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Yield-limiting nutrients for enhancing teff production in contrasting landscape positions and rainfall contexts

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KEYWORDS

Blended fertilizer, compound fertilizer, landscape position, nutrient omission, rainfall context, teff, yield-limiting nutrients

HIGHLIGHTS

- Landscape position and rainfall context influenced yield responses to nutrient applications.
- Yield was 28.7% more in lower-slope than upper-slope positions.
- Yield was 1.3 times higher in high rainfall areas than in low rainfall areas.
- Increasing blended nutrients (N, P, K, S, Zn and B) by 50% increased yield by 10%–154% in high and 5%–84% in low-rainfall areas.
- N and P are the most yield-limiting nutrients in different landscapes and rainfall conditions.

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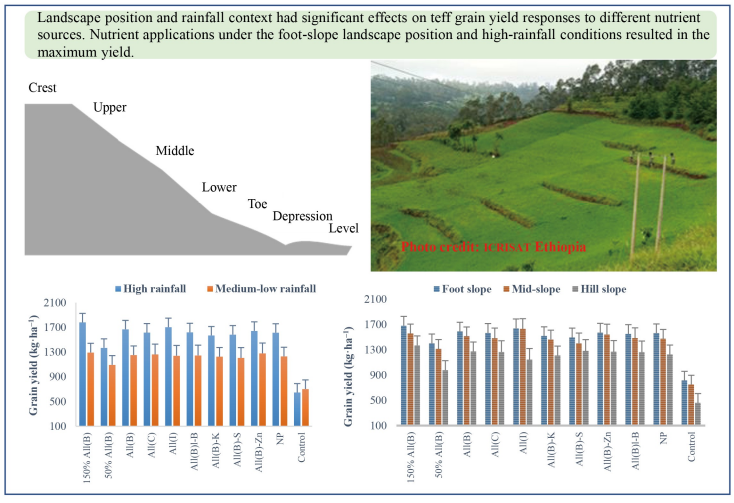
GRAPHICAL ABSTRACT



ABSTRACT

Multiple nutrient-omission field experiments were conducted in 2020 and 2022 across different landscape positions and rainfall contexts to investigate teff yield response to nutrient application. The treatments included All(B) (i.e., blended fertilizer containing N, P, K, S, Zn and B), All(C) (i.e., compound

fertilizer with the same nutrients), All(I) (i.e., individual fertilizers for each nutrient), All(B)-K, All(B)-S, All(B)-Zn, All(B)-B (i.e., All(B) minus the individual nutrients specified), NP, 50% and 150% of All(B), and a control without nutrients. These treatments were arranged in a randomized complete block design with two to three replicates. A linear mixed model was used to determine the effects of landscape position, rainfall context, and nutrients on teff yield. Results revealed significant differences in teff yield response to nutrients in different landscape positions and rainfall contexts. In a high rainfall area, the highest grain yield (1.52 t·ha^{-1}) was recorded from 150% of All(B), with grain yield increments of 6.3%, 10.3% and 154% compared to All(B), NP, and the control, respectively, and 3.2, 5.0 and 84.2% in a medium to low rainfall area. Omitting K, S, Zn, or B, or all four nutrients resulted in the yield penalties of 5.9%, 5.2%, 1.6%, 3.0% and 3.3%, respectively, under high rainfall, and 2.0%, 3.6%, –2.3%, 0.5% and 1.7% in medium to low rainfall contexts compared to All(B). N and P were the most yield-limiting nutrients under all landscape positions and rainfall contexts. Overall, identifying yield-limiting nutrients and their optimal use is vital for enhancing nutrient use efficiency and yield, helping producers achieve rewarding economic returns. Further research is suggested with soil tests across soil types and agroecological zones to determine appropriate NP rates and monitor the need for other nutrients for teff yield and quality.

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1 Introduction

Widespread soil degradation, accompanied by soil fertility depletion and low nutrient application, is the primary cause of low crop yields, declining per capita food production, and poor natural resource conservation in sub-Saharan Africa (SSA)[1,2]. Deterioration of soil fertility and nutrient mining are critical challenges for Ethiopian agriculture and sustainable crop production[3,4]. In Ethiopia, severe organic matter depletion is exacerbated by competing uses for crop residues, such as livestock feed and animal manure, as fuel sources for cooking[3]. Hence, low crop response to fertilizers is a major concern despite the consistent increase in fertilizer supply and use in the country.

Understanding soil fertility, as a key factor limiting crop productivity, is important for developing appropriate soil nutrient management recommendations. The effectiveness of matching fertilizer types to soil fertility constraints relies on the capability to identify limiting factors, characterize sites, and develop appropriate recommendations[5–8]. To identify nutrient management zones, the collection and interpretation of spatial data, including yield, altitude, landscape, rainfall, and soil fertility maps, are required[9,10]. A recent study reported that teff yield significantly responded to landscape positions, with a yield increase of 71% at the lower-slope compared to the upper-slope position[11]. Significant variations were observed in crop fertilizer response with topo-sequence due to substantial variations in soil organic carbon, clay content, and soil water content[11]. A study by Bufebo et al.[12] indicated that a decrease in slope gradient accounted for an increase in most soil physicochemical properties. Concurrently, a reverse trend was observed for sand content, bulk density, water-stable aggregates, mean weight diameter, structural stability index, soil organic carbon, total nitrogen, and available phosphorus[13].

Crop production in SSA is characterized by a wide yield gap compared to other parts of the developing world. This is partly due to the failure to appreciate the variability of crop response to external inputs across farms and landscapes[7,14–16]. Yield variability is greatly controlled by yield-limiting factors, including fertilizer, water, and climate[2]. Based on a topography-related approach, research to understand soil

variability and its potential effect on crop yield has continued for over a millennium; however, soils with varied landscape strata and poorly developed profiles were considered exceptions to the general trends of normal soils[17]. In recent years, variability in crop yields within and between farms[18,19] and across different landscape positions[20,21] has gained research attention in SSA. Researchers identified three different crop response categories to fertilizer application: responsive, fertile non-responsive, and degraded non-responsive to indicate yield variability in small-scale farms[5,22]. Research findings have verified that increasing fertilizer rates does not result in higher crop yields in fertile and degraded non-responsive soils[23,24]. Non-responsive degraded soils are associated with complex chemical, physical, and biological constraints that severely inhibit fertilizer response. The key soil characteristics that cause poor crop-nutrient response include low soil organic matter, clay content, acidity, nutrient imbalances, moisture deficits, and soil compaction[25–27]. Even with higher fertilizer rates, crop yields on marginal soils are lower than on moderately fertile soils[7,24]. However, there is a limited understanding of why there is a positive crop response in some farms, while a limited response in others within the same locality[5,22,28]. In some cases, positive crop responses and economic incentives for farmers to use higher mineral fertilizer application rates were rare[29]. Variations in crop response to fertilizer application could be partly due to the variability of farms and landscape positions and the failure to identify the right type and amount of nutrients required for a specific landscape niche[22,30]. This implies the need for site-specific nutrient management based on soil and crop requirements to improve the economic and environmental feasibility of fertilizer application.

Teff (*Eragrostis tef*), a major staple crop in Ethiopia, is mostly used for making different kinds of *Enjera* (pan-fried flat breads), porridge, and feed[31]. The special qualities of teff include its storage for many years without being seriously damaged by common storage insect pests; low on the glycemic index (making it suitable for consumption by type II diabetics), gluten-free and high in fiber; and tolerant to waterlogging, but teff is susceptible to lodging because of its weak stalks. Teff makes a high market price and is a viable option for farmers instead of alternative cash crops, such as coffee, tea, or cotton. It is suitable for diverse cropping systems, which can be used in risk management strategies. Teff straw is a valuable animal feed during the dry season when there is an acute feed shortage and is preferred by cattle over the straw of other cereals[32,33], thus demanding high prices in markets. Teff is characterized by variable and low yields. It is mainly cultivated as a monocrop or rotated as teff-wheat-food legumes and wheat-teff-food legumes[34]. The crop has an increasing trend in planted area, with about 3.1 Mha[35]. However, despite the potential to increase teff production, its yield is low, with an average yield of 1.85 $t \cdot ha^{-1}$. The low yield can be attributed mainly to poor soil fertility, inadequate nutrient supply, and crop management practices[3]. A significant variation in yield was also observed between the landscape positions, with a lower-slope position having a 71% yield advantage over an upper-slope position[11].

Variability in soil moisture and nutrient availability across landscape positions and soil nutrient management are key production factors that influence crop responses to fertilizer application, affecting nutrient use efficiency and crop productivity. Identifying the yield-limiting nutrients and applying them at the right source, rate, method, and time with appropriate management practices can improve nutrient use efficiency, yield, and farmers' profitability. Large differences in crop yield normally exist between farms applying similar types and rates of fertilizers. While satisfactory yields have been attained on some farms, other farms fail to realize their potential yields, which limits the opportunity to sustain any improvement in crop yield[36]. Differences in crop yields between farms are often the result of fertilizer recommendation systems that fail to consider the substantive variations in soil fertility, landscape strata, and other production factors that are commonly observed between adjacent farms. Such differences can prevent farmers from achieving the full benefit of adopting improved fertilizer application practices. This illustrates the need for optimized site-specific fertilizer recommendations that can identify these important differences between farms.

