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Effect of Extractant and Selected Soil Properties on Predicting the Correct Phosphorus Fertilization of Soybean

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ABSTRACT

The rate of phosphorus required to maximize soybean [*Glycine max* (L.) Merr.] yields is dependent on the concentration of extractable P along with other chemical and mineralogical characteristics of the soil. Clay content, surface area, P adsorption maximum, type of clay, and extractable phosphorus were evaluated in order to enhance the prediction of the rate of P required for optimum soybean growth on seven acid soils in the greenhouse. The soil test extractants were: Mehlich-1, Mehlich-3, Bray-1, and an ion exchange resin method. The critical P level by each extraction method was correlated with clay content and, in one case, also with type of clay. Clay content and surface area were the most effective additional criteria found to improve the prediction of P fertilizer rate. The Mehlich-3 extractant was superior to Bray-1 and the resin method; Mehlich-1 was least predictive. From a practical standpoint, clay content and extractable P offer the best means of predicting the rate of P required.

A SOIL TEST is a chemical extraction process of the soil by which the concentration of a nutrient or nutrients is determined in an effort to predict the amounts of supplemental fertilizer nutrients required to obtain optimum yields. In soil testing, this concentration is referred to as a level. The concentration of an extractable nutrient at which no crop response occurs upon addition of fertilizer is called the critical level. The relationship between soil test levels and the corresponding supplementary fertilizer requirements are established through field and greenhouse studies where soil test levels, fertilizer rates, and yield response are correlated.

In most cases, dilute acid extractants such as Mehlich-1 have been used successfully on acid soils in predicting the fertilizer P requirement at a given soil test level (Nelson et al., 1953). Other extractants such as Bray-1 and Mehlich-3 are also used. They utilize fluoride to enhance the extraction of plant available Fe- and Al-phosphates (Mehlich, 1984; Bray and Kurtz, 1945). Recently, exchange resins have been used successfully to estimate plant available soil phosphorus (Van Raij et al., 1986).

Extractable P alone, however, may not provide adequate information on the critical concentration of nutrients for predicting fertilizer recommendations. Other factors have been shown to be involved. For example, clay content has been shown to be correlated with P adsorption capacity (Olsen and Watanabe, 1963) along with the P buffering capacity of soils (Ozanne and Shaw, 1968). Phosphorus sorption is also influenced by the type of clay minerals in soils (Karim and Adams, 1984). McLean et al (1979) suggested using the P buffering capacity in conjunction with Bray-1 extractable P. Lins et al. (1985) showed improved prediction of the P requirement for soybean when clay content and Mehlich-1 extractable P were considered. According to Kamprath (1978), sandy Ultisols have a much higher P critical level than clayey ones.

Although it was observed by White (1981) that better characterization of soil P status could be made by identifying and considering soil properties that are correlated with P adsorption, few attempts have been made to utilize these factors in predicting fertilizer requirements. The objective of this study was to improve the prediction of P fertilizer requirements by combining soil properties with extractable P, as determined with Mehlich-1, Mehlich-3, Bray-1, and resin soil tests.

MATERIALS AND METHODS

Experimental Procedures

Seven surface-soil samples (0–20 cm) ranging in clay content from 12 to 68% were collected in the cerrado region of Brazil; six were Oxisols and one was a Quartzipsamment with oxic properties. Selected soil characteristics are given in Table 1. After analyzing for 1 *M* KCl extractable Ca, Mg, and Al, the soils were limed, moistened, and incubated for 30 d. The lime rate was based on twice the extractable Al plus the difference between 2 $cmol_c$ L^{-1} and the summation of extractable Ca and Mg. Four soil P levels were created in each soil by applying powdered triple superphosphate (20% P) at rates of 0, 66, 132, and 264 g P m^{-3}. In like manner, 30 g S m^{-3} and 100 g K m^{-3} were applied using K_2SO_4 and KCl. The micronutrients Fe, Mo, B, Zn, and Cu were added with 100 g BR-12 m^{-3}, a fritted trace element mix. The nutrient sources were thoroughly mixed with 4-kg increments of soil and put into pots. The treatments were replicated three times and arranged in a randomized complete block design in the greenhouse.

