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Research article

Precursor crop and vertisols type influences on teff (Eragrostis tef) response to fertilizer rates in the central highlands of Ethiopia

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A B S T R A C T

Optimization of fertilizer-N and -P is important to highland production of teff (*Eragrostis tef*) on Vertisols of central Ethiopia but may be affected by precursor crop and Vertisols type. On-farm experiments were conducted in three major teff growing districts of North Shewa (Moretina jiru, Ensaro, and Merhabete) in 2019 and 2020 with the main objectives was to determine the effect of precursor crops and Vertisols type on teff response to N and P rates. The N x P factorial combinations include 0, 60, 120, 180, and 240 kg N ha^{-1} and 0, 30, 60, and 90 kg P ha^{-1} applied each to light and heavy Vertisols with either cereal or pulse precursor crops in each district. In Merhabete, grain yield was significantly influenced by *Pc* x Vt x N and *Pc* x Vt x P but always with the lowest and highest grain yield with 0 and 240 kg N ha^{-1}, respectively. Yield was 394 % more with 240 kg N ha^{-1} compared with no N and P applied. The Vt x *Pc* × N interaction affected teff yield in Moretina Jiru as application of 240 kg N ha^{-1} increased teff yield by 440 %, 30 %, 23 %, and 7 % on light Vertisols compared with 200 %, 16 %, 13 %, and 2 % on heavy Vertisols. The 4-way interaction of Vt x *Pc* x N x P affected grain yield in Ensaro due to the low N and P status of the soil coupled with the distinct Vertisols type in the district. In all districts, yield response to N was greater with pulse compared with cereal precursor crops and with a greater response for heavy compared with light Vertisols in Moretina Jiru and Ensaro. In Moretina Jiru, application of 170 kg^{-1}N and soil maintenance level of 30 kg^{-1} of P ha^{-1} are recommended as an economic optimum rate (EOR). In Ensaro, the EOR for teff following cereal on light Vertisols are 166 kg N ha^{-1} and 65 kg P ha^{-1}. At Ensaro, needed rates for teff following pulse on light Vertisols are 198 N ha^{-1} and 48 kg P ha^{-1}. At Ensaro, needed rates for teff following cereal on heavy Vertisols are 240 N ha^{-1} and 90 kg P ha^{-1}. At Ensaro, needed rates for teff following pulse on heavy Vertisols are 240 N ha^{-1} and 80 kg P ha^{-1}. In Merhabete, the EOR for teff following cereal on light Vertisols are 182 kg N ha^{-1} and 60 kg P ha^{-1}. In Merhabete, needed rates for teff following pulse on light Vertisols are 206 N ha^{-1} and 64 kg P ha^{-1}. In Merhabete, needed rates for teff following cereal on heavy Vertisols are 240 N ha^{-1} and 90 kg P ha^{-1}. In Merhabete, needed rates for teff following pulse on heavy Vertisols are 218 N ha^{-1} and 58 kg P ha^{-1}. Therefore, those N and P rate are recommended for the study area, soil type and precursor crops.

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1. Introduction

Teff [*Eragrostis tef* (Zucc.) Trotter] was domesticated in Ethiopia where it is a major crop with wide adaptation [1] requiring relatively less water compared with most cereal crops [2]. It is of global interest among Ethiopian diaspora and because it is gluten-free [3]. The grain is highly nutritious and the straw is an important cattle feed source. It is a major market crop in Ethiopia [4]. The flour of teff grain is used to make injera a traditional fermented, soft porous pancake-like local bread. Teff covers about 30 % of the total cultivated land of cereal (3 million ha) and 19.5 % of grain production of the country [5]. The national average teff grain yield is estimated to be 1465 kg ha^{-1} with much variability [5]. Recommended fertilizer rates were 60 kg N and 26 kg P ha^{-1} for Vertisols clay soils but less N for sandy clay loam are [6]. Tesfahun [7]recommended the application of 120 kg NPS fertilizer, which is equivalent to 22.8, 20, and 8.4 kg ha^{-1} N, P, and S, respectively. Farmers often apply much higher rates for teff on highland Vertisols. Lentil (*Lens culinaris* Medikus), wheat ((*Triticum aestivum* L.), chickpea (*Cicer aritienum* L.), and tefff (*Eragrostis tef*) commonly precede teff producer on highland Vertisols.

The shrink-swell capacity, high cation exchange capacity and high water holding capacity are important characteristics of highland Vertisols in central Ethiopia due to high montmorillinte clay content [8]. The soil pH varies from slightly acidic to strongly alkaline [9]. Vertisols are important to agriculture in Ethiopia accounting for about 12.7 million ha of cropland (10.3 %), especially for wheat, teff and chickpea. Ethiopia ranks the third in the abundance of Vertisols after Sudan and Chad [10]. Eight million ha of Vertisols are found in the highlands area of Ethiopia [11]. The central highlands of Ethiopia shares 7.6 million hectares [12]. Vertisols are often low in available N and P [13–17]. Severe water logging often constrains productivity. Fertilizer-N application can increase teff yield on Vertisols [18].

Fertilizer recommendations for teff production are generalized with no consideration of production condition and of the farmers' practice of applying more N and P than recommended rate. Given the great importance of highland production of teff production Vertisols, fertilizer-N and –P need to be optimized for economic and environmental reason. The objective of this study was to accurately determine the effects of cereal compared to pulse precursor crops on heavy compared to light Vertisols on teff responses to fertilizer-N and -P.

2. Material and methods

2.1. Site description

The research was conducted in 2019 and 2020 on 24 farmers' fields in three districts of Amhara Regional State. The districts are Merhabete, Moretina jiru and Ensaro (Fig. 1). The mean precipitation, maximum air temperature, and minimum air temperature are,

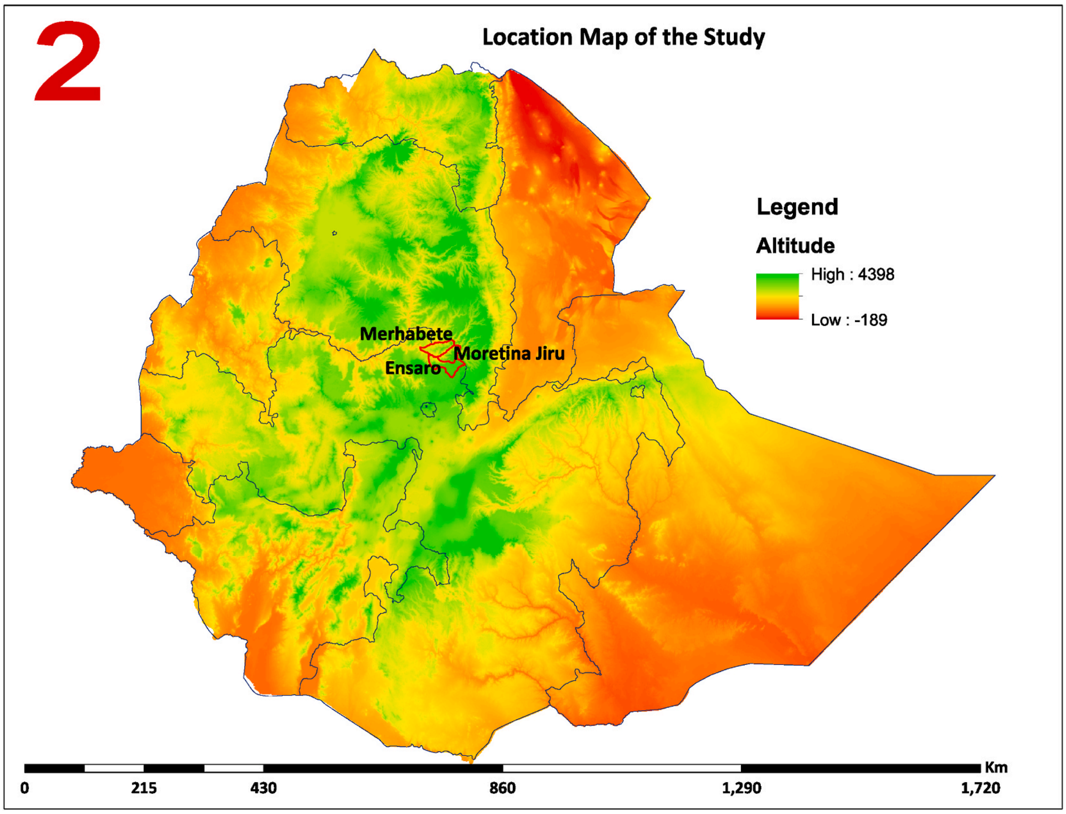

Fig. 1. Locations and DEMs of the landscapes of Moretina Jiru Merhabete and Ensaro district in Ethiopia.

