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Response of Teff ((Eragrostis *tef (zucc.) Trotter*) to nitrogen and phosphorus applications on different landscapes in eastern Amhara

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ABSTRACT

The dynamic nature of soil fertility status across different landscapes attracted research attention in Ethiopia and the globe. Teff [Eragrotis tef] is a major staple cereal crop in Ethiopia but yields are low due to inadequate nutrient supply and other constraints. A field study was conducted in 2020 and 2021 in the Habru district of Amhara Region to determine teff yield response to fertilizer-N and -P at hillslope, midslope, and footslope positions with slopes of >15%, 5–15%, and 0–5%, respectively. N and P fertilizer rates were factorially combined in randomized complete block design with three replications in each farmer's field. A linear mixed modeling framework was used to determine effects on grain yield due to N rate, P rate, slope, study sites, and years. Model fit was examined using Akaike's Information Criterion and Bayesian Information Criterion. Economic analysis was done with a quadratic response function to determine the economics of fertilizer. Yield response to fertilizer-P was affected by slope but the response to fertilizer-N was not affected. Teff yield increase with fertilizer-N application up to 92 kg ha^{-1} the economic optimum rate based on the yield response function for nitrogen fertilizer was 85.4 kg ha^{-1} to obtain maximum profit (86878.8 birr ha-1). Similarly, the optimum phosphorus fertilizer rate at the hill slope was 39.7 kg ha^{-1} ^{to} obtain a maximum profit of (96847.8 birr ha^{-1}). But there was not a profitable response at the midslope and foot slope positions. Therefore, for Habru district and similar agroecologies85.4 kg ha^{-1} N and 39.7 kg ha^{-1} P in hillslopes and only 85.4 N kg ha^{-1} for midslopes and foot slopes are expected to give the most profitable returns to fertilizer applied for tef production.

1. Introduction

Landscape as a role in soil fertility status, how landscape positions may be used to fine-tune fertilizer recommendations, and crop production variability within and between farms have all piqued interest in Ethiopia and throughout the world [1]. The terrain of utmost African agrarian geographies, which includes high-elevation hillslopes, midslopes, and bottom pitches that arise within short distances, necessitates a variety of agronomic stewardship and input levels. The impact of geography position brought a significant

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difference in soil nutrient status [2–4]. Much ecological study has focused on how nutrient resources differ across landscapes (Benning and Seastedt, 1995) [5]. Soil characteristics are affected by parent material [6], climate, and geological history. However, the primary factors affecting soil qualities are landscape position and land use [7].

Teff, *Eragrostis tef*(*Zucc. Trotter*) began and diversified in Ethiopia and is one of the major cereals grown for thousands of years [8]. Ecologically, tef is acclimated to different agroecological regions of Ethiopia and grows well under stressful climates better than wheat, barley, and other cereals known worldwide [9]. Because of this, it's said to be a" low-threat" crop for growers. According to Ref. [10], the plant can be grown from sea level up to 2800 m.a.s.l under varied rainfall conditions, temperature, and soil administrations. still, for better performance, it requires an altitude of 1800–2100 m.a.s.l, annual rainfall of 750–850 mm, and a temperature range of 10–27 °C. The crop plays a vital part in the country's overall food security and it's the staple food for the utmost Ethiopian people. Teff is the most precious cereal in Ethiopia and is used as a cash crop for the growers. This is because of the high request prices for both its grain and straw. moment, tef entered global attention as a health food because of its gluten-free nature which renders it suitable for people suffering from gluten allergy known as celiac disease [11]. Teff plays an important part in supplying the population of the country with protein, carbohydrates, and minerals. additionally, straw is an important cattle feed source.

The national average means grain yield teff is about 1465 kg ha- 1 for Ethiopia, and 1495 for Amhara Region [12], and the utmost variable. Most of the Ethiopian soils contain low nutrient content due to erosion and the absence of nutrient recycling [13]. The low availability of nitrogen and phosphorus has been demonstrated to be a major constraint to cereal production. Fertilizer usage plays a major role in the universal need to increase food production to meet the demands of the growing world population [14].

Generally, there's limited information on how landscape positions could be used for fine-tuning fertilizer recommendations. during this study, we used teff as a test crop, which was becoming an increasingly important crop, to know the factors affecting the crop response to the combination of fertilizers in the undulating setting of soils of the Ethiopian highlands across the catena.

The objectives of the research were.

To evaluate the response of Teff to N and P application on the various landscape and.

To determine the optimum rates of N and P on this landscape.

