a	2.12c	12.63a	6.40b	12.87a	0.63b
Gozamen	5.5c	1.55e	0.17 cd	8.96d	3.34a	9.66ab	15.22a	1.34d	0.39d
Lemo	5.6c	2.47b	0.23b	10.69b	2.55b	4.37 cd	4.41c	5.77b	0.52c
Machakel	5.5c	1.53e	0.19c	8.14e	3.43a	2.50d	14.51a	1.68d	0.46 cd
Anlemo	5.8b	1.96d	0.22b	9.08d	2.38b	7.18bc	2.18de	3.87c	1.24a
Bora	6.5a	1.01f	0.15d	7.18f	1.18d	11.44a	0.30e	1.50e	0.04e
Soro	5.1d	2.17c	0.22b	10.02c	2.55b	3.17 cd	5.92bc	3.31c	0.37d
$LSD_{0.05}$	0.26	0.39	0.04	0.45	0.37	3.67	3.16	1.19	0.19
p-Level	***	***	**	**	***	***	***	***	***
Landscape									
Foot slope	5.9a	2.00a	0.22a	8.69b	2.36b	17.31a	7.47a	6.53a	0.52a
Mid-slope	5.8b	1.92a	0.19b	9.95a	2.46b	12.86b	5.93b	2.80b	0.42b
Hillslope	5.6c	1.70b	0.17b	8.81b	2.68a	11.50b	6.31b	2.15b	0.45b
$LSD_{0.05}$	0.07	0.10	0.01	0.27	0.10	2.85	0.85	0.75	0.02
p-Level	**	**	**	*	*	***	**	***	**

LSD: least significant difference; TC: total carbon; TN: total nitrogen; Av. P: available phosphorus; S: sulfur; Al: aluminum; Zn: zinc; B: boron.

*, **, ***Significance levels at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively; Within a column means followed with different letters are significantly different at $p < 0.05$.

However, as low levels of boron may limit plant growth, high concentrations could also cause toxicity for plant growth (Horneck et al. 2011).

Soil moisture content during the crop's growing stage is important due to its significant implication on the growth and yield performance of the crop and its response to fertilizer application. Results showed that variations in soil water content were evident over districts and landscape positions, where soil water content increased from the hillslope to the foot slope position, and higher volumetric soil water contents were recorded in high rainfall than in low to medium rainfall experimental locations (Figure 2). The highest volumetric soil water content of 33% was measured in Ambo district at the foot slope position, followed by the soil water contents of 29.3 and 28.2% at Doyogena and Lemo districts, respectively at the foot slope position. In contrast, the lowest volumetric soil water contents of 8.7, 10.9, and 11.9% were recorded at the hillslope, mid-slope, and foot slope positions, respectively (Figure 2). Regardless of soil water content variability among landscape positions, the lower soil water contents were measured in low to medium rainfall drought-prone areas, such as Bora and Anlemo districts than in districts that receive high rainfall. Based on soil types, higher soil water content was measured on Vertisols in Ambo than on other soil types.

Wheat response to nutrient forms, rainfall regimes, and landscape positions

The mixed model analysis of variance (ANOVA) revealed that the main effects of rainfall regime (RF), landscape position (LS), and nutrient form and rate (NF) had a highly significant ($p < 0.001$) effect on total aboveground biomass and grain yield of wheat in the study areas (Table 4). The total wheat biomass ranged from 7.80 t ha^{-1} under low rainfall regimes to 11.01 t ha^{-1} under high rainfall regimes, representing an increase of over 41% (3.21 t ha^{-1}) in total biomass in high rainfall areas compared to low rainfall areas (Table 5). The highest total biomass was attained at the foot slope position while the lowest was recorded at the hillslope position. The total biomass at the foot slope was greater by 31.5% (2.58 t ha^{-1}) and 17.8% (1.54 t ha^{-1}), respectively, compared to the mid-slope and hillslope positions. Higher grain yields were attained at the foot slope position and under the high rainfall regime compared to yields at the hillslope positions and under the low rainfall regime (Table 5). The lowest grain yield was observed in the control treatment, which received no fertilizer, at the hillslope positions and under the low rainfall regime (Table 5).

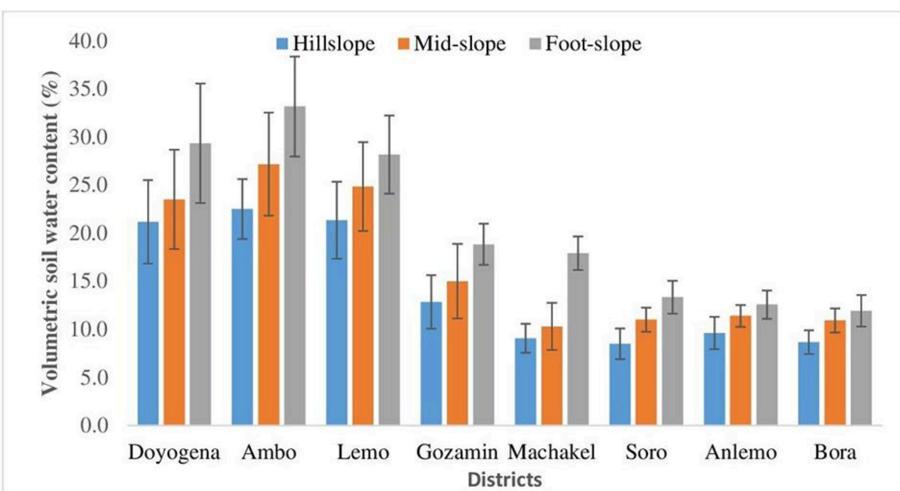

Figure 2. Volumetric soil water content (%) over districts where the trials were located along landscape positions.

Table 4. Mixed model ANOVA result for total aboveground biomass and grain yield of bread wheat as influenced by rainfall regime, landscape, and nutrient form.

	F-value		*p*-Value	
Effect	Total biomass	Grain yield	Total biomass	Grain yield
RF	27.32	21.49	<.0001	<.0001
LS	10.92	23.71	<.0001	<.0001
NF	77.05	94.35	<.0001	<.0001
RF × NF	6.52	8.82	<.0001	<.0001
LS × NF	1.27	0.77	0.1873	0.7538
RF × LS × NF	1.23	1.25	0.2075	0.1915

RF: rainfall; LS: landscape position: NF: nutrient form.

Table 5. Influence of rainfall regime, landscape position, and nutrient forms on grain yield and total biomass of bread wheat.

