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Soil Test Based Phosphorous Fertilizer Recommendation for Tef [Eragrostis Tef (Zucc.)Trotter] Production on Nitisols of Central Ethiopian Highlands

Legesse Admassu
Ethiopian Institute of Agricultural Research, Holeta Agricultural Research Center, P.O. Box 2003, Addis Ababa, Ethiopia

Abstract

Tef, Eragrostis tef (Zucc.) Trotter is an important cereal crop in Ethiopia. Obtaining Low yield of this staple crop is usually a major constraint. Tef grain yield is often affected by soil deficient phosphorous and its suboptimal application by farmers. Proper and balanced fertilizer recommendations is of paramount importance in order to confirm security and increase crop productivity in sustainable way for farmers and other stakeholders. Soil test based phosphorous calibration study was conducted for tef on Nitosols of farmers' fields in the West Shewa, central Ethiopian highlands. The experiment was arranged in a randomized complete block design with six levels of phosphorous fertilizer (0, 10, 20, 30, 40 and 50 kg ha^{-1}) with three replications. The result showed that P fertilizer application significantly affected yield and yield components of tef. Phosphorous fertilizer application at different rates increased grain yield of tef by 48to 70% compared to the control. Available soil test P concentrations analyzed three weeks after planting were affected significantly by P fertilizer application rate. Relative yield and Bray-2 soil test phosphorous value correlation indicated that soil test phosphorous values greater than 12.5 mg kg^{-1} was found to be sufficient for tef production. The average phosphorous requirement factor (P_f) calculated from soil test phosphorous values of all treatments for study area was 9.5. Most sites tested had Bray 2 P values <10 mg kg^{-1}. In the absence of a soil test, a recommendation of 30 kg P ha^{-1}, resulting in the best response overall, could be made for the first year of application. We also recommend that to prevent a potential loss of barley yield, a maintenance application of at least 5–10 kg P ha^{-1} be applied every year, irrespective of the calculated recommended rate, in order to replace P exported from the field in the form of grain and straw yield. Further field trials are required to determine interactions between P response and N fertilizer and other variables of like climate, soil properties, and other management practices.

Keywords: tef, Phosphorous calibration, Nitisols, phosphorous requirement factor, critical concentration.

1. Introduction

Tef, Eragrostis tef (Zucc.) Trotter is the major Ethiopian cereal grown for thousands of years (D'Andrea, 2008) and currently grown on 2.5 million ha annually, and accounts for 30 per cent of total acreage and 19 per cent of gross cereal production (CSA, 2008]. It is the only cultivated cereal in the genus Eragrostis (Abebe, 2001). Tef is a highly versatile crop with respect to adaptation to different agro-ecologies, widely grown from sea level up to 2800 m above sea level (a.s.l.) under various rainfall, temperature, and soil conditions (Ketema, 1997; 1993). It performs well in the Ethiopian highlands between 1700 and 2400 m which constitute 43% of the country but account for 95% of the cultivated area and support 88 and 75% of the human and livestock population, respectively (Yirga, 2013).The crop has both its origin and diversity in Ethiopia (Vavilov, 1951) and plays a vital role in the country's overall food security. Tef mainly used to make Injera (Yetneberk et al., 2005), a traditional fermented soft, thin, circular and Ethiopian pancake. Tef plays an appreciable role in supplying the population of the country with protein, carbohydrates and minerals. In recent years, tef has been receiving global attention as health food because of its gluten-free nature that renders it suitable for people suffering from gluten allergy known as celiac disease (Dekking and Koning, 2005). In addition, the straw is an important cattle feed source, and the high market prices of both its grains and the straw make it a highly valued cash crop for tef-growing smallholder farmers. Tef is the most expensive cereal in Ethiopia, justifying its prominence in urban and semi-urban areas where incomes are relatively higher. With increases in urbanization and income, demand for tef is likely to increase in Ethiopia. However, the average mean grain yield of tef in this part of the country is below 1000 kg ha^{-1} (Mebratu et al., 2016) and variable, mainly due to nutrient stress.