In Ethiopia, fertilizer experiments have been conducted for nearly half a century on research stations and a few selected testing sites, which do not accurately represent all cropland across landscape positions. Limited effort has also been made to extrapolate the results to a wider range of environments. This could be one of the reasons for yield variations in crops in the different areas, as soil properties are variable and change rapidly[15]. There is also limited information on how landscape positions could be used for refining fertilizer recommendations. Generally, research information about the effects of landscape position on crop yield response to different fertilizer sources is inadequate in the Ethiopian context. Thus, a comprehensive fertilizer experiment was conducted under field

conditions to test the hypothesis that applying different nutrient sources would improve soil nutrients and yield of teff in different landscape positions and rainfall contexts.

Despite the consistent increase in the adoption of inorganic fertilizers in Ethiopia, application rates are still generally considered agronomically suboptimal, resulting in low agronomic efficiency and crop yields. Lack of site-specific balanced fertilizer recommendations is a constraint for increasing the yield and quality of crops. This research aimed to offer practical, profitable, scale-appropriate nutrient management recommendations for healthier and more productive farming systems. This included developing and transferring soil fertility management that improves nutrient use efficiency, in association with the 4Rs principle of nutrient management (nutrient stewardship): the right source, right rate, right time, and right place. This is achieved by strengthening inorganic fertilizer-based systems and promoting integrated soil health and fertility management practices for optimal economic returns, focusing on smallholder cropping systems. Therefore, the major objectives of this research were: (1) to investigate the effect of landscape variability on teff yield response to different nutrient sources; (2) to evaluate the main and interaction effect of nutrient sources, landscape positions and rainfall context on teff yield and soil properties; and (3) to assess the state of soil nutrients (N, P, K, S, Zn and B) in different landscape positions and rainfall contexts, and their relations to applied nutrients for teff production.

2 Materials and methods

2.1 Characteristics of experimental sites

Landscape-based diagnostic on-farm nutrient omission trials were conducted over 180 fields (134 in the 2020 and 46 sites in the 2022 main cropping seasons). About 60 experimental sites were selected in 17 districts of Amhara, Oromia, Central, and South Ethiopia regions. Representative teff-producing districts selected for the study were Gozamen, Machakel, Gonji Kolela, Sekota, Tehuledere, and West Belessa in the Amhara Region; Adaa, Ambo, Bora, Dugda, Ejere, and Sekoru in the Oromia Region; Anlemo, Doyogena, Lemo, and Soro from the Central Ethiopia Region; and Boloso Sore in the South Ethiopia Region. The experimental locations in each district were selected based on landscape positions (upper/mid/ lower slope) and rainfall context criteria (high, low to medium), which are indicators of crop production potential in different agroecological zones in Ethiopia. The landscape positions were divided based on the slope gradient in the topo-sequence, with slope ranges of 0%–5%, 5%–15% and 15%–30%, respectively, as lower-, mid- and upper-slope positions (Fig. 1). Two to four farmers per landscape position were selected, with two to three replicates within a farmer site at each landscape position. The experimental locations, weather conditions, soil types, and agroecological zones of all the research sites are summarized in Table 1.

The selected experimental sites were characterized by unimodal and bimodal rainfall patterns with varying rainfall amounts, intensity, and duration. Variations in rainfall, minimum and maximum temperatures, soil types, and agroecological zones were observed in all on-farm experimental sites in the selected districts (Table 1). The average annual rainfall range and maximum and minimum air temperatures of the teff-growing locations are between 700 and 1445 mm, 23–32 °C, and 8.7–17 °C, respectively. According to the World Reference Base[37], Vertisols, Nitisols, and Cambisols are the dominant soil types, while tepid moist mid-highlands, tepid subhumid mid-highlands, and warm subhumid lowlands are the predominant agroecological zones based on the Ministry of Agriculture classification[38] in the study areas.

2.2 Treatments and experimental design

Growth and yield response of teff to different forms of nutrient sources, including N, P, K, S, Zn and B, was investigated under contrasting landscape positions and rainfall contexts as

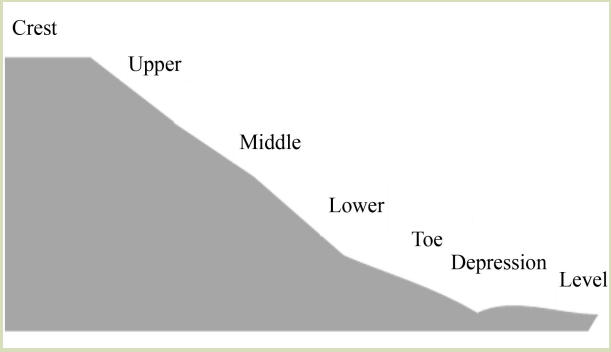

Fig. 1 A diagram showing landscape positions in a topo-sequence.

Table 1 General characteristics of teff experimental sites across districts and regions

District	Rainfall (mm)	Temperature (°C)		Soil type	Agroecological zone
		Minimum	Maximum		
Amhara region					
Gozamen	1279–1365 (1346)	9.7–10.2 (9.8)	23–24 (23.2)	Vertisols, Nitisols	Tepid moist mid-highlands (M3)
Machakel	1440–1445 (1443)	10.2–10.4 (10.3)	23–24 (23.2)	Vertisols	Tepid moist mid-highlands (M3)
Gonji Kolela	1378–1401 (1388)	8.7–8.9 (8.8)	24–25 (24.6)	Vertisols	Tepid moist mid-highlands (M3)
Sekota	762–808 (780)	11.1–14.1 (12.2)	27–30 (28.2)	Cambisols	Warm semiarid lowlands (SA2)
Tehuledere	700–975 (877.8)	11.4–17.3 (13.8)	25–31 (28.1)	Cambisols, Regosols, Xerosols, Leptosols	Warm moist lowlands (M2)
West Belessa	967–1012 (987)	14–14.6 (14.2)	30–32 (30.9)	Solonchaks, Leptosols	Warm semiarid lowlands (SA2)
Oromia region					
Adaa	884–893 (891)	8.7–8.9 (8.8)	24–25 (24.5)	Vertisols Cambisols	Tepid subhumid mid-highlands (SH3)
Ambo	1003–1129 (1057)	10.1–11.1 (10.6)	23–24 (23.5)	Nitisols	Tepid moist mid-highlands (M3)
Bora	832–1026 (871)	9.8–10.1 (10)	25–29 (27.4)	Cambisols Vertisols,	Warm sub-moist lowlands (SM2)
Dugda	885–886 (885)	10–10.9 (10.3)	26–27 (26.5)	Andosols	Warm sub-moist lowlands (SM2)
Ejere	846–870 (850)	10–10.3 (10.2)	23.5–24.3 (24.1)	Vertisols	Tepid moist mid-highlands (M3)
Sokoru	1120–1310 (1238)	11.8–16.3 (13.4)	26–29 (26.9)	Cambisols, Nitisols	Tepid subhumid mid-highlands (SH3)
Central Ethiopia region					
Anlemo	939–1217 (1112)	9.7–11.6 (9.9)	23–26 (23.2)	Cambisols, Luvisols	Tepid subhumid mid-highlands (SH3)
Doyogena	1115–1357 (1259)	9.4–15.2 (11.9)	24–28 (26.3)	Cambisols, Nitisols	Tepid subhumid mid-highlands (SH3)
Lemo	1092–1322 (1265)	9.5–13.1 (12.1)	23–27 (26.1)	Vertisols, Acrisols	Tepid subhumid mid-highlands (SH3)
Soro	1135–1140 (1137)	10.5–10.7 (10.6)	24–25 (24.8)	Vertisols	Tepid subhumid mid-highlands (SH3)
South Ethiopia region					
Boloso Sore	1304–1340 (1320)	13–16.3 (14.7)	27–29 (28.1)	Cambisols, Nitisols	Warm subhumid lowlands (SH2)

Note: Values in brackets are the average of ranges. Sources: soil type[37] and agroecological zones of Ethiopia[38].

presented in Table 2. At each landscape position, two to four experimental sites with two replicates per site and four to eight replicates per landscape position were selected based on the availability of suitable land for the experiment. The experiment included eleven treatments: (1) All(B) containing N, P, K, S, Zn and B nutrients in blended form; (2) All(C) containing N, P, K, S, Zn and B in the compound form; (3) All(I) containing N, P, K, S, B and Zn applied as individual forms; (4) All(B)-K containing N, P, S, B and Zn in blended form; (5) All(B)-S containing N, P, K, Zn and B in blended form; (6) All(B)-Zn containing N, P, K, S and B in blended form; (7) All(B)-B containing N, P, K, S and Zn in blended form; (8) NP containing the recommended rate of N and P nutrients only; (9) 150% All(B) containing 150% of the rate of each nutrient in blended form; (10) 50% All(B) comprising 50% of the rate of each nutrient in blended form; and (11) the control treatment without any nutrient.

