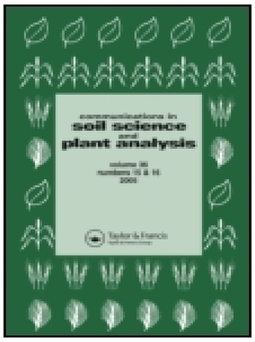

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Phosphorus Response and Fertilizer Recommendations for Wheat Grown on Nitisols in the Central Ethiopian Highlands

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The provision of farmers with proper and balanced fertilizer recommendations is becoming increasingly important, for reasons of crop productivity, food security, and sustainability. Phosphorus (P) response trials with wheat were conducted on Nitisols at 14 sites in the central Ethiopian highlands during the 2010 and 2011 cropping seasons. The treatments, comprising six levels of P fertilizer (0, 10, 20, 30, 40, and 50 kg P ha^{-1}), were arranged in a randomized complete block design with three replicates. Based on a yield difference between the control and the P treatments, 90% of sites responded to P fertilizer. Application of P fertilizer increased wheat grain yield, up to 30% more than the control. Extractable soil P concentrations (Bray 2, 0–15 cm deep) 3 weeks after planting significantly responded to P fertilizer rate. The critical P concentration (for 90% relative yield) was 13.5 mg kg^{-1}. Most sites tested had Bray 2 P values < 10 mg kg^{-1}. In the absence of a soil test, a recommendation of 40 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 wheat yield, a maintenance application of at least 5–12 kg P ha^{-1} be applied every year, irrespective of the calculated recommended rate, in order to replace P exported from the field in produce. Further field trials are required to determine interactions between P response and the effects of climate, soil properties, and other management practices.

Keywords Critical P concentration, Nitisol, phosphorus, relative yield, wheat

Introduction

Soil fertility depletion is a major constraint to agricultural production and food security globally, particularly in wheat and rice production areas of the developing world (Tan, Lal, and Wiebe 2005). The global average rates of soil nutrient deficit were estimated in 2000 as 18.7 kg nitrogen (N) ha^{-1}, 5.1 kg phosphorus (P) ha^{-1}, and 38.8 kg potassium (K) ha^{-1} (Tan, Lal, and Wiebe 2005). There are several economic and technological factors causing

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poor crop yields, including the fact that 80% of the total farm area in sub-Saharan Africa is made up of smallholder farms of less than 2 ha (Craswell and Vlek 2013). Although smallholder agriculture is dominant in most areas of Asia, high yields of crops were attained through intensification by using packages of irrigation, high-yielding crop varieties, and external inputs (Craswell and Vlek 2013). In sub-Saharan Africa, the major production factor contributing directly to the poor yields of crops is the inadequate use of external inputs. For instance, fertilizer use on arable land in sub-Saharan Africa in 2002 was only 13 kg ha^{-1} compared with 190 kg ha^{-1} in Asia (Craswell and Vlek 2013). The nutrient balance for sub-Saharan Africa appears to be negative, being currently minus 26 kg N, 3 kg P, and 19 kg K ha^{-1} $year^{-1}$ (Drechsel, Kunze, and De Vries 2001), while in Ethiopia the losses are larger, amounting to minus 122, 13, and 82 kg ha^{-1} $year^{-1}$ (Haileslassie et al. 2005). Thus Ethiopia is a country where severe soil nutrient depletion is a major restraint for agricultural productivity and economic growth.

In Ethiopia, 90% of the people and 95% of the land under crops are found in the central highlands region, an area with high population density, small farm size, and low farm income (Amede, Belachew, and Geta 2001). Wheat is grown over a large area (1.63 million ha), but productivity is as low as 2.1 t ha^{-1} (CSA 2013) because of poor soil fertility and crop management practices (Tarekegne and Tanner 2001; Zeleke et al. 2010) compared to the average cereal yields of 3 t ha^{-1} in the developing world. Limited use of legumes in the cropping system, continuous cropping, and applications of suboptimal rates of mineral fertilizers have aggravated the decline in soil fertility and crop yield (Tanner et al. 1999; Agegnehu et al. 2008; Zeleke et al. 2010; Tarekegne and Tanner 2001). Additionally, the removal of crop residues and manure for fuel are major causes of rapid soil fertility decline in fields distant from homes (Amede, Belachew, and Geta 2001; Zeleke et al. 2010).