In Sub-Saharan Africa (SSA), low and declining soil fertility due to net nutrient extraction by crops is responsible for low agricultural productivity and food insecurity (Nakhumwa, and Hassan, 2012). Moreover, the rampant soil degradation and the consequent decline of its productivity due to loss essential plant nutrients is among the underlying reasons for poor crop yield (Bekunda et al., 2012) and food insecurity (Sanchez, 2002). Footpaths develop into gullies, soils become thin and stony, topsoil is gone due to accelerated soil erosion (Stocking and Murnaghan, 2001). In addition, In SSA the major production factor contributing directly to the poor yields of crops is the inadequate use of external inputs more than the removal of nutrients in small holder farms (Sanchez and Jama, 2002). Over 50% of the highlands in general and cropped areas of Ethiopia are in an advanced stage of land degradation (Elias, 2002). Erosion on fields planted with small seed cereals such as tef was found to be high (Hurni, 1998) due to high tillage frequency (Kruger et al., 1996). SSA accounted for 3 percent of world fertilizer consumption in 2013 as compared to Asia that consumes 58.5 percent of the world total, the bulk of which is used in East Asia and South Asia (FAO, 2015). In terms of per hectare fertilizer application Asia is in the first place in fertilizer application per hectare (150.7 kg ha^{-1}) (Hossain, and Singh, 2000). While farmers in SSA estimated to have used 11 kg nutrients/ha in 2013, i.e. only 10% of the global average (Drechsel et al., 2000). Therefore, there are still large areas where farmers use little fertilizer and mine their soil nutrient reserves. Moreover, Low and declining soil fertility arises from continuous cultivation where levels soil replenishment, by whatever means are too low to mitigate the process of soil nutrient mining (Shishanya, 2009). According to (Stoorvogel and smalling, 1993) the annual average nutrient loss for SSA was 26 kg N, 3 kg P, and 19 kg K ha^{-1} yr^{-1} the yearly equivalent of US$ 4 billion worth of fertilizers (Drechsel et al., 2000). Whereas in Ethiopia the magnitude of nutrient loss is huge, quantified to 122, 13, and 82 kg ha^{-1} year^{-1} (Haileslassie,et al., 2005) resulting in a negative nutrient balance (Omotayo and Chukwuka, 2009). In contrast, farms in North America and Europe also have averaged net positive nutrient balances (Sanchez et al., 1994). Decline in the soil fertility is one of the major bottlenecks to agricultural production, productivity in the world particularly in Africa and specifically in Ethiopia (Giday et al., 2014). Agricultural production (particularly cereal production) must increase to meet the challenge of food security (Rosegrant et al., 2001). Therefore, greater use of mineral fertilizers is crucial to increasing food production and slowing the rate of soil degradation in Ethiopia since severe soil nutrient depletion is a major bottleneck for boosting production and productivity of tef. In Ethiopia in general, specifically in the central highlands, 70 to 80% of the fertilizer purchased by smallholders is known to be applied to tef fields (Kenea et al., 2001).

Phosphorous (P) is one of most limiting plant nutrients in the tropics (Brady and Weil, 1999) required in the early stages of growth (Grant et al., 2001) necessary for many plant processes including synthesis of phospholipids, energy transfer, and enzyme activation (Hawkesford, 2012) for optimum crop production. Inadequate P availability is a major limitation to plant growth and development (Schachtman et al., 1998) and consequently global crop production (Raghothama and Karthikeyan, 2005). It is usually the most yields limiting of soil-supplied elements, and soil P tends to decline when soils are used for agriculture (David and David, 2012. The low solubility of phosphates and their rapid transformation to insoluble forms makes P less available or unavailable to crops (Smil, 2000). It is estimated that 30–40% of global agricultural soils are limited by P availability and it is second only to nitrogen (N) in limiting agricultural productivity (Vance et al., 2003). Heavy rains during main cropping season cause substantial nutrient losses due to intense leaching and erosion on Nitosols (Woldeab et al., 1991). P is deficient in about 70% of the soils in Ethiopia (Mamo, and Haque, 1991). One of major constraints that are responsible for low yield is P deficiency (Balesh et al., 2005). According to Regassa and Agegnehu, (2011) Nitisols in the highlands are marginally to severely deficient in P. In addition, its low productivity may be due to several production constraints like soil acidity, broadcasting method of sowing, and low amount of nutrient application in the Ethiopian highland. The increase in food demand will require an increased use of resources such as water, land and nutrients to produce crops (Tillman et al., 2011). The Blanket fertilizer recommendations currently applied was released several years ago in Ethiopia, does not consider the differences in agro-ecological environments, are not suitable for the current production systems and for the foreseeable future (Ketema, 1997; Kenea et al., 2001). Since the spatial and temporal fertility variations in soils were not considered, farmers have been applying same P fertilizer rate to their fields regardless of soil fertility differences. For this reasons, the blanket recommendation will make inefficient use of these expensive nutrients which contribute to the depletion of scarce financial resources, increased production costs and potential environmental risks (Tarekegne and Tanner, 2001).

Sound soil test based and site specific nutrient management is essential in reversing this trend and increase crop yield in agricultural land. It is essential tool for successful fertilization program and crop production. It is a reliable and accurate method to identify the nutrient rates required to attain a desired level of plant growth and yield. It is important that results of soil tests be calibrated against crop response from applications of the plant nutrients in question (Wortmann, C.S., 2015). Calibration is a means of establishing a relationship between a given soil test value and the yield response from adding nutrient to the soil as fertilizer. It provides information how much nutrient should be applied at a particular soil test value to optimize crop growth without excessive waste. Calibration research predicts the probability of response from applying a given nutrient which must be determined experimentally in the field (Dahnke and Olsen, 1990). Calibrations are specific for each crop type, soil type, soil pH, climate plant species, and crop variety (Self, 2013; Agegnehu and Lakew, 2013; Sonon and Zhang, 2014). Soil testing particularly soil P, tests can be used for evaluating soil P availability and fertilizer recommendations. The most widely used available soil P test is Bray II (Bray and Kurz, 1945) on acidic soils (Bado et al., 2008). Instead of simple individual soil tests, soil calibrations of the relationship between soil test and yields of a specific plant are needed for fertilizer recommendation. A critical limit of available P and P requirement factors for a specific soil and crop have been conducted for major crops recently, but the critical limit of available P and P requirement factor is not established for tef. Different methods can be used to examine such a relationship. One example of simple graphical method is the Cate Nelson graphical method (Nelson and Anderson, 1977).