Fertilizer blending was carried out at Debre Zeit Agricultural Research Centre using a small cement mixer, following the International Fertilizer Development Center guidelines[39]. Blends were weighed for individual plots. The formulations of S-, Zn-, and B-containing fertilizers for the study sites were prepared based on the recommendations of the Ethiopian Soil

Table 2 Treatments and nutrient sources, and rates for teff under two rainfall contexts

Treatment	Nutrient rates in high rainfall area (kg·ha^{-1})						Nutrient rates in medium to low rainfall area (kg·ha^{-1})					
	N	P	K	S	Zn	B	N	P	K	S	Zn	B
All(B)	80	24.9	49.8	11.1	1.13	0.38	60	16.6	49.8	7.4	0.75	0.25
All(C)	80	24.9	49.8	11.1	1.13	0.38	60	16.6	49.8	7.4	0.75	0.25
All(I)	80	24.9	49.8	11.1	1.13	0.38	60	16.6	49.8	7.4	0.75	0.25
All(B)-K	80	24.9	0	11.1	1.13	0.38	60	16.6	0	7.4	0.75	0.25
All(B)-S	80	24.9	49.8	0	1.13	0.38	60	16.6	49.8	0	0.75	0.25
All(B)-Zn	80	24.9	49.8	11.1	1.13	0	60	16.6	49.8	7.4	0.75	0
All(B)-B	80	24.9	49.8	11.1	0	0.38	60	16.6	49.8	7.4	0	0.25
NP	80	24.9	0	0	0	0	0	0	0	0	0	0
150% All(B)	120	37.3	74.7	16.65	1.70	0.57	90	24.9	74.7	11.1	1.13	0.375
50% All(B)	40	12.4	24.9	5.55	0.57	0.19	30	8.3	24.9	3.7	0.375	0.125
Control	0	0	0	0	0	0	0	0	0	0	0	0

Note: All(B) containing N, P, K, S, Zn and B nutrients in blended form; All(C) containing N, P, K, S, Zn and B in the compound form; All(I) containing N, P, K, S, B and Zn applied as individual forms.

Information System[40]. The fertilizer forms were all granular: N as diammonium phosphate (DAP) or NPS (19-16.6-7) fulfilled by urea balance; P as DAP or NPS; K as KCl; S as $MgSO_4$; Zn as Zn sulfate monohydrate; and B as borax decahydrate. Coated Zn and B on NPK granules were used to ensure even distribution. All nutrients and fertilizers were applied at planting except N, which was applied in two splits, i.e., the first half at planting and the remaining half 30–40 days after planting and proper weeding. KCl was also top dressed at 24.9–74.7 kg·ha^{-1} K when the second 50% of N was applied to teff plants. Nutrient rates used for the fertilizer treatments were according to research recommendations for the different crops and rainfall contexts. Land preparation and other agronomic practices were done according to research recommendations for teff production in Ethiopia [33].

The experiment was arranged in a randomized complete block design with two to three replicates within a farmer site per landscape position, using a plot size of 3 m × 4 m (12 m^2). The spacings between blocks and plots were 1 m and 0.75 m, respectively. The space between the experimental plots and borders on all 4 sides was 1 m. Improved cultivars of teff suitable for each area were used at the seed rate of 15 kg·ha^{-1}. Kuncho (DZ-Cr-387 RIL355) and Kora (DZ-Cr-438 RIL133B) high-yielding teff cultivars were released in 2006 and 2014, respectively, which have been developed for the high rainfall and optimum moisture (high potential) areas of the country, with a respective yield potential of 2.0–3.2 and 2.5–3.2 t·ha^{-1}[33]. In contrast, Tseday (DZ-Cr-37), Boset (DZ-Cr-409 RIL50d), and Boni (DZ-Cr-498 (RIL37) early-maturing teff cultivars were released in 1984, 2012 and 2021, respectively, which have been developed for drought-prone areas in Ethiopia, with a respective yield potentials of 18–2.5, 1.9–2.6 and 2–3 t·ha^{-1}[33,41]. Other agronomic practices were applied uniformly to all plots during the crop-growing period according to the recommended on-farm practices. All nutrients except N were applied at planting in different forms, while N in the form of urea was applied in two halves: the first half at planting and the remaining half as top dressing at the tillering stage, just after weeding, and with adequate moisture in the soil. The recommended land preparation and agronomic practices were uniformly applied for the teff crop.

2.3 Soil Analysis and measurements of agronomic data

Over 200 representative soil samples were collected randomly before planting at the depths of 0–20 cm in 2020 and 2022 from three landscape positions (upper/mid/lower slope), following the standard soil sampling procedure. Five soil samples were collected to make one composite sample, and the samples were air-dried and milled to pass through a 2-mm sieve. Then they were sent to the laboratory of the IFDC in the USA for the analysis of soil pH, total carbon (TC), total

nitrogen (TN), S, available P, exchangeable Al, Zn, and B. Soil pH (H_2O) was measured according to the standard operating procedure for soil pH determination[42]. The dry combustion method was used to analyze the TC and TN[43,44]. Available soil P, S, Zn, B, and exchangeable Al were determined as Mehlich 3[45,46].

Data collected on major agronomic parameters included aboveground biomass, grain yield, straw yield, and harvest index of teff. At physiological maturity, all the plants in the plot were harvested manually close to the ground surface. The harvested plants were sun-dried in the open air and weighed to determine the aboveground biomass yield. After threshing, the seeds were cleaned and weighed. The grain moisture was adjusted to 12.5%. The grain yields (adjusted to a moisture content of 12.5%) were converted to $kg \cdot ha^{-1}$ for statistical analysis. The straw yield was measured by subtracting the grain yield of teff from the aboveground biomass yield (on a dry weight basis). Teff harvest index (HI) was calculated as the ratio of grain yield to aboveground biomass at harvest in kg.

2.4 Statistical analysis

Before statistical analysis, the 2020 and 2022 data were combined into a single dataset. The data were cleaned and arranged for statistical analysis. The data were analyzed using a mixed model in PROC MIXED of the SAS system (SAS/STAT version 9.3)[47]:

$$Y = \mu + \mathrm{RF} + \mathrm{LP} + \mathrm{NF} + \mathrm{RF} \times \mathrm{NF} + \mathrm{LP} \times \mathrm{NF} + \mathrm{RF} \times \mathrm{LP} \times \mathrm{NF} + \mathrm{Loc} + \mathrm{ST} + \mathrm{AEZ} + \varepsilon \tag{1}$$

where, Y is the measured value, μ is the grand mean, RF is the rainfall context, LP is the landscape position, NF is a nutrient form, ST is the soil type of the experimental sites according to World Reference Base, AEZ is the agroecological zone, Loc is farmers field in which the experiment is conducted and ε is the error term. The rainfall context, landscape position, and nutrient source are fixed components, while location, soil type, and AEZ are random components in the model.

The fit of the models was assessed using Akaike's information criterion (AIC) and Bayesian information criterion (BIC) before choosing a specific model. The model was ultimately selected as it had lower AIC and BIC values than the other models. Lower AIC and BIC values indicate a better model fit. As a general guideline, a difference in BIC of 2–6 shows weak evidence favoring the more complex model, whereas a difference greater than 10 provides 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 was calculated by comparing the covariance estimate of the random intercept to the covariance estimate of the residual intercept. This coefficient provides insight 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 $p \leqslant 0.05$.

The Tukey-Cramer method was used to adjust the P values for comparing means. Statistical inference was made based on least-squares estimates and the 95% confidence interval (CI). The 95% CI served as a conservative test for the hypothesis and provided a measure of uncertainty for sample statistics[48]. If the 95% CI of the means for two or more levels of a fixed effect did not overlap, it would indicate that they were significantly different from one another. Also, orthogonal contrasts were made using Scheffe's F test to determine the effect of fertilizer rate and sources. A total of 11 contrasts were made; however, one of the contrasts was planned to compare NP only with nutrient-omitted treatments, as the NP only is the positive control treatment for this experiment. Cluster analysis was conducted to group a set of trial sites into similar clusters and understand their response to applications of different fertilizer treatments.

3 Results

3.1 Landscape position and agroecological zone effects on soil properties and soil water content

The results showed that soil chemical properties, including soil pH, TC, TN and S, available P, exchangeable Al, Zn and B, and soil water content significantly varied with landscape position and agroecological zone (Fig. 2 and Table 3), with both soil nutrient and water content improvements from upper-slope to lower-slope positions. The soil pH values did not significantly differ between landscape positions and were slightly acidic[49]. However, according to Horneck et al.[50], statistically significant differences were observed in soil pH between districts and rainfall contexts, ranging from strongly acidic (5.1) in Soro district to slightly alkaline (8.1) in Sekota district. Based on soil pH categories, the experimental soils with pH

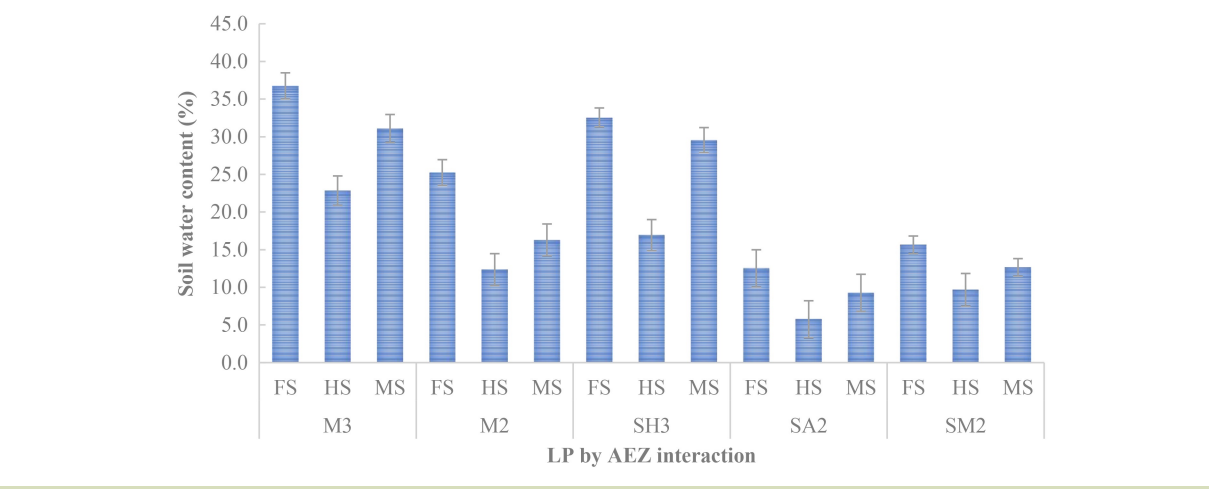

Fig. 2 Volumetric soil water content (%) in different agroecological zones (AEZ, as specified in Table 1) and landscape positions (LP).

