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Equations for Estimating Phosphorus Fertilizer Requirements from Soil Analysis for Maize (*Zea mays* L.) Grown on Alfisols of Northwestern Ethiopia

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ABSTRACT

Field and laboratory experiments were conducted to develop equations for estimating phosphorus fertilizer requirements of maize on Alfisols of Northwestern Ethiopia. The field experiment on 20 sites was arranged in randomized complete block design with five fertilizer rates and four replications. At maturity, three central rows were harvested and yield and yield components data were collected. Laboratory analysis of soil samples was conducted following chemical soil analysis methods: Bray-1, Bray-2, Olsen, Mehlich-1, anion exchange resin and extraction with 0.01*N* $CaCl_2$. Parameters of the Quantity/Intensity relationships were also determined. Reliable methods were identified by fitting relative grain, relative dry biomass and P yields in a double log curvilinear regression model and those availability indices giving superior correlation were selected. Consequently, grain yield data and phosphorus availability indices were fitted into the Mitscherlich-Bray model to develop fertilizer recommendation equations.

Results of the experiment revealed that among the methods giving quantity of available P, Bray-2 and Olsen methods gave the most reliable indices. Moreover, the intensity parameters in combination with the quantity parameters gave slightly superior correlation coefficient with yield parameters compared with their individual effects. The equations developed for estimating P fertilizer requirements of maize from soil analysis were: (a) log (100 - y) = 2 - 0.1468b - 0.007546x and (b) log (100 - y) = 2 - 0.1167b - 0.007546x for Olsen and Bray-2 methods, respectively, where y was desired relative grain yield (%); b was soil P availability index (mg kg^{-1}); and x was P fertilizer requirement (kg ha^{-1}). The two equations were statistically proven to provide equally reliable estimates of P fertilizer requirement of maize on Alfisols of Northwestern Ethiopia.

Key words: Alfisols, P availability indices, fertilizer requirement, maize, quantity/intensity relation

INTRODUCTION

In many areas of the tropics, population growth is rapid and there is a rapidly growing demand for food. Therefore, cultivation of subsistence crops must be stimulated and production augmented. Unfortunately, most tropical soils have low levels of soil fertility often caused by inherently low levels of available phosphate (Eijk, 1997). In P-deficient soils, crops

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usually recover less than 10 percent of the applied amount of phosphorus in the first season, even if they respond well and the total recovery after four years was often only 20-30 percent (Russel, 1972). Moreover, many tropical soils are able to fix large amount of fertilizer phosphate, a main factor lowering the recovery of fertilizer phosphate by plants. This is due to high amounts of iron and aluminum oxides in these soils. Therefore, following nitrogen, phosphorus is the most limiting nutrient in the tropics (Sanchez, 1976). Consequently, yields are low.

In many farming systems of Ethiopia, input of manures and fertilizers is still low and not sufficient to sustain the productivity of the soils. Bringing more land into cultivation is not possible in the densely populated areas. Preference, therefore, should be given to raising the production of subsistence crops by increasing the productivity of the soils on which crops are grown. Improving soil fertility is one of the major factors to improve soil productivity. Organic and inorganic fertilizers should, therefore, be applied to restore and improve the soil fertility and to compensate for the withdrawal and losses of nutrients during cultivation. Nevertheless, organic fertilizers are scarce resources in most farming households of Ethiopia where farmyard manure and crop residues are used as energy source to cook food. Therefore, efficient use of artificial fertilizers should be given due attention.

The role of chemical fertilizers in increasing yield is evident. Fertilizers accounted for more than 50% of the increase in yield (FAO, 1984) and phosphorus is of primary concern in the appraisal of the soil resources of Ethiopia (Miressa and Robarge, 1996). Fertilizers must be applied based on scientific understanding of the indigenous soil nutrient status. Since no universally accepted method exists for indexing availability of P, reliable methods must be selected so as to meet the specific conditions under which the crops are intended to grow.

Indices obtained from chemical soil analysis should be fitted into a mathematical model that integrates soil test results with crop nutrient requirement. The Mitscherlich-Bray model has been successfully used by many workers for such purposes (Matar *et al.*, 1987; Payton *et al.*, 1989; Santhi *et al.*, 1998). The objective of this study was, therefore, to develop equations for estimating phosphorus fertilizer requirements from soil analysis for maize (*Zea mays* L.) grown on Alfisols of Northwestern Ethiopia.