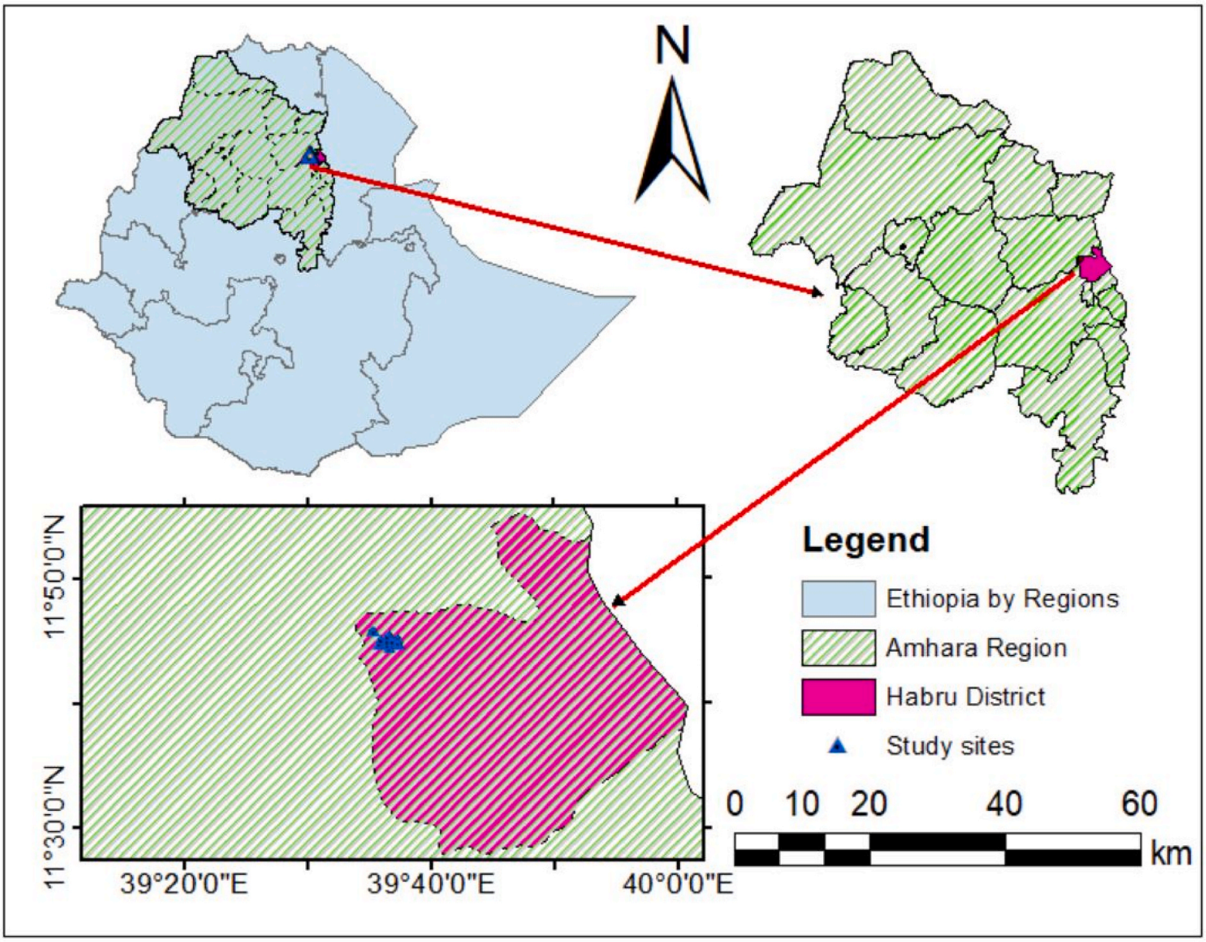

Fig. 1. The geographical location of the study district.

2. Materials and methods

2.1. Description of the study area

The trials were conducted during the 2019 and 2020 main cropping seasons on 17 growers' fields in the main teff-growing sections of Habra district, Amhara Regional State, Ethiopia. (Fig. 1). Geographically, Habra district has positioned at an altitude ranging from 1200 to 2350 m.a.s.l at 39° 2′16.8″ E longitude and 11° 2′ 6″ N latitude in the semi-arid tropical belt of North-Eastern Ethiopia. It's located 491 km from Addis Abeba to the north, 390 km from the regional city Bahr Dar, 290 km from Mekelle, and 654 Km from Debre Markos.

The district is characterized by a bimodal rainfall pattern entering a periodic rainfall of 1258.6 mm in 2019 and 1083.9 mm in 2020. The loftiest rainfall occurs from June to September in utmost cases and also the same happens in the study years. The yearly average rainfall and temperature of the quarter during the experimental years are presented in Figs. 2 and 3.

The farming system of Habru district is teff – sorghum and Depending on the occurrence of rainfall, the teff-growing period varies from June last to October. The soils of the locations are characterized by Vertisols in the lower landscape and shallow Regosols in the upper landscape.

2.2. Experimental design and treatments

In the Habru district, nine farmers filed were selected considering the slope and landscape positions in the first year (2019). Three farmers in each slope class were selected. The slope class was categorized as the slope of (0–5%, 5–15%, and >15% respectively for foot slope, mid-slope (back slope), and hill slope (shoulder)) across three different landscape positions in a catena. Similarly in the second year (2020), eight farmers' fields (i.e., 3 from the hill slope, three from the mid-slope, and 2 from the foot slope) were also selected on those slope classes to capture seasonal differences in the two years from the same district. A total of 17 farmers' fields were therefore selected to conduct landscaped nitrogen and phosphorus fertilizer rate on the response of teff yield.

The experiment comprised two factors with.

- ➢ Three levels of P application (0, 23, and 46 kg P_2O_5 ha^{-1}) and
- ➢ Four levels of N (46, 69, 92, and 115 kg N ha^{-1}) are combined in a factorial arrangement.
- ➢ The satellite treatment (0, 0) was included in each replication of the experimental sites for further economic analysis of the experiment

The experiment was conducted using a randomized complete block design (RCBD) with three replications. The three phosphorus rates and the four nitrogen rates were factorially combined so that there were 12 randomized treatments. These treatments are replicated three times in each farmer's field. The experimental design is similar for all landscape positions and similarly, the treatments

