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A Simplified Soil and Plant Phosphorus Model: II. Prediction of Labile, Organic, and Sorbed Phosphorus¹

A. N. SHARPLEY, C. A. JONES, CARL GRAY, AND C. V. COLE²

ABSTRACT

Surface samples and soil chemical, physical and taxonomic data for 78 soils from the continental U.S. and Puerto Rico were obtained from the U.S. Soil Conservation Service National Soil Survey Lab. Phosphorus was extracted with the following: $\text{NH}_4\text{F} + \text{HCl}$ (Bray I P), NaHCO_3 (Olsen P), $\text{HCl} + \text{H}_2\text{SO}_4$ (North Carolina P), and anion exchange resin (labile P). Organic P and an index of fertilizer P sorption were also measured. Soils were divided into three groups based on soil taxonomy and weathering. Regression analysis was used to obtain equations to predict labile P, organic P, and a P sorption index from soil chemical and physical properties. Labile P was related to extractable P; organic P to total N and pH; and P sorption to clay, CaCO_3 , labile P, and base saturation. These parameters accounted for up to 84% of labile P variation, 64% of organic P variation, and up to 78% of P sorption variation. Although the equations are empirical, independent variables chosen in the

stepwise regression were consistent with P mineralization and sorption relationships previously reported. These relationships were tested using independent data sets. They can be used to generate inputs for the soil P component of the Erosion-Productivity Impact Calculator crop management model from soil test P and data available in U.S. Soil Conservation Service/State Agricultural Experiment Station Soil Survey Investigation Reports.

Additional Index Words: base saturation, extractable P, nitrogen, organic carbon, pH, soil taxonomy, soil weathering.

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THE SIMPLIFIED soil and plant phosphorus (P) model described in the previous paper (Jones et al., 1984a) is designed to use soil chemical, physical, and taxonomic data available in U.S. Soil Conservation Service (SCS)/State Agricultural Experiment Station Soil Survey Investigative Reports (SSIRs) and SCS soil pedon descriptions. Soil P data are not normally included in these reports and descriptions, and must be obtained elsewhere. For this reason, data required to initialize the P model have been minimized.

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² Soil Scientist, USDA-ARS and Oklahoma State Univ., Southern Plains Watershed and Water Quality Lab., P.O. Box 1430, Durant, OK 74702; Plant Physiologist, USDA-ARS, Grassland, Soil and Water Research Lab., P.O. Box 748, Temple, TX 76703; Soil Chemist, Texas Agric. Extension Service, Soil Testing Lab., College Station, TX 77843; Soil Scientist, USDA-ARS and Colorado State Univ., Natural Resource Ecology Lab., Ft. Collins, CO 80523, respectively.

Three P-related parameters must be measured or estimated to use the soil and plant P model described in the previous paper. They are initial labile P (P_{il}), represented here by extraction with anion exchange resin, initial organic P (P_o), and an index of the availability of fertilizer P (F_l). None of these parameters are readily obtainable from soil testing services; therefore, P_{il} , P_o , and F_l must be estimated from more readily available data. In addition to its use in EPIC, F_l could be used as an index of fertilizer P availability in soil fertility studies.

The most frequently available measurement of soil P is soil test P determined with a common extractant such as $\text{NH}_4\text{F} + \text{HCl}$ [Bray 1 P (BP)], NaHCO_3 [Olsen P (OP)] or $\text{HCl} + \text{H}_2\text{SO}_4$ [double acid P (DP)]. The measurement of P_{il} by anion exchange resin is time consuming and is not normally used by soil testing laboratories. Soil P_o is estimated by difference using either ignition (Walker and Adams, 1958) or extraction (Mehta et al., 1954) methods. Such determinations are time consuming and are not always accurate, especially when P_o is small relative to total P (P_t). In addition, P_o is not routinely measured by soil testing laboratories.