MATERIALS AND METHODS

Site selection

To select the experimental sites, composite soil samples were collected from 52 farmlands that had different cropping history, slope and management practices. The collected soil samples were analyzed for available phosphorus content by Bray-2 method, texture and pH. Out of the sampled sites, 20 experimental sites covering the widest possible ranges of the indicated parameters were selected (Table 1).

Experimental design, field layout and cultural practice

At each site, a field experiment was arranged in randomized complete block design with five treatments and four replications. The treatments were five levels of P fertilizer rates (0, 30, 60, 90 and 150kg P_2O_5 ha^{-1}) as triple superphosphate (0-46-0). Gross plot size for the trial was 16.8m^2 and net plot size (harvestable plot) was 7.56m^2. Spacing between rows was 70cm and between plants within a row was 30cm. The gross plot had 3 harvestable and 2 boarder rows, and 2 plants at each end of the harvestable row were used as boarder plants. Seed beds for maize planting in each location were prepared following farmers' practice. Planting was conducted from May 28 to June 7, 2002 depending on the onset of rainfall in different areas. Planting was made by keeping two seeds in

Table 1 Locations and some chemical and physical characteristics of soils of the experimental sites.

Site No.	Altitude (meters above sea level)	Geographic position	Slope (%)	Bray-2 P (mg kg^{-1})	pH in H_2O (1:2.5)	Particle size (%)			Soil texture
						Sand	Silt	Clay	
1	2240.0	11º17.2'N 37º28.9'E	3.8	3.42	4.91	7	25	68	Clay
2	2243.1	11º17.3'N 37º28.8'E	2.6	2.55	5.21	5	25	70	Clay
3	2348.8	11º14.3'N 37º30.7'E	0.3	3.82	5.00	7	21	72	Clay
4	2347.9	11º14.2'N 37º30.9'E	2.3	2.81	5.35	13	17	70	Clay
5	1897.3	11º44.0'N 37º30.8'E	5.4	10.80	5.40	15	29	56	Clay
6	1918.0	11º44.7'N 37º31.9'E	5.1	3.13	4.73	5	17	78	Clay
7	1955.8	11º45.7'N 37º32.4'E	3.1	8.02	4.99	7	27	66	Clay
8	1969.8	11º46.8'N 37º33.2'E	2.3	10.73	4.83	9	27	64	Clay
9	1916.8	11º44.4'N 37º31.7'E	8.1	11.41	5.26	55	21	24	Sandy clay loam
10	2048.7	11º24.8'N 37º24.8'E	1.1	9.43	5.25	9	25	66	Clay
11	2067.6	11º25.0'N 37º07.9'E	3.5	7.59	5.25	15	49	36	Silty clay loam
12	2039.8	11º24.8'N 37º07.4'E	0.2	6.66	5.05	9	25	66	Clay
13	2038.9	11º24.6'N 37º07.1'E	0.3	6.48	5.13	11	23	66	Clay
14	2002.7	11º21.6'N 36º58.1'E	1.6	10.96	5.01	13	23	64	Clay
15	1900.0	10º80.0'N 36º85.0'E	5.0	7.96	5.75	11	21	68	Clay
16	2150.7	10º42.7'N 37º05.6'E	1.8	16.04	5.78	15	25	60	Clay
17	2106.3	10º42.2'N 37º06.3'E	5.2	9.48	5.43	9	21	70	Clay
18	1897.9	10º40.8'N 37º16.4'E	2.3	9.48	5.63	11	23	66	Clay
19	1888.4	10º40.5'N 37º16.4'E	2.9	4.14	5.42	11	23	66	Clay
20	1882.0	10º40.9'N 37º19.0'E	0.6	2.54	5.28	11	23	66	Clay

one hill at a distance of 30 cm within a row. Two weeks after emergence one seedling per hill was left and the remaining were pulled out. All of the phosphorus fertilizer for each treatment was applied at planting by banding along one side of the row at a distance of about 10 cm below and 5 cm aside the seeds. To each treatment, nitrogen (150 or 75 kg ha^{-1} for sites with organic matter content <5% and ≥5%, respectively) as urea (46-0-0) and potassium (60 kg K_2O ha^{-1}) as potassium chloride (0-0-60) were added as basal fertilizers. Two times ridging and, as necessary, weeding operations were performed to all sites.