Table 3 Soil chemical properties across districts and three landscape positions

Position	pH	Al	TC	TN	C:N	P	S	Zn	B
		cmol(+)·kg^{-1}	%			mg·kg^{-1}			
District									
Adaa	6.8	0.96	1.45	0.15	10.02	2.94	1.45	0.37	0.19
Ambo	6.5	1.50	1.67	0.19	8.88	2.92	1.98	1.21	0.06
Analemo	5.6	1.23	1.89	0.21	8.94	5.42	2.59	3.73	1.06
Boloso Sore	5.5	2.32	2.36	0.18	13.60	1.24	0.39	8.57	0.30
Bora	7	0.65	1.02	0.16	6.50	28.26	1.45	1.79	0.24
Doyogena	5.6	1.15	2.01	0.16	12.70	10.46	4.43	4.69	0.50
Gozamen	5.4	2.56	1.59	0.17	9.22	6.7	5.64	1.29	0.38
Lemo	5.6	1.68	2.47	0.24	10.40	4.01	4.68	6.46	0.56
Machakel	5.5	2.72	1.41	0.18	7.85	2.43	4.98	0.98	0.37
Sekota	8.1	1.08	0.77	0.08	9.33	9.69	3.19	0.91	0.43
Sokoru	5.4	1.85	1.34	0.15	8.32	0.1	0.9	0.55	0.07
Soro	5.1	2.70	1.74	0.17	10.01	2.21	4.13	0.53	0.31
Tehuledere	7.5	1.10	1.03	0.17	6.35	7.02	2.56	0.61	0.31
West Belesa	7.8	1.07	1.05	0.16	7.29	3.87	1.96	0.82	0.40
SE	0.04	0.03	0.04	0.003	0.18	0.84	0.25	0.18	0.02
Landscape									
Lower-slope	6.2	1.53	1.66	0.18	9.62	6.61	4.52	3.02	0.33
Mid-slope	6.3	1.64	1.55	0.17	9.15	6.54	4	2.13	0.4
Upper-slope	6.2	1.66	1.46	0.16	8.96	5.55	4.4	1.81	0.37
SE	0.02	0.02	0.02	0.002	0.07	0.52	0.15	0.11	0.01

ranges of 5.5–7.5 could be considered ideal for teff production. The soil organic carbon threshold for sustaining soil quality is widely suggested to be about 2%, below which deterioration may occur. According to Biernbaum[51], 11 of 14 districts hosting the experimental sites had TC contents below 2%, except for three districts within the medium range, including Lemo (2.47%), Boloso Sore (2.36%), and Doyogena (2.01%). The TC contents in the three landscape positions were in the low to medium range (1.46%–1.66%), with the lower-slope having higher TC content than the upper- and mid-slope positions. The total N content of the experimental soils is within the medium range of 0.15%–0.25%[52], with lower-slope and upper-slope landscape positions having higher and lower TN content, respectively. According to Hazelton and Murphy[49], the available P concentrations are low (< 10 mg·kg^{-1}) in all landscape positions and districts except for Bora, which has a high available P (28 mg·kg^{-1}). The three landscape positions had low soil S and B but sufficient Zn[50]. However, 9 of 14 districts had below 1.5 mg·kg^{-1} Zn, which is the sufficiency level of Zn for crop production[50]. Overall, the order of decreasing soil fertility was found to be lower-slope > mid-slope > upper-slope.

Soil water content is crucial during the growing stage of a crop due to its critical role in the growth and yield performance and its response to applied nutrients. According to soil moisture measurements, variations in soil moisture content were apparent over landscape positions and AEZ, where soil water content increased from the upper-slope to the lower-slope position, and higher volumetric soil water contents were recorded in high rainfall than in medium to low rainfall experimental sites (Fig. 2). Higher volumetric soil water contents were measured in M3, M2 and SH3 AEZs (Table 1) of high rainfall areas, which are characterized by tepid moist mid-highlands, subhumid mid-highlands and warm moist lowlands, with the highest volumetric soil water content of 36.8% at the lower-slope position (Fig. 2). However, the other AEZs lie in the low rainfall areas that are typified by warm semiarid lowlands and warm sub-moist lowlands, and the lowest soil water content of 5.8% was measured at the upper-slope position. Regardless of soil water content variability between landscape positions, lower soil water contents were measured in medium to low rainfall drought-prone areas, such as Sekota, Bora, Belesa, and Anlemo Districts, than in districts that receive high rainfall. Concerning soil types, higher soil water content measurements were recorded on Vertisol experimental sites, such as in Lemo, Ambo, Ejere, and Gonji Kolela, than on other soil types (Table 1).

3.2 Teff yield response to different nutrient sources in different landscape positions

The results of the combined analysis of the fixed effect of rainfall context, landscape position, nutrient source, and their interaction are presented in Table 4. Nutrient sources and landscape position significantly influenced the yield and yield-related traits of teff. Total aboveground biomass, grain yield, and straw yield significantly varied ($p < 0.05$ and $p < 0.001$) between rainfall contexts, landscape positions, and nutrient sources. Grain yield, total biomass, straw yield, and HI of teff were higher by 29%, 12.7%, 9.1%, and 18.2%, respectively, in high rainfall areas than in medium to low rainfall areas (Table 5). Grain yield, total biomass, straw yield, and harvest

Table 4 A significance level of the fixed effect of biomass, grain, and straw yields, and harvest index of teff as influenced by rainfall context, landscape position, fertilizer type, source, and their interaction

Effect	*F* value				*p* value			
	GY	TBY	SY	HI	GY	TBY	SY	HI
RF	18.4	3.7	1.45	4.7	< 0.001	0.056	0.229	0.030
LP	9.8	12.7	11.3	6.4	< 0.001	< 0.001	< 0.001	0.002
Fertilizer	119.7	100.2	71.9	0.6	< 0.001	< 0.001	< 0.001	0.842
RF×Fertilizer	10.8	4.3	2.4	1.1	< 0.001	< 0.001	0.008	0.327
LP×Fertilizer	0.5	0.7	0.8	1.7	0.960	0.833	0.675	0.033
RF×LP×Fertilizer	0.9	1.2	1.2	1.1	0.586	0.276	0.284	0.382

Note: RF, rainfall context; LP, landscape position; GY, grain yield; TBY, total biomass yield; SY, straw yield; and HI, harvest index.

Table 5 Effect of rainfall context, landscape position, and nutrient sources on grain yield, total biomass, straw yield, and harvest index of teff

Factor	Grain yield (kg·ha^{-1})	Biomass yield (kg·ha^{-1})	Straw yield (kg·ha^{-1})	Harvest index (%)
Rainfall context				
High rainfall	1530 ± 143	6320 ± 574	4810 ± 527	26 ± 2.8
Medium to low rainfall	1180 ± 145	5600 ± 591	4410 ± 541	22 ± 2.9
Landscape position				
Foot slope	1490 ± 143	6690 ± 584	5270 ± 535	26 ± 2.8
Mid-slope	1420 ± 145	6100 ± 577	4610 ± 528	25 ± 2.9
Hill slope	1160 ± 146	5090 ± 584	3940 ± 545	22 ± 2.9
Fertilizer rate and source				
All(B)	1460 ± 139	6350 ± 561	4890 ± 511	24.3 ± 2.8
All(C)	1440 ± 145	6330 ± 556	4900 ± 536	24.1 ± 2.9
All(I)	1470 ± 145	6270 ± 586	4800 ± 536	24.4 ± 2.9
All(B)-K	1400 ± 139	6080 ± 585	4690 ± 536	25.1 ± 2.8
All(B)-S	1390 ± 145	6070 ± 586	4680 ± 536	24.2 ± 2.9
All(B)-Zn	1460 ± 145	6360 ± 585	4910 ± 511	23.8 ± 2.9
NP only	1420 ± 139	6250 ± 556	4830 ± 511	24.5 ± 2.8
All(B)-B	1430 ± 145	6300 ± 586	4870 ± 511	24.1 ± 2.9
150% All(B)	1540 ± 140	6840 ± 561	5300 ± 512	24.5 ± 2.8
50% All(B)	1230 ± 140	5520 ± 561	4290 ± 515	24.1 ± 2.8
Control	674 ± 139	3190 ± 556	2520 ± 511	23.8 ± 2.8

Note: All(B) containing N, P, K, S, Zn and B nutrients in blended form; All(C) containing N, P, K, S, Zn and B in the compound form; All(I) containing N, P, K, S, B and Zn applied as individual forms.

index at lower-slope sites were greater by 28.7%, 31.5%, 33.7% and 18.0%, respectively, than at sites at upper-slopes (Table 5). At the mid-slope position, grain yield, total biomass, straw yield, and harvest index were higher by 22.6%, 19.8%, 17.0%, and 13.6%, respectively, compared to the measurements at the upper-slope positions (Table 5).