Phosphorus and N are the most limiting plant nutrients in the tropics (Mengel and Kirby 2001; Troeh and Thompson 2005). In the Ethiopian highlands, soil acidity and low nutrient availability are major constraints for wheat production and productivity (Tarekegne and Tanner 2001; Regassa and Agegnehu 2011). Studies have demonstrated that Nitisols in the highlands are marginally to severely deficient in P (Tarekegne and Tanner 2001; Regassa and Agegnehu 2011). Blanket fertilizer recommendations, presently in use all over the country, were issued several years ago and are not suitable for the current production systems (Bekele et al. 2002; Zeleke et al. 2010). Furthermore, farmers have been applying the same P fertilizer rate to their fields regardless of spatial and temporal variations in fertility. Soil testing is the key to efficient and effective use of P fertilizers. Tests to determine nutrient status of soils, calibrated to crop response, have been a major tool for improving and sustaining productivity through site-specific nutrient management. Soil-test calibration studies with particular soil type–crop combinations are essential for producing site- and crop-specific fertilizer recommendations (Evans 1987; McKenzie and Kryzanowski 1997; Heckman et al. 2006). However, such studies are rare, even for major crop production areas. The objectives of this study were to determine, for Nitisols of the central Ethiopian highlands, wheat yield response to P, the critical value of soil P, and recommendations for agronomic optimum P fertilizer rates.

Materials and Methods

Experimental Sites

Phosphorus fertilizer trials were conducted for wheat on farmers' fields in Welmera District in the central highlands of Ethiopia in the main cropping seasons of 2010 and

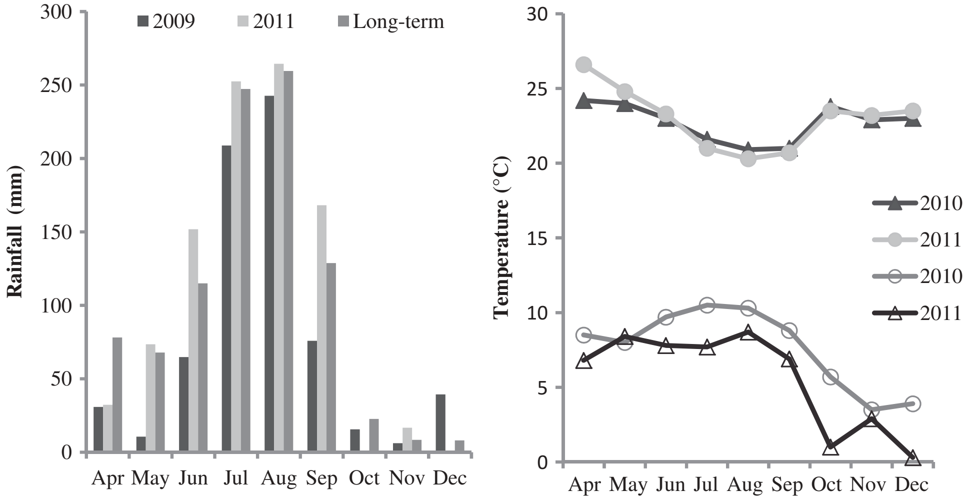

Figure 1. Monthly total rainfall, mean monthly maximum and minimum air temperatures for 2010 and 2011 crop growing seasons, and the 30-year average rainfall at Holetta Research Center.

2011. Wheat is widely grown in this area. The rainfall is bimodal with long-term average annual rainfall of 1100 mm, about 85% of which falls from June to September and the rest from January to May. Average daily minimum and maximum air temperatures are 6.2 and 22 °C, respectively (Figure 1). The environment is seasonally humid and the major soil type of the trial sites is Eutric Nitisol (IUSS Working Group WRB 2006).

