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Optimizing Phosphorus Fertilization Rates for Soybeans Grown on Oxisols and Associated Entisols[1]

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ABSTRACT

Although soils vary considerably in their P sorption characteristics, this factor is often not considered in a soil test interpretation. One soil property closely related to P sorption is clay content. Residual P studies were conducted for 4 yr on three tropical soils of similar clay mineralogy, two Oxisols of 63 and 27% clay, and a Quartzipsamment of 12% clay. The Mehlich 1 (1:10) extractable P level was described as a function of time, initial soil P level, and P fertilization rate. One crop of soybeans [*Glycine max* (L.) Merr.] was grown each year and the yield related to extractable P, which, in turn, was related to the initial P soil level and P fertilization rate for a period of 1 yr. Based on a soybean price of $0.23/kg and a fertilizer P price of $1.23/kg, rates of P were calculated for each of the three soils that would maximize net returns for various initial levels of extractable P. As these rates differed markedly with clay content, a soil test interpretation was created by multiple regression based upon both Mehlich 1 extractable P concentration and clay percentage to predict a recommended rate of fertilizer phosphorus (R) as follows: $R = 80 - 2.57(\text{soil P}) + 0.01386(\text{clay})^2 - 0.003281(\text{soil P})(\text{clay}^2)$. This function should be applicable to many soils with similar clay characteristics.

Additional Index Words: soil test, interpretation, calibration, sorption, clay, economic.

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THE OBJECTIVE of a soil test interpretation is to be able to recommend the optimum rate of fertilizer. One philosophy of achieving this is to maintain a nutrient so that its extractable concentration is sufficient for maximum yield. This would be applicable only if there is a measurable residual effect of the element applied. In order to compute the optimum rate of a given nutrient, three values are required: (i) the existing extractable nutrient concentration in the soil, (ii) the concentration sufficient for maximum yield, and (iii) a buffer capacity factor indicating the change in soil nutrient concentration during the period per unit of nutrient applied. With the inclusion of economic considerations, the interpretation may be modified to recommend the rate of fertilizer required to maximize net returns.

The concentration of extractable P sufficient for maximum yield varies with soil properties. Cope and Rouse (1973) stated that fine-textured, high cation exchange capacity (CEC) soils would produce maximum yields at lower soil test P levels than coarser-textured, lower CEC ones. Similarly, Kamprath (1978) reported that the Mehlich 1 extractable (1:5) P critical levels for clayey and sandy Ultisols were 10 and 20 mg/kg, respectively. Although it is known that P sorption or fixation varies with several soil properties, there have been few attempts to incorporate this information into

Table 1. Selected properties of the three soils prior to treatment.

Clay	pH	Al	Ca + Mg	K	Al sat.	P
%		cmol(+)/dm³			%	g/m³
63	4.9	1.12	0.68	0.10	59	0.[illegible]
27	4.6	1.26	0.96	0.12	54	1.4
12	5.2	0.34	1.04	0.09	23	2.2

a soil test interpretation. Such data are needed to determine the optimum rate of fertilizer for specific soil conditions. A mathematical approach to this was worked out by Cox and Lins (1984) for corn (*Zea mays* L.) grown on two Ultisols varying in clay content. Their technique should be applicable for other crops grown on other acid soils as well. The objectives of the current study were to (i) refine the mathematical approach, and (ii) determine the fertilizer P rate required for optimum yield of soybeans grown Oxisols and associated Entisols as influenced by extractable P concentration and clay content.

PROCEDURE

Field and Lab Methods

Phosphorus studies were conducted at three sites in the Cerrado area of Mato Grosso do Sul, Brazil. The soils were (i) a Typic Haplustox; clayey, kaolinitic, isohyperthermic, (ii) a Typic Haplustox; fine-loamy, siliceous, isohyperthermic, and (iii) a Typic Quartzipsamment; isohyperthermic, coated. Clay contents of the surface horizons were 63, 27, and 12%, respectively. Dolomitic limestone was applied 90 d before establishing treatments to eliminate Al toxicity. Soil P levels were created by incorporating broadcast triple superphosphate to supply P at rates of 0, 66, 132, and 264 kg/ha in four replications of a randomized complete block design. One crop of soybeans [*Glycine max* L. Merr.)] was grown each year for 4 yr and grain yields determined. General fertilization for the first two crops in kg/ha included 60 K, 2 Zn, 1 B, and 0.2 Mo. Only the K rate was continued thereafter (Table 1).

