Influence of landscape position on sorghum yield response to different nutrient sources and soil properties in the semi-arid tropical environment

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ABSTRACT

Understanding the response of crops to nutrient applications in undulating landscapes is imperative to improve nutrient use efficiency and crop yield. This study aimed to identify sorghum yield-limiting nutrients and characterize soil properties targeting landscape positions. The field experiments were conducted across 52 sites in four districts, covering three distinct landscape positions during the 2020 and 2022 cropping seasons. The treatments were All-blended, All- compound, All- individual, 150% of All- blended, All- blended-K, All- blended-S, All-blended-Zn, All -blended-B, recommended NP, 50% of All -blended, and control (no fertilizer). Treatment sequencing was randomized using a complete block design under foot slope (FS), mid-slope (MS), and hillslope (HS) positions. Results revealed that landscape position significantly affected the growth and yield of sorghum. Significantly higher yields were obtained from foot slopes than mid-slope and hillslope positions. Yield response to the application of nutrients significantly decreased with increasing slope. Overall, yield among all landscape positions was in the decreasing order of FS>MS>HS. The application of nutrients at different rates significantly improved sorghum total biomass and grain yield. Raising the all-blended treatment rate by 50% increased sorghum yield by 44% and 147% over the application of 50% of all nutrients and the unfertilized control treatment, respectively. Statistically significant yield differences were not observed among blended, compound, and separate applications of nutrients. The omission of K, S, Zn, and B did not show a significant variation in yield over the recommended NP fertilizer. The results of soil analysis results revealed that N and P are the most commonly deficient nutrients in sorghum-growing areas. The mean average volumetric soil moisture content ranged from 5.9-28.7% across landscape positions, with the highest at the foot slope and lowest at the hillslope position. Further research is suggested to determine economically optimum N and P rates across the three landscape positions.

Keywords: Blended fertilizer, Landscape position, Nutrient omission, Semi-arid, Soil properties, Sorghum yield

1. Introduction

In Ethiopia, agriculture remains a fundamental component of people's livelihoods. However, soil fertility depletion and nutrient mining significantly hinder achieving improved and sustainable agricultural production [1, 2]. Consistent nutrient mining over several years on farms in the undulating landscape of Ethiopia has resulted in severely eroded and degraded soils that produce 40% less than the global average [3]. These issues contribute to widespread soil degradation and fertility depletion, which are primary biophysical factors driving the declining per-capita food production and natural resource conservation in sub-Saharan Africa [4, 5]. Despite efforts to increase fertilizer supply and usage in the country, low crop response to fertilizers has been a major concern. Addressing this challenge requires effectively matching fertilizer types to specific soil fertility problems, which relies on identifying limiting factors, characterizing sites, and developing appropriate recommendations. Identifying nutrient management zones necessitates collecting and interpreting spatial data, including yield data, elevation, soil nutrient maps, and farmers' classification criteria. In response to these challenges, governmental and non-governmental research and development organizations in Ethiopia actively test and develop site-specific balanced fertilizer recommendations. These efforts aim to enhance crops' yield and quality, thus contributing to improved agricultural productivity and sustainability in the country.

Sorghum (*Sorghum bicolor* L. Moench) is among the global top carbohydrate-rich and the greatest drought-tolerant crops, i.e., widely used as food, forage, fodder, and biofuel [6]. It is also the fourth major cereal crop used as a staple crop in the semi-arid regions of Ethiopia after teff, maize, and wheat [7]. The crop shows an increasing trend in area coverage and production, with about 1.68 million ha and about 4.52 million tons produced in the main crop season, respectively [7]. The crop shares about 12.94% of the total cultivated area and contributes about 13.22% to the total crop production. However, despite the considerable potential to increase sorghum production, its average yield is still about 2.69 t ha^{-1}. This is mainly attributed to the prevailing rainfall variability, poor soil fertility, and crop management practices [8]. Farmers have been adopting early maturing sorghum varieties instead of long ones because of the variability in the onset and cessation of the main rainy season associated with climate change. Sorghum production could be expanded to drought-prone (moisture deficit) areas as the crop has the remarkable potential to grow under hostile environments consuming minimum input and crop management. The crop can be grown with fewer inputs under rainfed conditions because of its hardiness and will potentially contribute to food security as it has high yield potential [6]. Despite its natural adaption to resource-poor and stressful environments, increasing the yield potential of sorghum under more favorable conditions holds promise. Low sorghum yields are attributed to the soil, climate, and topographic factors [8].

Understanding the influence of landscape position on soil physicochemical properties is vital for improving soil and agricultural productivity and ensuring environmental sustainability [9-11]. Topographic gradient and land use types are key factors that affect soil property variability [10, 11] Sorghum yield response to fertilizer application is strongly linked to the spatial variation along landscape positions and varied over locations. Significant variations were observed in crop fertilizer response with topo-sequence due to a significant decrease in soil organic carbon, clay content, and soil water content [8, 12, 13]. The crop-fertilizer response at foot slopes was significantly higher compared to mid-slope and hillslope positions, where fields at foot slopes exhibited relatively homogeneous responses [8]. In Ethiopia, fertilizer trials were conducted for the last half a century on research stations and a few selected testing sites, with limited effort to extrapolate the results to a wider range of environments. This could be one of the reasons for the yield variation in crops in the different areas as soil properties are variable and change rapidly.

Despite the consistent increase in the adoption of inorganic fertilizers in Ethiopia, application rates are still generally considered agronomically suboptimal. There are no site-specific balanced fertilizer recommendations for increased yield and quality of crops. There is limited information on how landscape positions could be used for refining fertilizer recommendations. In this study, sorghum was used as a test crop to understand the factors affecting the crop response to different nutrient sources under different landscape positions. Generally, research information about the effects of landscape position variation in crop yield response to different fertilizer sources is inadequate in Ethiopia. The research aimed to identify limiting nutrients and develop and transfer soil fertility technologies that improve nutrient use efficiency in alignment with the 4Rs of Nutrient Stewardship: right source, right time, right rate, and right place. Multiple on-farm fertilizer trials were conducted to test the hypothesis that applying different nutrient sources would improve the growth and yield of sorghum under different landscape positions. The major objectives of this study were, therefore, to 1) investigate the effect of landscape variability on sorghum yield response to different nutrient sources; 2) evaluate the main and interaction effect of nutrient sources, landscape position on sorghum yield and soil properties; and 3) identify variations in soil nutrient status and yield-limiting nutrients (N, P, K, S, Zn, and B) for sorghum production.

2. Materials and methods

2.1. Description of trial Sites

On-farm nutrient omission trials were conducted in the 2020 and 2022 cropping seasons under different landscape positions (hillslope, mid-slope, and foot slope positions) and soil types in four representative sorghum-producing districts of Kewet in the North Shewa zone, Sekota in the Waghimra zone, Tehuledere in the South Wollo zone, and West Belessa in the central Gondar zone of the Amhara region, Ethiopia (Figure 1 and Table 1). While landscape position is a composite feature representing slope, slope shape, and altitudinal differences, for simplicity, we used slope gradient and altitudinal differences as criteria to classify and define topographical zones or landscape positions. Thus, as indicated in Figure 2, landscape positions were divided based on the topographic zone in the topo-sequence, with slope ranges of 0-5%, 5-15%, and 15-30%, respectively as foot, mid-, and hillslope positions (Amede et al., 2020). Variations in rainfall, minimum and maximum temperatures, soil types, and agroecological zones were observed in all on-farm trial sites of the selected districts (Table 1). The average range of annual rainfall and the maximum and minimum air temperatures of sorghum growing locations are between 929 mm and 1012 mm, 30-31 °C and 14.1-15.3 °C, respectively. Tepid moist mid-highlands are the major agroecological zones of the trial locations, while Cambisols and Regosols are the dominant soil types.