To select representative trial sites, about 600 soil samples (0–15 cm deep) were collected from farmers' fields (27 sites) across the district before the onset of the main rainy season in 2010 and 2011. Soil samples were collected from the upper 15 cm because P from fertilizers will stay in this layer due to strong sorption and precipitation. Soil samples from each site were combined into one composite for analysis. Soil samples were analyzed for pH using a ratio of 2.5 ml water to 1 g soil (Peech 1965); for P using the Bray-2 method (Bray and Kurz 1945); for organic C content using Walkley and Black (1954) method; for total N content using Kjeldahl method (Bremner and Mulvaney 1982); and for exchangeable cations and cation exchange capacity (CEC) using the ammonium acetate method (Chapman 1965), at the soil and plant analysis laboratory of Holetta Agricultural Research Center (Table 1). The soil samples were classified according to their Bray 2 P concentration into low (< 10 mg P kg^{-1}), medium (10–25 mg P kg^{-1}), and high (> 25 mg P kg^{-1}). Based on this rating, 17 farmers' fields with low or medium available P were selected as trial sites. Overall, trial sites that test below the soil test critical level are likely to respond positively to P fertilizer application (Heckman et al. 2006).Thus trials were conducted on seven sites in 2010 and ten sites in 2011. At three sites, crops performed poorly so no measurements were made, leaving fourteen sites for analysis (Table 1).

The total amount and distribution of rainfall in the 2010 and 2011 cropping seasons were similar to the long-term average (Figure 1). September was wetter than average in both years, and minimum temperatures were greater in 2010 than 2011. The 2010 cropping season was conducive for the development of wheat rust fungal disease (*Puccinia triticina*), which caused significant yield reduction across the country in that year.

Table 1

Soil chemical properties (0–15 cm deep) of the trial sites in Welmera District, Ethiopia, in [year(s) of sampling] before planting the fertilizer trials

Year	Site	pH (1:2.5 H_2O)	Total C (%)	Total N (%)	Bray 2 P (mg kg^{-1})	Exch. K ($cmol_c$ kg^{-1})	Exch. Ca ($cmol_c$ kg^{-1})	Exch. Mg ($cmol_c$ kg^{-1})	Exch. Na ($cmol_c$ kg^{-1})	CEC ($cmol_c$ kg^{-1})
2010	Aselefech	5.0	1.26	0.17	6.4	0.76	2.47	1.79	0.12	17.3
	Ashenafi	5.2	1.46	0.16	6.2	1.10	2.93	2.13	0.16	21.1
	Balcha	5.9	1.56	0.17	15.4	1.12	3.05	2.18	0.15	23.1
	Diro	5.3	1.62	0.15	6.7	1.18	3.04	2.26	0.12	23.4
	Erko	5.2	1.53	0.14	6.5	0.73	2.87	2.07	0.11	19.4
2011	Ashenafi	5.4	1.52	0.16	5.6	0.80	2.81	2.02	0.13	19.7
	Dejene	5.7	1.48	0.18	17.6	1.04	3.10	2.16	0.13	22.8
	Guta	5.0	1.29	0.17	7.6	0.67	3.06	2.12	0.13	21.1
	Diro	5.4	1.57	0.16	7.2	1.36	3.14	2.17	0.15	23.8
	Seyoum	5.6	2.03	0.18	7.4	0.72	2.91	2.22	0.15	20.4
	Tadesse	5.3	1.31	0.17	14.1	1.28	3.05	2.09	0.14	23.6
	Tamiru	5.6	1.58	0.17	18.2	0.81	2.94	2.21	0.11	22.2
	Teshome	6.0	1.74	0.18	7.6	1.30	3.21	2.19	0.15	21.8
	Workinesh	5.7	1.67	0.14	6.8	0.77	2.73	1.92	0.11	19.0

Note. CEC, cation exchange capacity.

Experimental Setup

The treatments, consisting of six levels of phosphorus (0, 10, 20, 30, 40, and 50 kg ha^{-1}) applied as triple superphosphate (TSP), were arranged in a randomized complete block design with three replications. The plot size was 4 m by 5 m (20 m^2), and the spacing between plots and blocks was 0.5 m and 1 m, respectively. Wheat (*Triticum aestivum* L., cultivar HAR 604) was sown on 24–28 June in 2010 and 22–26 June in 2011 and harvested in November in each year. The P fertilizer was applied at planting. The recommended N fertilizer rate (60 kg ha^{-1}, as urea) was applied across all plots in two doses, half at planting and half at tillering stage. Broad-leaf herbicide was sprayed 5 weeks after crop emergence to control weeds, and one hand weeding was also carried out. Farmers were advised to follow the recommended cultural practices for wheat production from seedbed preparation up to harvesting. They were also encouraged to assess and compare treatments based on their own criteria. Farmer research groups, agricultural extension personnel, and researchers evaluated each trial during grain filling stage. In the 2010 cropping season, fungicide was sprayed to control wheat rust disease.