Soil sample collection and analysis for indexing availability of P

At planting, from each replication of the selected 20 locations, one composite soil sample was collected from the top 0 - 20cm soil layer. The collected samples were air-dried under the shade and crushed to pass through 0.5 mm sieve. Indexing availability of phosphorus was conducted following six soil P analysis methods: Bray-1 (Olsen and Sommers, 1982), Bray-2 (Sahlemedihin and Taye, 2000), Olsen (Olsen and Sommers, 1982), Mehlich-1 (Tan, 1996), anion exchange resin (AER) extraction (Tan, 1996), 0.01*N* $CaCl_2$ extraction

(Olsen and Sommers, 1982), equilibrium P concentration (EPC), phosphorus buffering capacity (PBC) and labile P determined from Quantity/Intensity (Q/I) curves (Kpomblekou and Tabatabai, 1997). These methods were selected because indices from them were widely reported to be reliable in estimating availability of P.

Yield data collection, plant sampling and analysis

Grain and biomass yield data (grain plus stubble) were collected from the three central rows excluding the two boarder plants at each end of the row. Maize grain and stubble samples were collected to determine plant P uptake. For plant sample analysis, procedures outlined by Sahlemdihin and Taye (2000) were used.

Derivation of equations for calculating P fertilizer rates for desired maize yields

Calculation of relative yields

Relative grain and dry biomass yields were determined by calculating maximum values of each parameter using a second degree polynomial regression model: $Y = a + b_1x + b_2x^2$, where Y = the dependent variable (yield); x = the independent variable (P fertilizer rate); a = the intercept on the y-axis; and b_1 and b_2 = regression coefficients. The maximum values for grain and dry biomass yields were determined from the model after fitting obtained data. These values were regarded as 100% relative yield values. Other yield values were converted into relative yields as percent of their corresponding maxima (Suwanarit *et al*., 1999).

Examining relationships between the availability indices and the relative grain, relative dry biomass and P yields from crop data

P availability indices measured by different soil test methods and relative grain, relative dry biomass and P uptake of the control plots were fitted into double log curvilinear regression model: $\log y = a + b \log x$, where x = the obtained index value; y = the relative grain, relative dry biomass or P uptake of the control plots from crop data; a = the intercept at the y axis; and b = slope of the line. Availability indices giving superior and highly significant correlation with the above yield parameters were used to develop equations for calculating fertilizer rates for desired maize yields. Moreover, the single and multiple effects of the quantity/intensity parameters on relative yields and P uptake were compared using simple and multiple correlation coefficients.

Equations for calculating P fertilizer rates for desired maize grain yield

Relationships among relative grain yields, obtained P availability indices from reliable soil test methods and amount of fertilizer applied were expressed by the Mitscherlich-Bray model. The model for each selected chemical method was derived by calculating c_1 (coefficient of availability indices) and c (coefficient of fertilizer rates). First c_1 was calculated by substituting b (availability indices) from each replication of the experimental sites in the following equation: $\log (A - y) = \log A - c_1b$, where A = relative maximum grain yield; and y = the relative grain yield from unfertilized plots. Mean of all the c_1 values of all the locations was used for the model. Then the c value was calculated for each fertilized treatment by substituting calculated c_1 value of each replication in the following equation: $\log (A - y) = \log A - c_1b - cx$, where x = the P fertilizer rates used and y = relative grain yield of fertilized plots. Mean of all the c values of all the fertilized plots was used for the model.

Verifying reliability of obtained equations

Reliability of the derived equations was verified by comparing the actual maize grain yields with grain yields predicted by the obtained equation.

A linear regression technique was used to see the relationship between them. Significant correlation coefficient revealed reliability of the equation.

RESULTS AND DISCUSSION

Relationships among soil P availability indices and relative grain, relative dry biomass and P yields

All indices, except the parameters of the quantity/intensity relationships, highly significantly ($P < 0.01$) correlated with relative grain and dry biomass yields (Figure 1). The relative yield curves have shown more typical Mitscherlich type yield trend for Olsen, Bray-2, Mehlich-1, Bray-1 and AER methods. With other availability indices, the relative yield curves had either linear trend or had no significant relationship. This was especially true for those methods that extracted low amount of P from the soil. It was observed, however, that P uptake relatively poorly correlated with availability indices when compared with other yield parameters, and Mitscherlich type yield trend was not obtained. Among the parameters of the quantity/intensity curves, EPC (the x-intercept in the Q/I graph) had no significant relationship with relative grain yield but had significant relationship with relative dry biomass yield ($p < 0.05$) and P uptake ($p < 0.01$). Labile P (y-intercept in the Q/I graph) provided significant correlation coefficients at rather lower level of significance ($p < 0.05$) with relative grain yield and relative dry biomass yield. PBC ($\Delta Q/\Delta I$ in the Q/I graph) exhibited negatively significant ($p < 0.05$) relationship with relative grain yield ($r = -0.26^*$); and non-significantly negative relationship with relative dry biomass yield ($r = -0.18^{ns}$) and P uptake ($r = -0.17^{ns}$). Generally, only indices from Olsen and Bray-2 methods exhibited relatively higher correlation coefficient values exceeding 0.5 with relative grain and dry biomass yields.