At harvest, grain yields were determined and the soil sampled from each plot for analysis. Soil Al was extracted with 1 *M* KCl (1 soil/10 solution) and titrated to a bromthymol blue end point. Calcium and Mg were also determined on a portion of this extract by atomic absorption spectrophotometry (Lin and Coleman, 1960). Soil P and K were extracted with Mehlich 1, 0.05 *M* HCl + 0.0125 *M* H_2SO_4, (1 soil/10 solution) for 5 min and determined by spectrophotometry and flame photometry, respectively. Soil pH was determined in a 1:1 soil/water stirred suspension.

Mathematical Approach

Extractable soil P concentration (X) was expressed as a function of the initial soil test level (X_o), rate of fertilizer P(F), and time (T) at each site. The descriptive model developed by Cox et al. (1981) was used with one modification. In their model, the immediate effect of fertilizer rate, F, on extractable soil P concentration is given for only one initial soil test level, X_o, by the following quadratic expression:

$$X = X_o + b_1F + b_2F^2 \qquad [1]$$

where b_1 and b_2 are coefficients describing the buffer capacity of the soil. This expression must be modified if one is to consider other initial soil P concentrations. Two terms must be changed. The first is the intercept, X_o, which is replaced by the selected initial P concentration, X_i. The second is the slope at the intercept, b_1, which must be changed by a factor, E. This factor is the numerator of the solution of the quadratic equation for the new initial P concentration, X_i. It may be calculated as follows:

$$E = -b_1 + \mathrm{sqr}(b_1^2 - 4b_2(X_o - X_i)) \qquad [2]$$

where sqr denotes the square-root function.

With these changes to facilitate use of the descriptive model with a time function included, the expression to predict extractable P becomes:

$$X = X_{eq} + [X_i + (b_1 + E)F + b_2F^2 - X_{eq}]\exp(-kT) \qquad [3]$$

where X_{eq} is an equilibrium soil test level based on experience and exp denotes the value of "e" to the power given in the parentheses following. The data were fit to this model using the NLIN procedure for nonlinear models in SAS (SAS Inst., Inc., 1982).

A nonlinear model was also used to relate treatment mean grain yields (Y) to extractable soil P concentration (X) at each site. The form selected was as follows:

$$Y = A - B\exp(-CX) \qquad [4]$$

where A, B, and C are constants. The value of X was then expressed by Eq. [3] to give:

$$Y = A - B\exp\{-C[X_{eq} + [X_i + (b_1 + E)F + b_2F^2 - X_{eq}]\exp(-kT)]\}. \qquad [5]$$

Economic considerations are then inserted and net income (N) calculated as follows:

$$N = QY - SF \qquad [6]$$

where Q is the price of soybeans and S is the cost of fertilizer P. The yield, Y, in Eq. [6] is replaced by Eq. [5] to give:

$$N = Q\{A - B\exp\{-C[X_{eq} + [X_i + (b_1 + E)F + b_2F^2 - X_{eq}]\exp(-kT)\} - SF. \qquad [7]$$

Considering a time period of 1 yr ($T = 1$), the derivative of net income was taken with respect to fertilizer rate, F, and set equal to zero, as follows:

$$0 = QB\exp\{-C[X_{eq} + [X_i + (b_1 + E)F + b_2F^2 - X_{eq}]\exp(-k)\}\}(-C)\exp(-k)[(b_1 + E) + 2b_2F] - S. \qquad [8]$$

Solution of this equation will give the fertilizer rate for maximum net income for a given initial soil test level. This was done with the data from each site for eight initial levels between X_o and greater values up to where the effect of fertilizer rate became negligible. The 24 observations were then evaluated by multiple regression so that the fertilizer rate for maximum net income (R) was a function of initial soil test level (soil P) and clay content (clay). The concept developed by Cox and Lins (1984) in which the clay term is

Table 2. Coefficients or parameters for Eq. [1] and [2] for the three soils varying in clay content.