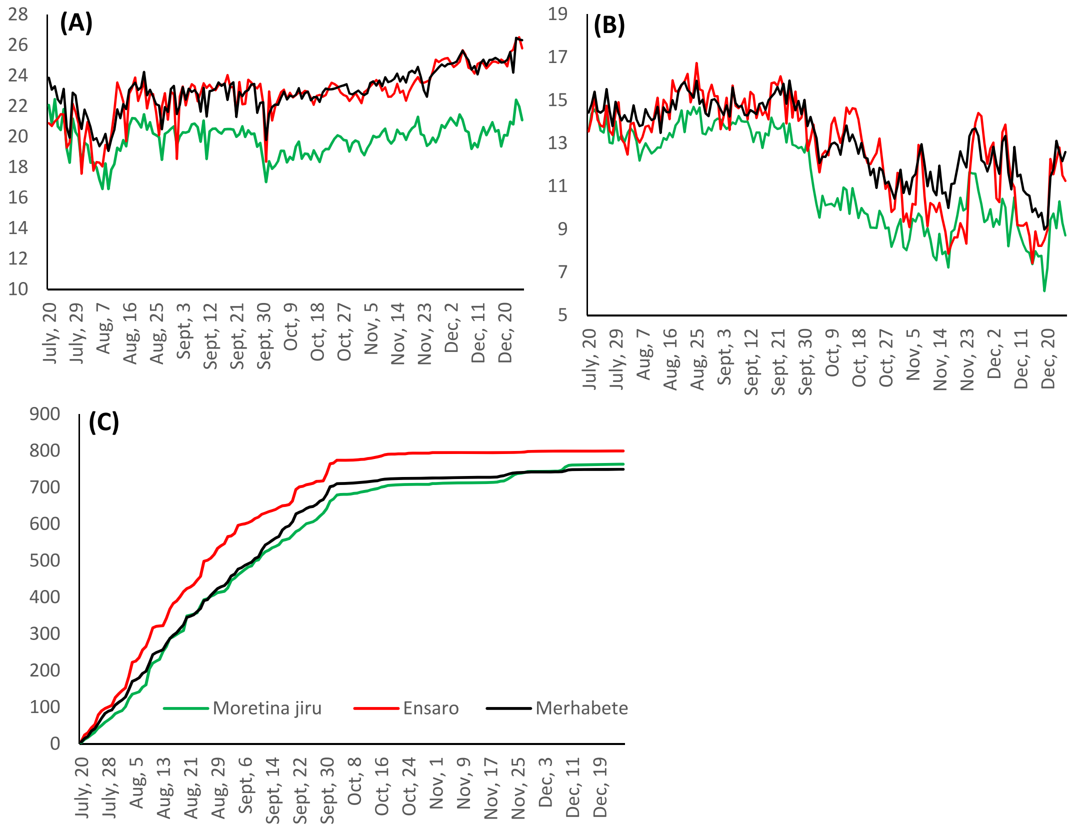

Fig. 2. Average daily minimum temperature; a = daily average maximum temperature, and b = and cumulative rainfall (C) in Moretina Jiru, Ensaro, and Merhabete district during the growth period (2019 and 2020).

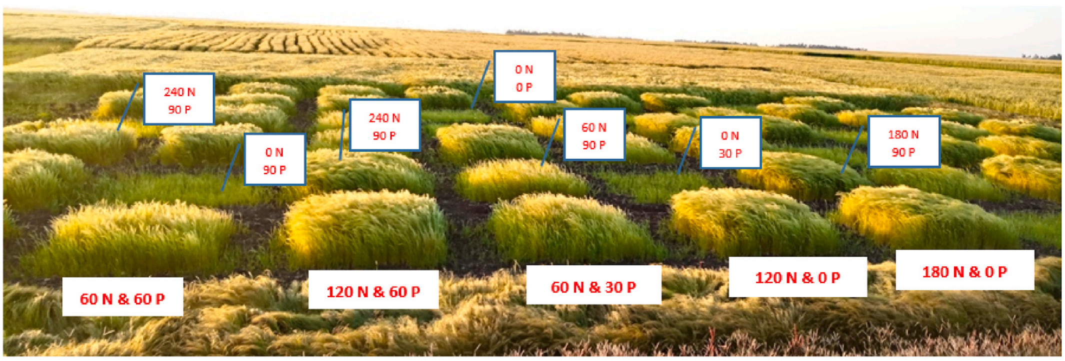

Fig. 3. Field performance of teff treatment in light Vertisols having cereal precursor crop in Moretina Jiru district during 2020.

respectively, 982 mm, 22.1 C, and 9.4 C for Moretina jiru; 1018 mm, 25.3 C, and 13.1 C for Merhabete; and 1276 mm, 22.2 C and 6.9 C for Ensaro. The rainfall is bimodal but most rainfall from July to August when the experimentation was conducted. The respective mean rainfalls recorded during the season of experimentation were 800, 750, and 763 mm (Fig. 2A–C). The geographic coordinates of each experimental site are presented in Table 1 (Fig. 3).

The farming system in all districts characterized by highland wheat mixed farming system and highland teff mixed farming system. Livestock are the most important component of the system providing manure, improving the native diet and being a means of cash income. In these system cattle dominate followed by sheep, goats and equines. Oxen are used for draught [19]. Crop residues and by-products have an important role as sources of animal feed as the livestock does not leave the area, particularly during the dry season [20,21]. Sorghum [*Sorghum bicolor* (L.), teff (*Eragrostis tef*), wheat (*Triticum aestivum*) and maize (*Zea mays*) are the major crops grown in Merhabete district for both household consumption and marketing. At Ensaro district wheat (*Triticum aestivum*), teff (*Eragrostis tef*), sorghum [*Sorghum bicolor* (L.), chickpea (*Cicer arietinum* L) and grass pea (*Lathyrus sativus*) are the most widely grown crops. While at

Table 1
Geographic coordinates of farmer's field used for the experiment in each Vertisols type and precursor crop combination in Moretina Jiru, Ensaro and Merhabete during 2019 and 2020.

Year	District	Heavy Vertisols						Light Vertisols					
		Cereal			Pulse			Cereal			Pulse		
		Lat	long	Alt	Lat	long	Alt	Lat	long	Alt	Lat	long	Alt
2019	Moretina Jiru	9.885621	39.166986	2668	9.889254	39.156586	2665	9.962870	39.221604	2655	9.896766	39.154670	2663
	Ensaro	9.810363	38.899772	2662	9.798319	38.898448	2652	9.819105	38.898148	2665	9.789936	38.936508	2619
	Merhabete	10.060922	38.975762	2141				10.052139	38.952813	2157	10.060159	38.974812	2141
2020	Moretina Jiru	9.859396	39.186028	2654	9.859496	39.182996	2655	9.905134	39.157300	2672	9.891871	39.162246	2161
	Ensaro	9.798267	38.899217	2654	9.786810	38.900747	2643	9.816436	38.899029	2663	9.790985	38.932587	2625
	Merhabete	10.058604	38.959216	2161	10.061090	38.961120	2163	10.061833	38.975478	2141	10.061698	38.973555	2146

Lat = latitude, long = longitude, Alt = altitude.

Table 2
Mean 0–20 cm soil test results for Vertisols clay soils in three districts of the central Ethiopia highlands (each combination in each district was the average of 4 sites).

Soil physico-chemical properties	Moretina jiru		Ensaro		Merhabete	
	LV	HV	LV	HV	LV	HV
Textural Class	Clay	Clay	Clay	Clay	Clay	Clay
Clay	73.85	78.83	66.1	70.2	62.4	65.4
Silt	27.95	10.47	24.5	22.2	22.9	21.5
Sand	8.2	10.7	9.4	7.6	14.7	13.1
pH	6.7	7.1	6.6	7	6.5	6.8
CEC (Cmol kg^{-1})	54	58	39	45	35	39
Soil OC (g kg^{-1})	9.9	7.6	10.6	9.3	11.5	9.3
TN (g kg^{-1})	0.9	0.7	1.1	0.79	0.97	0.79
Av.P (mg Kg^{-1})	12.6	16	5.5	8.3	4.4	6.2
K+ (cmo(+) kg-1 soil)	1.1	1.2	0.92	1.3	0.95	1

HVS = heavy Vertisols, LVS = light Vertisols.

Moretina jiru district wheat (*Triticum aestivum*), teff (*Eragrostis tef*), lentil (*Lens culinaris* Medikus), sorghum [*Sorghum bicolor (*L.) and faba bean (*Vicia faba*) are crops widely grown in the district.

The dominant soil for teff production for all the districts are Vertisols. For most crops except teff, the traditional manually formed broad bed and furrow are used to facilitate surface drainage of the excess water are practiced especially in Moretina jiru and Ensaro district on Vertisols. The following sequential operation are used to made broad bed and furrow: First seeds were spread out on a flat seedbed next an oxen-drawn plow are used to open furrow with an interval of 0.8 m and 0.2 m dead furrow using family labour. The soil is then scooped up from the furrows and dumped on the beds. By using this method, they not only form the broad bed and furrow but they also cover the seeds. The land preparation starts early following a small rain during April and May. Most crop including teff are sown at the start of July to beginning of August [22].

Teff productions in the districts are characterized by two to three tillage operations with oxen draft power. Then the soil is compacted by trampling with a large number of cattle, donkeys and humans right before broadcast sowing of seed and fertilizer on the compacted soil. Compaction of the soil is important to create smooth surface for better contact of the tiny teff seed with the soil, to prevent seeds from being washed away by rain before germination, to enhance root anchorage, and to prevent the soil surface from drying quickly in the early growth stage when drought is common [23].

All sites in all districts had clay soil (Table 2). The cation exchange capacity (CEC) was always high. Soil properties ranged from 6.5 to 7.1 for pH, 7.6–11.5 g kg^{-1} for OC, and 0.7–1.1 for total N. Heavy compared with light Vertisols, on average, had more clay, higher pH, and less soil OC and total N. Olsen P ranged from 4.4 mg kg^{-1} in light Vertisols of the Merhabete to 16 mg kg^{-1} in heavy Vertisols in Moretina Jiru. Soil exchangeable K (cmol kg^{-1}) ranged between 0.92 in light Vertisols to 1.30 in heavy Vertisols of Ensaro, between 1.1 and 1.2 in Moretina Jiru, and between 0.95 and 1.00 in Merhabete.