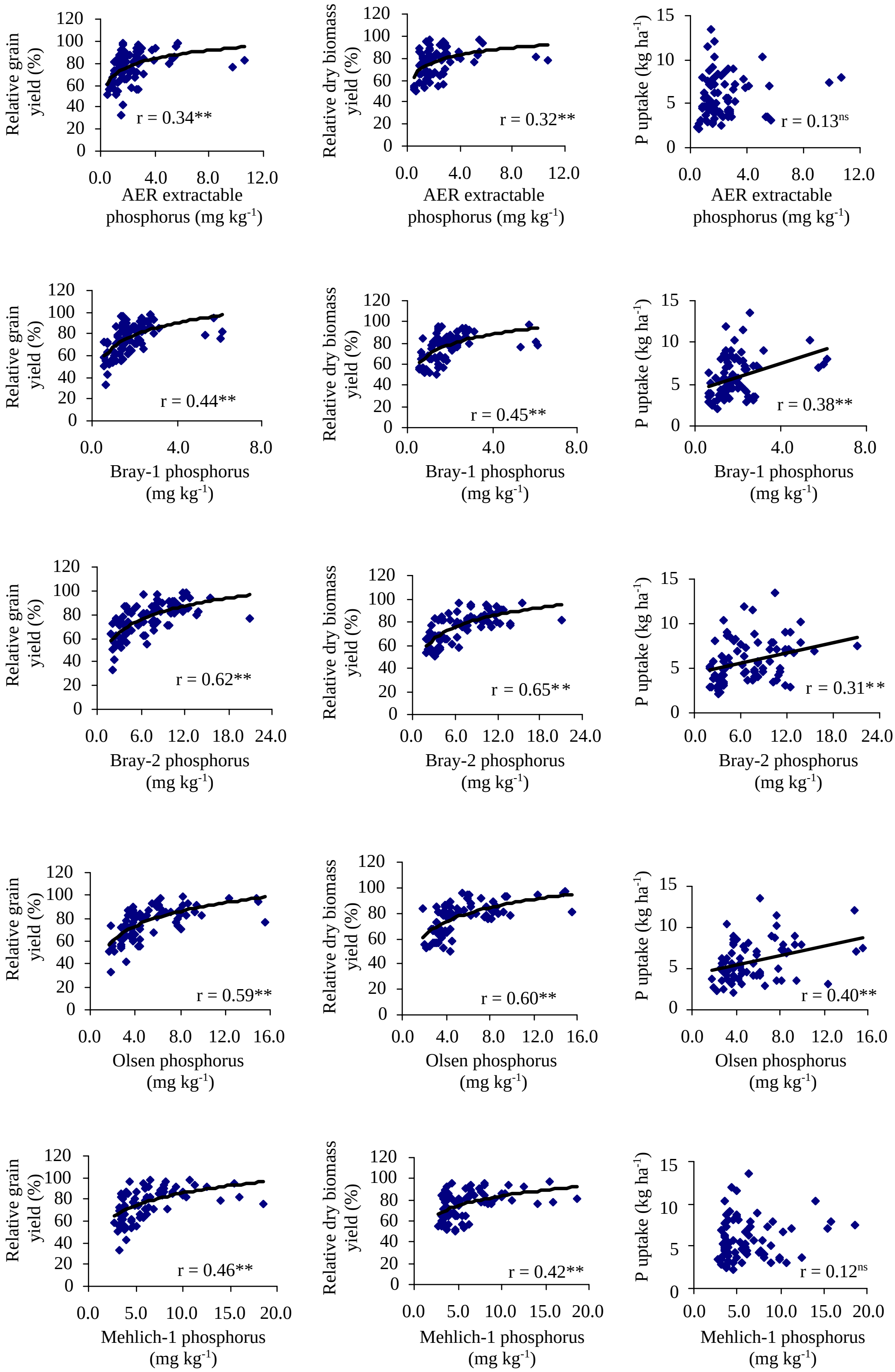
The correlation coefficient matrix among availability indices (Table 2) indicated that Olsen, Bray-2, Mehlich-1 and Bray-1 methods correlated highly significantly ($p < 0.01$) and with relatively higher r values among each other. Those methods that had non-significant correlation with yield parameters were also found to correlate with rather lower correlation coefficient values with indices of Olsen, Bray-2, Mehlich-1 and Bray-1 methods. PBC, however, significantly but negatively correlated with most of the indices.