Soybean seed inoculated with *Bradyrhizobium japonicum* were planted. The seedlings were thinned to four plants per pot, grown for 6 wk, and harvested by cutting at the soil surface. The soils were cropped in this manner four consecutive times. Plant tissue was collected after each harvest, dried at 70 °C for 72 h, and weighed.

After each harvest, K was added to each pot to keep extractable K at 100 g m^{-3}. During the third crop, Mn toxicity symptoms were observed, so after that harvest the soils were flushed with deionized water, air-dried, analyzed again, and relimed. Also, KH_2PO_4 was applied at 100 g P m^{-3} to all soils except the one with 12% clay, which received only 50 g P m^{-3}. After another incubation of 30 d, the soils were planted for the fourth crop.

Soil samples were collected after each harvest and analyzed on a volume basis. Aluminum was extracted with 1 *M* KCl (1 soil:10 solution) and titrated to a bromthymol blue endpoint. Calcium and Mg were also determined on a portion of this extract by atomic absorption spectrophotometry (Lin and Coleman, 1960). Soil pH was determined in water at 1:2.5. Soil P was assessed using Mehlich-1 (M1; 0.05 *M* HCl + 0.0125 *M* H_2SO_4 at 1 soil:10 solution), Mehlich-3 (M3; 0.2 *M* CH_3COOH + 0.25 *M* NH_4NO_3 + 0.015 *M*

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

Clay	pH	Al	Ca + Mg	K	Extractable P† M1	M3	B1	Resin
%		cmol L⁻¹			g m⁻³			
68	5.0	0.63	0.32	0.07	0.6	1.5	1.5	2.1
63	4.9	1.12	0.68	0.10	1.7	2.6	2.4	6.0
57	4.8	1.30	0.36	0.07	1.6	1.6	1.9	3.4
37	4.4	1.61	0.40	0.10	3.2	6.6	6.8	10.0
27	4.6	1.26	0.95	0.12	3.9	4.7	4.6	5.7
21	5.7	0.30	0.34	0.07	0.6	1.7	2.3	2.8
12	5.2	0.34	1.04	0.09	5.0	5.9	6.0	5.0

† M1, M3, and B1 correspond to the Mehlich-1, Mehlich-3, and Bray-1 methods of extraction.

NH_4F + 0.013 *M* HNO_3 + 0.001 *M* EDTA at 1 soil:10 solution), Bray-1 (B1; 0.025 *M* HCl + 0.03 *M* NH_4F at 1 soil:8 solution), and an anion-cation exchange resin. The use of M1 at a 1:10 ratio is a standard practice in Brazil and results in slightly more P being extracted than occurs with the 1:5 volume ratio commonly used in the USA. Shaking time used for the first three extractants was 5 min.

The resin is a 1:1 volume mixture of a strong base anion exchange resin (Amberlite IRA-400, Rohm and Haas, Philadelphia) and a strong acid cation exchange resin (Amberlite IRA-120). Details about the resin procedure are given by Van Raij et al., (1986). We did encounter one problem with this procedure when analyzing sandy soils; the 0.4-mm mesh sieve became clogged and required prolonged washing. Potassium was determined from the M1 extract by flame emission spectrophotometry. Soil P adsorption isotherms were determined according to the procedure of Fox and Kamprath (1970) except that 0.001 *M* $CaCl_2$ was the suspending salt solution. The data were fit to the Langmuir equation with the technique described by Olsen and Watanabe (1957) to obtain the P adsorption maximum and the P adsorption energy.

Phosphorus buffering coefficients, the change in extractable soil P per unit change in applied P, were obtained by three techniques differing markedly in incubation time. The first was a 2-h equilibration of soil with a range of P concentrations in each extractant (McLean et al., 1979). The second was a 1:1 soil/water mixture that is allowed to stand 4 d and dry (A.H. Hunter, 1974, personal communication). The third was an incubation at field capacity 3 wk before drying and analysis. The P rates used were the same as those described previously.

Clay mineralogy and surface area were determined by the North Carolina State University Soil Science Department mineralogy laboratory. Mineralogy is expressed as percentage mineral in the soil rather than that in the clay. Clay surface area was determined by N_2 adsorption after removal of organic matter, but prior to removal of Fe oxide. Total surface area of the soil was calculated as the product of clay surface area and percentage.