Several workers have observed a linear relationship between extractable or soil solution P and the amount of P added. The relationship has been found in both laboratory incubations (Barrow, 1974; Barrow and Shaw, 1975; Fuleky, 1978; McLean et al., 1983; Medina and Lopez-Hernandez, 1978; Romkens and Nelson, 1974; Sharpley et al., 1982) and field studies (Barber, 1979; Peterson and Krueger, 1980). In this study, the ratio of the increase in extractable soil P to amount of P added represents an index of fertilizer P availability (F_l). However, F_l is not available for a wide range of soils, it is difficult to obtain on a routine basis, and there is little information on the effects of soil chemical and physical properties on the relationship. In addition, little information is available on the relationship between labile P and other forms of mineral P, primarily due to the dynamic nature of these pools and the difficulty in quantifying mineral P (Posner and Bowden, 1980; Ryden et al., 1977).

This paper presents regression equations to estimate P_{il} , P_o , and F_l from data available in SSIRs and SCS pedon descriptions. The equations are derived from regression analysis of 78 soils from the continental U.S. and Puerto Rico.

MATERIALS AND METHODS

Surface samples (0–10 cm) and supporting laboratory and taxonomic data for 78 soils from the continental U.S. and Puerto Rico were obtained from the SCS National Soil Survey Lab. Soils were chosen on the basis of their agricultural importance, availability of soil samples, and availability of adequate laboratory data for the samples.

Anion exchange resin P was determined by adding 5 cm³ IRA-400 anion exchange resin (bicarbonate form) to 4 g soil in 40 mL H_2O . The sample was shaken on an oscillating shaker at 180 oscillations min^{-1} for 16 h. A 60-mesh screen was used to separate soil from resin. P_{il} was removed from the resin with 100 mL 1.5M NaCl for 24 h with occasional stirring. Bray P was determined by the method of Bray and Kurtz (1945), where 2 g soil was shaken in 20 mL of 0.03M NH_4F and 0.025M HCl for 5 min. Olsen P was determined

by the method of Olsen et al. (1954), where 1 g soil was extracted with 20 mL 0.5M NaHCO_3 (pH 8.5) for 30 min. Double acid P was determined by the method of Sabbe and Breland (1974), where 5 g soil was shaken with 20 mL of 0.05M HCl and 0.0125M H_2SO_4 for 5 min.

A literature review was conducted to determine the relationship between P_o and both N_i and pH. The P_o content of the 78 soils used in this study was estimated by the difference between acid extraction (0.05M H_2SO_4) of ignited and non-ignited samples (Walker and Adams, 1958). Data were obtained from Greb and Olsen (1967), Haas et al. (1961), Sharpley et al. (1982), Thompson et al. (1954), and Walker and Adams (1958).

F_l was estimated by adding 0, 60, 120, 240, and 480 μg P to 4 g subsamples of soil in small plastic vials. Soil was brought to field capacity with distilled water and was allowed to dry in the laboratory. The soil was rewet and allowed to dry twice more during a 6-month period before extraction with anion exchange resin. The relationship between P_{il} and P added (as g P/Mg soil) was determined by linear regression analysis, and F_l (g P extracted/g P added) is the slope of that relationship for each soil.

Other data used in regression analyses were obtained from the SCS pedon descriptions of the 78 soils. Regression analyses were conducted with the SAS STEPWISE and REG procedures (Barr et al., 1979).

RESULTS AND DISCUSSION

Preliminary analysis indicated that relationships of labile P (P_{il}) and fertilizer availability (F_l) with other soil properties differed among soils. STEPWISE multiple regression analysis (Barr et al., 1979) was used to determine the effects of numerous independent variables on P_{il} and F_l . However, errors in the estimation of P_{il} and F_l were smaller when soils were divided into groups based on the presence of CaCO_3 and the degree of weathering. Within these groups, P_{il} was estimated from soil test P, and F_l was estimated from different independent variables for each group.

The following groups were defined: calcareous soils—soils with free CaCO_3 ; highly weathered soils—Oxisols, Ultisols, Quartzipsamments, Ultic subgroups of Alfisols, and acidic Ochrepts; slightly weathered soils—all other soils. The ranges, means, and medians of several chemical and physical properties of the soils and the number of soils in each group are given in Table 1. Equations presented in this paper should not be used with soil data outside the ranges in Table 1.