Factor		Grain yield (t ha^{-1})	Total biomass (t ha^{-1})
Rainfall regime	High rainfall	3.69 ± 0.33	11.01 ± 1.08
	Medium-low rainfall	2.86 ± 0.35	7.80 ± 1.13
Landscape position	Foot slope	3.96 ± 0.34	10.78 ± 1.11
	Mid slope	3.08 ± 0.34	9.24 ± 1.12
	Hill slope	2.79 ± 0.34	8.20 ± 1.10
Nutrient form and rate	All-Blend	3.42 ± 0.33	9.67 ± 1.08
	All-Comp	3.50 ± 0.35	9.91 ± 1.08
	All-Ind	3.73 ± 0.37	10.45 ± 1.08
	150% All-Blend	3.90 ± 0.34	10.52 ± 1.08
	(All-Blend)-B	3.30 ± 0.37	9.59 ± 1.08
	(All-Blend)-K	3.28 ± 0.33	9.53 ± 1.07
	(All-Blend)-S	3.42 ± 0.37	9.88 ± 1.08
	(All-Blend)-Zn	3.39 ± 0.37	9.73 ± 1.08
	NP-only	3.34 ± 0.33	9.63 ± 1.07
	50% All-Blend	2.97 ± 0.34	8.64 ± 1.03
	Control	1.80 ± 0.33	5.93 ± 1.07

Note: All-Blend: N, P, K, S, B, and Zn nutrients in blended form; All-Comp: N, P, K, S, B, and Zn in the compound form; All-Ind: N, P, K, S, B, and Zn applied individually; NP: nitrogen and phosphorus.

Results showed that significant ($p < 0.001$) improvements were observed in the total biomass and grain yield of wheat due to the application of different nutrient forms and rates (Table 4). The highest aboveground total biomass (10.52 ± 1.08 tha^{-1}) was achieved from the application of 150% of all nutrients in the blended form (All-Blend), with the total biomass increments of 8.9, 21.8, and 77.4%, compared to the NP-only, 50% of all nutrients in the blended form, and the control treatment, respectively (Table 5). The lowest total biomass was recorded from the control treatment in the low rainfall regime. Similarly, applying 150% of all nutrients in the blended form resulted in the highest grain yield of 3.90 t ha^{-1}, with grain yield increments of 14.4, 31.3, and 116.7%, compared to the NP-only, 50% of all nutrients in the blended form, and the control treatment, respectively (Table 5).

The mixed model ANOVA showed that the rainfall regime by nutrient form interaction significantly ($p < 0.001$) influenced the total biomass and grain yield of wheat over locations and landscape positions (Table 4 and Figure 3). However, the three-way interaction of rainfall regime, landscape position, and nutrient form as well as the two-way landscape position by nutrient form interaction were not significant for the total wheat biomass and grain yields. The total biomass and grain yield ranged from 6.62–11.89 to 1.81–4.42 t ha^{-1} respectively, in the high rainfall regime, and between 5.24–9.14 and 1.80–3.38 t ha^{-1} in the low rainfall regime (Figure 3). The highest rate of 150% of all nutrients in the blended form resulted in total biomass and grain yield increases of 2.26 and 2.44 times in the high rainfall regime, and 1.74 and 1.88 times in the low rainfall regime, compared to the control treatment. Yield differences were more pronounced in the high rainfall than in the low rainfall regime as nutrient uptake and efficiency could be high in soils with adequate soil moisture. Similarly, the total biomass and grain yield ranged from

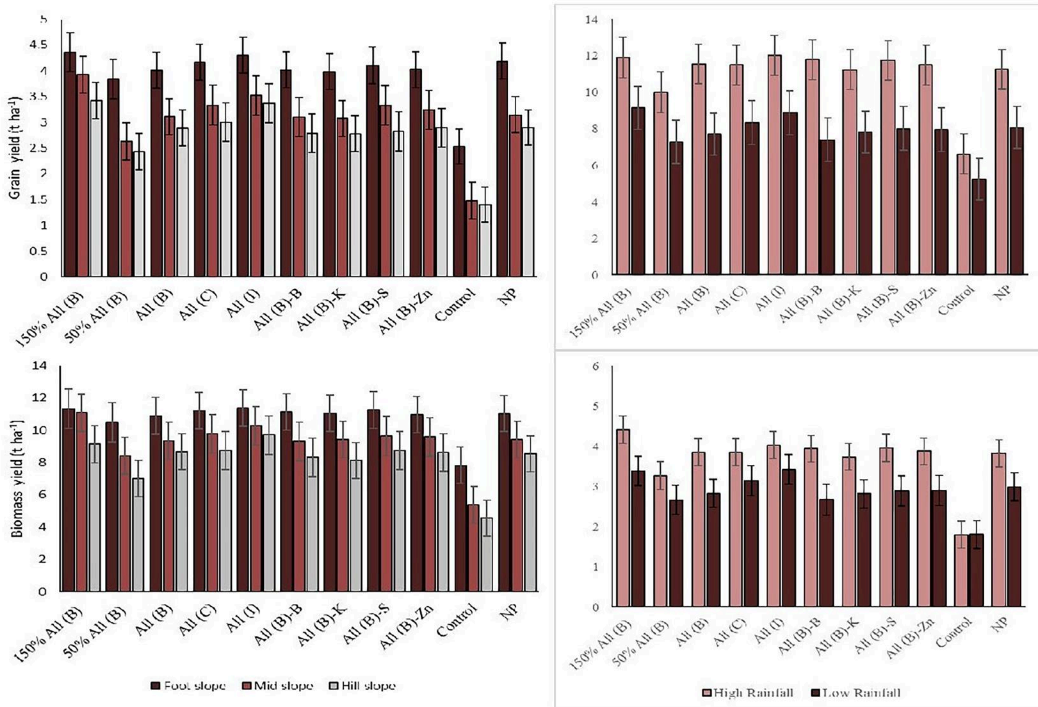

Figure 3. Response of wheat yield to the nutrient forms and rates under different landscape positions (left) and contrasting rainfall regimes (right).

4.57–11.34 to 1.40–4.36 t ha^{-1}, respectively across landscape positions, where the highest biomass and grain yield were at the foot slope position with the application of 150% of all nutrients in the blended form and the lowest at the hillslope position from the control treatment (Figure 3). The subsequent increases in the total biomass and grain yield at the foot slope position with applying 150% of all nutrients in the blended form were 2.48 and 3.11 times the control treatment at the hillslope position. Generally, for each treatment, the total biomass and grain yield recorded in the high rainfall regime and foot slope position were higher than in the low rainfall regime and hillslope position.