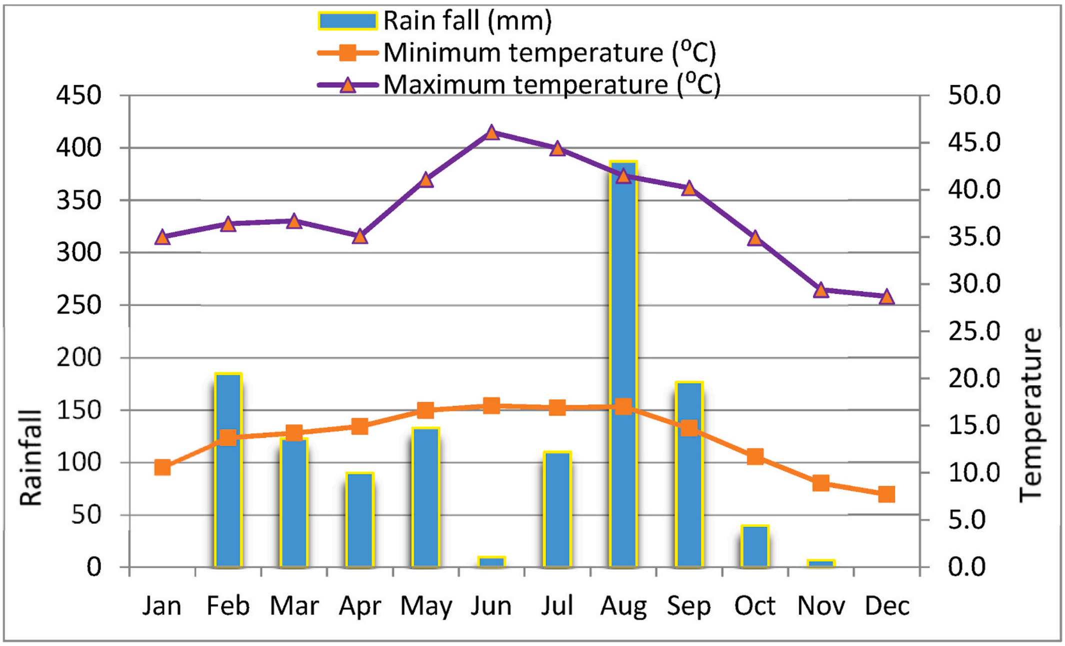

Fig. 2. Monthly rainfall and temperature of 2019.

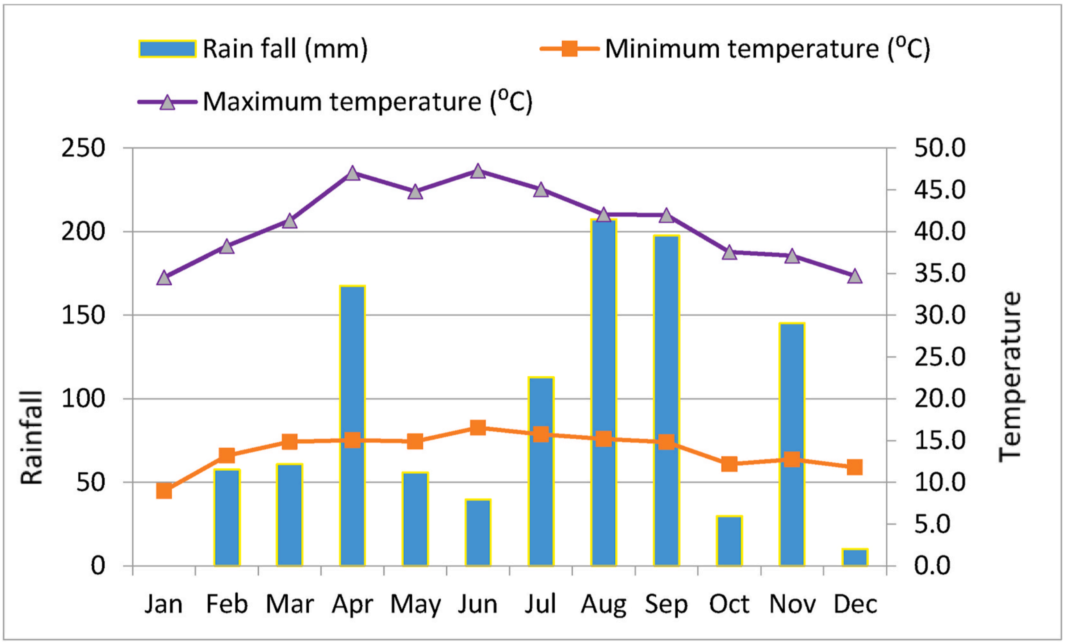

Fig. 3. Monthly rainfall and temperature of 2020.

are identical for all landscape positions.

The spacing was 1 m and 0.5 m between replications and plots respectively with a plot size of 3 m by 4 m. *Zobel* variety with 25 kg ha $^{-1}$ seed rate was used. Urea (46-0-0) and TSP (0-46-0) were used as a source of nitrogen and Phosphorus respectively. All amounts of Phosphorus and 1/2 split of nitrogen were applied at planting. The remaining 1/2 of nitrogen was applied at tillering stage. Ridges were made between plots and blocks to remove the cross-contamination of fertilizer from one plot and the block to others.

2.3. Soil sample collection and analysis

Composite surface soil samples (0–30 cm depth) were collected from each farm to determination of the Physicochemical properties of the soil. The soil was air-dried, ground, and mixed thoroughly and passed through a 2 mm sieve for most parameters except for OC and TN which passed through a 0.5 mm sieve. The samples were then labeled and stored in sealed plastic bags for laboratory analysis of; texture, pH, TN, OC/OM, CEC, and available phosphorous. Soil particle size distribution was determined by the hydrometer method [15]. Soil pH was measured with a digital pH meter potentiometrically in the supernatant suspension of 1:2.5 soil to distilled water ratio [16]. Organic carbon (OC) was determined by the dichromate oxidation method [17]. Total N in the soil was measured by the micro kjeldhal method [18]. Available P was also analyzed by the Olsen method [19] calorimetrically by the ascorbic acid-molybdate blue method [20]. Those soil parameters were prepared and analyzed in Sirinka Agricultural Research Center Laboratory.