The geographical locations and agroecological zones of all the study sites are summarized in Table 1. Kewet and Tehuledere districts are found in a Tepid moist mid-highlands (M3) agroecological zone, and West Belesa and Sekota are in Warm semi-arid lowlands (SA2). Monomodal and bimodal rainfall patterns with varying rainfall amounts, intensity, and duration characterize the selected sites. Kewet, West Belesa, and Tehuledere districts have bimodal rainfall patterns with low rainfall regimes. The highest rainfall usually occurs from June to September. The average annual rainfall and maximum and minimum air temperatures of selected study sites in each district are indicated in Table 1. The dominant soil types on the study sites are Cambisols, Regosols, Xerosols, Solonchaks, and Leptosols, where Cambisols cover 15.3% of the land area in Ethiopia. These

2.2. Treatments and experimental design

Nutrient omission field trials were conducted on 52 sites in the 2020 and 2022 cropping seasons using different sources and formulations of fertilizers, including nitrogen (N) and phosphorus (P), and with or without sulfur (S), potassium (K), zinc (Zn), and boron (B). The basis for formulating these fertilizers was an analysis of data collected under the Ethiopian Soil Information System (EthioSIS) project which identified K, S, Zn, and B as deficient nutrients in Ethiopian soils [14]. The fertilizers were blended at the Debre Zeit Agricultural Research Centre, following the International Fertilizer Development Center (IFDC) guidelines. Fertilizers containing different nutrient sources were mixed in a small cement mixer per treatment and blends were divided into quantities appropriate for individual plots. Nutrient rates used for the fertilizer treatments were according to research recommendations for the different crops and rainfall regimes. Nutrient rates agreed for the national fertilizer harmonization initiative were adopted. Land preparation was done according to the requirements of the test crop. The fertilizer sources 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 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 35-45 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 sorghum plants.

The experiment included 11 treatments (Table 2) arranged in a randomized complete block design, with two to three replications at each landscape position based on the availability of an adequate experimental field. Where the experimental plot was not adequate farmers were considered as replications. A plot size of 3 m by 4.5 m (13.5 m^2) was used for each treatment and the distances between blocks and plots were 1.5 m and 1 m, respectively. The distance between the experimental plots and borders on all 4 sides was 1 m. The treatments were applied following the appropriate experimental procedures. The inter-row and intra-row plant spacing of 75 cm and 15 cm, respectively was used to maintain the recommended plant population per hectare. Sowing was done in Kewet from the third week to the end of July, West Belessa from the end of June to the first week of July, Tehuledere in the third week of July, and Sekota at the first week of August. Sorghum varieties used were Melkam in Kewet and West Belessa, Miskir in Sekota, and Girana-1 in Tehuledere. Other agronomic practices were applied uniformly for all plots during the crop growth period according to the research-recommended practices for the crop. Herbicides were used to control broad-leaved and grass weeds and other farm operations were conducted using manual labor. Harvesting was done in the second week of November in Kewet, West Belesa, and Tehuledere, and the last week of November in Sekota.

2.3. Data collection

Representative soil samples were collected randomly before planting at two depths (0-20 and 20-60 cm) in the 2020/21 cropping season from each experimental site, targeting three distinctly identified landscape (hillslope, mid-slope, and foot slope) positions, following the random soil sampling procedure. Ten samples were collected from each trial plot to make one composite soil 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, soil organic carbon, total nitrogen and sulfur, available phosphorus, exchangeable aluminum, zinc, and boron. The pH of the soil was measured using the pH-water method by making a soil-to-water suspension of 1: 2.0 ratio and was measured using a pH meter. The total soil nitrogen and carbon were determined by the combustion method [15], an analytical method that determines quantitatively the total amount of nitrogen and carbon in soil using an instrument that utilizes a combustion system with an induction furnace coupled with a thermal conductivity detector (TCD) system and an IR detector system. Soil P, S, Zn, B, and Al were determined using the Mehlich 3 soil test extraction method [16, 17].

The aim of measuring soil water content and root depth was mainly to verify whether soil moisture content and rooting depth of the trial crops vary across landscape positions. TDR 300 portable soil moisture probe was used to measure soil moisture content, using a 20 cm rod size. Soil moisture content was measured from the three landscape positions: hillslope, mid-slope, and foot slope. Measurements of soil water content were taken at the beginning of September and October in the 2022 cropping season. Agronomic data were collected on yield and some yield components of sorghum. The physiological maturity was considered for harvesting, i.e., when the seed became hard and difficult to dent with a fingernail or if the sorghum's panicle or flower part became more compact and drooped downwards.

The plot was manually harvested at maturity to measure the total biomass and grain yield of sorghum. After threshing, the grains were cleaned and weighed, and the moisture content was measured. Grain yield (adjusted to a moisture content of 12.5 %), total biomass, and straw yield of sorghum recorded on a plot basis were converted to kg ha^{-1} for statistical analysis.

2.4. Statistical analysis

First, the 2020 and 2022 data were cleaned and combined into a dataset before performing statistical analysis. A homogeneity of variance test was conducted to check the normality of agronomic data before running the analysis of variance. The data were subjected to statistical analysis following a Proc mixed model using the SAS statistical package (SAS/STAT Version 9.4):

$$Y = \mu + LS + Nut + LS * Nut + Loc + \varepsilon$$

where Y is measured value, μ is the grand mean, LS is the landscape position, Nut is a nutrient type and source, Loc is the district in which the experiment is conducted and ε is the error term. Location is a random component in the model.

Before choosing a specific model, the fit of the models was assessed using Akaike's Information Criterion (AIC) and Bayesian Information Criterion (BIC). The model was ultimately selected as it had lowered AIC and BIC values compared to the other models. This is 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 in favor of the more complex model, while differences greater than 10 provide strong evidence favoring the more complex model. Therefore, the chosen 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 insight into how much the total variation in the outcome is valued by the location. Significance for the variations in yield with fixed effects was considered when $p \leq 0.05$.

The Tukey-Cramer method was employed to adjust the P values for comparing least-square means. Statistical inference was based on least square estimates and their 95% confidence intervals (CIs). The use of the 95% CI served as a cautious test for the hypothesis and provided a measure of uncertainty for sample statistics [18, 19]. 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. In addition, percent yield differences of sorghum were computed in two ways: First, sorghum yield from different forms of fertilizers (blended, individual, and compound) and fertilizer rates (150 All (B), 50% All (B) and control) were compared relative to the yield from NP. Second, yield from nutrient omitted treatments (All(B)-K, All(B)-S, All (B)-Zn All(B)-B) and other treatments (NP and the control) were compared relative to the yield from All (B).

Moreover, partial budget, dominance, and marginal analyses were performed to investigate the economic feasibility of the different fertilizer treatments. The average yield was adjusted downwards by 10% to reflect the difference between the experimental yield and the expected yield of farmers from the same treatment. Because experimental yields from on-farm experiments under representative conditions are often higher than the yields that farmers could expect using the same treatments [20]. The average market prices of maize grain and fertilizers were used for economic analysis.