Despite the RF × LS × NF interaction being non-significant, the highest grain yield (4.90 t ha^{-1}) and total biomass (13.75 t ha^{-1}) were recorded from the application of 150% of all nutrients in the blended form (All-Blend) in the high rainfall regime under foot slope landscape position and the lowest grain yield (1.22 t ha^{-1}) and total biomass (3.89 t ha^{-1}) from the unfertilized control treatment in the low rainfall regime under hillslope position (Table 6). In the high rainfall production areas, significant grain yield increments of 109.5% (2.54 t ha^{-1}), 160.3% (2.79 t ha^{-1}), and 188.8% (2.53 t ha^{-1}) were attained due to the application of 150% of all nutrients in the blended form at the foot slope, mid-slope, and hillslope positions, respectively compared to the control treatment. While in the low rainfall areas, yield increases of 72.5% (0.73 t ha^{-1}), 165.7% (1.66 t ha^{-1}), and 143.7% (1.44 t ha^{-1}) were attained with the same treatment at the foot slope, mid-slope, and hillslope positions, respectively compared to the control (Table 6). Increasing the rates of all nutrients from the control treatment to 150% of all nutrients in the blended form significantly increased the grain yield across landscape positions and rainfall regimes, where the increase in the yield was mainly related to the rise in the NP rates (Table 6). However, statistically significant differences between 150% of all nutrients in blended form *vs.* all nutrients applied in blended, compound, or individual forms were not observed. Applying S, Zn,

Table 6. The interaction effects of rainfall regime, landscape position, and nutrient source on the total biomass and grain yield of wheat.

	High rainfall			Low rainfall		
	Grain yield (t ha^{-1})					
Nutrients	Foot-slope	Mid-slope	Hill-slope	Foot-slope	Mid-slope	Hill-slope
All-Blend	4.51 ± 0.35	3.67 ± 0.36	3.42 ± 0.35	3.86 ± 0.42	2.57 ± 0.40	2.50 ± 0.39
All-Comp	4.58 ± 0.36	3.60 ± 0.37	3.38 ± 0.36	3.75 ± 0.43	3.07 ± 0.49	2.63 ± 0.48
All-Ind	4.86 ± 0.37	3.66 ± 0.37	3.53 ± 0.36	3.69 ± 0.43	3.32 ± 0.41	2.96 ± 0.40
150% All-Blend	4.90 ± 0.36	4.53 ± 0.38	3.87 ± 0.39	3.87 ± 0.51	3.37 ± 0.49	3.21 ± 0.48
(All-Blend)-B	4.53 ± 0.36	3.71 ± 0.37	3.58 ± 0.36	3.51 ± 0.43	2.49 ± 0.49	2.00 ± 0.48
(All-Blend)-K	4.37 ± 0.35	3.66 ± 0.36	3.17 ± 0.35	3.59 ± 0.42	2.48 ± 0.40	2.39 ± 0.39
(All-Blend)-S	4.63 ± 0.36	3.87 ± 0.37	3.38 ± 0.36	3.58 ± 0.43	2.80 ± 0.49	2.27 ± 0.48
(All-Blend)-Zn	4.56 ± 0.36	3.78 ± 0.37	3.30 ± 0.36	3.49 ± 0.43	2.71 ± 0.49	2.49 ± 0.48
NP only	4.48 ± 0.35	3.65 ± 0.36	3.31 ± 0.35	3.54 ± 0.42	2.61 ± 0.40	2.36 ± 0.39
50% All-Blend	4.04 ± 0.37	3.11 ± 0.38	2.66 ± 0.39	3.63 ± 0.51	2.19 ± 0.41	2.15 ± 0.41
Control	2.32 ± 0.35	1.74 ± 0.35	1.34 ± 0.35	2.73 ± 0.42	1.27 ± 0.40	1.22 ± 0.40
Total biomass (t ha^{-1})						
All-Blend	13.15 ± 1.13	10.75 ± 1.14	10.77 ± 1.13	9.33 ± 1.36	8.10 ± 1.30	6.75 ± 1.26
All-Comp	13.41 ± 1.14	10.40 ± 1.17	10.68 ± 1.15	9.02 ± 1.38	9.17 ± 1.50	6.80 ± 1.46
All-Ind	12.75 ± 1.14	10.99 ± 1.17	10.39 ± 1.15	8.98 ± 1.38	9.55 ± 1.49	7.89 ± 1.27
150% All-Blend	13.79 ± 1.18	12.54 ± 1.19	11.28 ± 1.20	9.92 ± 1.6	9.61 ± 1.31	8.12 ± 1.46
(All-Blend)-B	13.42 ± 1.14	11.04 ± 1.18	10.90 ± 1.15	8.86 ± 1.38	7.56 ± 1.49	5.75 ± 1.46
(All-Blend)-K	12.70 ± 1.13	11.19 ± 1.14	9.82 ± 1.13	9.38 ± 1.36	7.65 ± 1.30	6.45 ± 1.26
(All-Blend)-S	13.39 ± 1.14	11.14 ± 1.18	10.71 ± 1.15	9.09 ± 1.38	8.14 ± 1.49	6.80 ± 1.46
(All-Blend)-Zn	12.98 ± 1.14	11.15 ± 1.18	10.35 ± 1.15	8.97 ± 1.38	8.01 ± 1.49	6.91 ± 1.46
NP-only	12.72 ± 1.13	10.71 ± 1.14	10.31 ± 1.13	8.63 ± 1.36	7.95 ± 1.30	6.58 ± 1.26
50% All-Blend	11.67 ± 1.18	9.94 ± 1.19	8.35 ± 1.21	9.28 ± 1.56	6.91 ± 1.31	5.66 ± 1.27
Control	8.32 ± 1.13	6.28 ± 1.14	5.26 ± 1.13	7.33 ± 1.36	4.50 ± 1.30	3.89 ± 1.26

SE: standard error.

Note: All-Blend: N, P, K, S, B, and Zn nutrients in blended form; All-Comp: N, P, K, S, B, and Zn in the compound form; All-Ind: N, P, K, S, B, and Zn applied individually; NP: nitrogen and phosphorus.

and B in blended, compound, or individual forms with N and P did not result in statistically significant wheat yield differences between them which justifies that S, Zn, and B are not yield-limiting nutrients in most wheat-producing areas of Ethiopia (Tables 5 and 6).