2.2. *Fertilizer application inventory*

Before experimenting, we surveyed farmers' experience in the application of fertilizer for teff production. The field observation from Moretina jiru, Merhabete, and Ensaro districts on 46 farmer's fields indicated that farmers apply NP fertilizer beyond the recommended fertilizer rate. In Moretina jiru district 4.5 %, 59.1 %, 13.6 %, and 22.7 % of the interviewed farmers, apply N fertilizer at a rate of 60–120, 120–180, 180–240, and above 240 kg N ha^{-1}, respectively. Likewise, 36.4 % and 63.6 % of the interviewed apply P fertilizer at a rate of 30–60 and 60–90 kg P ha^{-1}, respectively. In Ensaro district 54 %, 33.3 %, 8.3 %, and 4.2 % of the interviewed farmers apply N fertilizer at a rate of 60–120, 120–180, and 180–240 and above 240 kg N ha^{-1}, respectively. Likewise, 4.2 % and 66.7 %, 2.5 %, and 4.2 % of the interviewed apply P fertilizer at a rate of 0–30, 30–60, 60–90, and above 90 kg P ha^{-1}, respectively. Indicating that farmers are not applying recommended NP fertilizer for the test crop on Vertisols (60 and 59.5 kg N and P_2O_5 ha^{-1}).

2.3. *Treatments, design and experimental procedure*

In each district and year, a farmers' field was selected for each combination of pulse (either lentil, grass pea, or chickpea) or cereal (wheat or teff) precursor crop with light or heavy Vertisols type giving 12 trials in each of the two years. The Vertisols types were according to farmers' differentiation with light Vertisols locally called "Bushella" and having comparatively low water holding capacity, better drainage, less fertility, and better workability compared with heavy Vertisols, called "kebad Mererie". The heavy Vertisols requires surface drainage such as with broad beds and furrows for most crops except teff. In each farmer's filed, the experiments were complete factorial factorials with randomized complete block designs and three replications. The fertilizer N x P rate treatment were all combinations of 0, 60, 120, 180, and 240 kg N ha^{-1} with 0, 30, 60, and 90 P ha^{-1}. Plots of 6.25 m^2 with 1 m spacing between plots and 1.5 m between blocks. Ridge was constructed in between plot to reduce nutrient movement between plot and hence to reduce boarder effect.

The fields were plowed twice with oxen-drawn 'maresha' plows for weed control, sown and trampling lightly by human-foot traffic to improve seed-soil contact for good germination and emergence. Teff seed was broadcast sown at 25 kg ha^{-1} in mid of July cv Dega at Moretina Jiru and Ensaro and cv Kora at Merhabete. Sulfur, Zn, and B were broadcast applied at sowing to full trial area at 10, 2, and

0.1 kg ha^{-1}, respectively together with fertilizer-P. Urea, triple super phosphate, calcium sulfate, zinc sulfate, and borax were nutrient sources. Urea-N was broadcast applied 50 % at sowing and 50 % at tillering when the soil is moist. Hand-weeding was done at the tillering stage and again two weeks later. Pests and diseases were not observed in any trials except the shoot fly observed in Merhabete in 2020. Harvesting was done from the first week of December in Merhabete and the second week of December in Moretina Jiru and Ensaro. The whole plot was harvested after checking no variability with in a plot because of the wider space left between plots and the ridge constructed in between two plots.

2.4. Crop data collection

The following data were collected for this study;

Plant height (cm): was measured at physiological maturity from the base of the main stem to the base of the fully opened top leaf (the collar of the flag leaf) from 10 randomly selected plants in each plot.

Panicle length (cm): was measured starting from the node where the first panicle branch emerged to the tip of the panicle from 10 randomly selected plants in each plot.

Number of total tiller per plant: The average number of tiller per plant was counted excluding the main shoot from 10 randomly selected plants in each plot.

Number of fertile/productive tiller: The number of productive/fertile tillers was determined by counting the tillers that produced panicles from 10 randomly selected plants in each plot.

Aboveground biomass (kg ha^{-1}): was measured from harvested from the net plot area after sun drying for two week.

Grain yield (kg ha^{-1}): was determined by harvesting and threshing the seed yield after adjusting to 12.5 % moisture content.

Straw yield (kg ha^{-1}): was calculated by subtracting grain yield from aboveground dry biomass yield.

Harvest index: was calculated as the ratio of the total grain yield to the total above-ground biomass yield.

2.5. Statistical analysis

A linear mixed model was used to determine the variation in yield and some yield components of teff with the different precursors, type of Vertisols, N rate, and P rate combining study site and years. Independent analyses were performed for each district. The fixed effects in the model were precursor crops, type of Vertisols, and N and P rate, with sites in each district as the random effect. The following model was used to conduct the statistical analysis using the SAS (Version 9.1) Statistical Software [24].

$$\mathrm{Y} = \mu + \mathrm{Y} + \mathrm{rep} + Pc + \mathrm{Vt} + \mathrm{N} + \mathrm{P} + Pc \text{ x } \mathrm{Vt} + Pc \text{ x } \mathrm{N} + Pc \text{ x } \mathrm{P} + \mathrm{Vt} \text{ x } \mathrm{N} + \mathrm{Vt} \text{ x } \mathrm{P} + \mathrm{N} \text{ x } \mathrm{P} + Pc \text{ x } \mathrm{Vt} \text{ x } \mathrm{N} + Pc \text{ x } \mathrm{Vt} \text{ x } \mathrm{P} + Pc \text{ x } \mathrm{N} \text{ x } \mathrm{P} + \mathrm{Vt} \text{ x } \mathrm{N} \text{ x } \mathrm{P} + Pc \text{ x } \mathrm{Vt} \text{ x } \mathrm{N} \text{ xP} + \text{location} + \varepsilon$$

where μ is the grand mean, Y is the year in which the experiment was conducted, rep is the number of replication in each farmer field, *Pc* is the precursor crop, Vt is a type of Vertisols based on the farmer's classification, N is the nitrogen fertilizer rate, P is the phosphorus rate, location is sites in each farmers field and ε is the error term. Location is sites in each district and it is a random component in the model.

Wherever the treatment effect was significant, mean separation was made using Tukey's HSD. Means were considered to be significant when $p \leq 0.05$. Multiple regressions analysis were also performed to fit the response curve of N, P, and their interaction in each location, Vertisols type and precursor crops.

2.6. Soil sampling and processing

Pre-plant soil samples of 0–20 cm depth were collected from each farmer's field with soil from 10 sampling spots composited in to one sample. The soil samples were air dried, ground, and passed through 2-mm sieved mesh for the analysis at the soil and water analysis laboratory of Debra Birhan Agricultural Research Center. The sample were analyzed for particle size distribution by the hydrometer method [25]. Soil pH with a digital pH meter potentiometrically in a supernatant suspension of 1:2.5 soil to distilled water ratio [26], soil organic carbon (OC) with Walkley and Black procedure [27], cation exchange capacity (CEC) with 1 M ammonium acetate extraction at pH 7 [28], total N by micro-Kjeldhal [29], and available P by the Olsen method [30] colorimetrically with the ascorbic acid-molybdate blue [31].

2.7. Economic analysis

Based on the procedure described by CIMMYT [32], economic analysis was carried out utilizing partial budget analysis. For partial budget analysis, the variable cost of fertilizer and labor were taken at the time of planting and during other operations. Teff grain at one month after harvest was valued at at 38 ETB kg^{-1} in Moretina Jiru and Ensaro, and 37 ETB kg^{-1} in Merhabete. Fertilizer use costs were 22.5 ETB kg^{-1} P and 32.9 ETB kg^{-1} N. Economic sensitivity of returns to fertilizer use was evaluated with 10 scenarios: the current fertilizer cost and grain value; 150 % of the current fertilizer cost with current grain value; 150 % of both current fertilizer cost and grain value; 50 % of current grain value with current fertilizer cost; 50 % of both current fertilizer cost and grain value; 200 % of current grain value with current fertilizer cost; 200 % of both current fertilizer cost and grain value; 200 % of current fertilizer cost with current grain value; 200 % of current grain value with current fertilizer cost; and 200 % of current fertilizer cost with 150 % of current grain value.

3. Result

3.1. Aboveground biomass yield

The result of the combined analysis of the fixed effect of precursor crop, type of Vertisols, N rate, and P rate are presented in Table 3. In Merhabete, aboveground biomass yield was affected by *Pc* x N, *Pc* x P, Vt x N, Vt x P, *Pc* x Vt x N, and *Pc* x Vt x P (Tables 3 and 4). The average biomass yield was 9154 kg ha^{-1} with the highest N rate and 6664 kg ha^{-1} at the highest P rate, and the average biomass yield increase was 389 % (7282 kg ha^{-1}) with N rate and 30 % (1521 kg ha^{-1}) with P rate. The *Pc* x Vt × N interaction was largely due the greatest biomass yield increase with N rate for heavy Vertisols following cereal and the least increase with heavy Vertisols following pulse with intermediate magnitudes of response for light Vertisols. In contrast, the *Pc* x Vt × P interaction was largely due the greatest biomass yield increase with P rate for heavy Vertisols following pulse and the least increase with light Vertisols following pulse with intermediate magnitudes of response for both Vertisols type following cereal.

In Ensaro, aboveground biomass significantly affected by the interaction of *Pc* x Vt x N, *Pc* x Vt x P, *Pc* x N x P, Vt x N x P, and Vt x *Pc* x N x P (Table 3). The average biomass yield was 7001 kg ha^{-1} and 5163 kg ha^{-1} with the highest N and P rate, respectively. The respective biomass yield increase was 402 % (5606 kg ha^{-1}) with N rate and 38 % (1434 kg ha^{-1}) with P rate. The *Pc* x Vt × N interaction was largely due the greatest biomass yield increase (631 %) with N rate for light Vertisols following cereal and the least increase (345 %) with heavy Vertisols following pulse with intermediate magnitudes of response for heavy Vertisols following cereal (355 %) and light Vertisols following pulse (468 %). In contrast, the *Pc* x Vt × P interaction was largely due the greatest biomass yield increase (142 %) with P rate for light Vertisols following cereal and the least increase (22 %) with heavy Vertisols following pulse with intermediate magnitudes of response for heavy Vertisols following cereal (27 %) and light Vertisols following pulse (35 %). With the interaction of Vt x *Pc* x N x P, biomass yield of teff varied from 475 to 10279 kg ha^{-1} with a yield improvement of 2064 % (Table 5). The interaction of Vt x *Pc* x N x P largely due the greatest biomass yield increase (1198 %) with N and P rate for light Vertisols following

Table 3
Analysis of variance for tef yield and other agronomic traits tested at five N rate, four P rate, and two precursor crops under two Vertisols type.