2.4. Data collection

Plant height: It was measured at physiological maturity from the ground level to the tips of the panicle from randomly selected 10 culms from the net plot area. The mean value from 10 culms was taken as plant height per plant.

2.4.1. Yield and yield component

Aboveground dry biomass yield: At physiological maturity, plants from the net plot area (2.5 m*3.5 m) were manually harvested close to the ground surface. The harvested plants were sun-dried in the open air until attain constant weight, and weighed to determine the above-ground biomass yield.

Grain yield: It was measured by harvesting and threshing the crop from the net plot area (2.5 m*3.5 m). Then 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 ha−1 before statistical analysis.

2.5. Data analysis

A linear mixed modeling frame was used to determine the variation in yield with the different situations of N and P by the landscape, study sites, and years. Landscape describes the landform on which the three slope classes are found in a similar catena (watershed) whereas the study site describes the seventeen farmers' field on which all the treatments are applied with three replication.

The linear mixed modeling frame(in PROC MIXED of the SAS system) was chosen for the different situations of analyses because it allows the modeling of hierarchical or clustered data arising from experimental studies through the addition of both fixed and random effects. The fixed effects in the model were landscapes, study sites, replication, nutrient rates(nitrogen and phosphorus) and their interaction, and nutrient and landscape interaction with year as the random effect. In mixed models, the random constituent specifies that the linear predictor contains a term that randomly varies with one or more ecological correlates of crop yield — for illustration, years. This helps to consider correlation(i.e., compliances in analogous years are likely to be more affiliated than compliances in other years, and that year is nested within landscapes or study sites). The PROC MIXED procedure uses the REML estimation system and the Prasad- Rao- Jeske- Kackar- Harville fixed effects method for estimating standard errors. The tested models were of the following form:

$$Model\ one : Y = \mu + Rep + N + P_2O_5 + Landscape + year + N * P_2O_{5+} Lanscape * N + landscape * P_2O_5 + site + \varepsilon \tag{1}$$

$$Model\ two : Y = \mu + Rep + N + P2O5 + Landscape + N * P2O5 + Lanscape * N + landscape * P2O5 + site + \varepsilon \tag{2}$$

$$Model\ three : Y = \mu + Rep + N + P2O5 + Landscape + site + N * P2O5 + Lanscape * N + landscape * P2O5 + year + \varepsilon \tag{3}$$

$$Model\ four : Y = \mu + N + P2O5 + Landscape + N * P2O5 + Lanscape * N + landscape * P2O5 + Rep + \varepsilon \tag{4}$$

$$Model\ five : Y = \mu + Rep + N + P2O5 + Landscape + N * P2O5 + Lanscape * N + landscape * P2O5 + year + \varepsilon \tag{5}$$

where μ is the grand mean yield(kg ha −1), and ε is the error term.

Before settling on a given model, however, model fit was examined using Akaike's Information Criterion(AIC) and Bayesian Information Criterion(BIC) (Supplementary Table 1). As a result Model, three was the chosen model as its AIC and BIC are lower as compared to the others(Supplementary Table 1). This is because the lower the AIC and BIC are the more the fitted model. As a rule of thumb, changes in BIC (differences between BICs of two models) of 2–6 give weak evidence favoring the more complex model, while differences> 10 give veritably strong substantiation favoring the more complex model. Consequently, the model above was supposed satisfactory(Supplementary Table 1). The infraclass correlation coefficient(ICC) was calculated as the rate of the covariance estimate of the random intercept and the covariance estimate for the residual intercept. The ICC indicates how important the total variation in the outcome is esteemed by the best-fitted model. The variations in yield with fixed effects were considered significant when $p \leq 0.05$ (Supplementary Table 2).

The Tukey- Cramer adjustment of P values was used for the difference between least-square means. Least square estimates and their 95 confidence intervals(CIs) were used for statistical inference. This is because the 95 CI functions as a veritably conservative test of the thesis and it also attaches a measure of a query to sample statistics [21]. The means for two or more levels of a fixed effect were significantly different from one another if their 95 CI wasn't overlapping.

2.6. Economic analysis

Based on the procedure described by Ref. [22], economic analysis was done using estimated quadratic response functions. The current grain yield price of teff on average was 44 birr kg^{-1}. Nitrogen and phosphorus fertilizer was sold for farmers with 46 and birr kg^{-1} respectively from farmer cooperatives. Therefore, the economic optimum rate based on the yield response function was calculated by setting the first derivative of the response function that is $Y = a + bX + cX^2$ to the price ratio of the N and P fertilizer kg^{-1} to the grain price kg^{-1} of teff.