The reliability of Bray-2 method was supported by Sahlemedihin and Taye (2000) and Enwezer (1977) who stated that Bray-2 method was effective for determination of available P in acidic soils. The Olsen (bicarbonate-P) extractant, which was initially developed for use in neutral

Table 2 Correlation coefficient matrix of soil P availability indices obtained with different methods.

Indices	Olsen	Bray-2	Mehlich-1	Bray-1	AER	$CaCl_2$	EPC	PBC
Bray-2	0.78**							
Mehlich-1	0.75**	0.80**						
Bray-1	0.73**	0.83**	0.84**					
AER	0.62**	0.59**	0.80**	0.76**				
$CaCl_2$	0.41**	0.52**	0.36**	0.44**	0.15^{ns}			
EPC	0.56**	0.47**	0.48**	0.56**	0.46**	0.22*		
PBC	-0.29*	-0.22*	-0.38**	-0.41**	-0.45**	0.08^{ns}	-0.15^{ns}	
Labile P	0.42**	0.36**	0.35**	0.20^{ns}	0.13^{ns}	0.22*	0.74**	0.15^{ns}

*, ** significant at 5% and 1% probability levels, respectively; ^{ns} non-significant at 5% probability level; n = 80.


Relative grain yield (%)
Relative dry biomass yield (%)
P uptake (kg ha-1)
AER extractable phosphorus (mg kg-1)
r = 0.34**
r = 0.32**
r = 0.13ns
Bray-1 phosphorus (mg kg-1)
r = 0.44**
r = 0.45**
r = 0.38**
Bray-2 phosphorus (mg kg-1)
r = 0.62**
r = 0.65**
r = 0.31**
Olsen phosphorus (mg kg-1)
r = 0.59**
r = 0.60**
r = 0.40**
Mehlich-1 phosphorus (mg kg-1)
r = 0.46**
r = 0.42**
r = 0.12ns