Data Evaluation

Yield of dry matter was related to extractable P concentration and the critical P level for each soil determined by three techniques: linear plateau (Anderson and Nelson, 1987), minimizing points in Quadrants II and IV (Cate and Nelson, 1965), and 90% of maximum yield. Also, using the descriptive model given by Lins et al. (1985), a predicted extractable P concentration was related to initial soil P concentration, rate of fertilization required to optimize growth, and time. We set the predicted extractable P at the critical level for each soil and the time at 0.125 yr, the period of cropping in the greenhouse. This left two variables in the model: initial soil P concentration and rate of fertilization. For each soil we arbitrarily selected six initial soil P concentrations below the critical level and calculated the rates of fertilizer required to optimize growth at those initial soil P concentrations. These data were combined for all seven soils and the rate of fertilizer predicted with multiple regression from soil P and another individual soil property that concerned P sorption. The coefficients of determination (R^2) from all of these analyses were then compared to evaluate the potential of including individual soil properties to create a single interpretation over all soils.

Table 2. The soil P critical level determined with four extractants for soybean grown in the greenhouse on soils differing in clay content.†

Clay	Extractant M1	M3	B1	Resin
%	P g m⁻³			
68	4	7	10	22
63	7	12	14	29
57	10	13	19	28
37	23	34	43	34
27	31	40	40	40
21	14	38	38	46
12	41	57	50	38

† Average of linear plateau, minimizing points in Quadrants II and IV, and 90% of maximum yield techniques.

RESULTS AND DISCUSSION

The critical levels determined by the three techniques were similar, so were averaged. There was a marked inverse relationship between these critical levels and clay content for the three routine extractants, M1, M3, and B1; that for the resin was less marked, but the critical level increased twofold as clay decreased from 68 to 12% (Table 2). The correlation coefficients for the relationship between critical level and clay content for the four extractants were −0.84, −0.98, −0.95, and −0.89, respectively.

The 21% clay soil was an exception to the good relationship between critical levels and clay content with M1 (Table 2). It had an unusually low critical level, as if it contained more clay than measured. It also had an unusually low P buffering coefficient with this extractant for a soil with 21% clay (data not shown). This may be because it contained a higher percentage of gibbsite (Table 3). Gibbsite apparently has a smaller particle size than normal for clay as evidenced by a greater surface area (Table 3). Increased surface area will result in greater P sorption (White, 1981).

Rates of fertilizer P sufficient to reach and maintain the critical P level for the period of cropping were calculated for each of six extractable P levels below the critical level for each soil. An example of the rates of P fertilizer required as a function of M3 extractable P is shown in Fig. 1. It is obvious from the data that the critical level varies with clay content. It is also apparent that the slope of the relationship varies among soils.

The data in Fig. 1 may also be used to amplify the need for this research—to improve the prediction of fertilizer P by considering properties other than extractable P. If the Mehlich-3 P were 30 g m⁻³, no fertilizer P would be needed on the three most clayey soils, 15 g m⁻³ would be needed on the soil with 37% clay, and about 30 g m⁻³ would be needed on the three

Table 3. Surface area, mineralogical composition, P adsorption maximum, and P adsorption energy of the seven soils.

Clay	Surface area	Gibbsite	Goethite	Kaolinite	Hydroxy interlayered vermiculite	Free iron oxides	P adsorption maximum	P adsorption energy
%	$m^2\ kg^{-1} \times 10^{-3}$	%					$mg\ kg^{-1}$	$L\ mol^{-1}$
68	35.4	44.2	3.4	20.4	0.0	2.7	704	0.113
63	32.1	12.6	14.5	28.4	7.6	12.8	664	0.078
57	30.8	6.7	7.2	28.8	5.3	6.2	645	0.058
37	15.4	1.9	4.4	27.0	3.7	4.0	456	0.015
27	11.6	0.5	3.0	20.5	3.2	5.1	425	0.014
21	13.9	17.9	2.1	2.1	0.0	1.5	486	0.038
12	6.8	0.1	2.3	7.8	1.8	2.0	146	0.013

least clayey soils. In prior research by these authors, differences in predicted fertilizer P have been ascribed to the combined effects of M1 extractable P and clay content (Lins et al., 1985).