Source	Df	Moretina Jiru		Ensaro		Merhabete	
		BY	GY	BY	GY	BY	GY
Rep	2	0.2172	0.7547	0.927	0.3275	0.12	0.3318
Year	1	<.0001	0.0001	0.6402	0.0678	0.8447	0.003
Precursor crop (*Pc*)	1	0.1501	0.0232	0.1056	0.1766	0.9538	<.0001
Vertisols Type (Vt)	1	<.0001	0.7139	0.044	0.0377	0.5066	<.0001
Nitrogen rate (N)	4	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Phosphorus rate (P)	3	0.0408	0.1893	<.0001	<.0001	<.0001	<.0001
Pc*Vt	1	<.0001	0.7133	0.9789	0.3297	0.705	<.0001
Pc*N	4	0.859	0.5604	<.0001	0.3072	0.8537	0.0002
Pc*P	3	0.9141	0.3184	0.1086	0.3691	0.0328	0.0489
Vt*N	4	0.5113	<.0001	<.0001	0.0005	0.4438	<.0001
Vt*P	3	0.0628	0.2021	0.0061	0.0175	0.0246	<.0001
N*P	12	0.4764	0.6442	<.0001	0.0576	0.0754	0.008
Pc* Vt*N	4	0.084	<.0001	0.0176	<.0001	0.0024	<.0001
Pc*Vt*P	3	0.0511	0.0891	0.0797	0.2584	0.0029	0.0093
Pc*N*P	12	0.4237	0.0669	0.0692	0.2878	0.8486	0.5317
Vt*N*P	12	0.5774	0.4243	0.0217	0.4443	0.5188	0.2149
Pc*Vt*N*P	12	0.8011	0.0802	0.0147	0.0434	0.579	0.4152

DF = degree of freedom, BY = biomass yield, GY = grain yield.

Table 4
Yield and some yield components of tef in Merhabete district as affected by precursor crop, type of Vertisols, N rates and P rate in 2019 and 2020 cropping seasons.

Biomass yield (kg ha^{-1})					Grain yield (kg ha^{-1})			
N rate	Heavy Vertisols		Light Vertisols		Heavy Vertisols		Light Vertisols	
	Cereal Precursor	Pulse Precursor	Cereal Precursor	Pulse Precursor	Cereal Precursor	Pulse Precursor	Cereal Precursor	Pulse Precursor
0	1302	2090	2196	1899	292	543	537	340
60	3918	3560	4718	4873	801	860	1158	1592
120	6652	6560	6895	7330	1402	1789	1586	2261
180	8588	7654	8303	9080	1927	1889	1708	2494
240	9231	8430	9113	9843	2143	1951	1679	2680
P rate								
0	4767	4251	4982	6573	961	1013	1069	1984
30	5930	5747	6291	6371	1317	1426	1357	1732
60	6430	6283	6540	6968	1475	1593	1401	1904
90	6626	6355	7168	6509	1498	1593	1508	1872

Table 5
Yield and some yield components of teff in Ensaro district as affected by precursor crop, type of Vertisols, N and P rates in 2019 and 2020 cropping seasons.

	Biomass yield (kg ha^{-1})									Grain yield (kg ha^{-1})							
	Cereal precursor					Pulse precursor				Cereal precursor				Pulse precursor			
	N rate	P rate				P rate				P rate				P rate			
		0	30	60	90	0	30	60	90	0	30	60	90	0	30	60	90
HV	0	1696	1649	1659	1884	2132	2117	2130	2236	643	599	504	582	1194	1088	1214	1131
	60	2965	3932	3563	3581	4082	4509	5233	5173	1027	1352	1302	1164	1558	1535	1828	1532
	120	4592	5201	5501	5352	6221	6907	7333	7677	1666	1752	1808	1544	1853	1759	1747	1747
	180	5612	5616	6751	7656	7574	8343	9258	9332	2030	1712	2159	2131	1921	1980	1913	2135
	240	6586	7781	8245	8742	8359	9564	10104	10279	2094	2348	2396	2507	1947	2081	2138	2338
LV	0	552	692	475	479	1107	1189	1144	1186	193	137	187	190	267	393	430	378
	60	2182	2352	2315	2709	2490	3315	3859	3363	120	527	363	660	789	1031	1249	1079
	120	1319	4382	4932	4352	4177	4618	5229	5351	130	827	1100	707	1204	1167	1472	1494
	180	1235	5049	4489	4142	4711	5756	6815	6317	190	1010	760	463	1313	1525	1784	1635
	240	2085	3680	4132	6165	4901	6699	7405	7290	180	403	343	1427	1299	1676	1819	1596

HV = heavy Vertisols; LV = light Vertisols.

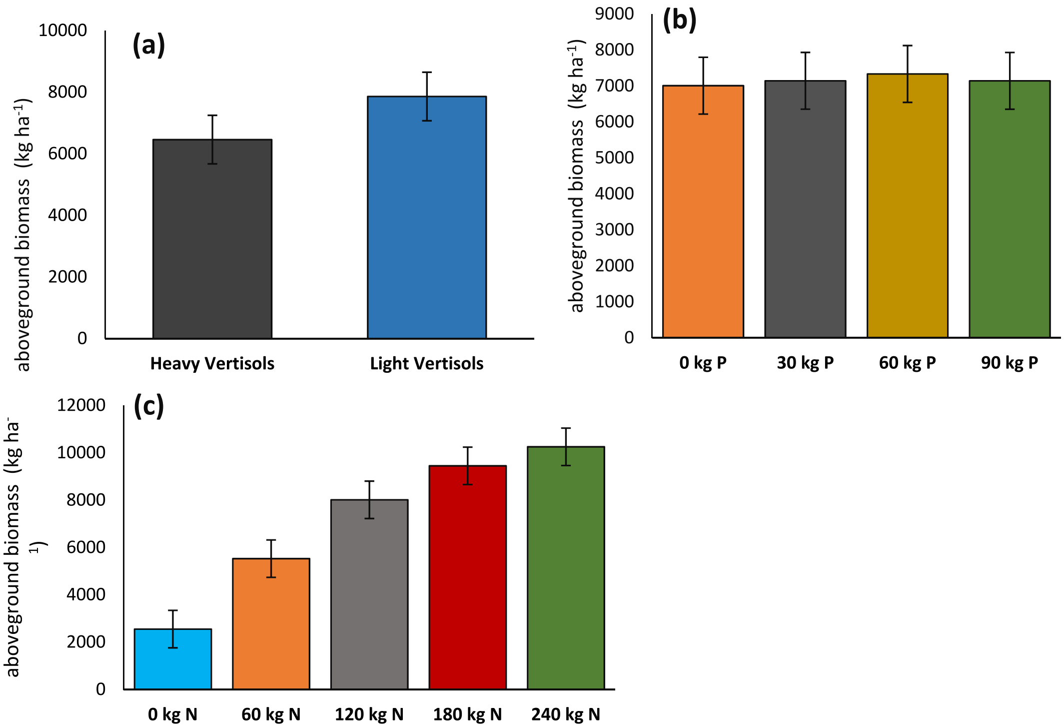

Fig. 4. Effect of precursor crop on teff aboveground biomass yield (A), effect of P rate on teff aboveground biomass yield (B) and effect of N rate on teff aboveground biomass yield (c) in Moretina Jiru in 2019 and 2020. Error bars represent ±1SE.

cereal and the least increase (386 %) with heavy Vertisols following pulse with intermediate magnitudes of response for heavy Vertisols following cereal (430 %) and light Vertisols following pulse (569 %).

In Moretina jiru, Vertisols type, N, and P rate had also significantly ($p < 0.001$, $p < 0.001$, and $p < 0.05$) influenced teff aboveground biomass (Table 3). Significantly the highest (7856 kg ha^{-1}) and lowest (6457 kg ha^{-1}) aboveground biomass yield was observed from pulse and cereal precursor crops, respectively (Fig. 4a). Similarly, aboveground biomass was significantly increased by increasing the N application rate (Fig. 4c). Application of the highest N rate increased aboveground biomass yield by 302 % (7697 kg ha^{-1}), 85 % (4721 kg ha^{-1}), 28 % (2237 kg ha^{-1}), and 9 % (804 kg ha^{-1}) compared with application of 0, 60, 120 and 180 kg N ha^{-1}, respectively (Fig. 4). Significantly, the highest (7333 kg ha^{-1}) and lowest (7008 kg ha^{-1}) teff yield was observed with the application of 60 and 0 kg P ha^{-1}, respectively (Fig. 4b). The interaction of *Pc* x Vt also significantly influenced biomass yield (Table 4). The highest (9051 kg ha^{-1}) and lowest (6661 kg ha^{-1})biomass yield was recorded from teff following pulse in light and heavy Vertisols, respectively.

3.2. Grain yield

The yield difference between years was found significant in Moretina jiru and Merhabete. In 2020, grain yield in Moretina jiru and Ensaro was significantly lower than in the previous year by 14.4 % in Moretina Jiru and 69.8 % in Ensaro. Nerveless, at Merhabete, the highest yield was observed during the 2019 cropping season. This is actually because of the occurrence of shoot flies during the 2020 cropping season. The analysis of variance showed that the interaction of *Pc* x Vt x N significantly influenced grain yield in all districts (Table 3).