Contrast and cluster analysis to compare yield response to nutrients

The contrast analysis indicated that comparisons between 150 and 50% of all nutrients in blended form ($p < 0.001$) and 150% All-Blend *vs.* NP-only ($p < 0.05$) were significant for total biomass and grain yield. Similarly, 50% of all nutrients in blended form and NP-only treatment significantly ($p < 0.05$) varied from the control treatment (Table 7). However, the comparisons between the treatments with each omitted nutrient (K, S, Zn, and B) *vs.* NP-only treatment and all nutrients applied in different forms were not statistically significant for grain yield and total biomass (Table 7). On the other hand, the comparisons of foot slope *vs.* mid-slope, and foot slope *vs.* hillslope were significant ($p < 0.001$) for grain yield, but the contrast between hillslope and mid-slope position was not significant for grain yield. Similarly, the contrasts of foot slope *vs.* hillslope, foot slope *vs.* mid-slope, and hillslope *vs.* mid-slope were significant ($p < 0.001$ and $p < 0.05$) for total wheat biomass. Remarkably, the comparison between high rainfall and low to medium rainfall regimes was highly significant ($p < 0.001$) for wheat total biomass and grain yield (Table 7).

Selected treatments were also compared to determine the magnitude of yield penalty because of the omission of nutrients under different landscape positions and rainfall regimes. About 27–70% yield penalty was observed because of fertilizer treatments compared to the control treatment across landscape positions in both rainfall regimes (Figures 4(a,b)). The omission of K reduced yield by <5.5% compared to all nutrients in the blended form at the foot and mid-slope positions

Table 7. Mean comparison of selected fertilizer forms and rate, landscape position, and rainfall regime in wheat biomass and grain yield.

	Grain yield		Biomass yield	
Selected treatments	*SE*	Adjusted *p*	*SE*	Adjusted *p*
Nutrient forms				
All-Blend *vs.* All-Comp	100.12	0.8580	258.74	0.9921
All-Blend *vs.* All-Ind	100.10	0.0045	258.70	0.0594
All-Comp *vs.* All-Ind	115.00	0.6725	296.57	0.7702
All-Comp *vs.* NP-only	100.12	0.9979	258.74	0.9964
All-Blend *vs.* NP-only	70.20	0.9939	181.04	1.0000
All (I) *vs.* NP-only	100.10	0.0569	258.70	0.0794
All-Blend *vs.* (All-Blend)-K	70.20	0.9990	181.04	1.0000
All-Blend *vs.* (All-Blend)-S	100.13	0.9990	258.77	0.9972
All-Blend *vs.* (All-Blend)-Zn	100.15	1.0000	258.83	1.0000
All-Blend *vs.* (All-Blend)-B	100.13	1.0000	258.77	1.0000
150% All-Blend *vs.* 50% All-Blend	113.99	<.0001	293.98	<.0001
150% All-Blend *vs.* NP-only	99.29	<.0001	256.70	0.0343
150% All-Blend *vs.* All-Blend	99.29	<.0001	256.70	0.0246
50% All-Blend *vs.* NP-only	99.29	0.0004	256.70	0.0035
50% All-Blend *vs.* All-Blend	99.29	0.0088	256.73	<.0001
Control *vs.* NP-only	70.21	<.0001	181.07	<.0001
Landscape				
Foot-slope *vs.* Hillslope	169.52	<.0001	566.17	<.0001
Foot-slope *vs.* Mid-slope	182.55	<.0001	608.47	0.0309
Hillslope *vs.* Mid-slope	146.48	0.1172	443.36	0.0504
Rainfall regime				
High rainfall *vs.* Low rainfall	177.54	<.0001	612.95	<.0001

Note: All-Blend: N, P, K, S, B, and Zn nutrients in blended form; All-Comp: N, P, K, S, B, and Zn in the compound form; All-Ind: N, P, K, S, B, and Zn applied individually; NP: nitrogen and phosphorus.

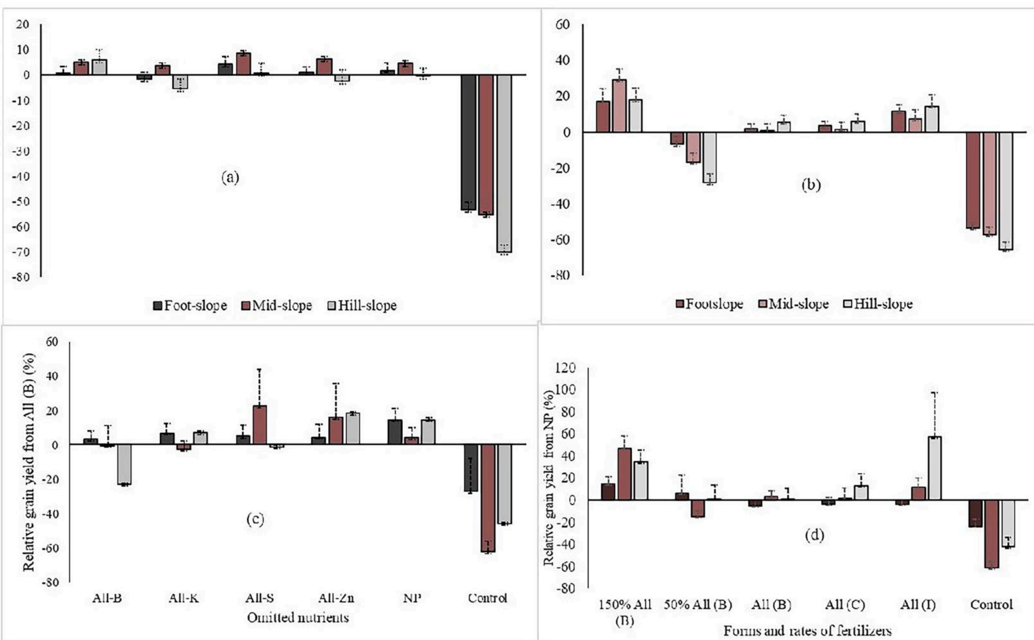

Figure 4. The response of wheat yield to nutrient forms under high (a) and low-to-medium (c) rainfall regimes, fertilizer forms, and rates under high (b) and low to medium (d) rainfall regimes.

under the high rainfall regime (Figure 4(a)). The omission of B reduced yield by 23.1% at the hillslope under low to medium rainfall regimes (Figure 3(a)). All nutrient rates applied in the blended form resulted in higher effects on grain yield under both rainfall regimes. About 16.8–

23.1% yield penalty was observed from the control treatment at the foot, mid-, and hillslope positions. Applying 150% of all nutrients in the blended form showed higher yield under all landscape positions and rainfall regimes. The yield variability between All-Blend, all-individual (All-Ind), or all-compound (All-Comp) *vs.* NP-only was observed (Figures 4(b,d)).