3. Results

3.1. Soil properties across districts and landscape positions

The soil analysis results for selected chemical properties under different landscape positions revealed that the soil reaction (pH) is moderately alkaline across experimental locations and landscape positions (Table 3). The total soil carbon (TC) is in the low range, while the total nitrogen (TN) content over the districts is in the medium and high categories [21]. The soil's total C and N contents at the foot slope position were higher by 18.3% and 14.3% than at the mid-slope position and 33.3% and 23.6 at the hillslope position, respectively (Table 3). This is because of soil organic matter and nitrogen deposition from the upper slopes and their subsequent accumulation and decomposition at the foot slope position [22]. The available soil P contents of the three districts and at the mid-slope and hillslope positions were below the critical levels which are rated low [23], except for the available soil P contents of 19.87 mg kg^{-1} in the Kewet district and 13.89 mg kg^{-1} at the foot slope position. The highest available soil P content (13.89 mg kg^{-1}) was recorded at the foot slope position which was greater by 5.6% and 245% at the foot slope than at the mid-slope and hillslope positions, respectively. The lowest soil P concentration of 4.02 mg kg^{-1} was observed at the hillslope positions. The total S contents of 1.89-3.86 mg kg^{-1} and 2.79-3.33 mg kg^{-1} of the experimental soils were rated in the sufficiency ranges over districts and landscape positions, respectively [21]. The soil Zn and B concentrations are marginal to adequate and marginal, respectively (Singh, 1998). Significantly higher soil Zn [22] and B concentrations [24] were reported at the foot slope than at the mid-slope and hillslope positions due to deposition and sedimentation of this nutrient from the upper slopes. However, this study found higher soil Zn concentration at the hillslope than at the mid-slope and foot slope positions (Table 3).

As shown in Figure 3, distinct variations were observed in soil water content among districts and landscape positions, where soil moisture content increased from hillslope to foot slope position, which means as the steepness of the land decreases the soil moisture content increases and vice versa. The volumetric soil moisture content ranged from 5.9-28.7% across the three landscape positions, with the highest at the foot slope and lowest at the hillslope position. The highest soil moisture content of 28.7% was measured in Kewot district of North Shewa zone because the area received adequate rainfall until late September, followed by the amount in Tehuledere/Haik district of the South Wollo zone. Landscape-wise, higher soil water contents of 11.8-28.7% were measured at the foot slope than at the mid-slope and hillslope positions across districts (Figure 3). Although differences were observed among landscape positions in soil moisture content, the lowest soil moisture content was measured in Sekota district of Waghimra zone followed by the value recorded in Belesa district of the central Gondar zone as they are drought-prone areas. Rough estimation was made using measuring tape on the root depth of sorghum under field conditions across locations and landscape positions. Like the soil moisture content, variations in sorghum root mass and depth were observed across the different landscape positions (data not shown). The root and depth tended to increase from the hillslope to the foot slope position which means as the steepness of the field decreases the root depth increases, and vice versa. Landscape-wise, the highest root length was recorded at the foot slope position and the lowest at the hill slope position.

3.2. Sorghum yield response to landscape position and nutrient sources

The mixed model analysis of variance showed that the responses of aboveground total biomass, grain yield, straw yield, and harvest index of sorghum were significant ($p<0.001$ and $p<0.05$) to source and rates of fertilizers under varying landscape positions (Table 4). However, landscape position by fertilizer interaction was not significant for these parameters. The intraclass correlation (ICC) analysis indicated that 61.1% of the variation is accounted for by location (Table 5). The highest sorghum aboveground biomass yield of 9964 kg ha^{-1} was recorded from the Zn-omitted treatment, followed by individual application of all nutrients (9501 kg ha^{-1}), and the lowest (5128 kg ha^{-1}) was recorded from the unfertilized control treatment (Table 6). The Zn omitted treatment increased sorghum total biomass by 94% (4837 kg ha^{-1}) and 8.6% (785 kg ha^{-1}) compared to the unfertilized control treatment and the recommended NP rate, respectively. The trial sites at the foot slope position resulted in total biomass, grain and straw yield, and harvest index increments of 41% (2972 kg ha^{-1}), 72% (1438 kg ha^{-1}), 29% (1532 kg ha^{-1}), and 17% (5.2), respectively compared to the values at the hillslope position. Similarly, total biomass, grain yield, straw yield, and harvest index at the foot slope position were higher by 15% (1,331 kg ha^{-1}), 42% (1018 kg ha^{-1}), 5% (325 kg ha^{-1}), and 17% (5.2), respectively than the values at the mid-slope position (Table 6). Overall, yield response to fertilizer application significantly decreased with increasing slope owing to the decrease in soil organic carbon and soil water content and the increase in soil acidity.

The results also demonstrated that increasing the fertilizer rate by 50% over the recommended rate significantly improved the grain yield of sorghum. The highest sorghum grain yield of 3,145 kg ha^{-1} was obtained from the application of 150% of the full rate of all nutrients applied in the blended form, followed by the yield of 2,885 kg ha^{-1} with the application of all nutrients without Zn. The lowest grain yield of 1274 kg ha^{-1} was recorded from the unfertilized control treatment, followed by the second lowest yield of 2180 kg ha^{-1} from the application of 50% of the full rate of all nutrients in the blended form (Table 6). The application of 150% of the full rate of all nutrients increased the grain yields of sorghum by 147% (1,871 kg ha^{-1}), 44% (965 kg ha^{-1}), and 13.5% (374 kg ha^{-1}) compared to the unfertilized control treatment, application of 50% all nutrients and the recommended NP rate, respectively. On the other hand, the highest (7082 kg ha^{-1}) and lowest (3867 kg ha^{-1}) straw yields of sorghum were recorded from the Zn-omitted treatment and the unfertilized control treatment, respectively. The harvest index of sorghum ranged from 35.9-28.3% with the application of 150% of the full rate of all nutrients in blended form and the unfertilized control treatment (Table 6).

Although the landscape position by fertilizer treatment interaction was not statistically significant for grain yield and total biomass of sorghum, clear yield differences were observed in these yield parameters among the three landscape positions (Figure 4). For instance, higher grain yield (4021 kg ha^{-1}) and total biomass (12298 kg ha^{-1}) of sorghum were recorded from All (B)-Zn treatment under foot slope position compared to the grain yield (2035 kg ha^{-1}) and total biomass (7943 kg ha^{-1}) at the hillslope position and grain yield (2499 kg ha^{-1}) and total biomass (9652 kg ha^{-1}) at the mid-slope position with the same fertilizer treatment (Figure 4). The result showed that grain and biomass yield increments of 61-96% and 27-55% were recorded at the foot slope position compared to the yield increments at mid-slope and hillslope positions for the same fertilizer treatment (Figure 4). Hence, fertilizer application resulted in considerable yield differences among landscape positions.

Treatment comparisons indicated a significant difference in total biomass and grain yield across contrasts: foot slope vs hillslope, foot slope vs mid-slope, and hillslope vs mid-slope. The highest values of the total biomass and grain yield were observed at the foot slope, while the lowest values were observed at the hillslope position. (Tables 6 and 7). The results of the comparisons of fertilizer treatments with different sources, rates, and nutrient formulations showed that significant variations were not observed in grain yield and total biomass of sorghum between All (B) vs All (C), All (B) vs. All (I), and All (C) vs. All (I) (Table 7). Similarly, significant differences were not observed in sorghum total biomass and grain yield when all nutrients were applied in blended, compound, and individual forms compared to the application of the recommended NP fertilizer alone (Table 7). Significant yield differences were also not observed between all blended and all blended minus K, -S, -Zn or -B, and NP alone. However, the treatment comparisons between 150% All(B) and 50% All(B), 50% All(B) and the control treatment, and NP alone and control treatment were significant for both sorghum grain yield and total biomass. In general, the analysis of treatment comparisons confirmed that applying each nutrient in blended, compound, and single forms did not result in significant sorghum yield compared to each other or over the NP treatment alone.