Based on the mixed model analysis, total aboveground biomass, grain yield, and straw yields of teff statistically significantly differed ($p < 0.05$ and $p < 0.001$) due to the interaction of rainfall context and fertilizer form (Table 4). In high rainfall areas, the highest teff total biomass yield of 7.46 t·ha^{-1} was recorded with 150% All(B), with total biomass yield increments of 27% and 148% compared to the total biomass yield of 5.87 t·ha^{-1} and 3.01 t·ha^{-1} obtained with 50% All(B) and the unfertilized control, respectively (Fig. 3(a)). In the medium to low rainfall areas, the highest total biomass yield of 6.21 t·ha^{-1} was recorded from 150% All(B) with an 84% increase compared to the lowest total biomass yield of 3.37 t·ha^{-1} obtained from the control treatment. Despite numerical variations, statistically significant differences were not observed between the fertilized treatments under both rainfall contexts. The result further showed significantly higher total biomass yields in high rainfall areas than in medium- to low rainfall areas for each fertilizer treatment (Fig. 3(a)). When averaged over the fertilized treatments, total biomass yield in high rainfall areas increased by 14% in contrast to medium- to low rainfall areas.

In high rainfall areas, the highest grain yield of 1.78 t·ha^{-1} was obtained with 150% All(B), which increased grain yield by 30% and 176% compared to 50% All(B) (1.37 t·ha^{-1}) and the control (646 kg·ha^{-1}), respectively (Fig. 3(b)). In medium to low rainfall areas, the highest grain yield of 1.29 t·ha^{-1} was attained with150% All(B), which increased grain yield by 18% and 84% compared to the grain yield obtained with 50% All(B) (1.09 t·ha^{-1}) and the control (702 kg·ha^{-1}) treatment, respectively (Fig. 3(b)). In both rainfall contexts, a significant

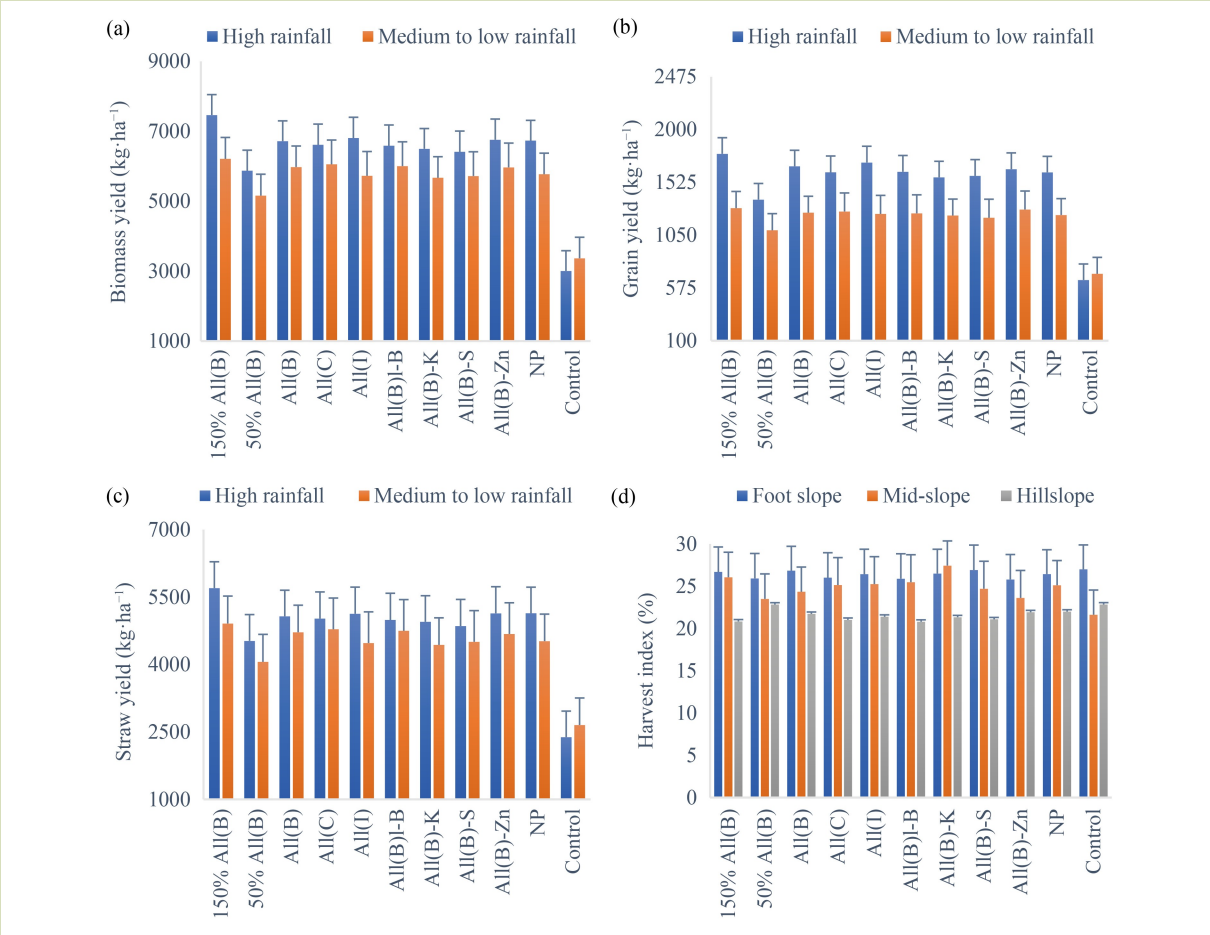

Fig. 3 Aboveground biomass (a), grain yield (b), and straw yield (c) as influenced by the interaction of rainfall context and nutrient form; and teff HI (d) as influenced by the interaction of landscape positions and nutrient forms.

difference was not observed in yield when comparing the application methods of nutrients, including blended, compound, and individual. The result also indicated that in each fertilizer treatment, the grain yield recorded from the high rainfall area was higher than the medium to low rainfall area (Fig. 3(b)). Averaged over the fertilized plots, teff grain yield in high rainfall areas increased by 31%, compared with medium to low rainfall areas. The highest (5.70 t·ha^{-1}) straw yield was with 150% All(B), which increased straw yield by 139% in comparison to the lowest straw yield of 2.38 t·ha^{-1} recorded from unfertilized control treatment in high rainfall. In addition, 150% All(B) increased yield by 25% compared to 50% All(B) (1.18 t·ha^{-1}). In the medium to low rainfall areas, the highest straw yield (4.91 t·ha^{-1}) was with 150% All(B), a yield by 85% more than the lowest straw yield of 2.65 t·ha^{-1} in the unfertilized control (Fig. 3(c)). In each fertilizer treatment, the results showed that teff had a significantly greater straw yield in the high rainfall region compared to the medium and low rainfall areas, with an average straw yield increase of 10% in high rainfall areas compared to medium to low rainfall areas.

The landscape position by nutrient source interaction was statistically significant ($p < 0.05$) for HI (Table 4). At upper-slope positions, the HI ranged between 21.6% with the control treatment and 27.4% in All(B)-B, resulting in a 27% HI increase (Fig. 3(d)). At the mid-slope position, the HI ranged from 20.8% in All(B)-B to 22.8% with the unfertilized control, resulting in a HI improvement of 10%. Despite numerical variations, significant differences were not observed between the fertilizer treatments in the HI at the lower-slope positions,