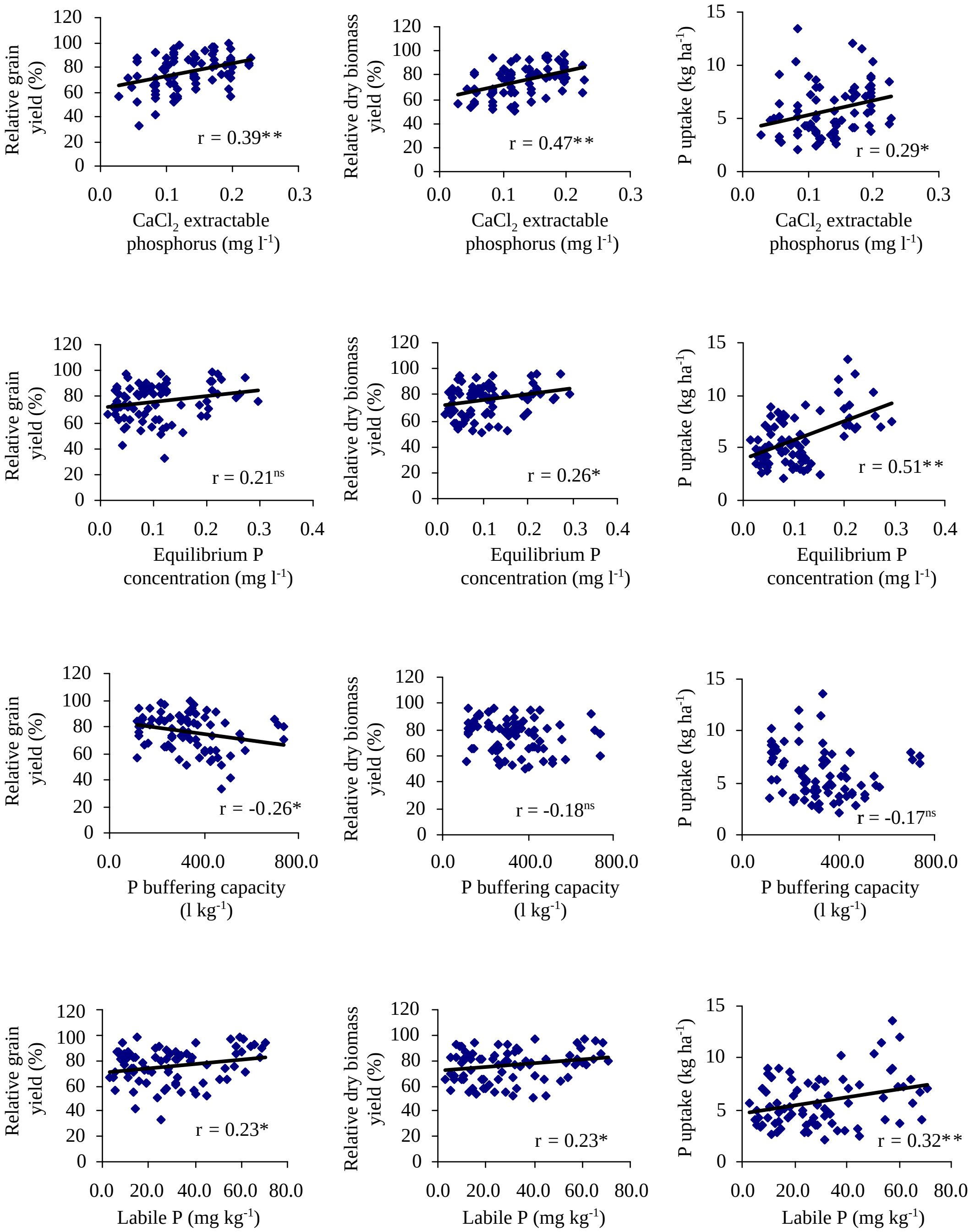


Figure 1 Relationships between P availability indices and relative grain, relative dry biomass and P yields (*, ** significant at 5% and 1% probability levels, respectively; ns non-significant at 5% probability level; n = 80).

and calcareous soils (Olsen *et al.*, 1954), has been also used in acidic soil conditions because the secondary precipitation reactions in acid soils are reduced to a minimum since the concentration of Al and Fe remain at a low level in this extractant (Olsen and Sommers, 1982). In agreement with the results of the present study, Taye and Hofner (1990) and Tekalign and Haque (1991) reported that Olsen method was the most reliable method for Ethiopian soils.

The negative correlation observed for PBC with relative yield values and actual P uptake can be justified as follows. If soils have high PBC, much of the fertilizer nutrient added in acidic soils poor in phosphorus will be sorbed and may not be easily available to plants until the sorption sites were saturated. It was only enough to note the change in PBC values measured along the Q/I curves of the experiment. PBC was very high when measured at lower part of the Q/I curve since most added P was sorbed by the solid phase; PBC was medium at the central part of the Q/I curve; and PBC diminished at upper part of the curve when the solid phase tended to saturate with P. Since most soil samples analyzed had low soil solution and available P, high PBC values that were measured at the lower part of the Q/I curve, where plants operate in actual circumstances, could not indicate accurately the capacity of the soil to replenish P to the soil solution. It rather indicates the capacity of the soil to adsorb P. Raven and Hossner (1993) indicated that the P buffering power of a soil apparently depended on the availability of P sorption sites and their degree of depletion, and was not always directly related to the ability of a soil to release P. Ozane and Shaw (1968) also reported that low levels of bicarbonate soluble P were adequate for maximum yield in soils of low PBC and higher levels of soluble P were required for near maximum yield in soils of higher PBC. Therefore, it is not expected that capacity indices should perform as independent measures of P availability (Holford, 1979).

Intensity (activity of P in the soil solution), quantity (amount of labile P or plant-available P), and phosphorus buffering capacity (PBC) which is the ability of soils to resist changes in P activity during P depletion, determine the flux of P to plant roots and yield of crops. This was explained by the Q/I concept of Schofield (1955) who argued that the availability of soil P for plant uptake does not necessarily depend on the size of labile P pool, but also on intensity and capacity factors. To verify which parameter more affected the relative yield parameters and P uptake, simple and multiple regression techniques were employed. The EPC (x-intercept of the Q/I curve) and soil solution P concentration obtained by equilibrating 50 ml 0.01*N* $CaCl_2$ with 5 gm of soil for 5 minutes (hereafter referred as “approximate EPC”) were regarded as intensity factors; the absolute value of the extrapolated y intercept in the Q/I graph (mg kg^{-1}), the Olsen and the Bray-2 extractable P values as quantity factors; and the slope ($\Delta Q/\Delta I$) of the linear graph developed from the lower part of the Q/I curve (where plants operate in actual circumstances) as the PBC (l kg^{-1}).