The percent sorghum grain yield penalty was estimated as the difference between the yields obtained from applications of nutrient-omitted treatments and the yields achieved from all nutrients applied in the blended form (Figure 5). Results revealed that a significant sorghum yield penalty was not observed because of the omission of K, S, Zn, and B nutrients compared to the application of all blended fertilizers in different forms. Most soils of the sorghum growing areas of different landscape positions had adequate K, Zn, and B nutrients. Across landscape positions, the highest yield gain and loss were observed from 150% All (B) and the control treatment, respectively compared to the NP treatment. The yield penalty and gain, in that order, ranged from -56.9% to 28.3% at the mid-slope, from -53.1% to 14.6% at the hillslope, and from -36.4% to 13.8% at the foot slope positions due to the control and 150%All(B) treatments compared to the NP treatment (Figure 5). Higher rates of N and P are required to achieve maximum yield. Application of 150% All (B) is the only treatment that gave a positive yield difference at all landscape positions relative to the NP treatment. However, at all landscape positions, 50% All (B) resulted in a negative yield difference from the NP treatment where the highest (-20.5%) and lowest (-8.1%) values were recorded at the mid-slope and foot slope position, respectively (Figure 5). Optimizing N and P rates appears more evident than fertilizer types and nutrient sources. The control treatment had a negative yield difference at all landscape positions relative to the All (B) treatment with a yield difference of -57.7% at the mid-slope, -49.7% at the hillslope position, and -35.1% at the foot slope position, respectively (Figure 5). At the mid-slope position, despite being from low to negligible yield penalty, negative yield differences of -2.5% and -0.2% were recorded from All (B)-S and All (B)-Zn treatments, respectively.

3.3. Economic analysis

The results of the partial budget analysis indicated that the three landscape positions required different treatments and generated net benefit response variabilities. All (B)-Zn and All (B)-B treatments generated the highest net benefits values for the foot slope position, followed by All (I) and All (C) treatments (Table 8). For the mid-slope and hillslope landscape positions, the treatment 150% All (B) generated the highest net benefit compared to other options. The next options were All (B)-B and All (B)-K treatments for the mid-slope position and All (B)-K and NP-only treatments for the hillslope position (Table 8). On the other hand, the marginal rate of return (MRR) and benefit-cost ratio (BCR) analysis showed that the treatment of 50% of All (B) provided the highest MRR and BCR across all landscape positions. The second alternative for the foot slope landscape position was the treatment All (B)-Zn which provided higher MRR and moderate BCR next to the treatment All (B)-K. For the mid and hillslope landscape positions, All (B)-K provided the highest MRR and BCR next to the treatment 50% of All (B). In general, the treatment 50% of All (B) gave the highest MRR and BCR across all landscape positions with a moderate yield penalty.

4. Discussion

4.1. Influence of landscape position on soil properties

Understanding how soil nutrients and crop yield vary across landscape positions has become the central point of research on soil and plant relationships. Results showed that the soil pH, total organic carbon, total nitrogen, available P, sulfur, Zn, and B concentrations were significantly higher at the lower slope position than at the upper and mid-slope positions. Dahlgren et al. [25] reported that soil pH decreased by about two units and base saturation decreased from 90% to 10% with increasing elevation. The total soil N and organic C at the foot slope position were significantly higher by 14.3% and 18.3% than at the mid-slope and 33.3% and 23.6% at the hillslope position, respectively. The available soil P concentration was also greater by 5.6% and 245% at the foot slope than mid and hillslope positions. This implies that the deposition and accumulation of nutrients from the upper slopes to the lower slopes through leaching and runoff was greater [22, 24]. Similar 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 [9, 13, 26]. Wang et al. [26] reported that the highest levels of soil organic carbon (SOC) and total N were observed at the foot slope position, with an increasing trend from the upper slope to the foot slope position. Previous studies also reported that lower landscape positions and forest land had higher mean values of soil OC, total N, available P, CEC, exchangeable cations, and available micronutrients, while lower mean values of these nutrients were recorded at upper landscape positions and intensively cultivated lands [13, 27]. According to Debebe et al. [28], most selected soil chemical properties, including pH, organic matter, total N, available P, exchangeable K, and CEC varied with land use types and elevation gradients, where the values of these soil chemical parameters increased from upland to lower land landscape strata. Hammad et al. [29] also reported that the addition of organic amendments significantly improved wheat yield response to inorganic fertilizer application, soil biophysical and chemical properties, and soil moisture content in dryland areas. Thus, the cultivated hilly lands should be rehabilitated before a threshold of soil OC of 2%, below which a potentially serious decline in soil quality will occur. The soil OC and nutrient status of the field trial soils were sub-optimal for wheat production, with as low as initial soil OC, total N, and available P of 0.98%, 0.10%, and 4.02 mg kg^{-1}, respectively. Interestingly, the soil pH is slightly alkaline which is a typical attribute of semi-arid areas, and the soil Al concentration is low.

Low fertilizer efficiency, inadequacy of current fertilizer recommendations, and disregarding nutrients other than N and P may limit crop production. Despite sulfur being non-limiting for sorghum growth and yield in this study, an assessment of nutrient deficiencies in maize in nutrient omission trials in the West African Savanna indicated that sulfur was limiting in 81% of the fields and was responsible for an average yield reduction of 20% [30]. According to Horneck et al. [31], the concentrations of Zn and B in the soil were low for Zn and medium for B, which ranged between 0.69-1.36 mg kg^{-1} DTPA Zn and 0.50–0.71 mg kg^{-1} B. Zinc deficiency is common in plants growing in highly weathered acidic or calcareous soils [32]. Wortmann [33] reported that Zn deficiency is less common in grain sorghum than in maize and could occur if calcareous soils are low in organic matter, or on sandy soils The benefit of Zn fertilizer applications on grain quality improvements above their baseline levels will also be affected by several soil factors, including landscape variability and soil pH. A deficiency of boron may occur if its extractable concentration is less than 0.5 mg kg^{-1} in most crops. Although low levels of boron may limit plant growth, high concentrations can be toxic. If the concentration of boron is greater than 2 mg kg^{-1}, it is excessive, and boron toxicity may occur in sensitive crops [31].

In this study, crops at foot slope positions were more vigorous and matured later than crops grown at mid-and hillslope positions, indicating the availability of adequate soil moisture and nutrients for crop growth. Yield differences among landscape positions have been attributed to soil erosion and differences in plant-available nutrients and soil water content, soil texture, bulk density, and surface soil depth [34]. Hence, soil management options should focus on scenarios that could improve the soil properties to improve agricultural productivity sustainably.

4.2. Influence of landscape position on sorghum yield response to nutrient sources

One of the most important factors that limit the production and productivity of sorghum in Ethiopia is the deficiency and availability of nutrients to plants in balanced and adequate amounts [35-37]. The study indicated that the crop response to nutrient applications was variable under different landscape positions. Landscape variability creates soil fertility variability in terms of soil organic matter, nutrient status, moisture content [13, 22, 24, 26, 34, 38], and crop productivity [8, 12].

In the present study, the total above-ground biomass and grain yield of sorghum significantly varied along with the three landscape positions. Landscape position significantly affected total biomass, grain and straw yield, and harvest index of sorghum. The total aboveground biomass and grain yield of sorghum decreased as the slope increased from foot to hillslope positions, which might be due to differential soil properties and processes related to elevation and climate [25] and soil fertility and soil moisture status [13]. Recent studies reported that total biomass and grain yields of wheat and teff [12, 13] and sorghum [8] significantly increased downward from hillslope to foot slope position.