Currently, soil fertility research improvement is geared towards site specific fertilizer recommendation. The establishment of a reliable soil test is able to assist in the determination of P requirements. It involves a correlation to find an extractant for soil nutrients for a laboratory test that will best mine an amount of a nutrient proportional to what a plant extracts (Seif, 2013). This will be followed by a calibration to relate soil test numerical value with field nutrient response in the form of crop yield from the addition of the fertilizer nutrient to the soil (Shaver, 2014). Therefore, the objectives of this study were to determine tef yield response to P, the critical P concentration, P requirement factor and establish agronomic recommendation for optimum P fertilizer rate on tef.

2. Materials and methods

2.1. Experimental site

Phosphorous response trials with tef were conducted on farmers' fields from 2012-2014 during the main cropping seasons in West Shewa zone, Welmera district in the central highlands of Ethiopia. Tef is grown mainly by subsistence farmers in the highlands of the country. The rainfall is bimodal with long-term average annual rainfall 1100mm, about 25% of which falls from June to September and the rest from January to May and average minimum and maximum air temperature of 6.2 and 22.1 ^{0}C, respectively. The environment is seasonally humid and major soil type of the trial sites is Eutric Nitisol (IUSS Working Group WRB, 2006).

In order to select representative trial sites across the area over 600 soil samples (0-20cm depth) were collected in three years from farmers' fields before the onset of the trial. Soil samples were analyzed for pH using in a ratio of 2.5 ml of water to 1 g soil available P using Bray II method (Bray and Kurz, 1945) organic C content using Walkey and Black method (Walkley and Black, 1954) total N using Jehldahl method (Bremner and Mulvaney, 1982) exchangeable cations and cation exchange capacity (CEC) using ammonium acetate method (Chapman, 1965). The available soil P (using Bray-2 method) ranges prior to planting considered for classification were <10 mg kg^{-1} for low, 10-25 mg P kg^{-1} for medium and >25 for high (Table 1). Based on this categorization 10 farmers with low and medium fields available P were selected for the first year, 5 farmers for the second year and 5 farmers with the same categories for the last two years, respectively.

2.2. Experimental setup

The experiment was arranged in a randomized complete block design with six levels of phosphorous (0, 10, 20, 30, 40 and 50 kg P ha^{-1}) with three replications. The plot size was 4m by 5m (20 m^2) and the spacing between plots and blocks were 0.5m and 1m, respectively. The harvested plot size was 16m^2. Tef (*var. Quncho)* was seeded at the recommended rate of 15 kg ha^{-1}. The experiment was planted in July. The sources of N and P were urea and triple super phosphate (TSP), respectively. The P fertilizer was applied at planting. While the recommended N fertilizer (60 kg ha^{-1}) was applied two doses; half at planting and half at tillering stage. Other agronomic practices were applied based on local research recommendations. Broad-leaf herbicide was sprayed 5 weeks after crop emergence to control weeds and one last hand weeding was also carried out afterwards.

Agronomic parameters collected were grain yield, aboveground total biomass, thousand seed weight, test weight, seed weight per plant, panicle length and plant height (average of 10 plants). One site in the third year was dropped due to poor crop performance and 19 sites were considered for harvesting, data analysis and interpretation in three years. To estimate total biomass and grain yields the entire plot was harvested at maturity in November. After threshing seeds were cleaned weighed and adjusted at 12% moisture level. Total biomass and grain yields recorded on plot basis were converted to kg ha^{-1} for statistical analysis.

Table 1: Soil nutrient contents of the trial sites before planting tef in 2012

Farmers names	pH (1:2.5 H_2O)	Total N (%)	P (mg kg-1)	K (cmol$_c$ kg^{-1}	Na (Cmol$_c$ kg^{-1})	CEC (Cmol$_c$ kg^{-1})
Teshome	5.4	0.16	6.6	1.39	0.11	19.2
Beyene	5.0	0.15	6.8	0.56	0.11	17.2
Bekele	5.5	0.14	4.6	0.68	0.15	17.1
Abera	6.2	0.19	7.4	1.69	0.12	31.5
Gudisa	5.4	0.19	8.2	0.72	0.19	21.2
Erko	5.0	0.14	6.8	0.73	2.87	19.6
Negesse	4.6	0.13	5.0	0.58	0.19	16.5
Tadesse	6.1	1.29	14.0	1.22	2.28	22.6
Fikadu	6.4	0.16	14.4	0.78	0.12	26.4
Seyoum	5.4	0.17	7.2	0.72	3.04	20.1

Note. CEC, cation exchange capacity

Determination of critical P concentration (Pc): to correlate relative yield vs. soil test P values and determine critical P concentration, the available P was extracted from the soil samples taken three weeks after planting from each plot of all experimental fields using Bray 2 method and three replications for each treatment.