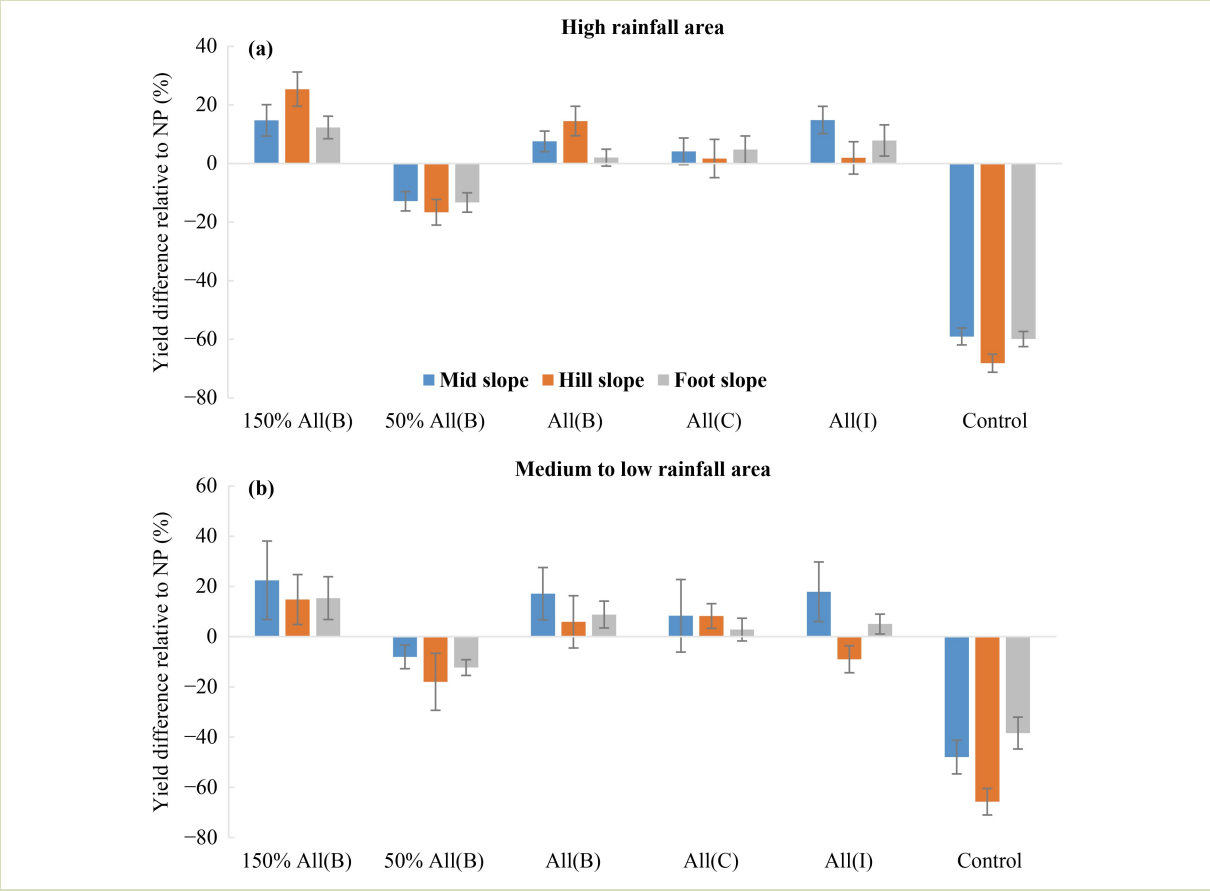

Fig. 4 Relative change in teff yield response to different nutrient forms and rates compared to NP fertilizer application in different landscape positions and rainfall contexts (high and medium to low rainfall areas). (a) High rainfall area; (b) medium to low rainfall areas.

which ranged from 25% with the control treatment to 27% in All(B)-B (Fig. 3(d)).

The change in grain yield response to the application of selected nutrients (150% All(B), 50% All(B), All(B), All(C) and All(I)) relative to NP application in high rainfall and medium to low rainfall teff-growing areas is presented in Fig. 4. The result revealed that the relative change in mean grain yield from NP had a positive yield response in all selected nutrient applications except for 50% All(B) and the control in both high and medium to low rainfall areas. In high rainfall areas, the significantly highest relative yield change ($p < 0.05$) was observed in 150% All(B) in all landscape positions, which increased 12%, 15% and 22% over the yield obtained from the application of NP only in the lower-, mid- and upper-slope landscape positions, respectively. Despite statistically non-significant differences in low rainfall areas, the highest relative yield change was observed in 150% All(B) across all landscape positions, with yield advantages of 15%, 22%, and 15% in the lower-, mid-, and upper-slope positions (Fig. 4).

To determine the effect of omitted nutrients, the yield response and relative contributions of N, P, S, K, Zn and B were computed using the grain yield obtained with All(B) and the corresponding omitted nutrients (K, S, Zn and B, or all four nutrients) (Fig. 5). The results showed that the omission of K, S and use of NP only had statistically significant differences ($p < 0.05$) in grain yields of teff compared to All(B). The average nutrient contribution rates (in decreasing order) for K, S, NP, B and Zn were 5.9%, 5.2%, 3.3%, 3% and 1.6%, respectively. Therefore, K was relatively the nutrient-limiting factor, followed by S and NP in high rainfall areas. However, in low-rainfall areas, despite a statistically non-significant difference between All(B) and the corresponding all-omitted nutrients,

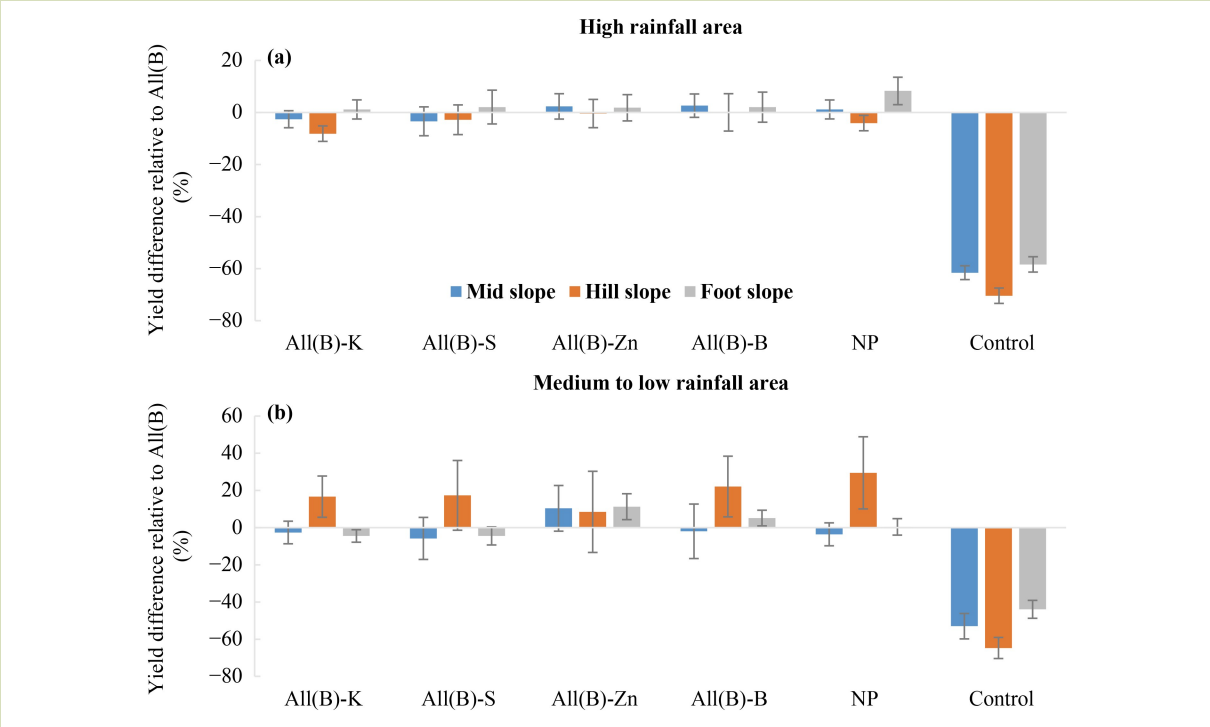

Fig. 5 The effect of omission of nutrients on teff yield relative to all nutrients applied in the blended form (All(B)) in high and medium to low rainfall areas and in different landscape positions. (a) High rainfall area; (b) medium to low rainfall area.

the nutrient contribution rates of S, K, and NP were relatively higher than those of other omitted nutrients that influenced yield (Fig. 5).

The cluster analysis (CA) grouped the trial sites into four clusters. The results of the CA showed that yield differences from the control treatment were significantly higher in high-potential experimental sites with fertilizer treatments than in low-potential experimental sites with fertilizer treatments (Fig. 6). Yield differences from the control treatment in low-potential districts were small compared to the control treatment due to the low efficiency of the applied nutrients (Fig. 6).

4 Discussion

4.1 Soil chemical properties as influenced by landscape position across districts

Variability in soil moisture and nutrient availability over landscape positions influences crop responses to nutrient applications. The soil analysis results revealed significant variations in soil chemical properties between districts and landscape strata. Soil tests for major soil chemical properties, such as total soil carbon (OC) and macro- and micronutrients, were low in most trial sites and landscape positions. Several researchers have shown 2% soil OC as the critical concentration for structural stability[53], water holding capacity[54,55], cation exchange capacity[56], and soil aggregate stability[57]. Studies conducted in sub-Saharan Africa reported high soil OC to be closely associated with high soil fertility and yield[19]. Musinguzi et al.[54] reported that low fertility fields (< 1.2% OC) resulted in the lowest response to N-application, while fields with > 1.2% SOC registered the highest agronomic efficiency and grain yield. However, models predicted 1.9% to 2.2% SOC as the critical concentration range for high yields[54]. Accordingly, most of the experimental sites were characterized by total C contents of < 1.9% and could be suboptimal for crop production. Except for Sekota, the N contents of all other districts were within medium ranges of 0.15% to 0.24%, with a C:N ratio of 6.35–13.6, i.e., an ideal range of C:N ratio to