The results of this study revealed that the omission of all nutrients substantially negatively affected sorghum yield across sites. The omission of all nutrients resulted in the lowest grain and biomass yields of sorghum with higher penalties indicating that the soils of the study areas are deficient in the major essential plant nutrients. The application of the right source and rate of nutrients at the right time and method determines the growth and yields of crops [39]. Harmonizing the precise fertilizer source and rate to the crop need is the major challenge in crop production [40]. Site-specific nutrient management as a component of precision farming enables agricultural management decisions to be tailored spatially and temporally [41, 42]. A similar research finding showed that targeted fertilizer application at the right agronomic practices increased wheat grain yield by 40-200% [3]. The results of the present study showed that increasing the fertilizer rate by 50% over the recommended rate significantly increased the total biomass and grain yield of sorghum. A similar study by Desta et al. [8] showed that increasing fertilizer application rate led to increased sorghum yield in sorghum growing areas, especially where the impact of soil moisture stress is not a constraint. Significantly higher total biomass yield was obtained from the application of the Zn omitted treatment compared to 50% of all nutrients and the control treatment, with the range of 9964 to 5128 kg ha^{-1}.

The study demonstrated that significant yield differences were not observed due to the application of all nutrients in blended, compound, and individual forms compared to the recommended NP fertilizer, implying that the addition of K, S, Zn, and B nutrients either separately or together did not contribute to significant yield improvements over the application of NP fertilizer alone. Similarly, despite numerical variations, a statistically significant difference in total biomass was not observed between the application of all nutrients in the blended, compound, and individual(straight) forms, denoting that the application of various nutrients either in mixture or compound form did not result in significant yield advantage over the application of individual forms. However, the application of each nutrient separately could take time and create difficulties in distributing small amounts of nutrients, especially micronutrients uniformly to the whole plot. Generally, the present study exhibited that the application of all nutrients in blended, compound, and single form did not significantly improve or cause significant yield penalty in sorghum yield owing to the omission of K, S, Zn, and B nutrients and the application of the recommended NP fertilizer alone. This means N and P are the main yield-limiting nutrients in the study areas. Hence, the application of these two nutrients to the levels of their recommendation for sorghum production gave a comparable yield relative to the application of all nutrients (N, P, K, S, Zn, and B). This implies that a significant yield penalty was not observed because of the omission of K, S, Zn, and B compared to the application of all blended fertilizers, where most of the soils of the experimental sites had adequate K, Zn, and B nutrients and they are not the yield-limiting nutrients in sorghum growing areas of the region under each landscape position. Increasing N and P rate is more important than fertilizer types irrespective of mid-slope position where All (B) gave a positive yield difference of 9% compared to the NP treatment alone. Overall, the application of the optimum rate of NP fertilizer could be adequate for sorghum production in the experimental districts and similar areas.

The highest and lowest sorghum grain yields of 3145 kg ha^{-1} and 1274 kg ha^{-1} yield were obtained from the application of 150% of all nutrients and the control treatment, respectively. As the fertilizer rate increased by 50% over the recommended rate, the yield of sorghum significantly increased by 44% and 147% compared to the application of 50% of all nutrients and the unfertilized control treatment, respectively. The significant yield variation between treatments (150% All(B), 50% All(B), and other treatments) could mainly be attributed to the variation in the amount of N and P applied rather than the source of fertilizer and omission or inclusion of K, S, Zn, and B nutrients. This indicates that higher rates of N and P are required to achieve maximum yield at all landscape positions. A recent study showed that the yield variation was mainly associated with the difference in applied N and P rates rather than nutrient sources [13]. Desta et al. [8] also reported that the combined application of NP with different levels of K and S or NP with Zn fertilizer rates did not result in significant yield differences compared to the application of NP nutrients alone. On the other hand, Shewangizaw et al. [43] indicated that the addition of 10 kg S ha^{-1} with N and P fertilizer resulted in a significant barley yield advantage, while Chala et al. [44] recommended the application of the lowest levels of K and S with N and P fertilizers as a maintenance strategy for teff production.

Despite considerable differences between the mean values of different fertilizer treatments under the three landscape positions, the landscape-by-fertilizer interaction effect on yield and some yield components of sorghum was not statistically significant which may be associated with high spatial variability in soil fertility and soil water content that could be justified by wide ranges of coefficients of variations. For instance, the highest sorghum grain yields of 4021, 2499, and 2135 kg ha^{-1} were recorded from all nutrients in blended form without zinc addition at foot, mid-, and hillslope positions, respectively, with the respective yield increments of 61 and 96% at foot slope position compared to the mid-and hillslope positions. Previous studies reported that the interaction of landscape position with fertilizer treatments resulted in significant yield increments of sorghum [8] and wheat [13]. An interaction between two or more factors occurs when the effect of one factor is dependent on the conditions of the other factor. As the field trials were conducted over several locations the variability in yield data for each landscape position was high as the data were analyzed over locations. The interaction between landscape position and fertilizer treatments was proved by analyzing the yield data collected for each site under three landscape positions where the variability was low. Hence, it does not mean that the effects of each independent variable are consistent across all levels of the other independent variable.

The results of the economic analysis revealed that the three landscape positions required different treatments and produced variabilities in net benefit response. All (B)-Zn and All (B)-B treatments resulted in the highest net benefits for the foot slope position, while the treatment 150% All (B) generated the highest net benefits for the mid-slope and hillslope positions. In contrast, the treatment 50% of All (B) provided the highest marginal rate of return (MRR) and benefit-cost ratio (BCR) across all landscape positions. In general, the MRR and BCR results could help farmers' decision-making on the rate of fertilizers to be used. Hence, it is suggested that resource-poor farmers could use the treatment 50% All (B), while farmers who have access to inputs could use the treatment All (B)-Zn to generate more net benefits from the land resource.

5. Conclusions

This research aimed to identify limiting nutrients and develop and transfer soil fertility technologies that improve nutrient use efficiency, following the 4Rs of Nutrient Stewardship: right source, right time, right rate, and right place. This could be 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 as indicated below. The present study revealed that the growth and yield response of sorghum to the applications of different sources and rates of fertilizers was statistically significant under the three landscape positions. However, the addition or omission of K, S, Zn, or B nutrients did not result in a significant yield penalty compared to the application of NP fertilizer alone, implying that the main yield-limiting nutrients for sorghum production seem to be nitrogen and phosphorus. Nitrogen and P omission had a significantly larger penalty in grain and biomass yield of wheat than other nutrients. Significant differences were not observed in sorghum yield among the different forms of fertilizer treatments. Significantly higher yields of sorghum were obtained at the foot slope compared to mid- and hill slope positions, with an increasing trend in growth and yield of sorghum from hill slopes to foot slopes. This indicates the need for considering landscape position to plan fertilization programs for attaining and sustaining optimum sorghum yield. Overall, based on the results of yield and soil analysis data, it could be concluded that deficient nutrients other than N and P were not observed in sorghum growing areas. Nitrogen is generally the most yield-limiting nutrient, followed by P for sorghum production in Ethiopia. The addition or omission of macro and micronutrients other than N and P didn't significantly affect grain and total biomass yields and agronomic N and P use efficiencies of sorghum in the major production belts (across all soil types and moisture domains) in Ethiopia. It is also suggested that further study is required to determine the best N and P rates under the three landscape positions.

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Data Availability

Data will be made available on request.

Declarations

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

Authors' Contributions

[1,2,3,4] These authors were involved in developing and designing the experiment, implementing the field trial, data collection and statistical analysis, and writing the manuscript. Other authors read, edited, and agreed to submit the manuscript for publication.

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Table 1

General characteristics of sorghum experimental sites in the Amhara region.