Clustering is a statistical data analysis for grouping a set of entities or units so that units in the same group or cluster are more similar in some specifics to each other than those in different groups or clusters. The cluster analysis (CA) broadly grouped the trial sites into four similar clusters. The results of the CA showed that yield differences from the control treatment were significantly greater in high-potential districts by fertilizer treatment interactions than in low-potential districts (Figure 5). Yield differences from the control treatment in low-potential districts were either very small or insignificant compared to the control treatment. The scatter plot revealed the relationship between grain yield and yield differences from the control without any fertilizer application, segmented by cluster (Figure 6). This visualization helped to understand how different clusters respond to the various nutrient treatments, and whether higher yields could correlate with larger yield improvements. Each point represents a location, and the color indicates its cluster. Sites under 0, 1, and 2 clusters showed more response to the fertilizer treatments than sites in cluster 3 where most of the less responsive sites for the treatments are under Bora and Dugda districts (Figures 5 and 6). The grain yield correlated linearly with the grain yield difference from the control, with greater yield response in high potential and high rainfall sites than low potential—low rainfall sites (Figure 6).

Discussion

Soil chemistry and water content over locations and landscape positions

Understanding soil nutrient and crop yield variability across landscape positions has become the central research theme on soil and plant relationships. The results of soil chemical properties for

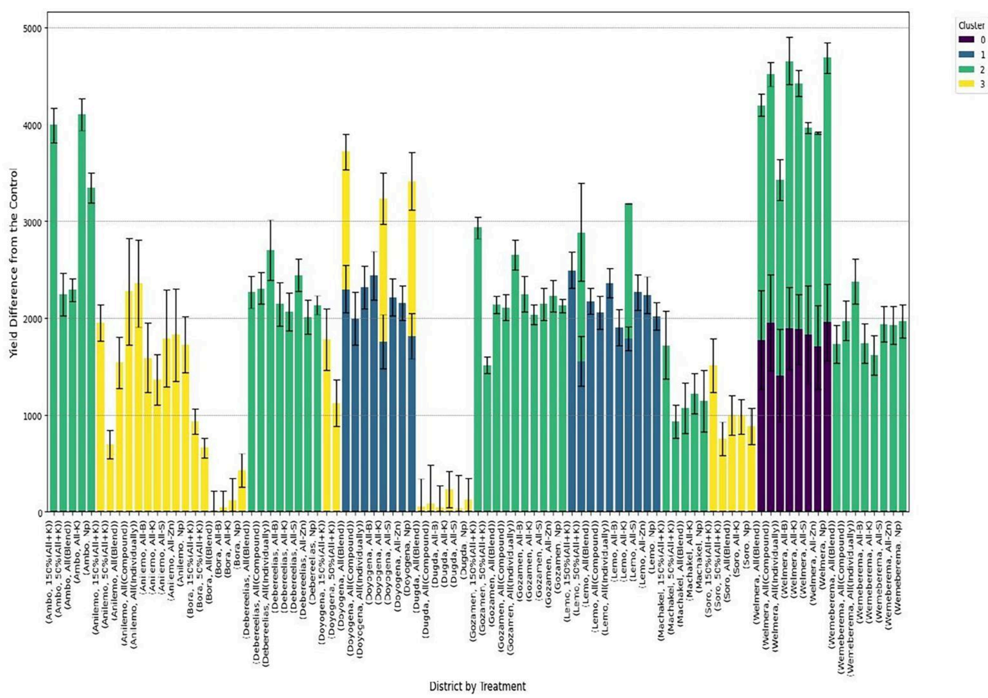

Figure 5. Yield differences between the district by nutrient forms and the control treatment. Error bars denote ±1*SE*.

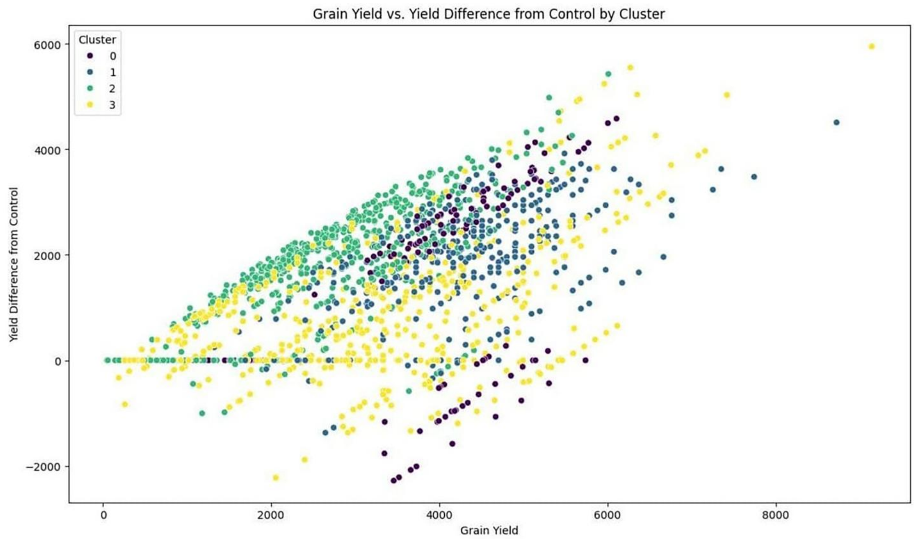

Figure 6. The relationship between grain yield and yield difference from the control treatment based on cluster analysis (CA).

samples taken before planting considered in this study indicated that lower soil nutrient concentrations were recorded at the hillslope than at the foot and mid-slope positions, indicating the leaching and deposition of soil nutrients from the sloppy areas to low laying topographic positions. Similar results were reported by Cornish, Kumar, and Das (2020) that lower soil pH, OC, and CEC were observed in rice fields of higher slope positions compared to fields of lower landscape positions. Wysocka-Czubaszek and Roj-Rojewski (2020) also reported that the concentrations of NO_3-N, available P, and K were high in the soil located on the toe-slope position, while the soil located on the crest had high NH_4-N, but poor in the plant-available forms of K and P.