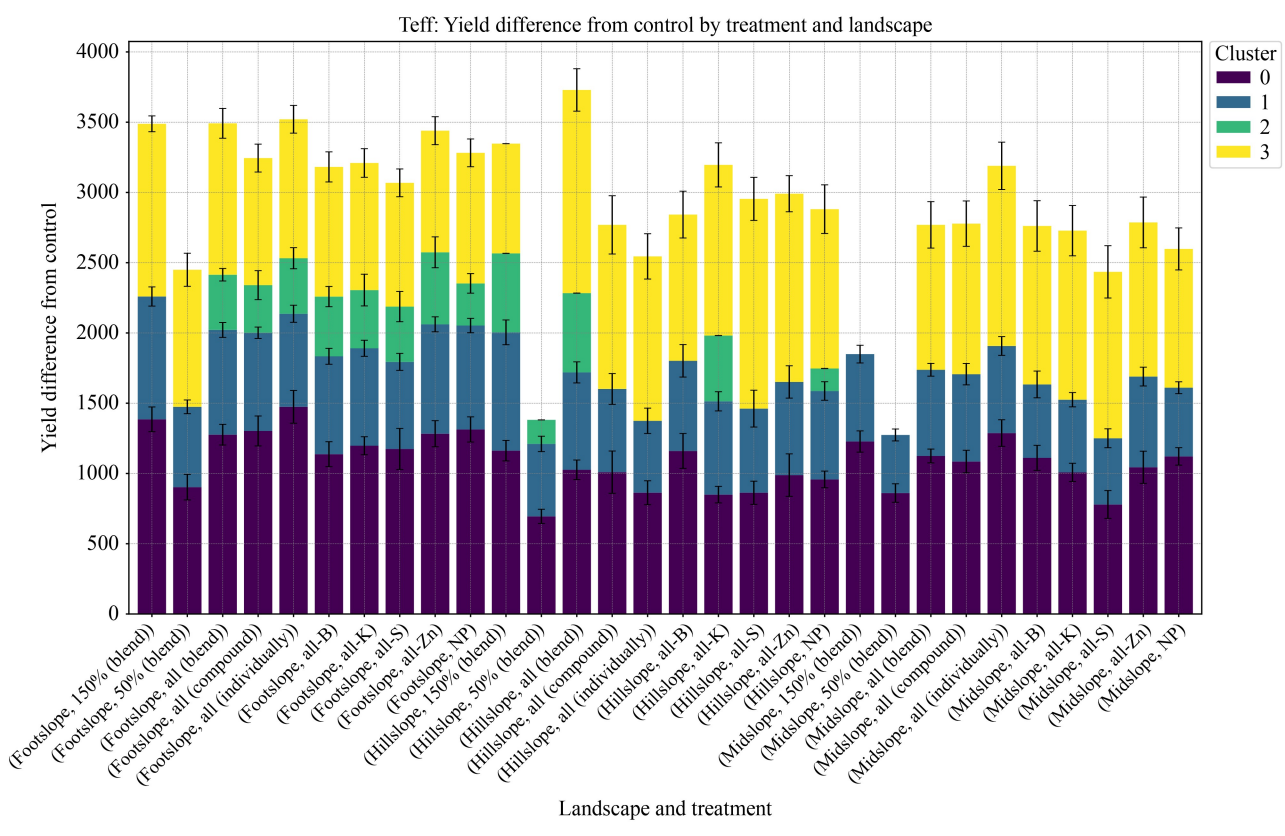

Fig. 6 Yield differences between the landscape position by nutrient forms and the control treatment. Error bars represent ± SE.

produce field crops. However, the other macro- and micronutrients, including available P, S, Zn and B, were below the critical range in most experimental sites. Available soil Olsen P below 10 mg·kg^{-1} or below 15 mg·kg^{-1} Bray P is categorized below the sufficiency range. Similarly, soil Zn below 1.5 mg·kg^{-1} and soil B below 0.5 mg·kg^{-1} are below the critical ranges to produce most field crops. A Zn soil test above 1.5 mg·kg^{-1} and a B soil test above 0.5 mg·kg^{-1} using the DTPA extraction method are sufficient for most crops[50]. Low levels of B may limit plant growth, while high concentrations can be toxic. Soil nutrient concentrations increased from upper- to lower-slope positions. Yao et al.[58] indicated that soil nutrients in sloping farmlands can be lost through runoff, leaching, and sediment transport, where the nutrient losses from sloping agricultural soils could lead to a significant decline in soil productivity and non-point source pollution. Previous research findings indicated that soil organic carbon and nutrients significantly increased from upper- to lower-slope position[12,59].

The variability in the amount and distribution of rainfall during a cropping season causes a significant effect on crop yields[60], where the terminal moisture stress during the grain-filling stage of the crop could impact crop yield. This might be due to the exposure of the crop to water scarcity during its grain-filling and maturity stages in drought-prone areas, in contrast to agricultural areas with adequate and well-distributed rainfall, where soil moisture may be available until the later crop growth period. Considerable soil water content variations were also observed between soil types, with higher soil water contents on Vertisols than on other soil types owing to the higher water-holding capacity of Vertisols[11].

The purpose of measuring volumetric soil water content was to verify the variability in soil water content over agroecological zones and landscape positions. Higher soil water contents ranging from 15.7% to 36.8% were measured at the lower-slope positions compared to 12.7%–31.1% at the mid-slope and 5.8%–22.8% at the upper-slope positions across AEZs

(Fig. 2), consistent with the patterns observed in other soil properties of this research findings (Table 3). Previous studies also reported lower bulk density and higher soil contents of up to 34.6% at the lower landscape positions [12], higher concentrations of soil OC, N and available P[11] at the lower-slope than at the mid- and upper-slope landscape positions, indicating a decrease in bulk density towards 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[12]. Also, other studies have reported that soil water content is positively correlated with soil organic matter content, which is a key input for storing water and nutrients in the soil[55,61,62]. While variations in water content between landscape positions were observed, lower soil water contents were measured in drought-prone areas, such as Bora, characterized by a low-lying topographic position. The soil water content was higher in the highland areas than in the lowland areas, which might be due to the cooler temperature and the availability of adequate and well-distributed rainfall during the crop developmental stages in the cropping season. This corresponds well with the variation in the rainfall amounts in different agroecological zones included in this research.

4.2 Teff yield response to different nutrient sources under three landscape positions

This research showed that the main effects of rainfall context, landscape position, nutrient source, and rate significantly affected grain yield, total aboveground biomass, and straw yield of teff (Table 4). Variability in crop response to nutrient application can arise from soil characteristics, nutrient availability, crop varieties, and environmental conditions[63,64]. Nutrient-holding capacities, soil pH, organic matter, and nutrient content varied with soil types (Table 3), which could influence nutrient availability and uptake by the plant. Different crop cultivars have varying nutrient requirements and efficiencies in utilizing available nutrients. The amount and distribution of seasonal rainfall are also important for rainfed agriculture. In areas with a high rainfall area, crops tended to have higher grain and total biomass yields than in medium to low rainfall areas. Though teff is a relatively drought-tolerant crop, it still requires a certain amount of water for optimal growth and development. In high rainfall areas, the soil moisture content is generally adequate to meet the water needs of the teff plants throughout the growing season, thus increasing photosynthesis and nutrient absorption, leading to robust growth and higher yields. Generally, teff yield variations among the study sites and agroecological zones could be mainly due to climatic and edaphic factors. Mihretie et al.[65] also reported that teff yields were highly variable within and across different agroecosystems.

The agricultural landscapes in Ethiopia consist of diverse topography, including high-elevation upper-slopes, mid-slopes, and lower-slopes, which are often found in proximity. Due to these topographical variations, different agronomic management practices and fertilizer rates are necessary to cultivate these areas effectively[7]. Field assessments revealed that farmers usually apply more fertilizer to upper-slopes and less to mid- and lower-slope positions[7,21], considering that upper-slopes are more nutrient-depleted and mid- and lower-slope positions are better in soil nutrient status than upper-slopes. However, Desta et al.[8] reported that landscape-specific fertilizer applications guided by crop-specific decision rules resulted in higher teff yield improvements of 56% and 6.5% at the lower-slope and mid-slope positions, respectively. Similarly, the current research indicated noticeable variations in all measured parameters in different landscape positions. The lower-slopes yielded higher total biomass, grain, and straw yields, and harvest index than sites in the upper-slopes by 20% (1.01 $t \cdot ha^{-1}$), 29 % (333 $kg \cdot ha^{-1}$), 17% (670 $kg \cdot ha^{-1}$) and 1%, respectively. This might be due to the spatial variations in soil moisture content and nutrient availability, resulting in yield variability across the landscape positions. Available soil nutrients were slightly higher at the lower-slope than at the upper- and mid-slope positions (Table 3), indicating that soils at lower-slopes are often richer in organic matter and nutrients due to the accumulation of organic debris and leaching of nutrients from higher elevations. This creates favorable conditions for plant growth and increased yields. In contrast, upper slopes, being situated at the highest positions, are prone to water erosion and runoff, resulting in the loss of topsoil and nutrients. Recent studies also reported similar results, where higher teff and wheat yields[11] and maize yield[66] were observed at the lower-slope than at the upper-slope position. Amare et al.[66] demonstrated that higher mean yields were found at deposition zones, followed by the middle zones, while the lowest value was obtained from the loss zones. Landscape position also affected crop yield through its impact on the availability of adequate soil moisture[12]. Thelemann et al.[30] reported that grain and stover yields of maize were lowest in

flat and depositional areas that retain water for longer periods and highest in well-drained upper-slope positions. Previous studies also showed that variations in topo-sequence position can affect soil properties and hydrological conditions, leading to differences in biomass and grain yield[67,68].

The nutrient source by rainfall context interaction was significant for grain yield, total biomass, and straw yield of teff. This interaction emphasizes the need for site-specific nutrient management. Applying 150% All(B) resulted in significant teff grain yield and total biomass improvements under the high rainfall context. Specifically, substantial improvements of 175% and 148% were recorded in grain and biomass yield, respectively, compared to the unfertilized control. However, biomass and grain yield increments were comparatively lower in medium to low rainfall areas than in high rainfall areas. Applying 150% All(B) increased total biomass and grain yield by 84% each compared to the unfertilized control, implying a higher fertilizer response in high rainfall areas than in low-rainfall areas. Adequate and reliable water availability in high rainfall areas assists in the dissolution and movement of fertilizer into the soil, ensuring that the nutrients are readily accessible to plants, which could lead to higher yields. This result is consistent with that of Balemi et al.[69], who reported that the response to nutrient application was significantly higher in high rainfall areas than in low rainfall/moisture-stress areas.