Data Collection

At harvest, the following parameters were measured: grain yield, aboveground total biomass, thousand-grain mass, test mass (kgL^{-1}), grain mass per spike (g100 $spikes^{-1}$), spike length, and plant height (average of 10 plants). To estimate total biomass and grain yields, a 12-m^2 area was harvested at maturity. After threshing, seeds were cleaned, weighed, and analyzed for moisture content. Grain masses were adjusted to an equivalent moisture content of 12.5% for statistical analysis. Total biomass and grain yields recorded on a plot basis were converted to kg ha^{-1} for statistical analysis. Harvest index was calculated as grain mass divided by total aboveground biomass.

Determination of Critical Soil P Concentration (P_c)

Soil P_c, the value of Bray 2 P above which there was little yield response, was determined using the relationship between yield (relative to maximum attained) and soil Bray 2 P concentrations for all 14 trials. Two methods were used for comparison. The first was the Cate-Nelson graphical method (Nelson and Anderson 1977). In it, a pair of intersecting perpendicular lines was drawn to divide the data into four quadrants. The intersecting lines were moved about on the graph, always parallel to the two axes on the graph, until the numbers of points in the upper right and lower left quadrants were at a maximum. P_c was taken as the point where the vertical line crosses the X axis. In the second method, an exponential rise to maximum (Mitscherlich) function,

$$y = a.(1 - e^{-b.x}) \tag{1}$$

in which y = relative yield, x = soil Bray 2 P concentration 3 weeks after planting, and a and b are fitted constants, was fitted to the data by minimizing the sum of squares of differences between the actual and fitted values, using iteration, in SigmaPlot. P_c was taken as the value of x for which yield was 90% of the maximum.

Determination of P Fertilizer Requirement

The amount of P fertilizer required to bring soil P concentration up to P_c was determined by quantifying the relationship between soil P content, with or without fertilizer applied, and the amount of fertilizer applied, using multiple linear regression in SigmaPlot.

Statistical Analysis of Response to Treatments

The data were subjected to analysis of variance (ANOVA) using the procedure of the general linear model (PROC GLM) of SAS statistical package version 9.1 (SAS Institute 2008). The total variability for each trait was quantified using the following model:

$$T_{ijk} = \mu + Y_i + R_{j(i)} + P_k + PY_{(ik)} + e_{ijk} \quad (2)$$

where T_{ijk} is total observation, μ = grand mean, Y_i = effect of the i^{th} year, $R_{j(i)}$ is effect of the j^{th} replication (within the i^{th} year), P_k is effect of the k^{th} treatment, $PY_{(ik)}$ is the interaction of 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 the least significant difference (LSD) test at the 5% probability level. Single degree of freedom orthogonal contrasts were performed to determine the nature of the crop response (linear and/or quadratic) to the rates of applied P fertilizer. The effect of "year" includes possible effects of sites, which differed between years.

Results

Yield and Yield Components

Analysis of variance over two cropping years showed that grain yield and yield components of wheat were significantly affected by year and P fertilizer rate (Tables 2 and 3). Grain yield, yield components, and percent seed moisture content differed significantly ($P \leq 0.01$ and $P \leq 0.05$) between years, but soil Bray-2 P concentration did not. The year by P fertilizer rate interaction effect was not significant for grain and yield components of wheat. The greatest mean grain yield (3576 kg ha^{-1}) was obtained at P rates of 30 kg ha^{-1} or more, in 2011, whereas the lowest (2748 kg ha^{-1}) was obtained at the lowest P rate in 2010. The application of P fertilizer at the rates of 10, 20, 30, 40, and kg P ha^{-1} resulted in a significant linear response with mean grain yield increases of 15, 20 30, 30, and 29%, respectively, compared to the control. The maximum total crop biomass, harvest index, thousand-grain mass, seed mass, plant height, spike length, and test weight were recorded in the same year and treatments as the maximum grain yield (Tables 2 and 3).