Regressing approximate EPC, quantity and capacity factors together improved the correlation with relative grain yield, relative dry biomass yield and P uptake than each of them regressed individually which was reflected by the increase in correlation coefficients (Table 3). Regressing EPC, which had non-significant relationship with relative grain yield and significant correlation but at rather lower level of significance ($p < 0.05$) with relative dry biomass yield, with Olsen and Bray-2 extractable P gave higher correlation coefficients with relative yields and P uptake than individual indices. Nevertheless, regressing EPC with y-intercept P gave reduced correlation coefficients with relative grain and relative dry biomass yields than their individual effects. Including PBC to EPC and y-intercept P, however, improved the correlation with relative grain, relative dry biomass and P yields.

Table 3 Simple and multiple correlation coefficients of the relationship between quantity, intensity and PBC with relative grain, relative dry biomass and P yields of maize.

Availability indices regressed (independent variables)		Dependent variables [1/]		
		RGY	RBY	PY
EPC from Q/I curves	(i)	0.21^{ns}	0.26*	0.51**
Approximate EPC	(i_1)	0.39**	0.47**	0.29**
Y intercept from Q/I Curve	(q_1)	0.23*	0.23*	0.32**
Olsen extractable P	(q_2)	0.59**	0.60**	0.40**
Bray-2 extractable P	(q_3)	0.62**	0.65**	0.31**
PBC from Q/I curves	(c)	-0.26*	-0.18^{ns}	-0.17^{ns}
$i + q_1$		0.23^{ns}	0.26^{ns}	0.53**
$i + q_2$		0.62**	0.61**	0.52**
$i + q_3$		0.63**	0.66**	0.51**
$i + c$		0.31*	0.29*	0.52**
$i_1 + q_1$		0.41**	0.49**	0.40**
$i_1 + q_2$		0.61**	0.65**	0.42**
$i_1 + q_3$		0.62**	0.67**	0.35**
$i_1 + c$		0.49**	0.52**	0.35**
$q_1 + c$		0.38**	0.32**	0.39**
$q_2 + c$		0.60**	0.60**	0.40**
$q_3 + c$		0.63**	0.65**	0.33**
$i + q_1 + c$		0.39*	0.32*	0.53**
$i + q_2 + c$		0.63**	0.61**	0.53**
$i + q_3 + c$		0.64**	0.66**	0.52**
$i_1 + q_1 + c$		0.52**	0.54**	0.45**
$i_1 + q_2 + c$		0.63**	0.65**	0.43**
$i_1 + q_3 + c$		0.64**	0.67**	0.38**

[1/] RGY = relative grain yield; RBY = relative dry biomass yield; PY = phosphorus yield;
*, ** significant at 5% and 1% probability levels, respectively; ^{ns} non-significant at 5% probability level; n = 80.

Inclusion of PBC, which correlated negatively and significantly ($p < 0.05$) with relative grain yield and non-significantly and negatively with relative dry biomass yield and P uptake, to intensity and quantity parameters did not diminish the regression coefficients but rather improved them in most of the cases. Generally, the results showed that the concept of Schofield remains applicable in Alfisols of Northwestern Ethiopia but the procedures are more costly and more time consuming than the procedures of Olsen and Bray-2 methods.

Considering with the ease and cost of doing soil analysis in addition to the reliability, Olsen and Bray-2 methods were selected for developing equations to calculate fertilizer requirements of maize on Alfisols of Northwestern Ethiopia.

Equations for calculating P fertilizer rates for desired maize grain yield

Equations for estimating P fertilizer requirements of maize from soil analysis results of

Table 4 Equations for estimating phosphorus fertilizer requirements of maize from soil analysis results of reliable methods.

Method	P availability index	Unit of index	Equation [1/]
Olsen	Olsen P	mg kg^{-1}	log (100-y) = 2 - 0.1468b - 0.007546x
Bray-2	Bray-2 P	mg kg^{-1}	log (100-y) = 2 - 0.1167b - 0.007546x

[1/] y = relative yield goal (as % of maximum yield); b = P availability index obtained from soil analysis (mg kg^{-1}); x = P fertilizer requirement (kg P_2O_5 ha^{-1}).

the reliable methods are presented in Table 4. Coefficients for indigenous soil P (c_1) and fertilizer rates (c) were calculated as mean of 80 and 280 data points, respectively. The Olsen method extracted less P than Bray-2 from most of the soil samples analyzed and eventually the c_1 value was higher for the former than the latter. From the models it was possible to make predictions that for a unit increase in soil P concentration (mg kg^{-1}) measured by Olsen and Bray-2 methods, the amount of P fertilizer to be applied shall be reduced by 19.4 and 15.4 kg P_2O_5 ha^{-1}, respectively, taking 98% as optimum relative yield goal (calculation of the optimum relative yield goal is not presented in this paper).