3. Results

3.1. Soil analysis result

As it is indicated in Table 1, the pH range is neutral for lower landscapes and slightly acidic for medium and top landscapes [23,24]. This pH range is conducive to crop production at this range. According to Ref. [24], the organic matter content is very low for the top landscape and low for the medium and lower landscape. This is attributed that in the top landscape, there is a gradual loss of organic materials deposited in the medium and lower landscape. Total nitrogen is in the medium range according to Refs. [24,25]. But according to Ref. [23], the top landscape is rating as low for crop production. Available phosphorus is high and adequate for all

Table 1
The average value of soil analysis results of the testing sites at each landscape landscape

landscape	Soil parameters					
	pH (1: 2.5H2O)	OC (%)	TN (%)	AV. P (mg kg-1)	CEC(cmol$^+$ kg-1)	Textural class
Foot slope	6.76	1.280	0.118	20.375	60.2	Clay
Mid slope	6.25	1.190	0.106	14.653	57.3	Clay, clay loam
Hill slope	6.22	0.333	0.085	7.953	41.8	Clay, clay loam, sandy clay loam

Where OC = Organic carbon, TN = Total nitrogen, AV.P = Available phosphorus.

landscapes according to Ref. [19]. But to Ref. [26], it is high for lower landscape, medium for medium landscape, and low for lower landscape. The CEC of soil is very high for all landscapes according to the rating developed by Ref. [27]. As it is observed in Table 1, despite the CEC being very high for all landscapes numerically it is high at the lower landscape and it is attributed due to the difference in organic carbon. Hence as the organic carbon is increased the CEC of the soil increases.

3.2. Yield and yield-related parameters results

The two objectives of the study were tested with the chosen model(model three) and indicated that the landscapes were significant as well as different rates of nitrogen and phosphorus significantly affected the grain yield of teff(Supplementary Table 2). The significance of fixed effects as shown in the supplementary table(2), site, replication, landscape, N, and the combined effect of P and landscape are significant. The main effect of P, the interaction effect of N and P, the interaction effect of N and landscape, and the interaction effects of N, P, and landscape aren't statistically significant. The yield-related parameters (i.e., biomass yield, and plant height) are highly correlated with the grain yield of tef (Supplementary Table 3).

The grain yield of teff was statistically significantly affected by the rate of nitrogen application (Table 2). Thus the application of 69 kg ha^{-1} nitrogen significantly increased the grain yield of teff. Further application of nitrogen more than 69 kg ha^{-1} didn't bring a significant yield difference though biologically 92 kg ha^{-1} nitrogen brought maximum teff grain yield. The biomass weight and plant height are rather maximum at the application of 92 kg ha^{-1} nitrogen. Application of nitrogen of more than 92 kg ha^{-1} leads to decreasing the grain yield of teff and the graph decline as the rate of nitrogen increases to 115 kg ha^{-1} (Fig. 4).

As the rate of phosphorus fertilizer is different in the different landscapes, different rates of fertilizer rates are going to be recommended in the study area (Supplementary Table 2). Thus as is indicated in Fig. 5, the grain yield of teff positively increases with the increasing phosphorus rate on the hill slopes. As a result, the higher rate of phosphorus (46 kg ha-1) brought the biologically higher teff grain yield in the study area. In the mid slopes, phosphorus fertilizer didn't bring a significant difference in teff grain yield (Fig. 6). The grain yield of teff in this landscape is not statistically significant as the standard errors are overlapping. The grain yield of (Figur 7) statistically significantly decreases with the increasing use of phosphorus fertilizer rates in the foot slopes. The highest grain yield was recorded from the control treatment (0 kg phosphorus ha-1).

3.3. Economics of fertilizer requirement

The ratio of fertilizer cost to the price of teff kg ha^{-1} for N fertilizer was 1.05. Using the quadratic response function (Table 3) and the cost-price ratio, the economically optimum N fertilizer was 85.4 kg ha^{-1}. The optimum grain yield of teff can be obtained by substituting this fertilizer from the quadratic equation.

$$Y = 1584.2 + 10.171X - 0.0534X^2$$

grain yield = 1584.2 + 10.171(85.4) – 0.0534(85.4^2).
Grain yield = 2063.8 kg ha^{-1}
The maximum profit was calculated by substructing the total cost of fertilizer to the total price of grain.
Maximum profit = (2063.8 kg ha^{-1} *44 birr kg^{-1}) – (85.4 kg ha^{-1} *46 birr kg^{-1}).
Maximum profit = 86878.8 birr ha^{-1}

Therefore, the economic optimum rate based on the yield response function for nitrogen fertilizer was 85.4 kg ha^{-1} to obtain maximum profit (86878.8 birr ha^{-1}). Similarly, the optimum phosphorus fertilizer rate at the hill slope was 39.7 kg ha^{-1} to obtain a maximum profit of (96847.8 birr ha^{-1}) (Table 4).

For mid-slope and foot slopes, the response curve is negative means that there is no positive response for the applied fertilizer as it is presented in Figs. 6 and 7. Therefore the application of phosphorus fertilizer for the foot slope and mid-slope is not economical.

4. Discussion

4.1. Grain yield of teff as affected by nitrogen fertilizer rate

There was no interaction effect between nitrogen fertilizer and landscape in the study area (Supplementary Table 2). This is contrary to the study of [28] who stated that there were significant interactions between nitrogen fertilizer treatment and landscape

Table 2
Effect of nitrogen fertilizer rates on teff grain yield and related-yield parameters.

N rates (kg/ha)	Grain Yield (kg/ha)	Biomass weight (kg/ha)	Plant height (cm)
46	1938.1^{b}	6712.2^{b}	110.12^{b}
69	2035.9^{a}	6948.4^{b}	110.75^{ab}
92	2065.2^{a}	7108.6^{a}	112.93^{a}
115	2049.2^{a}	7066.2^{a}	111.19^{ab}
CV	18.87	32.26	9.86

Within a column figures with different letters are significantly different at P-5%).