The Cate-Nelson graphical method (Nelson and Anderson, 1977) was used to determine the critical P value using relative yields and soil test P values obtained from 18 P fertilizer trials conducted at different sites, to assess the relationship between grain yield response to nutrient rates and soil test P values, relative grain yields in percent were calculated as follows:

$$Relative\ yield\ (\%) = (\frac{Yield}{maximum\ yield})\ X\ 100 \qquad (1)$$

The scatter diagram of relative yield (Y-axis) versus soil test value (X-axis) was plotted. The range in values on the Y-axis was 0 to 100%. A pair of intersecting perpendicular lines was drawn to divide the data into four quadrants. The vertical line defines the responsive and non-responsive ranges. The observations in the upper left quadrants overestimate the P fertilizer P requirement while the observations in the lower right quadrant underestimate the fertilizer requirement. The intersecting lines were moved about horizontally and vertically on the graph, always with the two lines parallel to the two axes on the graph, until the number of points in the two positive quadrants was at a maximum (or conversely, the number of points in the two negative quadrants was at a minimum). The point where the vertical line crosses the X-axis was defined as optimum critical soil test level (Nelson and Anderson, 1977).

Determination of P requirement factor (Pf): phosphorous requirement factor (Pf) is the amount of P in kg needed to raise the soil P by 1 mg kg^{-1}. It enables to determine the quantity of P required per hectare to raise the soil test by 1 mg kg^{-1}, and to determine the amount of fertilizer required per hectare to bring the level of available P above the critical level (Nelson and Anderson, 1977). It was calculated using available P values in samples collected from unfertilized and fertilized plots. Phosphorous requirement factor was expressed as:

$$\mathrm{Pf} = \frac{\mathrm{kg\ P\ applied}}{\Delta\ \mathrm{soil\ P}} \qquad (2)$$

Therefore the rate of P fertilizer to be applied (Pa) was expressed in terms of critical P concentration (Pc), initial soil P value (Pi) and P requirement factor (Pf).

$$\mathrm{Pa} = (\mathrm{Pc} - \mathrm{Pi})\ \mathrm{x\ Pf} \qquad (3)$$

2.3. Statistical analysis

The data were subjected to analysis of variance using the procedure of the of SAS statistical package version 9.0 (SAS Institute, 2001). The total variability for each trait was quantified using the following model.

$$Tijk = \mu + Yi + Rj(i) + Pk + PY(ik) + eijk \qquad (4)$$

Where T_{ijk} is the total observation, μ = grand mean, Yi = effect of the i^{th} year, Rj(i) is the effect of the j^{th} replication (within the i^{th} year), P_k is the of the k^{th} treatment, $PY_{(ik)}$ is the interaction of the k^{th} treatment with i^{th} year and e_{ijk} is the random error. Means for the main effects were compared using the means statement with least significant difference (LSD) test at the 5% level.

3. Results

3.1. Weather

The total rainfall amount and precipitation pattern for 2012 was significantly higher compared with long-term average, 2013 and 2014 (Figure 1). The rainfall amounts recorded for July and September were considerably higher in 2012 than in 2013 and 2014. When compared with a 30 year average, rainfall in July was higher by 41 mm in 2012, but lower by 122 and 126 mm in 2013 and 2014 respectively, which entails average moisture received in 2012 was conducive for barley growth and development. Moisture deficiency in July and September critically affects tillering and grain filling, respectively.