Application of P fertilizer consistently increased total biomass (linear, r^2 = 0.98), plant height, harvest index, and thousand-grain mass. However, despite numerical variations, statistically significant differences were not observed among P levels for harvest index and thousand-grain mass (Table 2). Test mass and seed mass per spike also increased as the P rate increased (Table 3). Observations showed that plant heights were taller and heading was earlier in plots treated with P fertilizer than untreated plots. The combined analysis of variance across sites revealed that yield and yield components of wheat differed significantly ($P \leq 0.01$) among trial sites (data not shown). Grain yield, total aboveground biomass, thousand-grain mass, seed mass per spike, test mass, spike length, and plant height all responded positively ($P \leq 0.05$) to P fertilizer rate (Tables 2 and 3). Statistically

Table 2
Table of means for main effects of year and P fertilizer rate on wheat grain yield and yield components

Factor	Grain yield (kg ha^{-1})	Total biomass (kg ha^{-1})	Harvest index (%)	TGM (g)
Year				
2010	2601	6596	40.4	33.1
2011	3625	8540	42.8	39.2
Significance level	***	***	*	**
$LSD_{0.05}$	239	537.2	2.3	0.77
Phosphorus (kg ha^{-1})				
0	2748	7227	38.8	33.9
10	3162	7618	42.1	37.1
20	3307	7858	42.7	37.1
30	3571	8266	43.8	36.7
40	3576	8636	41.2	37.5
50	3544	8134	43.7	37.2
Significance level	**	*	*	**
$LSD_{0.05}$	379	853	3.7	1.3
CV (%)	19.2	18.1	14.5	5.9
Control vs. P fertilizer	***	*	*	**
P_{linear}	***	**	Ns	**
$P_{quadratic}$	ns	ns	*	*

Notes. Significant at *$P \leq 0.05$, **$P \leq 0.01$, *** $P \leq 0.001$; ns, not significant; LSD, least significant difference; HI, harvest index; TGM, thousand-grain mass.

significant ($P \leq 0.05$) differences were not observed among yields for P fertilizer rates beyond 30 kg P ha^{-1}, indicating that P levels between 10 and 30 kg ha^{-1} may be adequate, depending on soil P status (Table 2). The flattening of response for most parameters at high levels of P fertilizer application resulted in a significant quadratic component to the model (Tables 2 and 3).

Critical Soil P Concentration and Fertilizer Requirement

Soil Bray 2 P values determined three weeks after planting increased significantly ($P \leq 0.01$) in response to P fertilizer application level. The relationship between Bray 2 soil P concentration and P fertilizer application rate was curvilinear (similar to the relationship between yield and P fertilizer rate, Table 2), reaching a maximum of 12.1 mg kg^{-1} at 40 kg ha^{-1} applied P (Figure 2). The two methods used to determine P_c gave very similar results. However, the curve-fitting approach had the advantage of providing confidence intervals. The P_c determined by the Cate-Nelson method was 13.5 mg P kg^{-1}, with mean relative grain yield of 90% (Figure 3). The P_c determined by the curve fitting method (using a relative yield of 90%) was 13.9 mg P kg^{-1}, with 95% confidence limits of 12.4–17.7 mg kg^{-1} (Figure 3). Soil Bray 2 P concentrations before the trials commenced were less than P_c for 10 of the 14 sites (Table 1). Three weeks after planting, they were less than P_c for 13 of the 14 trials (Figure 4).

Table 3
Table of means for main effects of year and P fertilizer rate on wheat yield components

Factor	Test mass (kg L^{-1})	Seed mass (g100 $spikes^{-1}$)	Plant height (cm)	Spike length (cm)	Moisture content (%)
Year					
2010	74.7	107.3	87.2	6.5	9.1
2011	77.8	147.0	100.1	7.1	9.3
Significance level	**	**	**	**	*
$LSD_{0.05}$	0.42	5.7	1.9	0.15	0.11
Phosphorus (kg ha^{-1})					
0	75.3	109.8	90.5	6.5	9.0
10	76.7	131.3	94.4	6.9	9.3
20	76.9	133.3	95.0	7.0	9.2
30	76.3	134.3	96.1	7.0	9.1
40	76.8	136.1	96.1	6.9	9.2
50	77.0	135.0	95.1	6.9	9.2
Significance level	**	**	*	*	*
$LSD_{0.05}$	0.72	9.8	3.2	0.25	0.18
CV (%)	1.5	12.4	5.5	5.9	3.2
Control vs. P fertilizer	***	***	**	***	*
P_{linear}	**	***	**	*	ns
$P_{quadratic}$	*	*	ns	**	*

Notes. Significant at *$P \leq 0.05$, **$P \leq 0.01$, *** $P \leq 0.001$; ns, not significant; LSD, least significant difference.