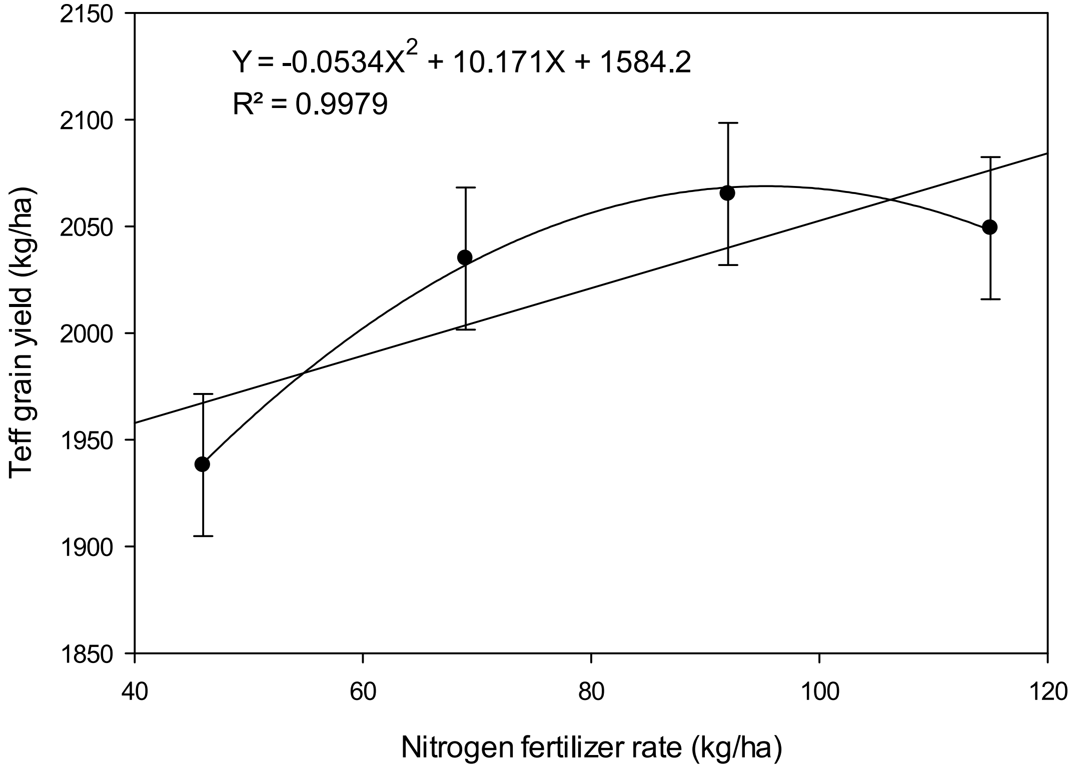

Fig. 4. Nitrogen rate curve on grain yield of teff in Habru district.

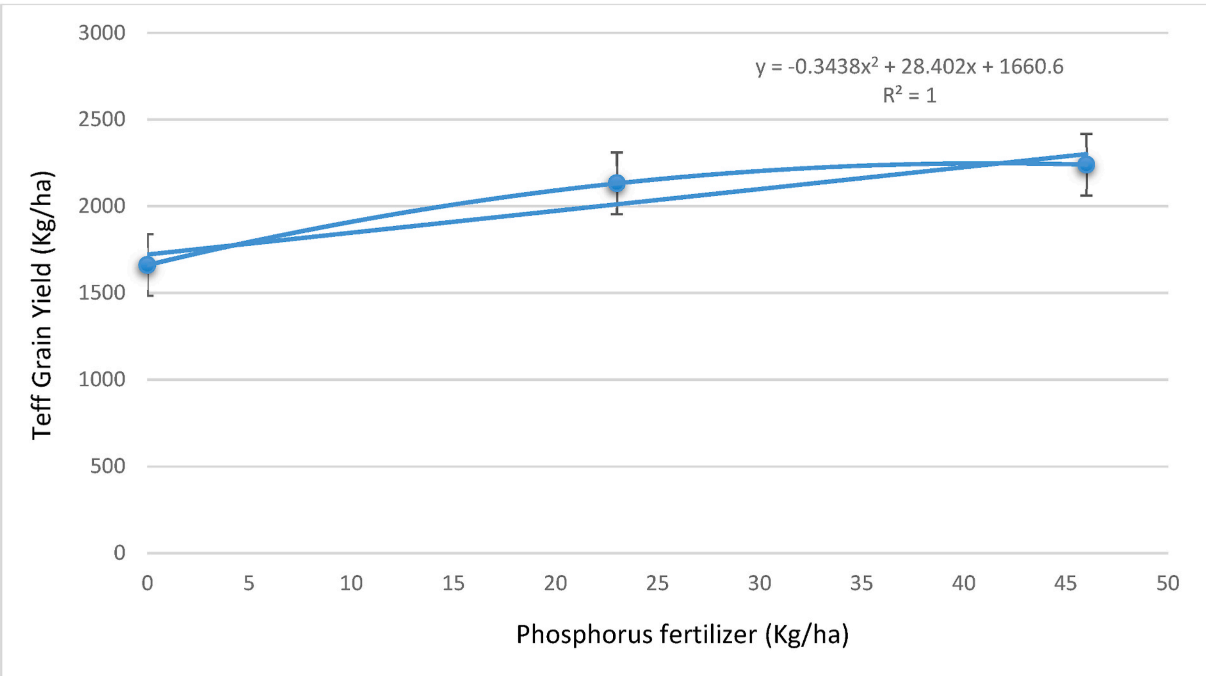

Fig. 5. Phosphorus fertilizer rate across hill slopes on grain yield of teff in Habru district.