The soil pH and concentrations of all nutrients increased from hillslope to foot slope positions, except for Mehlich extractable exchangeable Al where its relative concentration decreased from hillslope to foot slope position. For instance, the soil pH was higher by 0.30 units but exchangeable Al was lower by 0.32 cmol(+)kg^{-1} at the foot slope than at the hillslope position, implying that the exchangeable Al concentration and extent of soil acidity were greater on hillslopes than on gentle and foot slope positions (Agegnehu et al. 2023). This necessitates different intervention measures to manage and restore the fertility of depleted hillslope soils. However, the difference between the foot slope and mid-slope position was non-significant for soil nutrient concentrations. The total soil C, N and available P at the foot slope position was significantly higher by 1.2, 1.3, and 1.5 times, respectively than at the hillslope position, indicating that the deposition and accumulation of nutrients from the upper slopes to the lower slope positions and bottom lands through surface runoff and leaching was greater (Rodrigues et al. 2021; Sharma et al. 2022). Recent studies indicated that the status of soil nutrients at the foot slope had a larger amount of soil OC, N, P, and B compared to the mid and hillslope positions (Agegnehu et al. 2023; Bufebo, Elias, and Agegnehu 2021; Wang, Liu, and Dang 2011). Previous studies also reported that the highest concentrations of soil OC and total N were observed at the foot slope position, with an increasing trend from the upper slope to the foot slope position (Agegnehu et al. 2023; Wang et al. 2001) while lower mean values of these nutrients were recorded at upper landscape positions and intensively cultivated lands (Agegnehu et al. 2024; Negasa et al. 2017). As the prospects of investing in soil fertility management practices on hillslope farms are very limited for farmers where crop response to fertilizer application and profitability are poor, an integrated soil fertility management approach involving organic and inorganic amendments and sustainable land management practices is needed to restore the fertility of the soil (Amede et al. 2022). 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, identifying the right sources and rates of nutrients based on landscape position and other crop production factors will reduce input costs, improve nutrient use efficiency, and improve yield and farm profitability while protecting the environment.

The measurement of soil water content aimed to verify whether the soil water content varies across experimental locations and landscape positions. Higher volumetric soil water contents ranging from 11.9 to 33.2%, were measured at the foot slope position compared to 10.9–27.2% at the mid-slope and 8.7–22.5% at the hillslope positions, consistent with the patterns observed in other soil properties of this research findings (Table 2 and Figure 2). Similarly, Bufebo, Elias, and Agegnehu (2021) measured the highest soil water content of 34.56% at the lower landscape position. Studies also indicated lower bulk density (Bufebo, Elias, and Agegnehu 2021) and higher concentrations of soil OC, N, and available P (Agegnehu et al. 2023) at the foot slope than at the mid-and hillslope landscape positions, indicating a decrease in bulk density toward down landscape position but increase in the soil OC and other nutrients. Soil bulk density is inversely correlated with soil water content and soil OC where higher values of these parameters were recorded from soils with lower bulk density (Agegnehu et al. 2023). However, other studies demonstrated that 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 (Amede et al. 2021; Lal 2020; Rawls et al. 2003). While variations in water content among landscape positions were observed, lower soil water contents were measured in drought-prone areas, such as Bora, characterized by a low-lying slopes. In the highland areas, the soil water content was comparatively high which could be due to the cooler temperature and the availability of well-distributed rainfall in an adequate amount.

The seasonal variability in the amount and distribution of rainfall causes a significant effect on the crop yield in drought-affected areas (Agegnehu et al. 2023), where the terminal moisture stress during the grain-filling stage of the crop could impact wheat yield. This might be due to the exposure of the wheat crop to water scarcity at its later growth stages in drought-prone areas in contrast to the high rainfall and Vertisol agricultural areas where soil moisture could be available until the crop maturity (Agegnehu et al. 2023). A considerable soil water content difference was also observed between soil types, where higher soil water contents were measured on Vertisols (e.g. in the district of Ambo) than on other soil types, signifying the higher water holding capacity of Vertisols.

Wheat response to nutrient forms, rainfall regimes, and landscape positions

Supply of essential nutrients at balanced and required rates is one of the most important factors in increasing crop yields (Fageria 2001). This research revealed that wheat total biomass and grain yield highly and significantly responded to nutrient forms, contrasting rainfall regimes, and landscape positions. The highest grain yields (3.69 ± 0.33) and total biomass (11.01 ± 1.08) were obtained in the high rainfall regime, compared to the low rainfall regime (Table 5). Over 38% grain yield and 41% total biomass increments were attained in the high rainfall regime because the availability of adequate moisture during the crop's growing season plays a great role in expressing the crop's genetic potential and enhancing nutrient uptake, which agrees with the findings of previous studies (Balemi et al. 2019; Ngetich et al. 2014). This is also related to the long growing period and the subsequent high dry matter accumulation of the crop in the high rainfall regime compared to the low rainfall regime which contributes to higher grain yield. Wang, Liu, and Dang (2011) indicated that unless adequate soil water is available, greater water stress may result from well-fertilized crops, possibly during later critical crop development stages, thereby reducing nutrient use efficiency and crop yield. Despite the availability of high seasonal total rainfall in most crop-growing areas of the country, particularly in the highlands, the problem is its poor temporal distribution across the season. Accordingly, it will be vital to consider the amount and distribution of rainfall over time, space, and seasons to recommend different fertilizer rates based on production potential.

Landscape position had a significantly stronger effect on the growth and yield of wheat, where the highest total biomass and grain yield were recorded at the foot slope position. This might be attributed to the fact that landscape position affects the biophysical and chemical properties of soils due to soil erosion from the hillslope and mid-slope positions and depositing it at the foot slope or low-laying landscape strata (Balasundram et al. 2006; Moges and Holden 2008; Wezel, Steinmüller, and Friederichsen 2002). Landscape position also affects the growth and yield of crops through its impact on the storage and availability of soil moisture (Agegnehu et al. 2024; Bufebo, Elias, and Agegnehu 2021). For instance, crops planted at the bottom of a slope may receive more water due to runoff from steep areas, which could influence crop growth and yield (Madin and Nelson 2023; Zhang et al. 2020). Not only water but also loss of nutrients in the soil is sensitive to the slope gradients of the cultivated hillsides. Thus, an integrated management strategy is needed to reduce runoff and nutrient loss in sloppy landscapes.