Soil Bray 2 P concentration 3 weeks after planting was related to Bray 2 P concentration of soil without fertilizer and the amount of fertilizer P applied (Figure 4). The relationship could be described by the equation

$$P_{fert} = 0.236 + 0.973P_{zero} - 0.00610R + 0.00876P_{zero}.R \quad (3)$$

in which P_{fert} is soil Bray 2 P concentration 3 weeks after planting (mg kg^{-1}), P_{zero} is soil Bray 2 P concentration with no applied fertilizer (mg kg^{-1}), and R is the amount of fertilizer P applied (kg ha^{-1}). The coefficients for P_{zero} and the interaction term were both significant ($P < 0.001$) and the relationship had and adjusted $r^2 = 0.925$. Rearranging the equation allows the fertilizer P rate to be calculated for any value of P_{zero} (for which the initial value can be used) and P_{fert} (for which the target value, P_c, can be used):

$$R = (-0.236 + P_{fert} - 0.973P_{zero})/(-0.00610 + 0.00876P_{zero}) \quad (4)$$

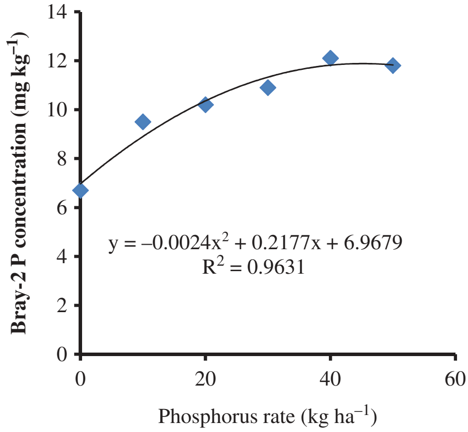

Figure 2. Relationship between soil Bray 2 concentration, analyzed 3 weeks after planting (Std = 0.85), and fertilizer P application rate.

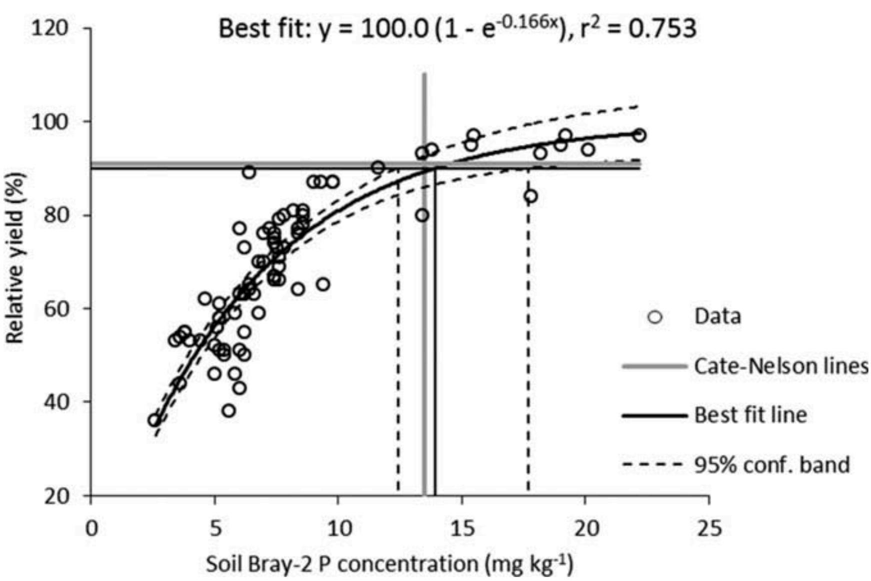

Figure 3. Relationship between relative grain yield and soil Bray 2 P concentration 3 weeks after planting. Lines show the determination of critical P concentration (P_c) using the Cate-Nelson graphical method (gray lines) and curve-fitting method (black lines).