Location (District)	Rainfall (mm)*	Minimum temp (°C)*	Maximum temp (°C)*	Soil type	Agroecological zone
Kewet	678-1012 (874)	11.3-17.4 (13.8)	26-32 (29.7)	Eutric and chromic Cambisols	Tepid moist mid-highlands (M3)
Sekota	766-792 (775)	12.9-13.9 (13.6)	29-30 (29.3)	Eutric Regosols and Eutric Cambisols	Warm semi-arid lowlands (SA2)
Tehuledere	678-969 (864)	11.8-17.4 (14.2)	26-32 (28.4)	Vertic Cambisols, Eutric Regosols, Haplic Xerosols	Tepid moist mid-highlands (M3), warm moist lowlands (M2)
West Belessa	929-1012 (975)	14.1-15.2 (14.5)	30-31 (31.9)	Orthic Solonchaks and Leptosols	Warm semi-arid lowlands (SA2)

*Range (average value)

Table 2

Treatments and nutrient rates under low-medium rainfall regime

Treatments	Nutrient rates (kg ha $^{-1}$)							
	B	Zn	**N**	P_2O_5	K_2O	S	B	Zn
Control	0	0	0	0	0	0	0	0
50% All (B)	0.25	0.75	37.5	19	30	3.7	0.125	0.375
NP	0	0	75	38	0	0	0	0
150% All (B)	0.75	2.25	112.5	57	90	11.1	0.375	1.125
All (B)	0.5	1.5	75	38	60	7.4	0.25	0.75
All (C)	0.5	1.5	75	38	60	7.4	0.25	0.75
All (I)	0.5	1.5	75	38	60	7.4	0.25	0.75
All (B)-K	0.5	1.5	75	38	0	7.4	0.25	0.75
All (B)-S	0.5	1.5	75	38	60	0	0.25	0.75
All (B)-Zn	0.5	0	75	38	60	7.4	0.25	0
All (B)-B	0	1.5	75	38	60	7.4	0	0.75

All (B): application of all nutrients in blended form: All (C): application of all nutrients in compound form, All (I): application of all nutrients individually, 150% All (B): application of 150% of all nutrient in blended form, 50% (B): application of 50% of all nutrient in blended form, All (B)-K, S, Zn, and B: Omissions of K, S, Zn and B from all nutrients in blended form, NP: recommended N and P, Control: no fertilizer applied

Table 3

Soil chemical properties across districts and landscape positions.

	pH	Exch. Al	OC	TN		Av. P	S	Zn	B
District		cmol (+)/kg	%		C: N	(mg kg^{-1})			
Kewot	8.0	0.97	1.35	0.13	10.2	19.87	3.86	1.8	0.71
Sekota	7.9	1.07	0.98	0.10	9.78	4.49	3.03	0.69	0.60
Tehuledere	7.9	0.95	1.41	0.17	8.23	5.99	3.63	1.18	0.50
West Belesa	7.8	1.06	1.07	0.16	7.22	4.62	1.89	0.88	0.37
SE	0.04	0.02	0.03	0.002	0.26	0.76	0.14	0.07	0.02
Landscape position									
Foot-slope	8.0	1.0	1.36	0.16	10.02	13.89	3.33	0.97	0.59
Mid-slope	7.9	0.99	1.15	0.14	8.41	8.31	3.17	1.09	0.55
Hillslope	7.8	1.04	1.10	0.12	8.15	4.02	2.79	1.36	0.50
SE	0.03	0.01	0.03	0.002	0.2	0.71	1	0.06	0.01

Exch. Al: Exchangeable aluminum, OC: Organic carbon, TN: Total nitrogen, Av. P: Available phosphorus, S: Sulfur, Zn: Zinc, B: Boron, SE: Standard error

Table 4

The significance level of the fixed effect of landscape position, fertilizer type, and source, and their interaction on biomass, grain and straw yield, and harvest index of sorghum.

Effect	DF	P > F			
		Total biomass	Grain yield	Straw yield	Harvest index
Landscape position	2	<.0001	<0.0001	<0.0001	<0.0001
Fertilizer	10	<.0001	<0.0001	<0.0001	0.0123
Landscape*fertilizer	20	0.7067	0.2167	0.9325	0.9956

Table 5

Covariance parameter estimates.

Cov Parm	Subject	Estimate	Value	Pr Z	ICC
Intercept	Location	1111605	1.22	0.111	61.1
Residual		707612	20.27	<0.0001	

ICC is the intraclass correlation.

Table 6

The main effect of landscape position, fertilizer source, and rate, and their interactions on yield and some yield components of sorghum with standard errors in parenthesis.

Effects	Total biomass (kg ha^{-1})	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index
Landscape position				
Foot-slope	10196± (1334.48)	3434.8± (530.98)	6761.25± (1062.85)	35.53± (5.39)
Mid-slope	8865.44± (1328.05)	2416.37± (529.96)	6435.78± (1056.98)	30.30± (5.26)
Hill slope	7223.68± (1329.87)	1996.29± (530.25)	5228.94± (1058.64)	30.29± (5.17)
Fertilizer source and rate				
150% All (B)	9458.68± (1367.29)	3144.98(536.23)	6283.2(1092.77)	35.86± (5.50)
50% All (B)	7351.3± (1367.29)	2179.81± (536.23)	5171.12± (1092.77)	33.16± (5.50)
All (B)	8689.78± (1346.36)	2667.37± (532.87)	6022.97± (1073.69)	33.31± (5.43)
All (C)	9373.87± (1411.88)	2741.39± (543.5)	6635.45± (1133.25)	30.45± (5.67)
All (I)	9501.09± (1411.88)	2744.84± (543.5)	6759.04± (1133.25)	30.36± (5.66)
All (B)-B	9495.87± (1411.88)	2850.58± (543.5)	6648.15± (1133.25)	31.60± (5.67)
All (B)-K	9193.06± (1346.36)	2826.71± (532.87)	6324.21± (1073.69)	33.44± (5.43)
All (B)-S	9045.4± (1411.88)	2688.71± (543.5)	6359.52± (1133.25)	32.21± (5.66)
All (B)-Zn	9964.29± (1411.88)	2884.8± (543.5)	7082.38± (1133.25)	30.49± (5.66)
NP	9178.94± (1346.36)	2770.58± (532.87)	6408.88± (1073.69)	33.26± (5.43)
Control	5127.59± (1346.45)	1274.25± (532.89)	3866.98± (1073.78)	28.28± (5.43)

All (B): Application of all nutrients in blended form; All (C): Application of all nutrients in compound form; All (I): Application of all nutrients individually; 150% All (B): Application of 150% of all nutrient in blended form; 50% (B): Application of 50% of all nutrient in blended form; All (B)-K, S, Zn, and B: Omissions of K, S, Zn and B from all nutrients in blended form; NP: Recommended N and P; Control: No fertilizer applied

Table 7

Mean comparison of landscape positions and selected fertilizer treatments for sorghum biomass and grain yield.

	Grain yield		Total biomass	
Landscape positions	**SE**	**Ad. p**	**SE**	**Ad. p**
Foot slope vs hillslope	82.47	<.0001	327.84	0.0001
Foot slope vs mid-slope	81.08	<.0001	322.32	<.0001
Hillslope vs mid-slope	75.69	<.0001	300.90	0.0062
Selected fertilizer treatments				
All (B) vs all (C)	151.82	1.0000	603.52	0.9886
All (B) vs all (I)	151.82	1.0000	603.52	0.9607
All (C) vs all (I)	183.86	1.0000	730.92	1.0000
All (B) vs 150% All (B)	124.62	0.0064	495.41	0.9014
All (C) vs NP	151.82	1.0000	603.52	1.0000
All (B) vs NP	108.71	0.9972	432.18	0.9887
All (I) vs NP	151.82	1.0000	603.52	1.0000
All (B) vs All (B)--K	108.71	0.9306	432.18	0.9860
All (B) vs All (B)-S	151.82	1.0000	603.52	1.0000
All (B) vs All (B)-Zn	151.82	0.9401	603.52	0.5691
All (B) vs All (B)-B	151.82	0.9817	603.52	0.9624
150% All (B) vs 50% All (B)	138.08	<.0001	548.94	0.0062
150% All (B) vs NP	124.62	0.0948	495.41	1.0000
50% All (B) vs control	124.68	<.0001	495.65	0.0004
NP vs 50% All (B)	124.62	0.0001	495.51	0.0108
NP vs Control	108.79	<.0001	432.49	<.0001

All (B): All nutrients in blended form; All (C): All nutrients in compound form; All (I): All nutrients applied individually

Table 8

Partial budget and dominance analysis of different fertilizer treatments for sorghum production.