In Merhabete, grain yield was significantly ($p < 0.001$) influenced by the interaction of *Pc* x Vt x N and *Pc* x Vt x P. In cereal precursor crops, the average grain yield was 1911 kg ha^{-1} with the highest N rate and 1015 kg ha^{-1} at 90 kg P ha^{-1}, and the average grain yield increase was 361 % (1497 kg ha^{-1}) with N and 48 % (488 kg ha^{-1}) with P. In pulse precursor crops, the average grain yield was 2316 kg ha^{-1} with the highest N rate and 1733 kg ha^{-1} at 90 kg P ha^{-1}, and the average grain yield increase was 425 % (1875 kg ha^{-1}) with N and 16 % (234 kg ha^{-1}) with P. In heavy Vertisols, the average grain yield was 2047 kg ha^{-1} with the highest N rate and 1516 kg ha^{-1} at 90 kg P ha^{-1}, and the average grain yield increase was 390 % (1627 kg ha^{-1}) with N and 56 % (559 kg ha^{-1}) with P. In light Vertisols, the average grain yield was 2180 kg ha^{-1} with the highest N rate and 1690 kg ha^{-1} at 90 kg P ha^{-1}, and the average grain yield increase was 397 % (1742 kg ha^{-1}) with N and 11 % (163 kg ha^{-1}) with P (Table 4). The *Pc* x Vt × N interaction was largely due the greatest yield increase (689 %) with N rate for light Vertisols following pulse and the least increase (213 %) with light Vertisols following cereal with intermediate magnitudes of response for heavy Vertisols following pulse (259 %) and heavy Vertisols following cereal (634 %). The *Pc* x Vt × P interaction was largely due the greatest yield increase (57 %) with N rate for heavy Vertisols following pulse and the least increase (15 %) with light Vertisols following pulse with intermediate magnitudes of response for light Vertisols

Table 6
Grain yield of tef in Moretina Jiru as affected by the interaction of precursor crop, type of Vertisols, and N rates in 2019 and 2020 cropping seasons.

Type of Vertisols	N rate	Cereal precursor	Pulse precursor
Heavy Vertisols	0	478	1016
	60	1517	1716
	120	1954	2018
	180	2222	2179
	240	2311	2176
Light Vertisols	0	669	237
	60	1580	1489
	120	1822	2159
	180	2164	2391
	240	2315	2578

following cereal (41 %) and heavy Vertisols following cereal (56 %).

In Ensaro, grain yield was significantly influenced by *Pc* x Vt x N x P. In cereal precursor crops, the average yield was 1462 and 1117 kg ha^{-1} with the highest N and P rate, and the average yield increase was 621 % (1260 kg ha^{-1}) with N and 44 % (344 kg ha^{-1}) with P. In pulse precursor crops, the average yield was 1862 and 1507 kg ha^{-1} with the highest N and P rate, and the average yield increase was 144 % (1100 kg ha^{-1}) with N and 16 % (203 kg ha^{-1}) with P. In heavy Vertisols, the average yield was 2231 and 1698 kg ha^{-1} with the highest N and P rate, and the average yield increase was 157 % (1362 kg ha^{-1}) with N and 16 % 9 % (136 kg ha^{-1}) with P. In heavy Vertisols, the average yield was 1093 and 925 kg ha^{-1} with the highest N and P rate, and the average yield increase was 384 % (366 kg ha^{-1}) with N and 80 % (411 kg ha^{-1}) with P. The *Pc* x Vt x N × P interaction was largely due the greatest yield increase (1089 %) with N and P rate for light Vertisols following cereal and the least increase (115 %) with heavy Vertisols following pulse with intermediate magnitudes of response for heavy Vertisols following cereal (397 %) and light Vertisols following pulse (581 %) (Table 5).

In Moretina Jiru, grain yield was significantly ($P < 0.01$) influenced by Vt x *Pc* x N. The analysis result indicated that irrespective of Vertisols type and precursor crop, application of N fertilizer increased teff grain yield (Table 4). In heavy Vertisols, the yield improvement ranges from 4 % (89 kg ha^{-1}) to 383 % (1833 kg ha^{-1}) in cereal precursor crop and from 7 % (158 kg ha^{-1}) to 114 % (1160 kg ha^{-1}) in pulse precursor crops (Table 6). In heavy Vertisols, the yield improvement ranges from 7 % (151 kg ha^{-1}) to 246 % (1646 kg ha^{-1}) in cereal precursor crops and from 8 % (187 kg ha^{-1}) to 988 % (2341 kg ha^{-1}) in pulse precursor crops (Table 6). The main effect of the P rate and its interaction with other factors were found non-significant (Table 3). This was explained by the fact that the comparatively the highest soil P status of the experimental soil of this district (Table 2). The *Pc* x Vt × N interaction was largely due the greatest yield increase (987 %) with N rate for light Vertisols following pulse and the least increase (114 %) with heavy Vertisols following pulse with intermediate magnitudes of response for light Vertisols following cereal (246 %) and heavy Vertisols following cereal (383 %).

3.3. *Correlation among different parameters*

The Pearson correlation analysis indicated that biomass yield strongly and significantly correlated with plant height ($r = 0.706$), panicle length ($r = 0.590$), grain yield ($r = 0.816$), and straw yield ($r = 0.984$). The correlation between biomass yield with the number of total tillers (0.144), and number of the fertile tiller ($r = 0.194$) was found significant but less strong (Table 7). There was also a negative association between the harvest index and the number of sterile tillers ($r = -0.283$) and the biomass yield ($r = -0.037$). Grain yield strongly and significantly correlated with plant height ($r = 0.549$), panicle length ($r = 0.486$), aboveground biomass yield ($r =$

Table 7
Pearson Correlation analysis of yield and some yield components of tef averaged over the three locations in 2019 and 2020 cropping season.

	PH	PL	NT	NFT	NIFT	BY	GY	SY	HI
PH	1	0.882**	0.075**	0.114**	−0.124**	0.706**	0.549**	0.701**	−0.318**
PL	0.882**	1	0.169**	0.201**	−0.087**	0.590**	0.486**	0.578**	−0.244**
NT	0.075**	0.169**	1	0.876**	0.538**	0.144**	0.324**	0.077**	0.161**
NFT	0.114**	0.201**	0.876**	1	0.065*	0.194**	0.378**	0.122**	0.160**
NIFT	−0.124**	−0.087**	0.538**	0.065*	1	−0.037	0.025	−0.054*	0.085**
BY	0.706**	0.590**	0.144**	0.194**	−0.037	1	0.816**	0.984**	−0.283**
GY	0.549**	0.486**	0.324**	0.378**	0.025	0.816**	1	0.699**	0.205**
SY	0.701**	0.578**	0.077**	0.122**	−0.054*	0.984**	0.699**	1	−0.414**
HI	−0.318**	−0.244**	0.161**	0.160**	0.085**	−0.283**	0.205**	−0.414**	1

PH = plant height, Pl = panicle length, NT = number of total tiller $plant^{-1}$, NFT = number of fertile tiller $plant^{-1}$, NIFT = number of infertile tiller $plant^{-1}$, BY = biomass yield, GY = grain yield, SY = straw yield, HI = harvest index.

0.816), and straw yield (r = 0.699). The correlation of grain yield with the number of total tillers, the number of fertile tillers, and the harvest index were significant but the correlation was not strong. The correlation of grain yield with the number of infertile tillers was found non-significant (r = 0.025). The correlation between plant height with panicle length was found positive and significant (r = 0.882) and with harvest index was found significant and negative (r = −0.318) (Table 7).

4. Discussion

4.1. Effect of prior crop on grain and aboveground biomass yield

The present study established a higher response of teff yield to pulse precursor compared to cereal precursor crops by 46 % (455 kg ha^{-1}), 24 % (316 kg ha^{-1}), and 5 % (93 kg ha^{-1}) in Ensaro, Merhabete, and Moretina jiru district, respectively. This is because pulse crops can fix atmospheric nitrogen and make a portion of the fixed N for the preceding crops [33,34]. Soil fertility through the reduction of soil erosion and hence soil depletion is improved by crop rotation that involves legume crops [35]. Pulse crops also reduce disease, increase the availability and uptake of P, K, and S nutrients from the soil, improve the structure of the soil, and release crop growth-promoting substances [36–38]. Similarly, different authors reported the impact of pulse precursor crops on subsequent crops [39–45]. Generally, the yield observed from pulse precursor crops is higher than cereal precursor crops. The yield variation was higher in Ensaro and Merhabete. The yield variation between the two precursor crops was low in the Moretina jiru district. This mainly because farmers in this area are apply urea fertilizer for pulse production, especially in lentils. Similarly, Pampana, Masoni [46] reported that the application of nitrogen above 120 kg N ha^{-1} for production of chickpea, pea, and white lupin decreased the level of N2 fixed, thus indicating that the high supply of N fertilizer decreased the level of N2 fixed to such an extent that the full N2-fixing potential might not be achieved. Saito, Tanabata [47] also reported that nodulation in soybean is inhibited by the application of nitrogen levels exceeding 5 mM. Similarly, Akter, Pageni [48] reported that a high dose of nitrogen fertilizer application inhibits nitrogen fixation from 16 common bean genotypes.