Discussion

Our study showed clear positive effects of native and applied P on wheat yield in the study region, with a significant effect of cropping year. In rain-fed environments, the maximum yield attainable at any given location depends not only on the soil available nutrients and the amounts of fertilizer applied but also on the amount and distribution of rainfall during the crop season, and incidence of diseases, insect pests, and weed infestation. Although yield-limiting factors are complex, the major cause for lower yield in 2010 appeared to be the

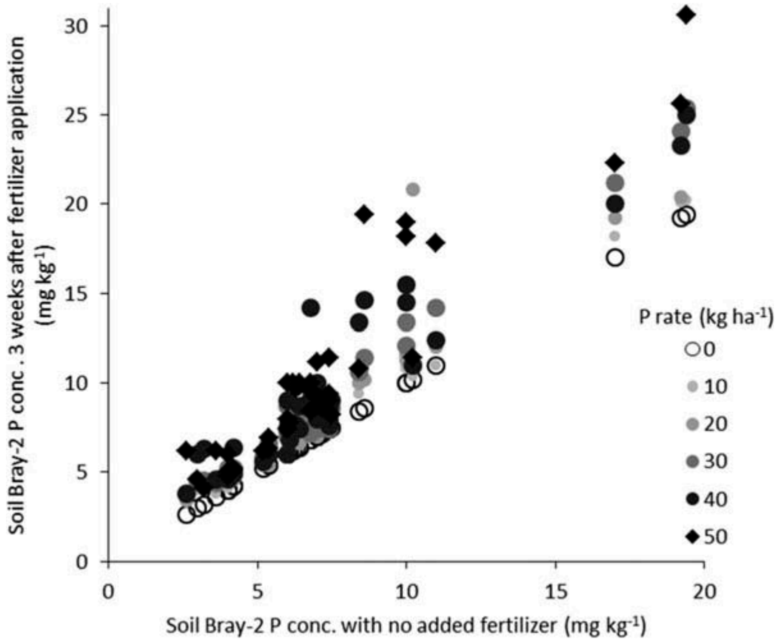

Figure 4. Relationship between soil Bray 2 P concentration 3 weeks after planting, Bray 2 P concentration with no applied fertilizer, and the amount of fertilizer applied.

occurrence of a fungal wheat rust disease across trial sites during the critical crop growth period and grain-filling months of September and October, based on earlier studies of fungal disease in the region (Agegnehu et al. 2008). Wheat yield in 2010 was about 39% lower than in 2011, and was far below the expected yield. Uptake of nutrients, especially P and K, and thus crop response, is also affected by soil water (Smilde 1987), which differs from year to year. This indicates that success of a soil-test-based fertilizer program is reliant on rainfall and soil moisture status. Carrying out more trials over a range of climatic conditions would allow rainfall to be built into the response function (Harmsen 2000). Availability of nutrients to crops is a function of the soil, crop, environment, and management; their interaction affects fertilizer use efficiency and the crop growth condition (Smilde 1987; Fageria 2009). These factors need to be considered when using methods to calibrate soil-test nutrient values with relative grain yields. Something that should be considered in this region in the future is the interaction of P response with N supply, soil pH, and with weather condition.

Yield increased consistently and significantly up to 30 kg P ha^{-1}, but not significantly beyond this rate; a slight decline in yield was even observed at the greatest P rate (Table 3). This suggests that the magnitude of wheat response to P might be limited by low soil pH or supply of other nutrients, particularly N. Plant growth on low pH soils may be limited by deficiencies of nitrogen, phosphorus, potassium, calcium, magnesium or molybdenum (N, P, K, Ca, Mg, or Mo) or toxicity of aluminum or manganese (Al or Mn) (Mengel and Kirby 2001). Interactions between N and P in relation to yields are common and are primarily owing to N-induced increases in P absorption by plants (Fageria 2001; Sumner and Farina 1986; Tarekegne and Tanner 2001). Nitrogen deficiency causes a marked reduction in uptake of P, K, Ca, Mg, Mn, copper (Cu), and zinc (Zn) (Mengel and Kirby 2001).