	Foot slope			Mid-slope			Hillslope		
Treatments	NB/ha	MRR	BCR	NB/ha	MRR	BCR	NB/ha	MRR	BCR
150% All B	101822.70	-0.12	15.25	93180.28	3.45	14.04	69910.79	0.67	10.79
50% All B	83553.09	22.56	36.15	58513.77	25.42	25.61	55389.34	14.29	24.30
All B	94256.94	-5.17	20.80	77677.61	-1.25	17.32	61783.65	-3.53	13.98
All C	108716.19	4.15	23.84	72165.44	-4.80	16.16	63126.98	-2.66	14.26
All I	109898.10	4.91	24.09	78941.55	-0.43	17.59	56381.24	-7.01	12.85
All (B)-B	113288.14	7.60	25.33	80677.16	0.74	18.33	58706.88	-5.90	13.61
All (B)-K	100841.23	-4.21	29.41	83358.84	10.97	24.49	67843.11	1.72	20.12
All (B)-S	103870.71	1.18	23.78	73545.80	-4.49	17.13	61086.14	-4.56	14.40
All (B)-Zn	117830.53	10.27	25.96	76595.89	-1.99	17.22	63978.08	-2.16	14.55
NP only	102278.35	D	D	79612.71	D	D	67254.80	D	D

NB: Net benefit; MRR: Marginal rate of return; BCR: Benefit-cost ratio; D: Dominated treatment

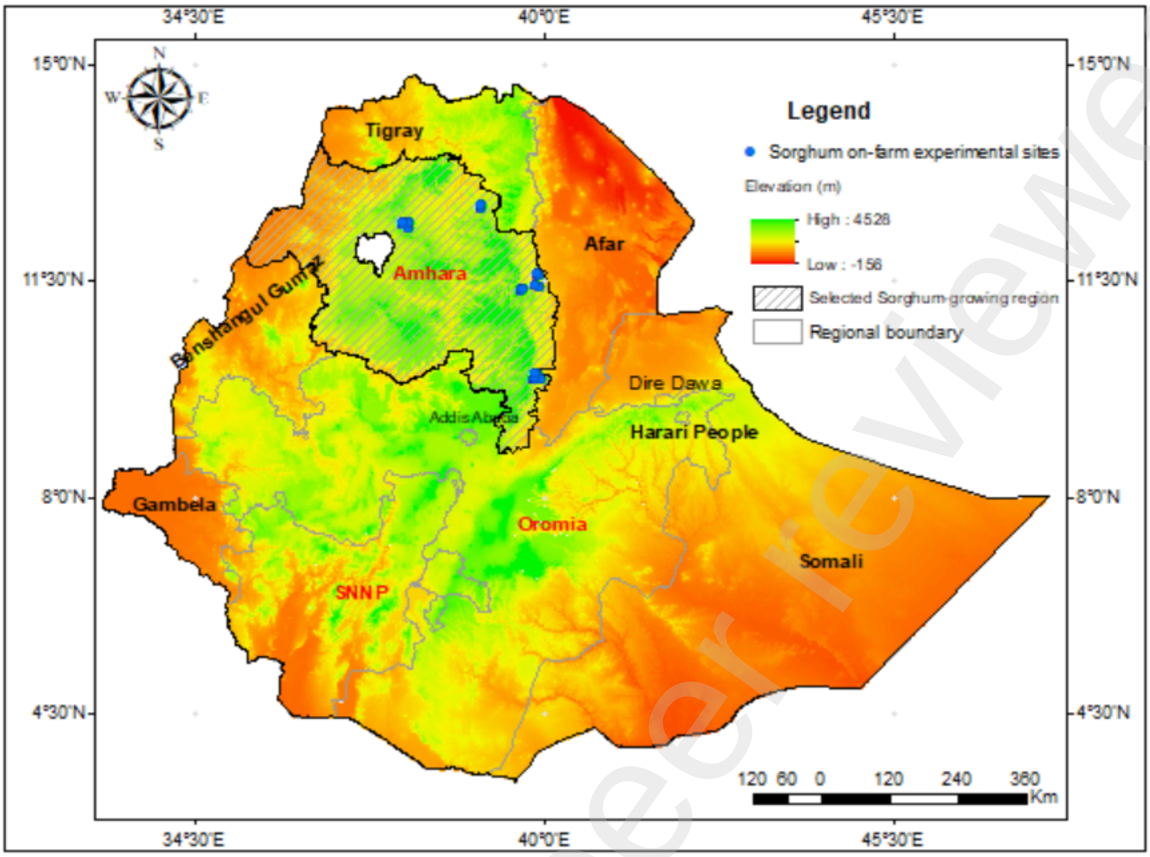

Fig. 1. Distribution of sorghum nutrient omission experimental sites across the Amhara region in the 2020 and 2022 cropping seasons

Fig. 2. Landscape position classification. Source: [3]

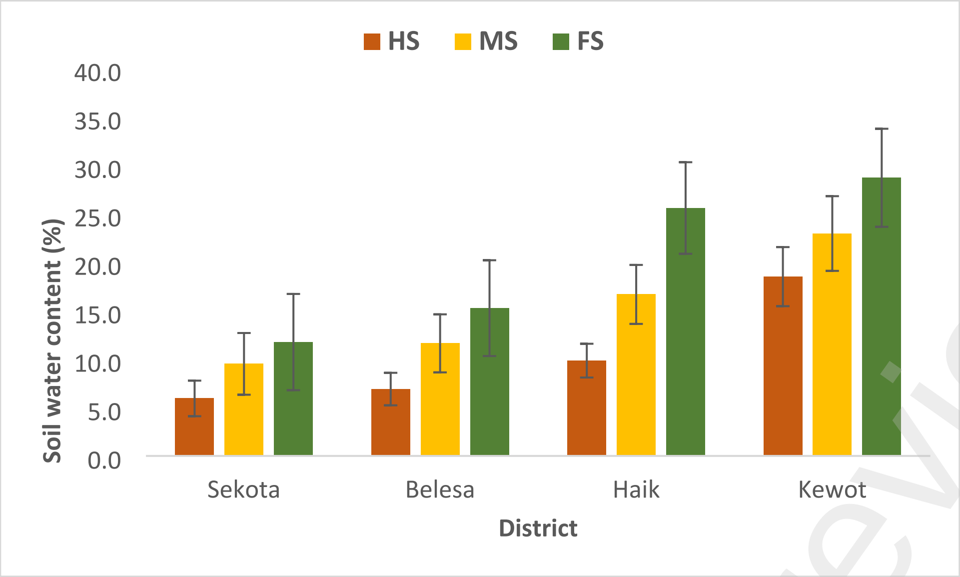

Fig. 3. Landscape-based percent volumetric soil moisture content across districts measured from sorghum field. FS: Foot slope, MS: Mid-slope, HS: Hillslope