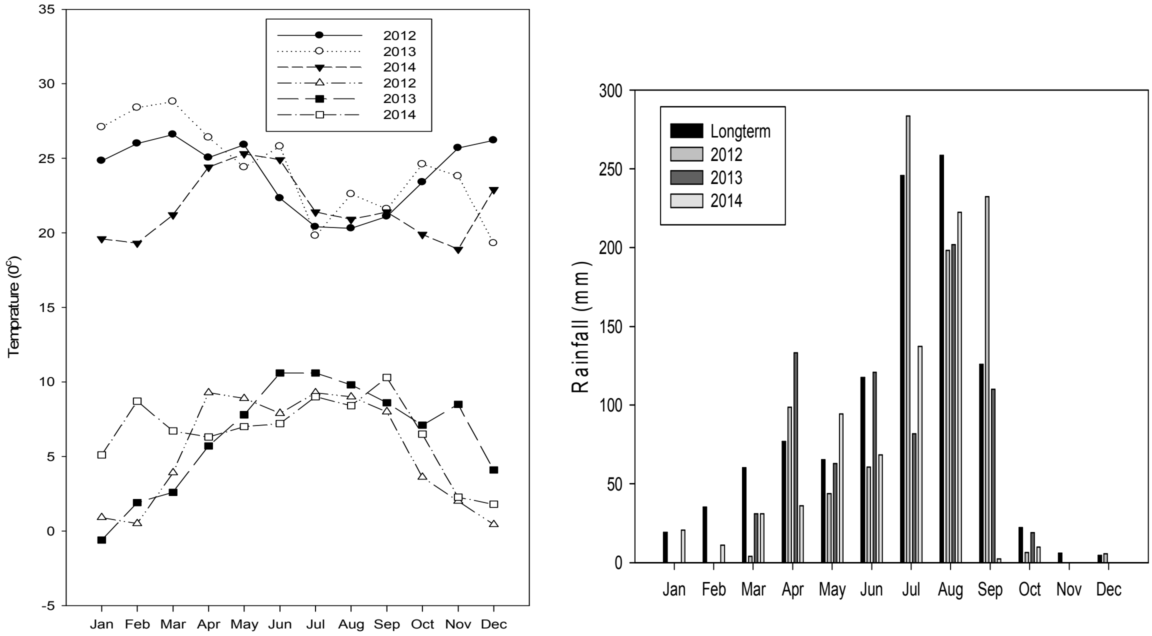

Figure 1. Mean monthly maximum, minimum air temperatures and monthly total rainfall for 2012, 2013 and 2014 cropping seasons, and the 30-year average rainfall at Holeta Research Center.

Table 2: Effects of year, P fertilizer rate and their interaction on yield and yield components of tef across sites in 2012, 2013, and 2014

Parameters	**Year (Y)**	**Phosphorous (P)**	**YxP**
Grain yield	***	***	Ns
Biomass yield	***	***	Ns
Harvest index	***	**	**
Seed yield	***	**	***
Panicle length	***	***	ns
Plant height	***	**	ns
Days to flowering	***	***	ns
Days to maturity	***	***	ns

Notes. Significant at **P ≤ 0.01, *** P ≤ 0.001; ns, not significant

3.2. Yield and yield related parameters

The responses of grain yield and yield components of tef to phosphorus fertilization, year and interaction of year by phosphorous of the combined data of over three years are presented in Table 2. Data analysis of variance for three cropping year revealed that grain yield and yield components of tef were significantly affected by year and P fertilizer. Analysis of variance over three cropping seasons indicated that the year effect was highly significant ($P<0.001$) for grain and yield components of tef (Table 2). The year by P fertilizer rate interaction was not significant for harvest index and seed yield per plant. The highest mean grain yield (1593 kg ha^{-1}) was obtained in the year 2012 compared to the lowest (1221 kg ha^{-1}) recorded in 2014. The maximum biomass yield, harvest index, seed yield, panicle length and plant height also recorded in the same cropping season (Table 3 and 4).

Grain yield, biomass yield, harvest index, seed yield per plant, panicle length, plant height days to 50% flowering and days to maturity of tef significantly responded ($p<0.01$) to P fertilizer application rate (Table 2). Grain yield significantly ($p<0.001$) affected by P rate. Application of 50 kg P ha^{-1} gave significantly higher grain yield. The application of P fertilizer rate of 10,20,30,40, and 50 kg ha^{-1} increased grain yields of tef by 48, ,58, 64, 65 and 70 %, respectively, compared to the control (without P fertilizer). Application of P fertilizer consistently increased biomass yield (linear, $r^2 = 0.98$), grain yield, harvest index, seed yield per plant, panicle length, Plant height, consistently increased as P rate increased, but showed slight decrease beyond 40 kg ha^{-1} for seed yield and harvest index. These results are in general accordance with the results of several studies, which showed the positive response of tef grain yield and other cereals to phosphorous fertilization in Ethiopian highland areas (Admassu, 2017; Agegnehu et al., 2015; Balcha, 2014). In addition, increasing P rate from 0 to 50 kg P ha^{-1} reduced days to 50% flowering and maturity by 17 and 12 days, respectively (Table 4). Physical observations revealed that heading and flowering stages were earlier and higher plant height was recorded in plots that received P fertilizer compared with untreated plots. The combined analysis of variance across all experimental locations signify that tef yield and yield components differed significantly (P<0.001) among trial locations (data not shown).

3.3. Critical P concentration (Pc) and P requirement factor (Pf)

Soil P values determined three weeks after planting differed significantly (P<0.01) among P levels. The main effect of P fertilizer resulted in mean soil test P values of 8.9 to 17.2 mg kg^{-1}. Bray-2 soil test P values below 10 mg kg^{-1} are considered low. The increase in soil P response to P fertilizer application was linear up to 50 kg P ha^{-1}. The highest mean soil P concentration (17.2) was recorded from 50 kg P ha^{-1} (Figure 2).