The coefficient of determination from multiple regression analysis was used to evaluate selected soil properties in addition to extractable P to determine the fertilizer P rate for optimum growth of soybean under greenhouse conditions. Considering all seven soils, clay and surface area were the best additional properties for all four extractants (Table 4). Surface area appeared to be slightly better than clay for M1, but the reverse seemed to be true for M3. For the routine extractants, M1, M3, and B1, the squared terms of clay and surface area were even better. No need was shown to square these terms with the resin. The P adsorption maximum, P buffering coefficients, and percentages of the clay minerals also were less useful in predicting fertilizer rates.

The coefficients of determination using M1 extractable P and an additional soil property were not as large as those with the other three extractants (Table 4). Mehlich-3 appeared to be the best extractant when used in this manner, followed closely by Bray-1 and the Resin method.

The prior observation that clay type (gibbsite) affected the critical P level suggested that the P rate predictions might be improved by grouping the soils. To test this, the 68 and 21% clay soils containing high amounts of gibbsite were dropped and multiple regression analyses were run on the data from the remaining five soils.

The coefficients of determination from these analyses were slightly greater than those from the analyses of the data from all seven soils (data not shown). Differences were small, however, especially for useful relationships where the coefficient was already >0.8. It seems that when a large percentage of the variation is being explained, it is difficult to make any improvement by classifying according to clay type. Some improvement was shown with M1, but probably because the coefficients were generally less for this extractant than the others.

Prior field studies have shown that inclusion of the clay squared term with extractable P markedly improved the prediction of the rate of fertilizer P that should be applied (Lins et al., 1985). In the current study, although detailed measurements were taken on P adsorption maximum, buffering coefficients after various lengths of incubation, and type of clay, the best combinations included either surface area or clay. This is fortunate considering the potential use of this concept in a soil testing program, as clay content can be estimated or measured readily. Also, rough estimates are available from known classification or soil maps. It would be simple and advantageous, therefore, to improve the soil test interpretation for P by inclusion of an estimate of clay content.

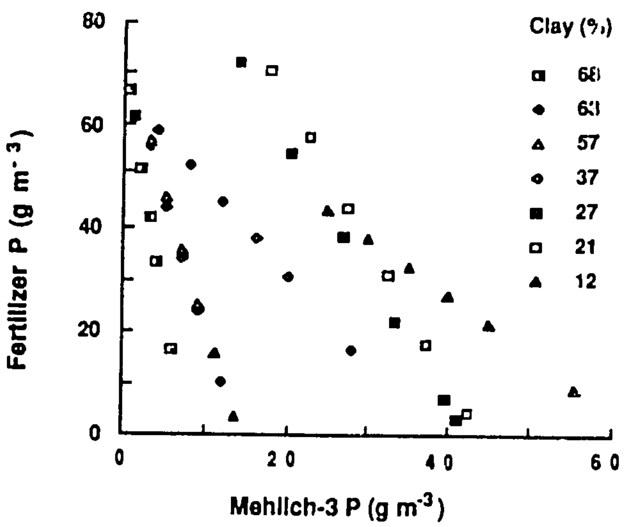

Fig. 1. Fertilizer P required to reach and maintain Mehlich-3 extractable P at the critical level for a cropping period in relation to the extractable P concentration of seven soils varying in clay content.

Table 4. Coefficient of determination obtained when predicting P rates to grow soybean under greenhouse conditions as a function of extractable P and another soil property.

Soil property	P extractant			
	M1	M3	B1	Resin
	R^2			
Extractable P	0.38†	0.32	0.53	0.67
Extractable P plus:				
Clay, %	0.48	0.81	0.66	0.84
$Clay^2$, %	0.55	0.89	0.80	--
Surface area, $m^2\ kg^{-1} \times 10^{-3}$	0.58	0.75	0.68	0.81
Surface $area^2$, $m^2\ kg^{-1} \times 10^{-3}$	0.67	0.83	0.82	—
P adsorption maximum, $mg\ kg^{-1}$	0.46	0.59	0.59	0.75
P buffering coefficient				
2 h	0.54	0.42	0.54	0.75
4 d	0.50	0.41	0.57	0.69
8 wk	0.47	0.67	0.57	0.69
Kaolinite, %	0.44	0.51	0.67	0.78
Goethite, %	0.59	0.60	0.69	0.76
Gibbsite, %	0.61	0.32	0.54	0.67
Hydroxy interlayered vermiculite, %	0.41	0.43	0.63	0.75
Free iron oxides, %	0.42	0.46	0.65	0.74

† All R^2 values shown are significant at $P < 0.01$.

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