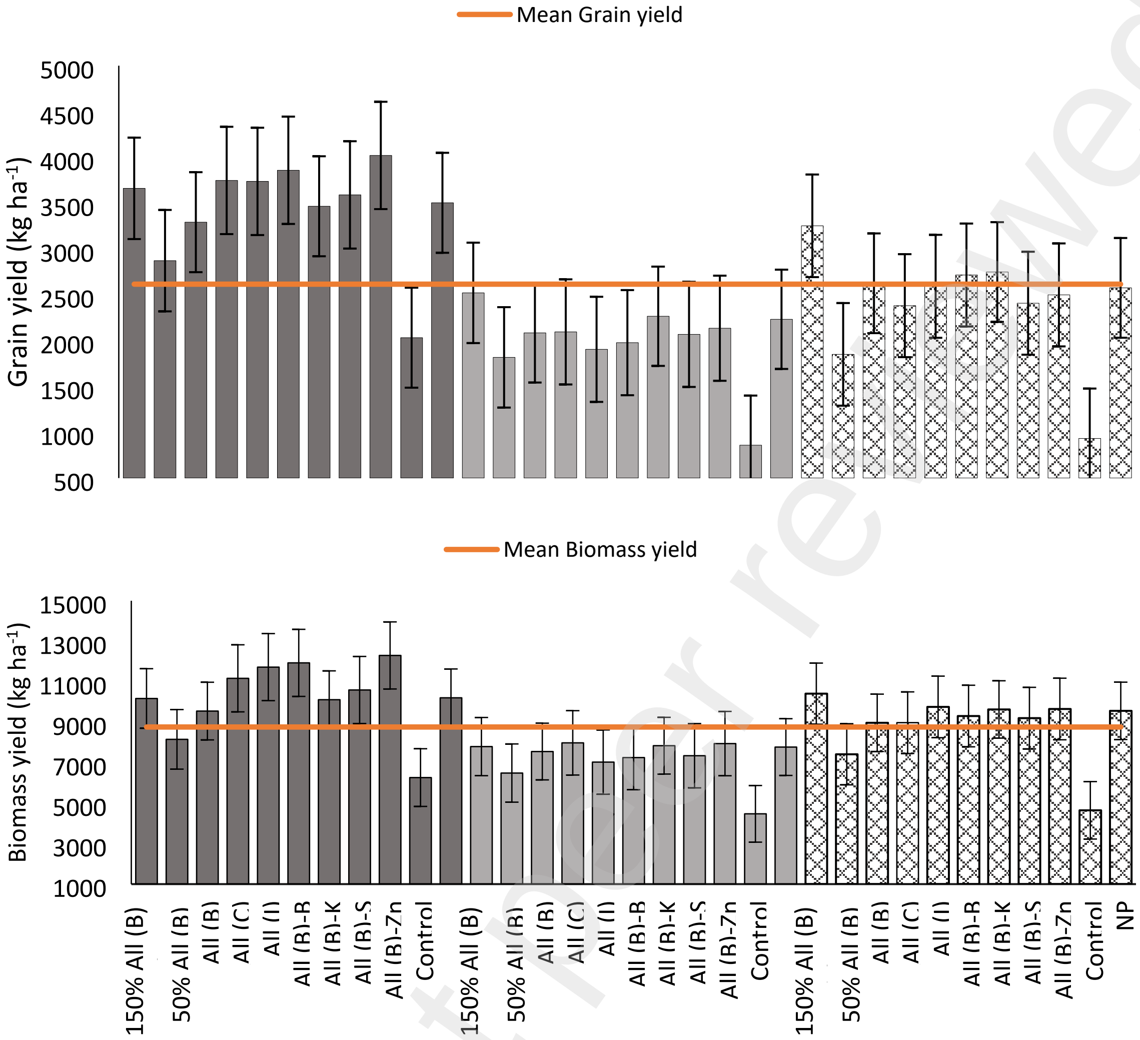

Fig. 4. Effect of fertilizer and landscape position on sorghum grain yield (upper) and total biomass (lower).

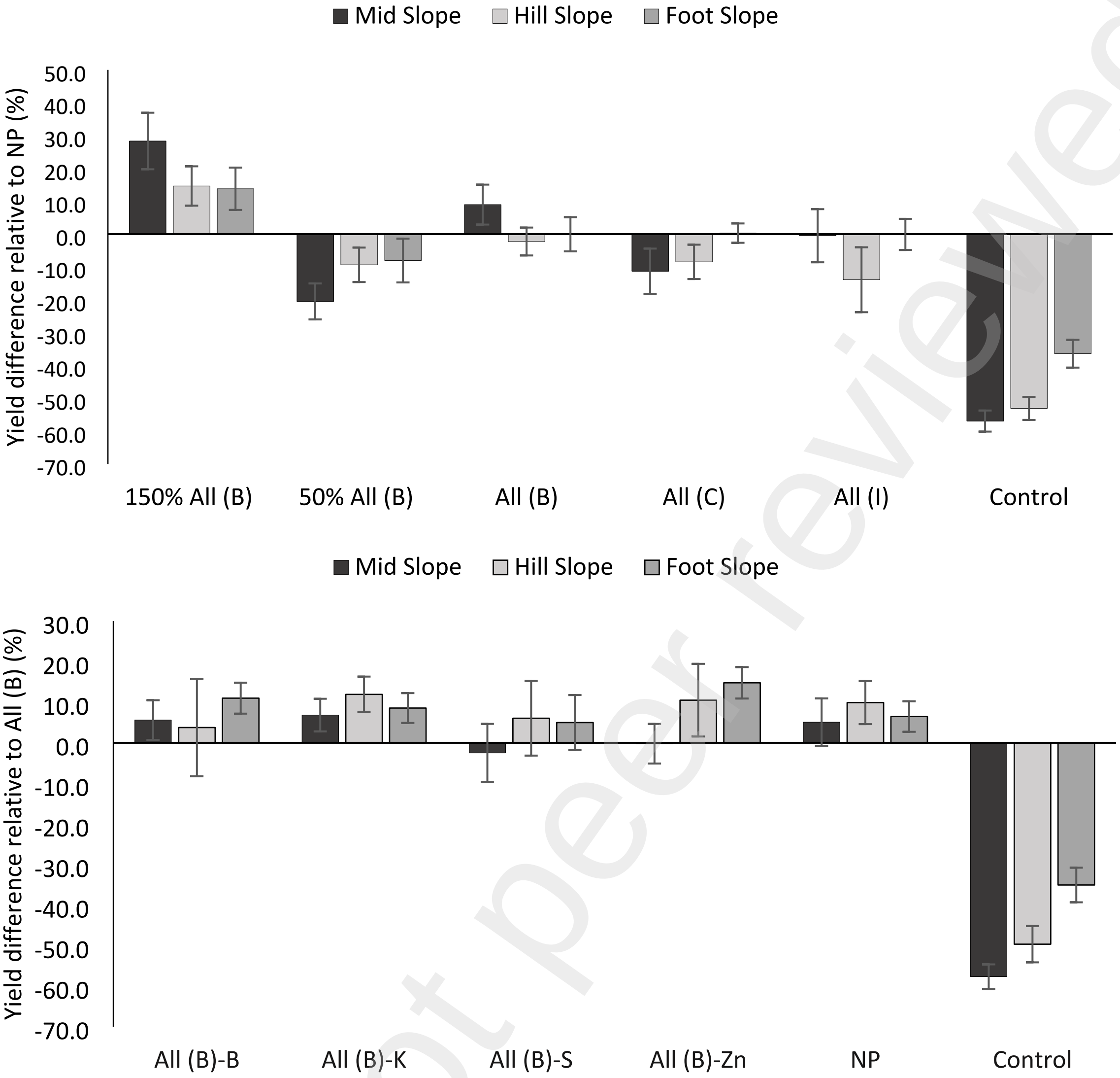

Fig. 5. Grain yield difference of forms and rates of fertilizers relative to recommended NP (upper), and grain yield difference due to omission of nutrients relative to All(B) (lower).