3.4. P requirement factor (Pf)

This factor enables one to determine the quantity of P required per hectare to raise the soil test by 1 mg kg^{-1} (1 part per million), and to determine the amount of fertilizer required per hectare to bring the level of available P above the critical level. It was calculated using available P values in samples collected from unfertilized and fertilized plots.

Table 3: Table of means for main effects of P application year and fertilizer rate on tef yield and yield related parameters in 2012, 2013 and 2014

Factor	Grain yield (kg/ha)	Biomass yield (kg/ha)	Harvest index (%)	Seed yield/plant (gm)
Year				
2012	1593a	6006a	26.7a	0.66a
2013	1305b	5143b	25.3ab	0.63ab
2014	1221b	5194b	24.5b	0.58b
Significance level	***	***	**	*
Phosphorous				
0	949c	4538c	21.1c	0.32d
10	1406b	5575b	25.3b	0.55c
20	1498ab	5638ab	26.7ab	0.58c
30	1554a	5669ab	27.7a	0.71b
40	1566a	5776ab	27.3a	0.83a
50	1615a	6071a	27.1a	0.81a
Significance level	***	***	**	**
CV	19.8	18.8	13.8	18.7
P_{linear}	***	***	**	**

Within each column, means with different letters are significantly different at p < 0.05; CV, coefficient of variation

Table 4: Table of means for main effects of P application year and fertilizer rate on tef yield and yield related parameters in 2012, 2013 and 2014

Factor	Days to flowering	Days to maturity	Panicle length (cm)	Plant height (cm)
Year				
2012	53.4a	106a	32.1a	88.2a
2013	51.9b	97b	30.9ab	82.0b
2014	50.3c	95c	29.9b	71.3c
Significance level	***	***	***	***
Phosphorous				
0	64a	108a	29.4b	77.1b
10	54b	103b	31.1a	84.0a
20	52c	101c	31.5a	85.1a
30	50d	99d	31.9a	85.4a
40	48e	98e	32.0a	85.8a
50	47f	96f	32.3a	86.9a
Significance level	***	***	***	***
CV	3	2.4	8.9	9.0
P_{linear}	***	***	***	***

Within each column, means with different letters are significantly different at p < 0.05; CV, coefficient of variation

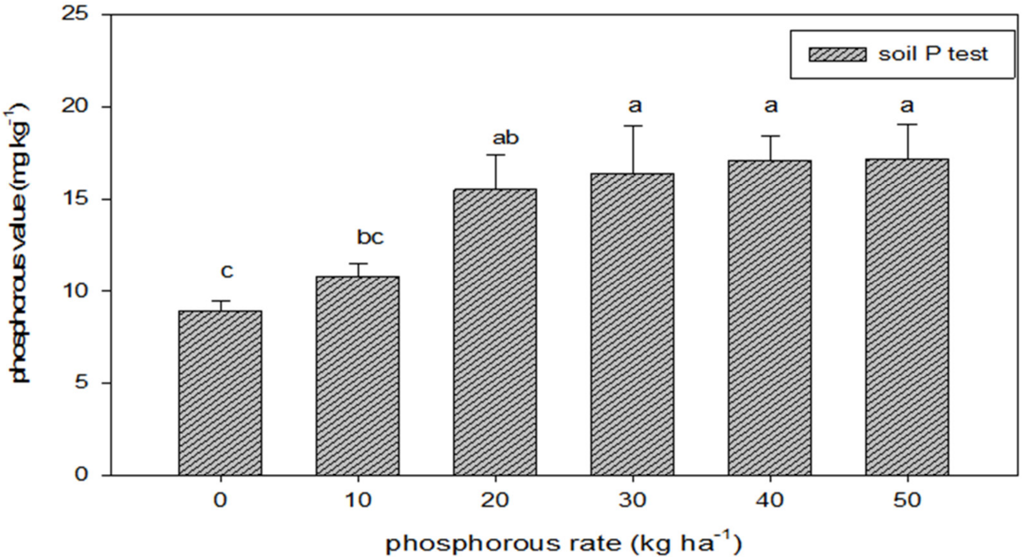

Figure 2: effect of available soil test phosphorous value analyzed three weeks after planting to P fertilizer rate in 2012, 2013 and 2014. Error bars with standard error.