Although wheat yield responded strongly and significantly to the different fertilizer treatments (Table 4), the applications of K, S, Zn, and B did not lead to significant yield differences when compared to the recommended N and P fertilizers regardless of the contrasting rainfall regimes and landscape positions (Table 6 and Figure 3). Our findings did not align with those of Karim et al. (2012), who reported that the application of Zn and B improved wheat yield under drought conditions. In contrast, our results are consistent with those of Desta et al. (2022) on sorghum and Balemi et al. (2019) on maize, which found no significant yield benefit from applying K, S, Zn, and B compared to N and P in the low rainfall areas of Ethiopia. This suggests that soils in the study areas, both in high and low rainfall regimes, have sufficient K, S, Zn, and B content (Table 2) to support wheat production, contradicting the recommendations by EthioSIS (2015). In this study, the highest yield was attained from applying 150% of all nutrients in the blended form (All-Blend), where yield increased with the increase in the rates of nutrients from 0 to 150% in both high and low rainfall regimes. However, the yield increase was not because of applications of K, S, Zn, and/or B but rather due to the increase in N and P rates, which is consistent with the findings of Lollato et al. (2019). In contrast, Dargie et al. (2022) reported that not only N and P but also K and S are required to improve the growth and yield of wheat. Maharjan, Das, and Shapiro (2022) also indicated that maize yield difference was observed in N and P treatments with and without S and Zn only in the first year (12.3 and 11.6 t ha^{-1}). Still, grain yields were similar in treatments with S and Zn combined (9.7–12.4 t ha^{-1}) or blended (9.7–12.2 t ha^{-1}) in all experimental years. In low rainfall areas, yield was low across the treatments suggesting lower benefits of adding major nutrients (N, P), let alone S or Zn, when moisture is limiting.

In a study involving two or more independent variables, it is important to examine whether the effect of one variable depends on the level of one or more other variables. Interaction effects between variables occur when one variable's impact depends on another variable's level. Our results denoted that the rainfall regime by the nutrient form interaction highly significantly influenced the total biomass and grain yield of wheat over landscape positions (Figure 3), indicating the impact of the availability of adequate moisture in the soil on nutrient uptake and efficiency, growth, and yield of the crop. Increased soil-water storage and availability to crop plants at critical growth stages improves nutrient utilization efficiency (Singh et al. 2015; Waraich et al. 2011). The findings of an experiment conducted for 16 years in China indicated that responses of maize to P and K and the highest yields were achieved only in the normal rainfall years (Ma et al. 2010). However, the three-way interaction of rainfall regime (RF), landscape position (LS), and nutrient forms (NF) as well as the two-way landscape position by nutrient form interaction were not significant for wheat total biomass and grain yield. The absence of interactions in two-way (NF × LS) and three-way (NF × RF × LS) mixed model ANOVA could be because of the large spatial variations within landscape positions and experimental locations in rainfall amount and distribution, soil fertility and the subsequent high coefficient of variations among the levels of these independent variables. The total biomass and grain yield were 1.80 and 2.44 times higher in the high rainfall and 1.74 and 1.88 times in the low rainfall regime, respectively (Figure 3), compared to the control treatment. In general, the findings of this research indicated that wheat yield response to K, S, Zn, and Bacross different landscape positions, rainfall regimes, and application forms was not significantly greater than the response to N and P applications. Therefore, priority should be given to nitrogen and phosphorous sources of fertilizers to enhance wheat productivity and achieve maximum economic returns, thereby improving food security and contributing to poverty reduction.

Proper plant nutrition is an effective strategy to enhance water use efficiency and increase crop yields (Waraich et al. 2011). Field assessments reveal that farmers typically apply more fertilizer to hillslopes and less to mid-slope and foot-slope positions, based on the belief that hillslopes are more nutrient-depleted while mid- and foot-slope positions have better nutrient status. However, Desta et al. (2023) reported that farmers' practices of applying more fertilizers on hillslopes resulted in low profitability and low nutrient use efficiency. Moreover, landscape-specific fertilizer application, guided by optimized crop-specific decision rules, resulted in significantly higher wheat yield improvements of 23 and 21% at the foot slope and mid-slope positions, respectively, compared to the yield at the hillslope position (Desta et al. 2023). Nutrient losses from sloping farmlands could lead to a deterioration of soil fertility, crop yield, and nonpoint source pollution (Yao et al. 2021). Our results also indicated that landscape position significantly affected grain yield and total biomass. The yield difference among landscape positions ranged from 2.79 to 3.96 t ha^{-1} for grain yield and 8.20–10.78 t ha^{-1} for total biomass (Table 5). At the foot slope position, grain yield increased by 41.9 and 10.4% and total biomass by 16.7 and 31.5%, compared to the mid-slope and hillslope positions. This might be attributed to the improved soil fertility at the gentle slope and low-laying landscape positions, where nutrients accumulate due to erosion and deposition from the hillslope landscape strata. This finding aligns with similar studies (Agegnehu et al. 2024; Amare et al. 2013; Amede et al. 2022), which also reported the highest yield at the foot slope and the lowest at the hillslopes. Wheat yield increases were more pronounced when the fertilizer rates were raised from 0 to 150% of all nutrients in the blended form across all landscape positions (Figure 3). However, the response was more pronounced at the foot slope than at the mid-slope and hillslope positions, indicating the responsiveness of the soil to the fertilizer application at the foot slope positions. Previous studies showed that the yield increment could not be attributed to the increase in K, S, Zn, and B rates; it could rather be a simultaneous increase in N and P rates (Alemayehu, Adgo, and Amare 2023; Amare et al. 2022; Shewangizaw et al. 2022).

The deficiency of secondary and micronutrients negatively affects plant metabolic functions and reduces the yields of crops. These nutrients are applied in small quantities and are physically blended or chemically fused with primary nutrients to enhance the uniformity of application (Maharjan, Das, and Shapiro 2022). However, our findings indicated that applying K, S, Zn, and B nutrients with N and P in blended, compound, and individual forms did not produce statistically significant wheat yield improvements compared to the recommended NP-only across landscape positions. This did not justify the hypothesis that the forms of these nutrients could influence the response of wheat growth and yield, which is in line with similar studies (Agegnehu et al. 2024; Alemayehu, Adgo, and Amare 2023; Amare et al. 2022). Both positive and negative yield responses have been reported for cereal crops as a result of adding K, S, Zn, and B nutrients with N and P to soils (Agegnehu et al. 2024; Bazie et al. 2024; Desta et al. 2022; Elias, Biratu, and