Coefficient or parameter	Clay (%) 63	27	12
A	2759	2664	1925
B	5608	4752	2751
C	0.4590	0.2257	0.1346
X_{eq}	2.0	5.5	9.0
X_o	3.5	6.2	11.0
b_1	0.021	0.246	0.256
b_2	0.0003	0.0006	0.0011
k	0.152	0.363	0.246

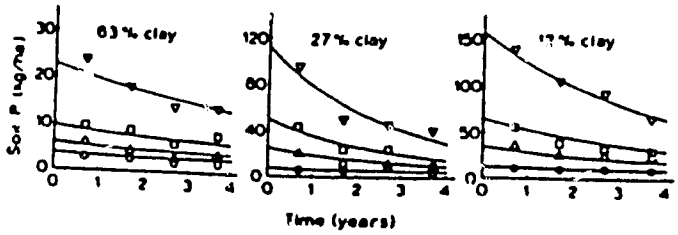

Fig. 1. Change in extractable soil P concentration of three soils with time after an application of (in ascending order) 0, 66, 132, and 264 kg P/ha.

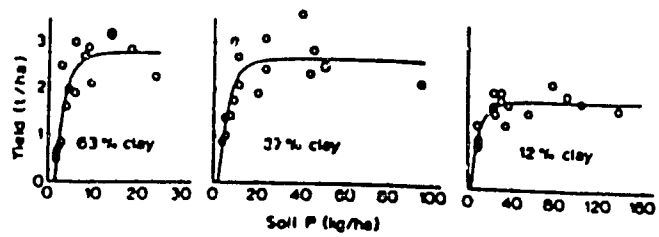

Fig. 2. Yield of four crops of soybeans grown on three soils varying in clay content in relation to extractable soil P concentration.

squared was used. This expression includes the interaction and may be written as follows:

$$R = a + b(\text{soil P}) + c(\text{clay})^2 + d(\text{soil P})(\text{clay})^2 . \quad [9]$$

With this expression, the fertilizer P rate for maximum net income becomes a continuous function of initial soil test level and clay content.

RESULTS AND DISCUSSION

The initial effect of a given rate of P on the soil test P concentration was greatest on the lowest clay content soil and least on the one with the highest clay content (Fig. 1). The data from each site fit a descriptive model (Eq. [3]) quite well with the coefficients given in Table 2. The rate of continued decline in soil P with time is described by the coefficient k. With these soils, the parameter does not appear related to the b_1 value, as hypothesized by Cox et al. (1981), or to the clay content.

Soybean yields markedly increased with the initial increase in concentration of extractable P at each of the three locations (Fig. 2). Coefficients for fitting the data to an exponential function (Eq. [4]) were determined and are given in Table 2. There is some variation in the observed yields at the higher levels of soil P. Much of this is associated with the fact that the data from 4 yr are shown and are not adjusted for a year effect. Maximum yields were somewhat greater for the latter 2 yr of the study than for the first. This effect could be removed by adjusting soybean yields to an average, but this would not really affect the function derived, so it was not done.

The fertilizer P rates to maximize net returns at various initial soil P levels for the three soils are shown by the calculated points in Fig. 3 for a soybean price of \$0.23/kg and a fertilizer P cost of \$1.23/kg. For the clay soil, very high rates of P would be recommended at very low soil P levels. The recommended rate decreases rapidly with increasing soil P, however, and none would be recommended if the extractable P concentration exceeded 9 kg/ha. For the more sandy soils, a lower rate of P would be recommended at the very low soil P levels, but some would continue to be recommended until the extractable P concentration exceeded about 25 kg/ha.

The modification in the quadratic function, Eq. [1], to consider other initial P concentrations has affected the relationship between fertilizer P rate and soil P concentration shown in Fig. 3. As viewed from the origin, the response is slightly convex. Without this modification, the response is definitely concave (Cox and Lins, 1984). Convex functions have been proposed before and are in use in North Carolina (Hatfield and Hickey, 1983). The current response, however, has such a small change in slope that a simple linear function should suffice.

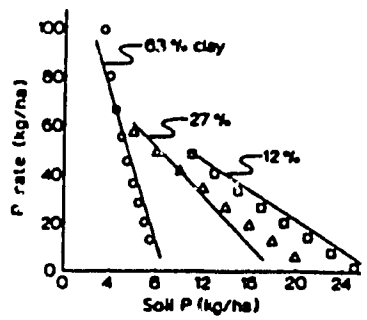

Fig. 3. A soil test interpretation for P showing the calculated (points) and predicted (lines) optimum P rates for three soils varying in soil P and clay content for a soybean price of \$0.23/kg and a fertilizer P cost of \$1.23/kg.