Labile Phosphorus

Labile P was linearly related to the amount of P extracted by the Bray, Olsen, and double acid techniques (Table 2). In most cases, more than 70% of the variation in P_{il} was explained by the regression equations. For the slightly weathered soils, DP explained less than 40% of the variation in P_{il} . In the calcareous and highly weathered soils, the DP and OP techniques, respectively, explained slightly more than half of the variation in P_{il} (Table 2). This may be attributed to the fact that OP was developed in the Great Plains where calcareous and slightly weathered soil predominate, and the DP extractant was developed in the southeastern U.S. where more highly weathered soils are common.

The relationships given in Table 2 were tested using data presented by Enwezor (1977), Maida (1978), and

Table 1—Means and ranges of properties of three groups of soils used in this study.

	pH	Sand	Silt	Clay	Calcium carbonate	Organic carbon	Total nitrogen	Base saturation	Cation exchange capacity	F_i	Organic phosphorus	P_{il}	OP	BP	DP
					%	cmol (p)/kg	$\mu\text{g P/g}$								
Calcareous (N = 20)															
Mean	7.7	35	41	24	9.1	1.4	0.13	100	20	0.51	166	17	13	20	67
Median	7.7	35	42	23	0.8	1.4	0.13	100	17	0.53	147	13	9	11	34
Minimum	7.1	4	17	10	0.5	0.4	0.04	100	8	0.19	33	6	3	1	3
Maximum	8.4	71	62	67	54	3.2	0.26	100	55	0.66	403	56	38	77	338
Slightly weathered (N = 35)															
Mean	6.4	27	51	22	--	1.7	0.15	89	17	0.48	218	19	13	24	53
Median	6.3	18	53	22	--	1.7	0.13	95	16	0.49	193	16	12	21	36
Minimum	5.2	1	6	6	--	0.2	0.03	40	5	0.07	37	4	3	4	3
Maximum	8.3	87	85	62	--	3.5	0.27	100	43	0.74	442	53	42	79	215
Highly weathered (N = 23)															
Mean	5.6	55	30	15	--	1.6	0.11	58	8.2	0.26	231	13	20	66	43
Median	5.6	59	28	10	--	1.4	0.08	77	7.6	0.25	182	11	19	47	42
Minimum	4.4	6	1	0.4	--	0.4	0.03	11	1.3	0.06	29	3	2	3	2
Maximum	6.8	96	76	76	--	3.8	0.32	100	20.5	0.51	656	43	50	222	147

Table 2—Relationships between labile P (P_{il}) and Olson P (OP), Bray P (DP), and double acid (DP).

Equation	Number of observations	Root mean square error	R^2
Calcareous			
$P_{il} = 0.55 \text{ BP} + 6.1$	20	6.1	0.83
$1.09 \text{ OP} + 3.2$		6.5	0.74
$0.10 \text{ DP} + 10.2$		9.0	0.51
Slightly weathered			
$P_{il} = 0.56 \text{ BP} + 5.1$	35	5.2	0.79
$1.07 \text{ OP} + 4.1$		5.4	0.77
$0.13 \text{ DP} + 11.4$		8.8	0.39
Highly weathered			
$P_{il} = 0.14 \text{ BP} + 4.2$	23	4.7	0.76
$0.55 \text{ OP} + 2.1$		6.1	0.61
$0.24 \text{ DP} + 2.9$		3.9	0.84

Rudd and French (1976). In these studies both P_{il} (resin extractable) and BP or OP were determined on the same soils from southeastern Nigeria, Malawi, and South Australia, respectively. A highly significant relationship ($R^2 = 0.83$, $P > 0.99$) was found between measured P_{il} and that predicted from BP or OP (Fig. 1).

Organic Phosphorus

The organic P (P_o) content of soils in this study was linearly related to total nitrogen (N_t) in all groups of soils (Fig. 2, Table 3). Organic P was also linearly related to organic carbon (C_o), but the correlation was lower, and addition of other independent variables did not improve the estimation of P_o (data not shown). These results are consistent with previous studies (Table 3). For example, in a group of 25 paired virgin and cultivated soils (0–18 cm depth) from Iowa, Texas, and Colorado, Thompson et al. (1954) found that P_o was positively correlated with N_t and C_o .