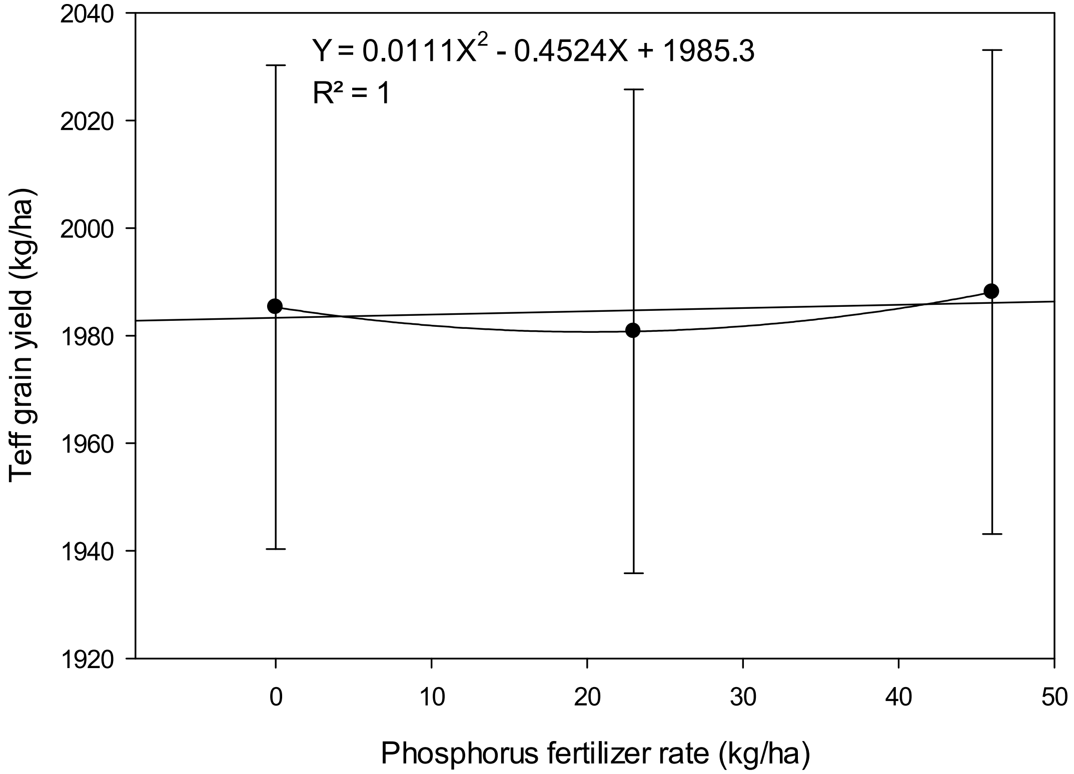

Fig. 6. Phosphorus fertilizer rate across mid slopes on grain yield of teff in Habru district.

Table 3
Quadratic response of nitrogen and phosphorus fertilizers.

Fertilizers	Landscape	Quadratic equation	R^2
Nitrogen	–	$Y = 1584.2 + 10.171X – 0.0534X^2$	0.9979
Phosphorus at hill slope	Hillslope	$y = 1660.6 + 28.402X −0.3438X^2$	1.000
Phosphorus at mid-slope	Midslope	$Y = 1985.3–0.4524X + 0.0111X^2$	1.000
Phosphorus at the foot slope	Footslope	$Y = 2226.3–13.766X + 0.188X^2$	1.0000

Table 4
Optimum fertilizer rate and maximum profit for nitrogen and phosphorus fertilizer.

Fertilizers	CPR	Optimum fertilizer rat (kg ha^{-1})	Maximum Profit (birr ha^{-1})
Nitrogen	1.05	85.4	86878.8
Phosphorus at hill slope	1.14	39.7	96847.8

Note: 1 USD = 52.3 ETB at the time of this economic analysis.

position. But in our study, the grain yield of teff is influenced by the application of nitrogen fertilizers rather than the landscape. This may be, in the study area, the nitrogen level is from medium to low level (Table 1) rating by Refs. [23–25] which is expected to respond in all the landscapes. The other reason for positive fertilizer response may be at foot slopes, which is related to better soil water content, and at hillslopes, which is related to poor soil nitrogen content that results in higher yield response in both cases. Thus for all landscapes, the optimum amount of nitrogen fertilizer is required. In support of our study [29], stated that the seed yields of wheat were very similar to the landforms.

Regarding the main effect of nitrogen fertilizer, the same result as our result is obtained from the work of [30] who stated that the mean grain yield of teff was significantly affected by main nitrogen fertilizer rates. These may be attributed that at the low and medium levels of nitrogen (Table 1) in the soil, grain yield of teff is responded to nitrogen fertilizer [31,32]. also indicated that the grain yield, biomass yield, and plant highest response to the application of nitrogen fertilizer rates.