Further, high rainfall may cause nitrate N leaching and decrease N recovery, thus increasing the amount of fertilizer can supplement the loss of nutrients and reduce the adverse impact of heavy rainfall on crop yield. Li et al.[70] reported that water supply and nutrient efficiency are closely related; balanced application of nutrients and determination of their types, rates, and methods are crucial. The recommended fertilizer rate may increase towards the higher end of the range to achieve higher yield in high rainfall areas, because increased rainfall can lead to lower soil N supply, possibly due to leaching[71]. In most cereal crops, better growth, greater tillering capacity, and higher yields of improved cultivars are achieved with greater amounts of fertilizer, particularly N and P, than are required for local cultivars that have lower potential yields[72,73]. Tailoring fertilizer applications to meet the specific needs of different cultivars leads to improved resource management and enhanced crop productivity.

The interaction of landscape position with the fertilizer treatments showed statistically significant differences in the harvest index of teff (Table 4 and Fig. 3(d)). The highest HI of teff was obtained at the lower-slope position compared to the upper-slope and mid-slope positions. At the upper-slope position, applying all nutrients with K omitted gave the highest harvest index, and the unfertilized control plot gave the lowest harvest index; however, at the lower- and mid-slope positions, the highest HI was observed in the unfertilized plot. The lowest HI in the highest fertilized plots might be due to the highest biomass production (148% for 150% All(B) and 84% for 50% All(B) fertilized plots compared to unfertilized ones). Fertilization can stimulate vegetative growth in teff, leading to an increase in overall biomass production. However, when excessive vegetative growth occurs, the allocation of resources to the reproductive organs (such as grain) decreases, resulting in lower HI values. This indicates that the grain yield did not increase proportionally to the overall increase in biomass in fertilized plots in the lower slope positions, as teff plants are susceptible to lodging with higher N application rates. The harvest index of teff is lower than that of other small grain cereal crops due to its higher straw yield compared to its grain yield. In most cases, when the vegetative growth of teff is high, lodging occurs, which could tremendously decrease the grain yield of teff. This is also evident when high N fertilizer is applied, and the soil fertility status is high. Fan et al.[74] reported that the increase in HI for different crops was significantly correlated with grain yield.

While the fertilizer treatment by landscape position interaction was not statistically significant, higher teff grain and biomass yields were obtained at the lower-slope than at the mid- and upper-slope positions due to the interaction of the two factors, possibly due to the higher soil organic carbon and water content at the lower landscape positions. In contrast, Desta et al.[21] found a significant interaction effect of fertilizer application and landscape position on sorghum yield. They further explained that yield response across different landscape positions and locations highlights the importance of conducting location-specific fertilizer experiments. Capturing the diverse environmental domains in experimental areas may enable the development of fertilizer recommendations that consider the variability in yield potential associated with specific landscape positions. This approach may ensure that fertilizer application practices can be tailored to the unique characteristics of each location and optimize crop productivity.

The findings of this study further demonstrated the effects of

K, S, Zn and B nutrients on aboveground biomass, grain, and straw yields of teff. The interactions and synergistic effects of nutrients play major roles in plant metabolism and omission of one nutrient may disrupt these interactions and lead to imbalances and reduced growth and yield[75]. Despite significant teff yield responses to the different fertilizer treatments, the application of K, S, Zn and B did not result in significant yield differences compared to NP only. These results are consistent with those of Desta et al.[21] on sorghum and Balemi et al.[69] on maize, Bazie et al.[76], in their study on wheat and teff, found no significant yield benefit from applying K, S, Zn and B compared to NP only. This indicates that soils in the study areas, both in high and low rainfall areas, have adequate K, S, Zn and B content for teff production. In this study, the highest yield was attained from the application of 150% All(B), where yield increased with the increase in the rates of nutrients from 0% to 150% in both high and low rainfall areas. However, the yield increase was not because of K, S, Zn and B applications but rather due to the increase in N and P rates, which is consistent with the findings of Lollato et al.[77]. Yield was low, particularly in low rainfall areas, across the treatments, suggesting lower benefits of applying the major nutrients (N and P), let alone S or Zn, when moisture is limiting. The application of All(B)-K, All(B)-S, and NP only resulted in statistically significant differences in teff grain yields compared to All(B) in high rainfall sites. Yield penalties of 5.9%, 5.2%, 1.6% and 3% under high rainfall and 2%, 3.6%, –2.3% and 0.5% under medium to low rainfall areas occurred due to the omission of K, S, Zn and B, respectively, relative to All(B), indicating that the relative yield penalties were higher in high than in low rainfall areas. Even the very low yield increment relative to the negative yield was recorded in low rainfall areas, implying that the application of these nutrients had no significant yield advantage over NP only. Nziguheba et al.[78] reported that application of macronutrients (N, P, K, S, Ca and Mg) and micronutrients (B, Mn, Cu, Co and Mo), the omission of P, Ca, N and Mg significantly depressed rice shoot and root dry biomass. The recent finding of Bazie et al.[76] also demonstrated that N and P are the most yield-limiting nutrients for teff and bread wheat. Hence, this research confirms that N and P are the primary yield-limiting nutrients for teff productivity in Ethiopia.

Cluster analysis (CA) helps identify subfields within the field that have similar characteristics internally. The CA indicated that the similarities in trial sites and environments in the same group are more than those in other groups. In this study, the results of the CA revealed that sites located in different landscape positions were grouped into three clusters under high rainfall environments based on the extent of their response to fertilizer applications (Fig. 6). Conversely, the lower responsive sites were clustered into one group only under a low rainfall area for teff yield response to different fertilizer treatments in different landscape positions, with several trial sites within each landscape position. The results of the CA showed that trial sites in the high rainfall area and lower landscape positions are more suitable for teff production than the trial sites under the low rainfall area and upper landscape positions. Minh et al.[79] also used CA to identify and group critical parameters affecting the soil environment for crops and characterized three areas suitable for developing perennial crops. The spatial variability had a greater influence on the variability in the teff yield response to different fertilizer treatments. This could be due to differences in soil nutrients and soil moisture status among landscape positions and various sites within each landscape position. Recent studies also reported the impact of spatial heterogeneity on wheat[24] and sorghum[21] yield response variability to the various fertilizer treatments.

5 Conclusions

Understanding the principles of soil fertility management is central to efficient nutrient use, crop production, and environmental protection. This research revealed that rainfall context, landscape position, fertilizer rate, and source significantly impacted the growth and yield of teff. The amount and distribution of rainfall during the growing season is a major factor in determining teff yield, where areas receiving adequate and well-distributed rainfall generally produce higher total biomass and grain yield. Higher rainfall areas tended to have a greater response to fertilizer application than low rainfall areas, as soil water is a critical factor affecting the absorption of nutrients in plants through roots. The harvest index of teff is influenced by the interaction of landscape position, fertilizer rate, and source, with lower-slope positions generally resulting in the highest harvest index. The landscape position, specifically the lower-slope, gave a higher yield compared to the yields at mid-and upper-slope landscape positions, where the fertility of steep slope lands, particularly upper-slopes, is depleted in soil organic matter and nutrient reserves. The response of such soils to nutrient application is low, which requires the restoration of soil fertility through the adoption of an integrated soil-crop system for improved crop-

nutrient response and yield. Significant yield differences were not observed between the three nutrient application forms, i.e., all nutrients applied in blended, individual, and compound forms. The omission of K, S, Zn and B separately or together with NP did not result in significant yield reduction compared to NP fertilizer alone, despite the slight occurrence of yield penalties when certain nutrients are omitted under high rainfall conditions. Overall, applying different nutrients in different forms, their omission, and variation in rates had varying effects on the growth and yield of teff. This research highlights the importance of tailored fertilizer recommendations based on location-specific factors to optimize teff productivity as well as nutrient use efficiency. The constraints to crop production vary considerably even within a site; hence, addressing yield-limiting nutrients and increasing soil organic matter content will improve the soil moisture content and crop response to fertilizer applications. Hence, for sustainable crop production intensification in smallholder farming systems, developing soil and crop management strategies is needed to improve the efficiency of fertilizer use and other inputs, recognizing the site-specific nutrient response patterns at various spatial scales. Further research is suggested on the optimization of nitrogen and phosphorus rates, including other important nutrients, to enhance the productivity of grain and straw yield and quality of teff at different landscape strata and moisture contexts.

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Compliance with ethics guidelines

Getachew Agegnehu, Gizaw Desta, Gizachew Legesse, Tadele Amare, Birhanu Agumas, Almaz Meseret, Erkihun Alemu, Zerfu Bazie, Abate Abera, Samuel Adissie, Fayisa Bulo, Mulugeta Demiss, Workat Sebnie, Hirut Birhanu, Girma Chala, Beamlaku Alemayehu, Ewunetie Melak, Mesfin Hundessa, Baye Ayalew, Tulu Degefu, Tesfaye Fayisa, Rebbie Harawa, and Tilahun Amede declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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