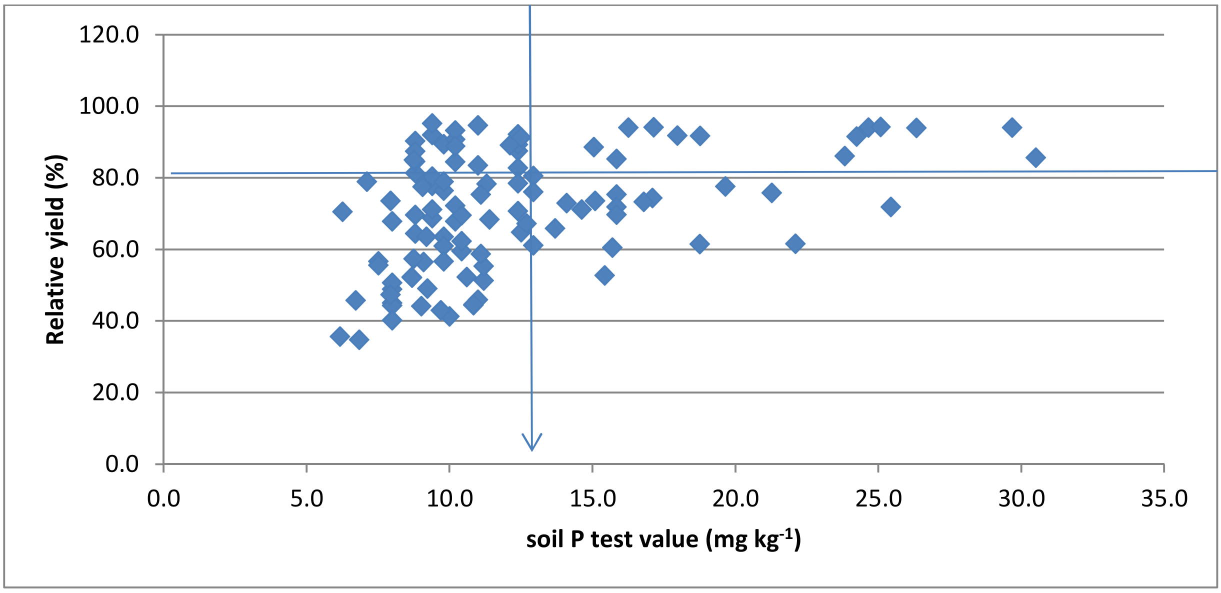

Figure 3: Relationships between soil extractable P measured using Bray-2 method and tef relative yield (percentage of the maximum yield). Using the graphical method of Nelson and Anderson a critical limit of 12.5 mg P kg^{-1} of soil extractable P was identified.

Table 5: Determination of P requirement factor for tef on Nitisols in 2012, 2013 and 2014

Phosphorous rate (kg/ha)	**Soil test P (Bray-II)**		**P increase over control**	**P requirement factor (Pf)**
	Range	**Average**		
0	3.0-17.2	8.9		
10	2.6-20.6	10.5	1.5	6.7
20	3.0-24.5	11.4	2.5	8.0
30	3.8-27.2	11.7	2.8	10.7
40	6.0-24.7	12.9	4.0	10.0
50	7.2-27.0	13.0	4.1	12.2
			Average	**9.5**

The correlation between relative tef grain yield response and soil P measured with Bray-2 method is indicated in Figure 3. The critical P concentration (P_c) was determined from the scatter diagram drawn using relative grain yields of tef and the subsequent soil test P values for all P levels (0-50 kg P ha^{-1}). The Pc defined by the Cate Nelson method in this study was about 12.5 mg P kg^{-1}, with mean relative yield response of about 80% (Figure 3). When the soil test value is below the critical value additional information is needed on the quantity of P required to elevate the soil P to the required level. This is the P requirement factor (P_f), the amount of P required to raise the soil test P level by 1mg kg^{-1}, computed from the difference between available soil test P values from plots that received 0-50 kg P ha^{-1} using the second formula mentioned above. Accordingly the calculated Pf were 6.7 to 12.2 and the overall average P_f of all treatments for the study area was 9.5 (Table 5). Thus the rate of P fertilizer required per hectare can be calculated using the soil critical P concentration, initial soil P determined for each site before planting (Table 1) and the P requirement factor as indicated above in the third formula.

4. Discussion

This research work clearly revealed positive effects of application of P on tef yield in this part of the country with a significant effect of cropping year. Inconsistency in cropping season's rainfall amount and its distribution has brought about significant differences in yield and yield components. Results have indicated that the amount of seasonal rainfall received and in the growing season greatly impacts the response to P fertilizer application in increasing productivity of tef. In 2013 and 2014, lower yield and yield components were recorded due to early insufficient amount of rainfall in all trial sites during the tillering period in the month of July. The yield obtained was lower in 2014 compared to 2013 because the amount of moisture received in September 2014 was lower during the critical period of grain filling stage. The amount of precipitation received in July 2013 and 2014 was half and one third of the precipitation received in 2012, respectively. Tef yield in 2014 was about 30% and 22% lower than in 2012. Studies have indicated that grain yield and nutrient uptake of crops were greater in a relatively wetter season than the drier ones (Agegnehu et al., 2006). With increasing soil moisture P uptake by plants generally increases the reason of which is higher solubility of P and further development of the root caused by moisture (Misra, 2003). According to (Jones et al., 2011) low nutrient uptake early in a plant's growth lowers nutrient quantity for the seed affecting yield in the contrary. Crop uptake of nutrients is affected by soil and climatic conditions. One of the constraints is low soil moisture that restrict uptake of plant nutrients. The changes in crop production related climatic variables will possibly have major influences on regional as well as global food production (Abraha and Savage, 2006) This indicates that a successful soil test based fertilizer recommendation program depending on the results of calibration of soil-test nutrient values with relative grain yields is conditional on rainfall and soil moisture status which influences the response of crops and yield to a greater extent than fertilizer applications.