Reliability of the equations

Simple linear regression technique employed to see the relationships between actual grain yields obtained from the experimental plots and predicted grain yields by the developed equations indicated that the relationships were linear, with highly significant ($P < 0.01$) and almost equal correlation coefficients both for Olsen and Bray-2 methods (Figure 2). The two methods, therefore, can be interchangeably used as reliable P availability indices depending on laboratory reagents available.

Determination of the critical soil P concentration

The Cate-Nelson graphical technique (Cate and Nelson, 1965) was compared with the developed equations in determining the P critical level. The former method involves superimposing vertical and horizontal lines on a scatter diagram so as to maximize the number of points in the positive quadrants. The vertical line divides the data into two classes (high probability of response and low probability of response).The point where the vertical line intersects the x axis has been termed as the critical level. Based on this, the critical P concentration beyond which applied fertilizer becomes non-responsive was identified to be about 10.5 and 14.5 mg kg^{-1} for Olsen and Bray-2 methods, respectively. In the latter method, the P critical level (b when x = 0) was determined by substituting 0 for x (fertilizer rate) and 98% for y (relative yield goal) in the developed equations. Based on this, the equations provided comparable critical P concentration values of 11.6 and 14.6 mg kg^{-1} for Olsen and Bray-2 methods, respectively.

Different values have been reported in literature regarding the critical levels of phosphorus. SPAC (1992), for example, indicated that 12 mg kg^{-1} Olsen P to be the critical limit above which plants do not respond to applied P. Tekalign and Haque (1991), however, has shown that critical Olsen P values to be 8 mg kg^{-1} for Ethiopian soils. Quite recently, Taye *et al.* (2000) reported that 10 mg kg^{-1} to be the critical Olsen P level for wheat in soils of Hetosa district, Ethiopia. The variation in critical P concentration values among different soils is an indication that the soil-plant relationship is governed by various physico-chemical characteristics of soils besides to the indigenous P available in the soil and the type of

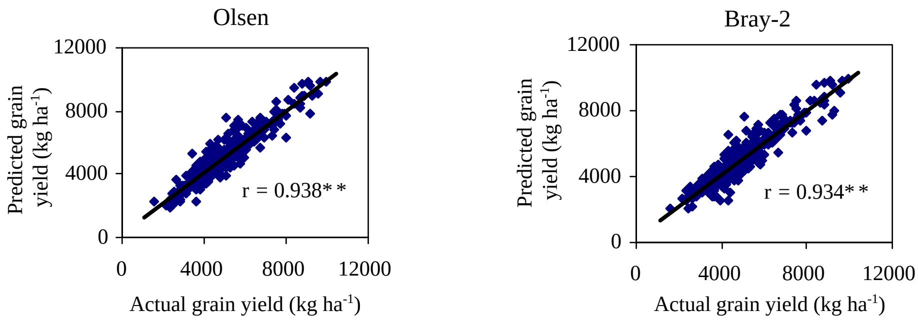


Figure 2 Relationships between actual and model predicted grain yields using indices from Olsen and Bray-2 methods (** significant at 1% probability level; n = 400)

crop grown. It is apparent, however, that in acidic soils like Alfisols of the study area, the inherently low P content coupled with high P fixation capacity makes application of larger amount of P fertilizer of paramount importance.

CONCLUSIONS

From the results of the experiment it is possible to draw the following conclusions:

1. From the soil P analysis methods incorporated in the experiment, Bray-2 and Olsen methods were found to be superior in providing reliable indices of indigenous P availability in the soil.

2. The Mitscherlich-Bray equations developed for the two reliable soil P extraction methods were statistically proven to provide reliable estimates of P fertilizer requirements of maize on Alfisols of Northwestern Ethiopia.

3. Considering intensity, quantity and capacity parameters improved yield predictions more than each of them being used separately. However, since Q/I studies are costly and time consuming, reliable methods like Olsen and Bray-2 can be successfully used to estimate plant-available P for fertilizer recommendation purposes in the study area.

4. The critical P concentration beyond which applied fertilizer becomes non-responsive was identified to be 11.6 and 14.6 mg kg^{-1} for Olsen and Bray-2 methods, respectively.

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