4.2. Effect of vertisols type on grain and aboveground biomass yield of teff

The present study establish a higher response of biomass yield to light Vertisols in Merhabete and Moretina Jiru area by 22 % and 11 % compared with heavy Vertisols. In Merhabete, application of N fertilizer significantly improved biomass yield in both Vertisols type. In heavy Vertisols yield improved by 609 % in cereal precursor and 303 % in pulse precursor crops. In light Vertisols, yield improved by 315 %, in cereal precursor and by 418 % in pulse precursor (Table 4). In both soil types, pulse precursor crops were significantly higher aboveground biomass than cereal precursor crops. The yield increase was 5 % in heavy Vertisols and 6 % in light Vertisols, respectively. Similarly, the interaction of *Pc* x P rate also significantly influenced aboveground biomass yield. Compared with the control, application of 90 kg ha^{-1} improved aboveground biomass yield by 39 %, 49 % and 44 % in heavy Vertisols following cereal, heavy Vertisols following pulse and light Vertisols following cereal, respectively. The result demonstrated that the yield improvement with the application of P fertilizer in light Vertisols following pulse precursor crop was found comparatively low. In this combination, the highest (6968 kg ha^{-1}) and lowest (6371 kg ha^{-1}) aboveground biomass was observed with the application of 60 kg and 30 kg P ha^{-1} respectively (Table 4). The respective improvement was 9 %. Irrespective of Vertisols types, the highest and lowest teff yield were recorded with the application of the highest (240 kg N ha^{-1}) and lowest (0 kg N ha^{-1}) N rate, respectively. Application of 240 kg N ha^{-1} increased grain yield by 634 %, 259 %, 213 %, and 688 % in heavy Vertisols following cereal precursor, heavy Vertisols following pulse precursor, light Vertisols following cereal precursor and light Vertisols following pulse precursor crops, respectively (Table 5) compared with the control. In heavy Vertisols, the yield observed from pulse precursor is higher than cereal precursor crops in the first three N rates (0, 60, and 120 kg N ha^{-1}) with respective yield improvement of 86 %, 7 %, and 28 %, respectively. If the N rate increased beyond 120 kg ha^{-1}, the yield observed from cereal precursor crop was found higher than pulse precursor crop by 2 % and 10 % at 180 and 240 kg N ha^{-1}, respectively. In light Vertisols, the yield observed from light Vertisols is higher than light Vertisols (except for the lower rate of N). The interaction of *Pc* x Vt x P rate also significantly ($p < 0.05$) influenced grain yield in this location. Compared with the control, application of 90 kg ha^{-1} improved grain yield by 56 %, 57 %, and 41 % in heavy Vertisols following cereal, heavy Vertisols following pulse and light Vertisols following cereal, respectively. The result demonstrated that the yield improvement with the application of P fertilizer in light Vertisols following pulse precursor crop was found comparatively low (Table 5). In this combination the highest (1984 kg ha^{-1}) and lowest (1732 kg ha^{-1}), grain yield was observed with the application of 0 kg and 30 kg P ha^{-1} respectively (Table 5). The analysis of variance also showed yield observed from pulse precursor crop were higher than cereal precursor crops in all Vertisols type. The yield variation ranges from 6 % to 8 % in heavy Vertisols and from 24 % to 86 % in light Vertisols.

In Ensaro, heavy Vertisols were significantly 57 % (2062 kg ha^{-1}) higher aboveground biomass than light Vertisols. The analysis of variance showed that the yield difference between heavy and light Vertisols was higher at low N rate and it ranges from 11 % to 293 % (Table 5). Application of N fertilizer significantly improved grain yield in all Vertisols types. Indicating, N is the most important nutrient in determining grain yield of teff. Generally, grain yield observed from heavy Vertisols increased grain yield by 46 % (455 kg ha^{-1}) compared with light Vertisols. In heavy Vertisols, the importance of pulse precursor crops in increasing grain yield was observed in the first three rates of N (0, 60, and 120 kg N ha^{-1}). Afterward, the yield observed from cereal precursor crop is higher than pulse precursor (Table 4). The result showed that the yield difference between the two Vertisols types was higher in cereal precursor crops and it ranged from 70 % to 1063 %. In pulse precursor, the yield difference ranges from 7 % to 347 % (Table 4).

The interaction of *Pc* x Vt x N rate had a substantial ($P < 0.01$) impact on teff yield of Moretina Jiru (Table 3). Increasing the N rate progressively increased yield on both Vertisols types (Table 6). However, the rate at which yield increased tends to decrease with increasing N rate (Table 6). In both soil types, application of higher (240 kg ha^{-1}) and lower (0 kg ha^{-1}) rates of N resulted in the highest and lowest teff yield in both soil types. In light Vertisols, application of 240 kg N ha^{-1} increased teff yield by 440 %, 30 %, 23 %, and 7 % compared with application of 0, 60, 120 and 180 kg N ha^{-1}, respectively. In heavy Vertisols, application of a higher rate of N fertilizer improved teff yield by 200 %, 16 %, 13 % and 2 % compared to the application of 0, 60, 120 and 180 kg N ha^{-1}, respectively.

4.3. Effect of NP application on yield and biomass

Application of N fertilizer significantly improved grain yield in all districts, soil types, precursor crops, and P rate, indicates N is the most important nutrient in determining grain yield of teff. This was justified by the fact that the soil N content of all site were low (Table 2).In all locations, application of the highest (240 kg N ha^{-1}) and lowest (0 kg N ha^{-1}) N rate resulted in the highest and lowest teff yield, respectively. This is attributed probably because of the highest loss of applied N from the soil. The mode of application of fertilizer for teff cultivation is broadcasting the fertilizer on the surface of the soil without covering the fertilizer with soil by trampling using a large number of cattle or donkeys immediately before broadcast sowing on the compacted soil. This will contribute to the highest loss of N from the surface of Vertisols via different routes [49–59]. This loss includes surface washing of fertilizer with rainfall through erosion especially when the highest rainfall comes immediately after fertilizer application. Trampling of the soil before broadcasting the seed and fertilizer also increases surface washing of fertilizer from the soil by decreasing infiltration and hence aggravating soil erosion [60,61]. The crop's poor root growth conditions and root form may also have an indirect impact on how effectively the teff crop uses nitrogen. Teff has a short rooting depth of only 4–8 cm and a fibrous root structure with fine roots [62]. Poor aeration caused by the high moisture content of Vertisols hinders normal root development and reduces nutrient availability and uptake.

Yield reduction due to the application of a low N rate was the highest in Merhabete, with 394 %, and the lowest in Ensaro with 245 %. The yield reduction with a low application N rate in Moretina jiru was found 291 %. Similarly, Asargew, Bitew [63] reported that an un-adequate supply of N has adversely affected crop growth, and development and can lead to a total loss of grain yield in extreme cases. This suggests that N is the most crucial nutrient for determining teff yield and that applying N to the soil enhanced teff yield [64, 65]. In all locations, the application of N nutrient progressively increased biomass and grain yield. Compared with the control, application of the highest rate of N (240 kg ha^{-1}) increased biomass yield by 302 % (7697 kg ha^{-1}), 402 % (5606 kg ha^{-1}), and 389 % (7282 kg ha^{-1}) in Moretina jiru, Ensaro, and Merhabete areas respectively. The increase in grain yield with the same rate was 291 % (1745 kg ha^{-1}), 245 % (1180 kg ha^{-1}), and 394 % (1686 kg ha^{-1}) in Moretina jiru, Ensaro, and Merhabete areas respectively. Indicating that both biomass and grain yield increased even with increasing N rates beyond 240 kg ha^{-1}.

The N rate at which the highest grain yield was recorded with the current finding was found higher than the previously recommended N rate for the same soil type [66–70]. The fertilization recommendation of the former research conducted in Vertisols of Ethiopia ranged from 41 to 80 kg ha^{-1}. This might be probably because of the depletion of this nutrient from the soil through time. For instance, Haileslassie, Priess [71] reported that N nutrient depletion of −147 kg ha^{-1} was recorded from the Amhara region. This rate is the highest compared with other regions of Ethiopia. The same authors also reported that the main determinants of nutrient depletion are nutrient removal through harvested product, residual removal, leaching, denitrification, and erosion. Van Beek, Elias [72] also noted that diverse Ethiopian agroecologies experience accelerated soil nutrient depletion that is severe in N, with average annual depletions of 0.2 % of the entire stock, or 4.2 % of the accessible soil N pool. Other authors also reported nutrient depletion especially N in Ethiopia [71,73,74].

In Merhabete, the application of a higher P rate increased aboveground biomass by 30 % (1521 kg ha^{-1}), 10 % (580 kg ha^{-1}), and 2 % (109 kg ha^{-1}) compared with 0, 30, and 60 kg P ha^{-1}, respectively. In the Ensaro, the respective aboveground biomass increment was 38 % (1434 kg ha^{-1}), 11 % (496 kg ha^{-1}), and 3 % (109 kg ha^{-1}). Nevertheless, in the Moretina Jiru district, the highest (7333 kg ha^{-1}) and lowest (7008 kg ha^{-1}) biomass yield was observed with the application of 60 and 0 kg P ha^{-1}, respectively. In the Merhabete district, the application of a higher P rate (90 kg P ha^{-1}) increased grain yield by 29 % (361 kg ha^{-1}), 11 % (160 kg ha^{-1}), and 2 % (24 kg ha^{-1}) compared with the application of 0, 30, and 60 kg P ha^{-1}, respectively. In the Ensaro district, the respective aboveground biomass increment was found to be 26 % (273 kg ha^{-1}), 6 % (75 kg ha^{-1}), and 0.2 % (3 kg ha^{-1}). The application of P fertilizer didn't bring any significant improvement teff grain yield in the Moretina jiru district. This was explained by the fact that the soil P status of this district was comparatively higher than other districts. Similarly, Alemayehu [75] reported that seed weight was 0.25–0.38 when the P rate was increased from 0 to 9 g/m2 P_2O_5. Ayalew, Kena and Dejene [76] also reported that the application of phosphorus significantly improved by the application of P fertilizer on Profondic Luvisols, Haplic Alisols, and Vitric Andosols. Application of 30 kg P ha^{-1} resulted in the highest teff grain yield of 1571 kg ha^{-1} and even application of 10 kg P ha^{-1} increased from 788 to 1377 kg P ha^{-1} with a respective yield increment of 75 %. In Ensaro and Merhabete areas, the combined application of N and P resulted in significant yield differences. In Merhabete, the lowest (340 kg ha^{-1}) and highest (2256 kg ha^{-1}) yield of teff was recorded from the application of zero, zero, and 240, 90 kg N and P ha^{-1}, respectively. In Ensaro, the lowest (478 kg ha^{-1}) and highest (2256 kg ha^{-1}) yield of teff was recorded from the application of 0, 90, and 240, 90 kg NP ha^{-1}, respectively. The respective increase in yield due to the