The calculated fertilizer rates for all three soils shown in Fig. 3 were then used to predict a recommended rate based on both extractable P and clay content. It was found necessary to square the clay term in the multiple regression analysis, as had been noted previously by Cox and Lins (1984). The equation to predict the optimum rate (R) was as follows:

$$R = 80 - 2.57(\text{soil P}) + 0.01386(\text{clay})^2 - 0.003281(\text{soil P})(\text{clay})^2 . \quad [10]$$

The predicted rates from Eq. [10] are shown by the lines in Fig. 3 for the three soils. In general, the prediction fits the calculated points well. For the clay and loamy sand soils, the predicted rate was slightly greater than that calculated at the highest soil P levels applicable to each. The opposite trend was observed with the sandy clay loam, but these discrepancies were minor.

Insertion of more stringent economic conditions, through higher fertilizer cost and/or lower soybean price, would have the effect of moving the results shown in Fig. 3 to the left. Less P would be recommended for a particular soil at a given initial soil P level. Also, the soil P concentration at which no fertilizer P would be recommended, one definition of the critical level, would be reduced. By this definition, the critical levels predicted by the lines shown in Fig. 3 are 9, 18, and 27 kg P/ha for the 63, 27, and 12% clay soils, respectively.

Ulrich and Hills (1973) recommended establishing critical levels at 90% of maximum yield. If this is done with the data in Fig. 2, the comparative critical levels would be 6.5, 13, and 20 kg P/ha for the three soils. Other approaches may also be applied to show the

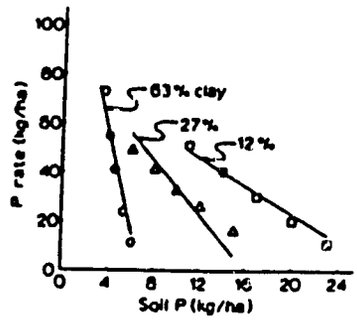

Fig. 4. A P soil test interpretation for soybeans showing the calculated (points) and predicted (lines) optimum P rates for three soils with mean critical levels of 6, 15, and 23 kg/ha.

relationship between critical level and clay content. Application of the Cate-Nelson (Cate and Nelson, 1971) method to the percentage yield per crop by treatment means and the soil P concentration showed that the range in critical levels for the three soils was even wider, being 5.4, 20, and 26 kg P/ha. Critical levels were also determined with a segmented analysis, a linear plateau, at the junction of the sloping and nonsloping portions of the curve. The results were 6, 11, and 24 kg P/ha for the three soils, respectively.

The three techniques just mentioned do not contain economic considerations and give similar results. The mean critical levels are 6, 15, and 23 for the 63, 27, and 12% clay soils, respectively. The rate of fertilizer P required to achieve those levels and maintain them for 1 yr can be calculated from Eq. [3]. The results of this approach are shown by the points in Fig. 4. For the clay and sandy clay loam soils the predicted fertilizer rates to be suggested are more conservative than those from the economic approach (Fig. 3), as would be expected with lower critical levels. Little difference was shown with the loamy sand, however, between the two methods. As shown by the lines in Fig. 4, these data also fit the multiple regression model well.

If the lines in Fig. 4 are extended to the soil P concentration at which no fertilizer P would be recommended, the values on the x-axis are 7, 16, and 28 kg P/ha. These values, derived from a mean of three techniques dividing yields into responsive and nonresponsive segments, are quite similar to the 9, 18, and 27 kg P/ha found by the economic analysis. This tends to substantiate many of the earlier works done on soil test interpretation for P that were not based upon economic considerations.

The lowest point for each soil shown in Fig. 4 is at the assumed critical level, and the P rate for that concentration is the amount of fertilizer required to maintain the critical level for 1 yr. These rates range from 11 to 16 kg P/ha. For following years, therefore, this would be the quantity of P needed. This quantity should increase with increasing clay content (buffering capacity). Such a relationship was not clear with the current set of data. Predicting fertilizer requirements for a period of years would be of great advantage to both the farmer and the soil testing laboratory.

In the Cerrado region, the current critical level of P extracted with the Mehlich 1 is 18 kg/ha (9 ppm) for Oxisols. Texture is known to alter the rate required to change the soil P level (EMBRAPA/CPAC, 1979, 1981) but that fact is not incorporated in the soil test interpretation. There is interest, however, in a recommendation scheme based on extractable P, texture, and kind of farming system (Goedert, 1983). If soybeans are grown in the rotation, the work reported here will provide a convenient method in which economic considerations may be imposed to optimize P fertilization rates based on extractable P and texture.

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