Analysis of variance indicated that P had a highly significant effect on yield and yield component of tef. Yield increased consistently and significantly up to 50 kg P ha^{-1}, but the increase in yield was not significantly different beyond 20 kg P ha^{-1} rate; (Table 3). This implies that the quantity of tef response to P application might be constrained by soil acidity or supply of other nutrients mainly nitrogen. Aluminum and manganese (Mn) toxicity is a potential growth-limiting factor for plants grown in acid soils in many parts of the world (Foy, 1996). Excess Al even induces iron (Fe) deficiency symptoms in rice (Oryza sativa L.), sorghum and wheat (Clark et al., 1981; Furlani and Clark, 1981). At elevated Al concentrations in the soil solution, root tips and lateral roots become thickened and turn brown, and P uptake is reduced. Growth of plants on low pH soils may be constrained by deficiencies of N, P, potassium (K), calcium (Ca), magnesium (Mg) or molybdenum (Mo) (Brady and Weil, 1999). According to (Sumner and Farina, 1986) interactions between N and P in relation to yields are common and are primarily owing to N-induced increases in P absorption by plants. In addition, nitrogen deficiency reduced the uptake of sulfur (S), sodium (Na), K, calcium, Mn, Fe, and zinc (Zn) (Das & Sen, 1981). One of the factors why the potential yields are not obtained is the deficiency or imbalance of nutrients (Lobell et al., 2009). Because of the projected increase in demand for food that has to be produced sustainably, there is a need to increase fertilizer use efficiency. i.e. to obtain more yield per unit of fertilizer applied. Increasing fertilizer use efficiency requires balanced application of fertilizers. i.e. best fertilizer formulations supplied to the plant for uptake.

According to the Nelson and Anderson method, the critical level of Bray-2 P in the top 15 cm of soil was about 12.5 mg kg^{-1}. At values of greater than or equal to 12.5 mg kg^{-1}, the crop achieved about 80% of its maximal yield in the absence of P fertilizer application (Figure 3). This implies that P fertilizer application could be recommended for a buildup of the soil P to this critical value, or maintaining the soil P at this level. Increasing P beyond this level, the cost of additional P fertilizer to produce extra yield would likely be greater than the value of the additional yield. Similar studies reported critical concentrations of 12.5 and 13 and 13.5 mg P kg^{-1} using Bray 2 test for food barley, malting barley and wheat on Nitisols, respectively (Admassu, 2017; Agegnehu and Lakew, 2013; Agegnehu et al., 2015). Hence in soils with available P status below 12.5 mg kg^{-1} yield of tef could show significant response applications of P fertilizers. Whereas in areas with available P status below 12.5 mg kg^{-1} the P concentration in the soil exceeds crop needs so that further addition of P fertilizer may not result in a profitable yield increase. To protect a potential loss of tef yield at least maintenance application of 10 kg ha^{-1}

may be required depending on grain yield goal and profitability. Similar studies have recommended maintenance applications of P for response sites that had soil test P levels above the critical level (Agegnehu and Lakew, 2013; Agegnehu et al., 2015).

In most cases, soil pH less than 5.5 is deficient in available P and exchangeable cations (Brady and Weil 2010). In such soils the proportion of P fertilizer that could be available to a crop becomes inadequate (Brady and Weil 2010), unless amended through organic matter maintenance or liming to increase soil pH between 6.5 and 7 (Wortmann et al., 2013) for acid neutralization and applied through proper placement to increase the efficiency of utilization of the applied fertilizer. Higher coefficient variability in grain yield of tef on Nitisols may have been related to greater variability within and among less fertile on farm sites.

5. Conclusion

The results of this field work clearly revealed the importance of soil test based P fertilizer application for improving yield and yield components of tef under field conditions on Nitisols central highlands of Ethiopia. In this part of the country, soil fertility depletion is severe and use of external input is very low. The critical available soil P concentration (12.5) mg kg^{-1}) in Bray-2 method and the average P requirement factor (9.5) on Nitisols have been established for the study sites and similar areas. The results could be used as a pillar for soil test P fertilizer recommendations for the production of tef on Nitisols areas of central Ethiopian highlands. It will provide very important information to soil fertility specialists, extension personnel, investors and decision makers on the practical use of soil test based fertilizer phosphorous recommendation program in the country. They can also be used for future intensification in the other areas for developing a system for soil test based fertilizer recommendation. It is also very important to raise the soil pH through amendments like lime based on the soil acidity level before applying P fertilizers. Nevertheless, further soil test P calibration field trials involving different N levels may be required to generate more reliable information to maximize production and productivity of tef.

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