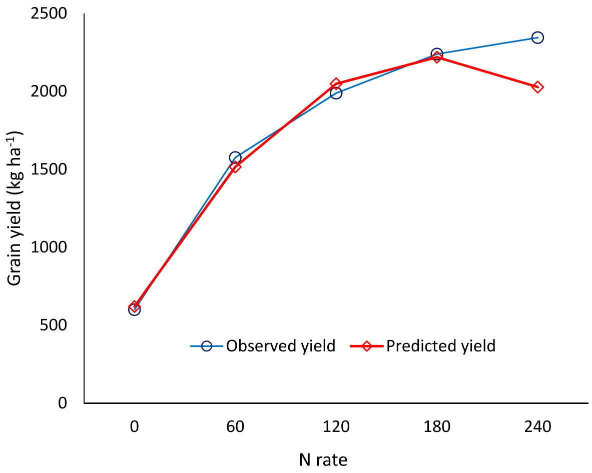

Fig. 5. Observed VS Predicted grain yield (Based on regression equation in Table 8) in Moretina Jiru district as influenced by N rate for all soil type and precursor crops.

combined application of NP ranged from 202 % (688 kg ha^{-1}) to 398 % (1788 kg ha^{-1}) in Merhabete and from 83 % (396 kg ha^{-1}) to 237 % (1163 kg ha^{-1}) in Ensaro area.

Nevertheless, the application of P fertilizer alone had little effect on teff yield response in all locations. In order of influence, the highest (0.00687) and lowest (0.00122) P effect was observed in Merhabete and Moretina Jiru, respectively (Table 3). In between, the effect of P was observed in the Ensaro. This is justified by the fact that the soil available P value also followed this trend. Agronomic optimum grain yield was determined using the developed regression equation for each district. In Moretina jiru district, the highest grain yield was recorded from application of 178 kg N ha^{-1}. The lowest yield of both parameters was recorded from the lowest N rate (Fig. 5). In this area, soil maintenance level of P (30 kg ha^{-1}) is sufficient for current teff production. In Merhabete, the N and P requirement for maximum grain yield ranges from 199 to 240 kg N ha^{-1} and from 36 to 90 kg P ha^{-1}, respectively (Table). In Ensaro, the N and P requirement for maximum grain yield ranges from 195 to 240 kg N ha^{-1} and from 69 to 90 kg ha^{-1}, respectively (Table 8).

Based on the regression equation in Table 8, the predicted yield for both Vertisols type, and precursor crops were produced and compared with observed yield (Figs. 5 and 6 (a-d), and 7 (a-d)). The equation well predict grain yield in Moretina jiru and Merhabete area (Figs. 5 and 7 (a-d)). In Ensaro, the prediction in light Vertisols if teff following cereal is low with R^2 value of 0.69 (Fig. 6d and Table 8). Sensitivity analysis using predicted yields (based on equations in Table 8) indicated that N/P requirement with different economic scenarios ranges from 240/90 to 164/24 in Merhabete, from 116/0 to 240/90 in Ensaro and from 161/0 to 174/0 in Moretina Jiru district (Table 9). In all locations, lowest economic return was observed if current fertilizer cost increased by 200 % with current grain price. In Ensaro and Merhabete, application of highest rate of N (240 kg ha^{-1}) and P (90 kg ha^{-1}) generally resulted in the highest net benefit in most of the economic scenarios. In Moretina jiru areas, the application of 170 kg N ha^{-1} resulted in the highest net benefit in most of the economic scenarios. The sensitivity analysis result indicated that the range in fertilizer recommendation with different scenarios was narrow in all locations. In all locations, the lowest N and P rate with the highest net benefit with the highest net benefit was observed if the fertilizer price increased by 200 % with the current fertilizer price (Table 9).

Table 8
Regression equation for different precursor crops, Vertisols type in Merhabete, Ensaro and Moretina Jiru district.

District	Combination	Equation	AOR		EOR	
			N	P	N	P
Merhabete	Cereal-LVS	$3315 + 12.097\ N + 8.327P- 0.032N^2 -0.05014P^2+ 0.00602NP$, $R^2 = 0.97$	199	90	182	60
	Cereal-HVS	$61.58 + 9.88\ N + 10.72592P-0.01312N^2-0.09250P^2+0.02915NP$, $R^2 = 0.97$	240	90	240	90
	Pulse-LVS	$569.99 + 20.697N-8.2761P-0.05095N^2+0.061P^2+0.0186NP$, $R^2 = 0.96$	210	36	206	64
	Pulse-HVS	$55.154 + 12.79\ N + 16.72226P-0.02654N^2-0.11482P^2-0.00027811NP$, $R^2 = 0.86$	241	73	218	58
Ensaro	Cereal-LVS	$43.72229 + 8.37924\ N + 9.4521P-0.0298N^2-0.09316P^2+0.03638NP$, $R^2 = 0.69$	195	89	166	65
	Cereal-HVS	$609.04524 + 10.35562\ N + 1.05667P-0.01691N^2-0.02062P^2+0.01955NP$, $R^2 = 0.97$	240	90	240	90
	Pulse-LVS	$213.15119 + 11.00065\ N + 9.75676P-0.0266N^2-0.08295P^2+0.00808NP$, $R^2 = 0.97$	217	69	198	48
	Pulse-HVS	$1186.88413 + 5.43489\ N + 1.39731P-0.00966N^2-0.01905P^2+0.0164NP$, $R^2 = 0.93$	240	90	240	80
Moretina jiru	All combination	$620.0255 + 17.94509\ N–0.05034N^2$, $R^2 = 0.99$	178	30	170	30

LVS = light Vertisols, HVS = heavy Vertisols, N==N rate, P==P rate, AOR = agronomic optimum rate, EOR = economic optimum rate.

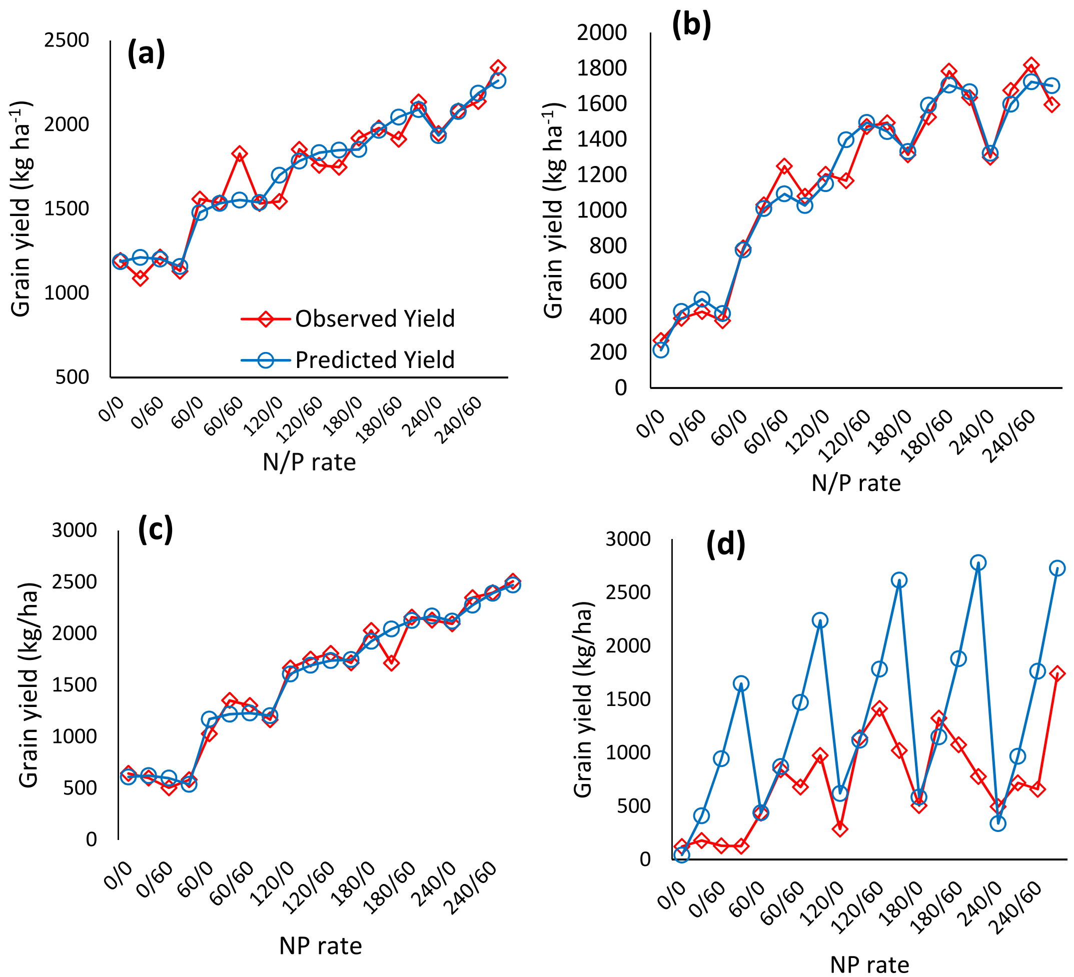

Fig. 6. Observed VS Predicted grain yield (Based on regression equation in Table 8) in Ensaro as influenced by N and P rate for; a = in heavy Vertisols if teff following pulse, b = in light Vertisols if teff following pulse, c = in heavy Vertisols if teff following cereal, and d = in light Vertisols if teff following cereal.