A few soils, primarily Inceptisols and Ultisols, had very high or very low ratios of P_o/N_t . When soils with $P_o/N_t > 3000$ or < 800 were omitted, N_t explained 75% of the variation in P_o , and the intercept of the relationship was not significantly different from 0.0 (Table 3).

Several studies have shown that N_t and pH account

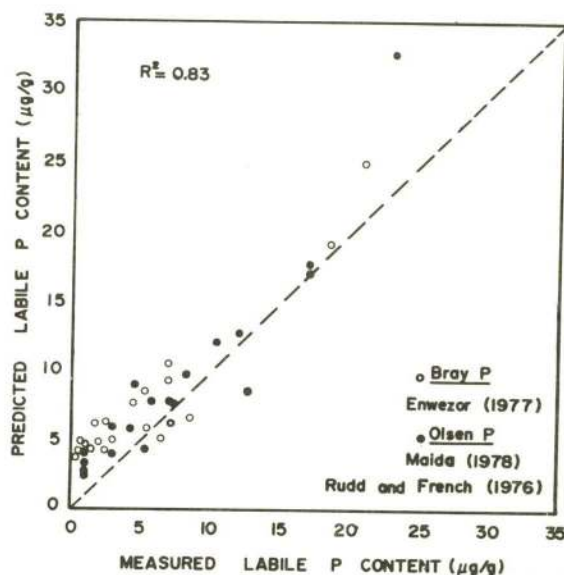


Fig. 1—Relationship between measured labile P and that predicted from Olsen and Bray P. No significant difference between measured and predicted values at the 1% level as determined by analysis of variance.

for more of the variation in P_o than N_t alone (Greb and Olsen, 1967; Walker and Adams, 1958; Thompson et al., 1954). However, the effect of pH is positive in some studies and negative in others (Table 3). This study found that pH does not improve the estimation of P_o . The relationship presented in Table 3 for the surface soils of this study was tested using data presented by Grunes et al. (1955) and Sharpley et al. (1982). A highly significant relationship ($R^2 = 0.72$, $P > 0.99$) was found between measured P_o and that predicted from N_t (Fig. 3).

Phosphorus Sorption

The model described in Jones et al. (1984a) uses a laboratory estimate of the fraction of fertilizer P which remains in the labile (anion exchange resin-extractable) form after a 6-month incubation at 25°C during which several wetting and drying cycles occur. This

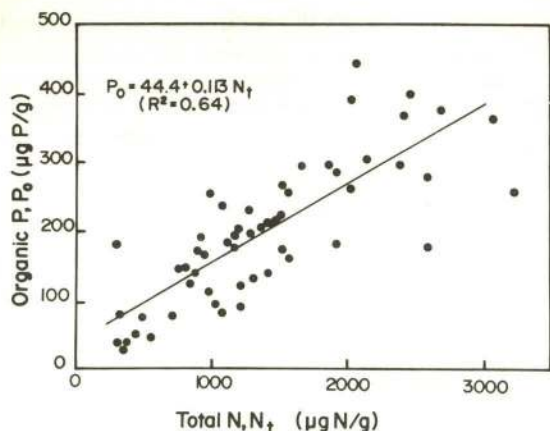


Fig. 2—Relationship between total N and organic P. No significant difference between measured and predicted values at the 1% level as determined by analysis of variance.

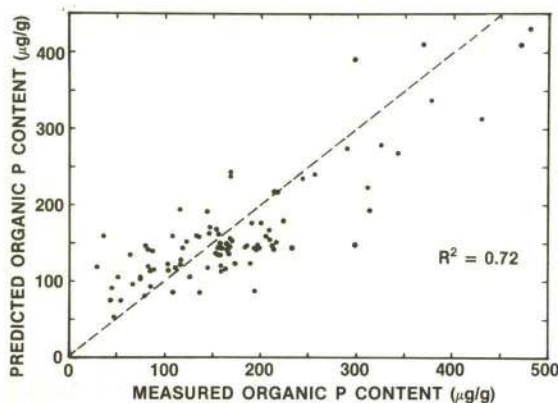


Fig. 3—Relationship between measured organic P and that predicted from total N. No significant difference between measured and predicted values at the 5% level as determined by analysis of variance.