Smaling 2022). For instance, previous studies showed that applying S and Zn with N and P nutrients did not result in significant increases in barley grain yield and grain Zn concentration (Gebreslassie et al. 2023), or S, Zn, and B with N and P in teff and wheat yield (Elias, Biratu, and Smaling 2022), compared to NP or NPS fertilizer. Likewise, Shewangizaw et al. (2022) reported that significant yield improvements were not obtained in barley yields due to K and S fertilizer application on Vertisols and Cambisols. A recent finding by Bazie et al. (2024) also indicated that applying blended fertilizers without empirical evidence is not recommended for smallholder farmers in the study areas. Other researchers, on the other hand, reported the importance of the application of K, S, B, and Zn to improve the yields of crops (Abebe, Abera, and Beyene 2018; Dibabie, Bekele, and Yassen 2007; EthioSIS 2015; Sigaye, Nigussei, and Yacob 2022). For example, research findings indicated significant yield advantages of food barley (Elias et al. 2020) and wheat (Terfa et al. 2023) owing to applications of N, P, S, Zn, and B as blended fertilizers. Nevertheless, our research findings proved again that N and P are still the key yield-limiting plant nutrients to produce wheat under all landscape positions and rainfall regimes. The yield gaps among and between the landscape positions were not related to the deficiency of K, S, B, and Zn, it was rather due to the deficiency of N, P, and other soil properties including soil organic matter (Amare et al. 2013) and soil moisture content (Agegnehu et al. 2023). Therefore, applying nutrients other than N and P at all landscape positions could not be economically and environmentally justified for wheat production in the study and similar areas. However, periodic soil testing will be important to monitor and identify limiting macro- and/or micronutrients that can be supplemented at the required rate and time. The yield response is also supported by the preplanting soil analysis results where soil nutrients including K, S, and Zn, considered yield-limiting in the nutrient omission research, were found above the critical level required by the crop across landscape positions, except for boron in most districts. In contrast, Abebe, Abera, and Beyene (2018) indicated that S, B, and Zn were deficient nutrients for wheat productivity.

Contrast and cluster analysis for treatment comparisons and defining similar groups

A contrast analysis can offer additional insight into group differences, as it may test for more precise and specific differences among data groups (Nogueira 2004). In this research, the contrast analysis unveiled that comparisons between nutrient sources, rates, and nutrient forms varied significantly for wheat total biomass and grain yield. Interestingly, the comparisons between the treatments with all nutrients *vs.* NP-only; treatments with omitted nutrients (K, S, Zn, and B) *vs.* NP-only; and all nutrients applied in different forms *vs.* NP-only treatment were not statistically significant for wheat yield, suggesting that grain quality analysis could be required whether the addition of the omitted nutrients influenced the production of nutrient-dense wheat grains. However, the contrast between 150% of All-Blend *vs.* other treatments with various nutrient sources and forms was significant for wheat yield, implying that the differences could be attributed to higher rates of N and P nutrients in All-Blend than other treatments. Landscape-wise, the contrast between foot slope *vs.* mid-slope and foot slope *vs.* hillslope significantly differed for grain yield. The contrast between high rainfall and low to medium rainfall regimes was highly significant for wheat total biomass and grain yield. Likewise, researchers reported that contrasts between landscape position, fertilizer application, and their interaction effects were significant for teff and wheat yields (Agegnehu et al. 2023) and sorghum yield (Desta et al. 2022).

Cluster analysis (CA) enables the identification of subfields in the field which internally have similar characteristics. The CA could be used to identify and define intervention areas based on their response to the application of nutrients under different landscape positions and rainfall regimes. The cluster data analysis indicated that the sites and environments in the same group are more similar than those in other groups. For instance, high-potential sites located in different districts were grouped into three clusters under high-rainfall environments based on the extent of their response to fertilizer applications. In contrast, the lower responsive sites were grouped only into one cluster under a low-rainfall environment, which agrees with the yield response of wheat to different fertilizer treatments under different rainfall regimes and landscape positions, with several trial sites within each landscape strata. The results of the CA showed that the trial sites under the high rainfall regime and lower landscape positions are more suitable for wheat production than trial sites under the low rainfall regime and hillslope positions. Similarly, Minh et al. (2023) used CA to group and identify critical parameters affecting crops' soil environment and identified three districts suitable for developing perennial crops. According to the results of the CA, the spatial variability had a greater influence when considering the variability in wheat yield response to different fertilizer treatments (Figure 1). Despite the application of uniform crop management practices, this could be attributed to differences in soil nutrient status and soil water content among landscape positions and several sites within each landscape position. Desta et al. (2022) also reported the impact of spatial heterogeneity on the variability of sorghum yield response to the different fertilizer treatments.

Conclusions

This research revealed that landscape positions, contrasting rainfall regimes, nutrient sources, forms, and rates influenced growth and yield of wheat. The highest wheat total biomass and grain yield were attained under the high rainfall regime at the foot slope position with an application rate of 150% of all nutrients in blended form. This shows the need for increasing the N and P rates for wheat production, particularly in the high rainfall areas where the production potential is high to produce higher yields of most field crops. Lower yields were obtained in a low rainfall regime on sites located at the hillslope positions. Substantial wheat yield increase was not observed due to S, Zn, and B applications in blended, compound, or individual forms. Moreover, the contrast analysis between applications of all nutrients in blended, compound, and individual forms showed that significant differences were not observed in wheat yield. The comparisons of different treatments with the recommended NP-only were not statistically significant for wheat yield. In most farming systems of Ethiopia, applications of K, S, Zn, and B have not been found as yield-limiting nutrients for wheat production. Consequently, higher rates of N and P in high rainfall and high potential areas and modest rates of these nutrients in low-to-medium rainfall areas could be the right options for smallholder farmers in Ethiopia. However, based on soil test results and crop responses, the roles of K, S, Zn, and B are valuable in improving crop yield and nutritional quality, and they can be applied where necessary based on the requirements of crops.

The findings of this research suggest that because of large topo-sequence effects on soil nutrients and water availability, it would be vital to consider landscape positions and rainfall regimes for site-specific fertilizer recommendations. To sustain soil and crop productivity and maintain healthier and more productive farming systems, it will also be important to develop holistic solutions for enhancing soil health and fertility and nutrient use efficiency to offer practical, profitable, scale-appropriate soil and land-use management technologies and recommendations. This could be achieved by strengthening and promoting integrated soil health and fertility management practices for optimal economic returns, focusing on smallholder cropping systems based on landscape and rainfall potentials. Emphasis needs to be given to an integrated soil fertility management approach, combining organic and inorganic amendments and conservation agriculture to restore the soil fertility status of degraded hillslope landscape positions. We suggest that the available research information on application forms of fertilizers in blended, individual, or compound forms is inadequate to infer a conclusion. Thus, further research is suggested to confirm which forms of fertilizer and nutrients are best for future crop production under specific conditions where soils are deficient in essential macro- and micronutrients.

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Data availability statement

Data will be made available on request.

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