Application of P fertilizer could be recommended to raise soil P to the critical value and maintain it there. To increase P beyond this level, the cost of additional P fertilizer to produce extra yield would likely be greater than the value of additional yield. Similar studies reported critical concentrations of 10 mg P kg^{-1} using the Olsen test for wheat on Haplic Luvisols and Eutric Vertisols (Bekele et al. 2002), 12 mg P kg^{-1} using Bray 2 test for malting barley on Nitisols (Agegnehu and Lakew 2013), and 13 mg P kg^{-1} for maize using Bray 1 test (Mallarino 2003; Dodd and Mallarino 2005). According to Bell et al. (2013) there was no evidence showing that critical concentrations for wheat would be different from those for barley on the same soils. Considerably greater critical values for Bray 2 P (90% relative yield) have been found for wheat in Australia, being 33 mg kg^{-1} (Holford and Cullis 1985) or 45 mg kg^{-1} (Holford et al. 1985). The differences are presumably due to wheat variety, soil properties (particularly phosphate sorption characteristics), and climatic conditions. In Ethiopia, different soil P-extraction methods including Bray 2, Olsen, and Mehlich 3 have been tested for different soil types. As a result, the Bray 2 method was found most appropriate for soils with pH < 6.5 and the Olsen method for soils with pH > 6.5 (Bekele et al. 2002).

Soil fertility is suboptimal for the production of wheat in Ethiopian highlands, particularly on Nitisols where soil pH and the associated P availability is low. Following the preplanting soil analysis results, out of 14 trial sites 10 sites had soil P values lower than the critical soil P concentration (Table 1). At the sites with low initial P concentration, response of soil P to fertilizer application was also limited (Figure 4), indicating that added P was bound into nonextractable forms. Available P concentrations are largely controlled by reactions with Al and iron (Fe) oxides and other species in soils with pH levels below about 6.5, leading to lower availability at lower pH (Troeh and Thompson 2005). In most cases, soils with pH less than 5.5 are deficient in available P and exchangeable cations (Mengel and Kirby 2001; Troeh and Thompson 2005). In such soils the proportion of P fertilizer that could be available to a crop becomes inadequate, unless amended through liming. It is possible that wheat yield and response to P fertilizer in the Nitisols of Ethiopia may be improved by liming, but the possibility has yet to be investigated.

Using our results, P fertilizer recommendations can be made for Nitisols in the central Ethiopian highlands using an initial soil Bray 2 P concentration, a target or final Bray 2 P value (13.5 mg kg^{-1}, the P_c), and Eq. (4), bounded by minimum and maximum recommended rates. For example, using the average initial Bray P value of 6.7 mg kg^{-1}, the recommended application rate would be 128 kg P ha^{-1}. However, seeing the trials assessed rates up to only 50 kg P ha^{-1}, we recommend that no more than 50 kg ha^{-1} be applied in any one year. Most sites tested had Bray 2 P values <10 mg kg^{-1}, so in the absence of a soil test, a recommendation of 40 kg P ha^{-1} (which gave the best response overall) could be made for the first year of application. Also, we recommend that at least 5–12 kg P ha^{-1} be applied every year, irrespective of the calculated recommended rate, in order to replace P exported from the field in produce. The range of values 5–12 kg P ha^{-1} corresponds to an export of 3500–8000 kg ha^{-1} of dry matter (lower value being typical for grain only and the upper value being for total biomass) with a P content of 0.15%. Finally, it should be noted that this discussion assumes the economic optimum fertilizer rate is the same as the agronomic optimum (determined here). That assumption should be assessed for every situation, based on prices of produce and fertilizer application rate.

Conclusion

There were clear positive effects of P fertilizer on yield and yield components of wheat on Nitisols of central Ethiopian highlands. Across all 14 sites, the critical soil P concentration was 13.5 mg kg $^{-1}$ (Bray 2 method). The results may be used as a basis for P fertilizer recommendations for the production of wheat on Nitisol areas of Ethiopian highlands. They can also be used for future intensification in other areas for developing a system for soil-test P fertilizer recommendations. Further field trials involving different N levels, climatic conditions, soil P test methods, and perhaps liming treatments, would further our understanding of limiting factors and facilitate better fertilizer recommendations.

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