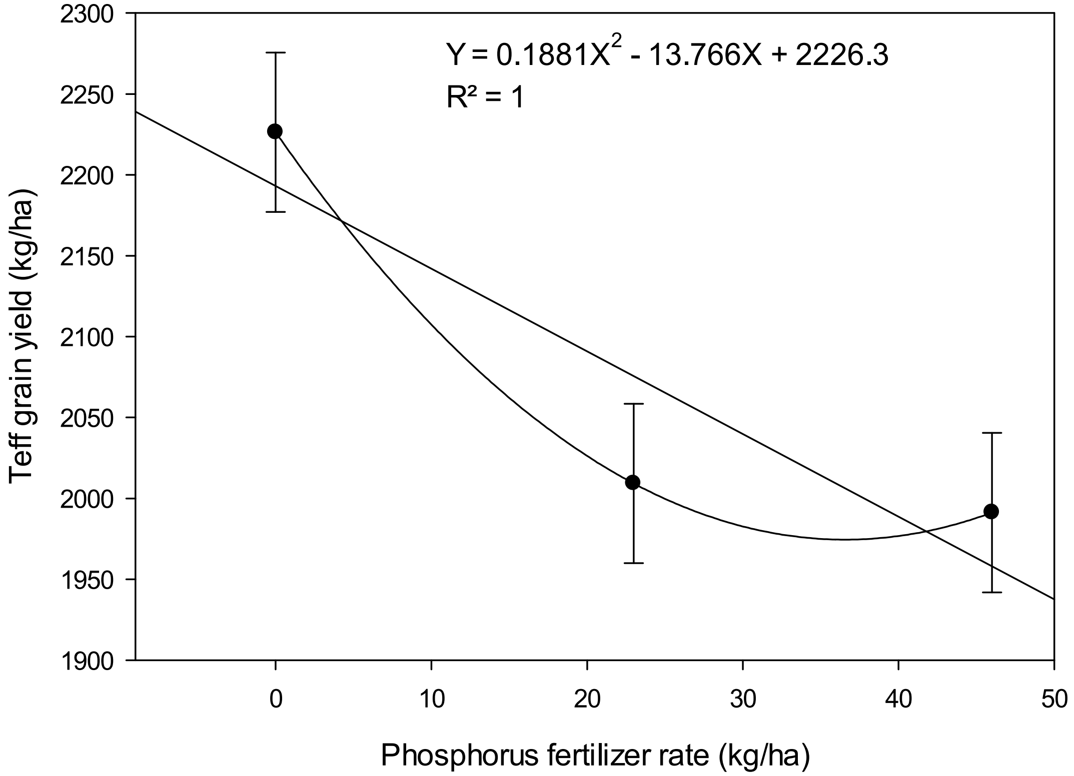

Fig. 7. Phosphorus fertilizer rate across foot slopes on grain yield of teff in Habru district.

4.2. Response of Tef grain yield to phosphorus fertilizer rates

There was an interaction effect between phosphorus fertilizer rate and landscape in the study area (Supplementary Table 2). As a result, different fertilizer rates are recommended for the three landscape positions. Similar studies demonstrated that landscape positions have significantly affected grain yields of cereals to differing phosphors rates [2,3]. Landscape positions have significantly affected yield response to differing phosphors. Thus as is indicated in Fig. 5, the grain yield of teff positively increases with the increasing phosphorus rate on the hill slopes. As a result, the higher rate of phosphorus (46 kg ha^{-1}) brought the biologically higher teff grain yield in the study area. This is attributed that, in the hill slopes, there is a gradual loss of monovalent cations and predominantly replaced by acid-bearing trivalent cat ions like Al and Fe. Thus, the probability of phosphors fixation is higher and thereby increases the demand for phosphorus to bring maximum yield. In the mid slopes, phosphorus fertilizer didn't bring a significant difference in teff grain yield (Fig. 6). The grain yield of teff in this landscape is not statistically significant as the standard errors are overlapping. The grain yield of (Fig. 7) statistically significantly decreases with the increasing use of phosphorus fertilizer rates in the foot slopes. The highest grain yield was recorded from the control treatment (0 kg phosphorus ha^{-1}). This is probably due to the higher accumulation of phosphorus in the foot slopes. According to Cottenie (1980) [26], the critical rating level of phosphorus is higher in the lower landscape (Table 1) and this may lead to decreasing the grain yield of teff due to competition for water and antagonistic effect on Zn and other nutrients. Different studies also show that in the lowland areas, there is not a significant yield increment for the application of phosphorus for different cereal crops [33,34]. This may also be due to the lower landscape of most Ethiopian soils, especially in the rift valley of Ethiopia, the soil is rich in phosphorus content as it is transitional basalt from the geological formation.

5. Conclusion and recommendation

1. Nitrogen and phosphorus fertilizer rates are differently affected by landscape position in the study area.
2. From the result, there are differences in teff yield response to phosphorus mineral fertilizers among landscape positions. But nitrogen fertilizer is not significantly affected by landscape position for grain yield response in our study area.
3. In all the landscapes, different rates of phosphorus fertilizer brought maximum yield. The mean grain yield is lower in hillslopes but it demands more phosphorus fertilizer and is highly responded. In foot slopes, the mean grain yield is relatively higher compared to the mid and hill slopes but phosphorus is surplus in this landscape.

The above findings indicated that the policy in the application of similar phosphorus fertilizer rates in all landscape positions has to be changed. Application of similar rates of phosphorus fertilizer in this study is found to be a loss of resource labor and environmental damage to the soil resource. In drought-prone areas of Ethiopia like the Habru district, the application of overdosed fertilizer has a devastating environmental effect and crop yield as it is related to rainwater competition between the crop and the added fertilizer. Thus, landscape-based phosphorus fertilizer application is recommended in Habru district and similar agro-ecologies.

On the other hand, gradual losses in hill slopes and relative accumulation of nitrogen in foot slopes with a probable advantage of response for higher water holding capacity of soil in foot slopes brought similar response for nitrogen fertilizer. Accordingly, the application of a similar nitrogen fertilizer rate is recommended in Habru district and similar agro-ecologies.

However, we recognize that the scope of our study was limited for a district and it should be verified on a large scale. We also suggest further research work to validate this work in other crops in the study areas and similar agro-ecologies. Generally, to have economically feasible fertilizer rates, the landscape should be considered in fertilizer recommendation works. Should also consider conservation practices and organic fertilization to overcome the loss of nutrients in hillslopes.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17813.

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