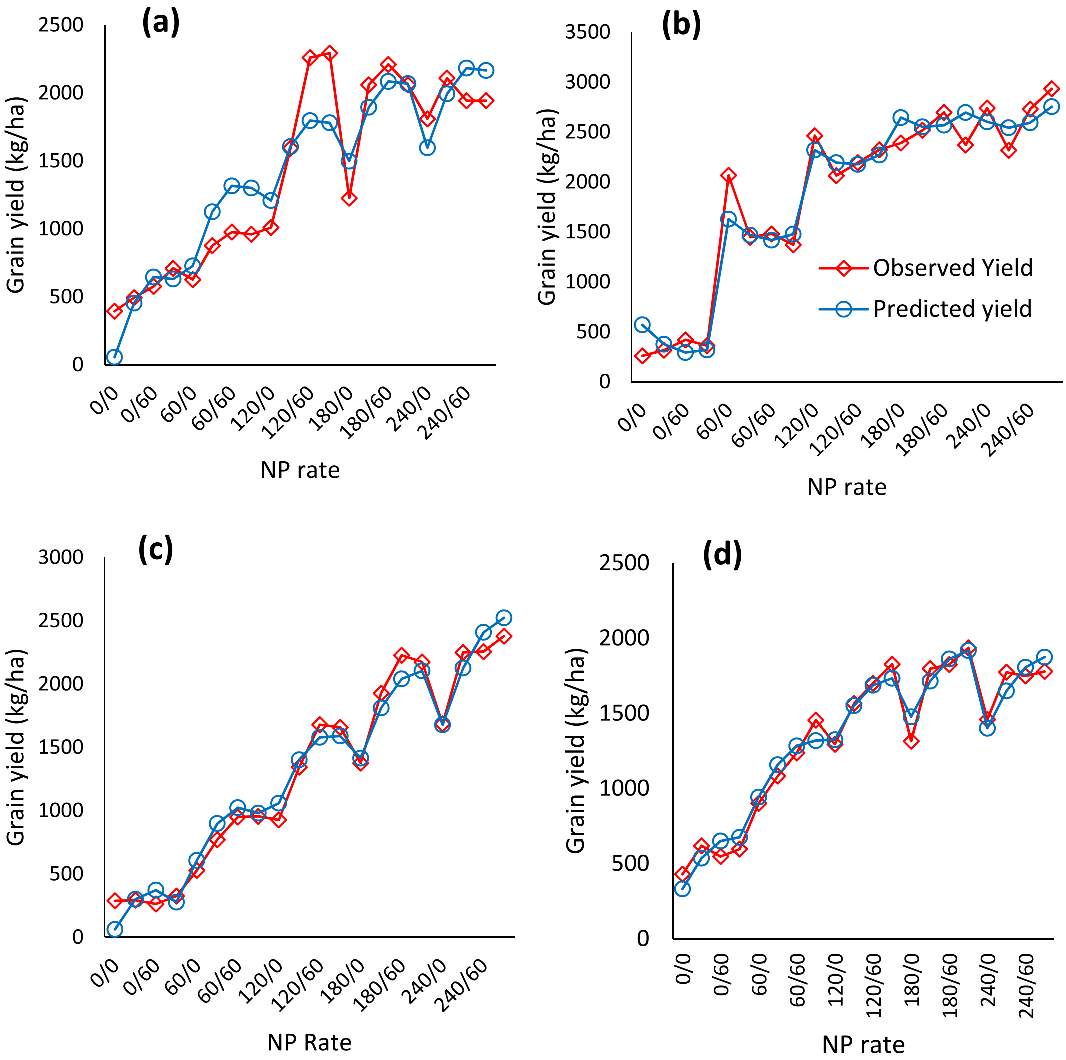

Fig. 7. Observed VS Predicted grain yield (Based on regression equation in Table 8) in Merhabete as influenced by N and P rate for; a = in heavy Vertisols if teff following pulse, b = in light Vertisols if teff following pulse, c = in heavy Vertisols if teff following cereal, and d = in light Vertisols if teff following cereal.

Table 9
Different economic scenario for change in input and output price in the three districts.

District	Combination	150 % of the CFC with CGV (N/P)	150 % of both CFC and CGV (N/P)	50 % of CGV with CFC (N/P)	50 % of both CFC and CGV (N/P)	200 % of CGV with CFC (N/P)	200 % of both CFC and CGV (N/P)	200 % of CFC with CGV (N/P)	200 % of CGV with CFC (N/P)	200 % CFC and 150 % CGV (N/P)
Merhabete	Cereal-LVS	173/42	182/60	150/24	182/60	190/77	182/60	164/24	190/77	176/48
	Cereal-HVS	240/90	240/90	240/78	240/90	240/90	240/90	240/84	240/90	240/90
	Pulse-LVS	204/79	206/64	194/90	206/64	208/50	206/64	203/90	208/50	205/74
	Pulse-HVS	216/50	224/58	191/43	224/58	232/65	224/58	207/43	232/65	218/53
Ensaro	Cereal-LVS	151/53	166/65	120/38	166/65	180/77	166/65	137/42	180/77	156/57
	Cereal-HVS	240/90	240/90	207/0	240/90	240/90	240/90	240/0	240/90	240/60
	Pulse-LVS	188/38	198/48	162/26	198/48	208/59	198/48	178/27	208/59	191/41
	Pulse-HVS	210/0	240/80	46/0	240/80	240/90	240/80	116/0	240/90	240/24
Moretina jiru	All combination	165	170	152	170	174	170	161	174	167

LVS = light vertisols, HVS = heavy Vertisols, N/P==N and P rate, CGV = current grain value, CFC = current fertilizer cost.

5. Conclusion

We found strong evidence in teff response to the application of N and P fertilizers in different precursor crops and Vertisols types. Indicating teff yield increased with application of N and P, selection of appropriate precursor crops and types of Vertisols, possibly due to differences in physicochemical properties. Teff yield response to N and P rate is affected by Vt and *Pc* in Ensaro and Merhabete but there was negligible effect in Moretina Jiru. The following economically optimal rates (EOR) are with the cost of fertilizer use equal to 32.5 ETB kg^{-1} of N and 22.9 kg^{-1} of P. Therefore in Moretina Jiru, single response functions each for N and P rate are needed for determination of grain yield responses. These predict rates of 178 kg N ha^{-1} and soil maintenance level of 30 kg P ha^{-1}, respectively, for maximum yield and 170 kg^{-1} of N and soil maintenance level of 30 kg^{-1} of P EOR. The conclusions are more complex for Ensaro and Merhabete. At Ensaro, needed rates for teff following cereal on light Vertisols are 195 kg N ha^{-1} and 89 kg P ha^{-1}, for maximum yield and 166 kg N ha^{-1} and 65 kg P ha^{-1} for maximum economic return. At Ensaro, needed rates for teff following pulse on light Vertisols are 217 N ha^{-1} and 69 kg P ha^{-1} for maximum yield and 198 N ha^{-1} and 48 kg P ha^{-1} for maximum economic return. At Ensaro, needed rates for teff following cereal on heavy Vertisols are 240 N ha^{-1} and 90 kg P ha^{-1} for both maximum yield and for maximum economic return. At Ensaro, needed rates for teff following pulse on heavy Vertisols are 240 N ha^{-1} and 90 kg P ha^{-1} for maximum yield and 240 N ha^{-1} and 80 kg P ha^{-1} for maximum economic return. At Merhabete, needed rates for teff following cereal on light Vertisols are 199 kg N ha^{-1} and 90 kg P ha^{-1}, for maximum yield and 182 kg N ha^{-1} and 60 kg P ha^{-1} for maximum economic return. At Merhabete, needed rates for teff following pulse on light Vertisols are 210 N ha^{-1} and 36 kg P ha^{-1} for maximum yield and 206 N ha^{-1} and 64 kg P ha^{-1} for economically maximum economic return. At Merhabete, needed rates for teff following cereal on heavy Vertisols are 240 N ha^{-1} and 90 kg P ha^{-1} for both maximum yield and maximum economic return. At Merhabete, needed rates for teff following pulse on heavy Vertisols are 241 N ha^{-1} and 73 kg P ha^{-1} for maximum yield and 218 N ha^{-1} and 58 kg P ha^{-1} for maximum economic return. Therefore, N and P rate having maximum economic return were recommended for the respective district, soil type and precursor crops. Nevertheless, we also suggest further research on proper application and management fertilizer to increase nutrient efficiency in this soil type since the highest yield and yield component of teff with farmer's application practice was observed with the highest NP rate due to the highest N loss from this soil.

We suggest further research on proper management fertilizer to increase nutrient efficiency in this soil type since the highest yield and yield component of teff with farmer's application practice was observed with the highest NP rate.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Data availability statement

The data used to support the findings of this study can be accessed from the corresponding author upon request.

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CRediT authorship contribution statement

Beza Shewangizaw: Writing – review & editing, Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Shawl Assefa:** Writing – review & editing, Data curation. **Kenzemed Kassie:** Data curation, Conceptualization. **Yalemegena Gete:** Data curation. **Lisanu Getaneh:** Data curation. **Getanh Shegaw:** Data curation. **Tesfaye Sisay:** Data curation. **Getachew Lemma:** Data curation.

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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