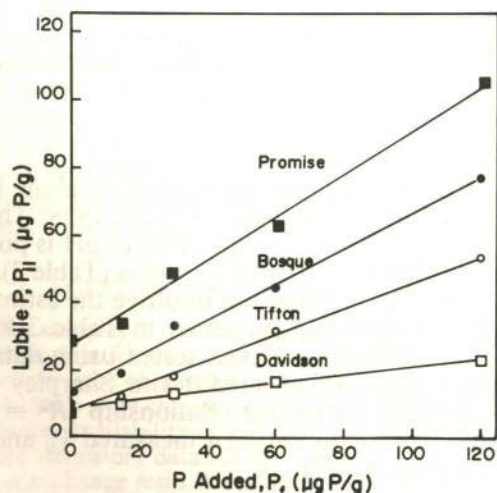


Fig. 4—Relationship between added P and labile P in four soils.

fraction (F_l) is an index of the amount of added P (P_f) remaining in an extractable form. F_l is the slope of the linear relationship between P_{il} and P_f , and examples of this relationship are given in Fig. 4.

Table 3—Relationship between organic P (P_o , µg P/g soil and total N (N_t , %) and pH (PH) in this and other studies.

Reference	Number of observations	Equation	R^2 **
This study (top layer)	56	$P_o = 44.4 + 1130 N_t$	0.64
		$P_o = 21.8 + 880 N_t + 9.96 \text{ PH}$	0.64
	42	$P_o = 1464 N_t$	0.75
Sharpley et al. (1982) and A. N. Sharpley (unpubl.)	67	$P_o = 19.1 + 1000 N_t$	0.77
		$P_o = 11.2 + 1050 N_t + 1.13 \text{ PH}$	0.77
Greb and Olsen (1967)	35	$P_o = 55.7 + 9.23 N_t$	0.87
		$P_o = 83.8 + 916 N_t - 3.5 \text{ PH}$	0.87
Haas et al. (1961)	13	$P_o = 2.61 + 931 N_t$	0.94
Thompson et al. (1954)	50	$P_o = 1.55 + 900 N_t$	0.57
		$P_o = 522 + 780 N_t - 82.8 \text{ PH}$	0.78
Walker and Adams (1958)	22	$P_o = -262 + 2960 N_t$	0.85
		$P_o = -102.5 + 2870 N_t + 136 \text{ PH}$	0.87

** All relationships significant at 99.9% level.

Table 4—Equations for estimation of fertilizer P availability index (F_l) from CaCO_3 (%), labile P (P_{il} , µg P/g soil), base saturation (BS, %), pH (PH), clay (CL, %), and organic carbon (OC, %).

Equation	Number of observations	Root mean square error	R^2
<u>Calcareous</u>			
$F_l = -0.0061 \text{ CaCO}_3 + 0.58$	20	0.069	0.71
<u>Slightly weathered</u>			
$F_l = 0.0043 \text{ BS} + 0.0034 P_{il} + 0.11 \text{ PH} - 0.70$	35	0.098	0.75
<u>Highly weathered</u>			
$F_l = -0.047 \ln \text{ CL} + 0.0045 P_{il} - 0.053 \text{ OC} + 0.39$	23	0.070	0.78

Regression analysis was used to relate F_l to soil data available in SSIRs and SCS pedon descriptions (Table 4). Fertilizer P availability increased with a decrease in CaCO_3 and clay content, for the calcareous and highly weathered soils, respectively. For the slightly weathered soils an increase in P_{il} , BS, and pH was associated with an increase in F_l . These results are consistent with those of previous studies which have shown that in calcareous soils, P sorption increases with increasing CaCO_3 content (Larsen and Widdowson, 1970; Williams et al., 1971) and that P sorption is reduced by previous additions of fertilizer P (Barrow, 1974). In addition, P sorption has been shown to be positively correlated with clay content (Juo and Fox, 1977; McCallister and Logan, 1978; Syers et al., 1971) and organic C (Harter, 1969; Lopez-Hernandez and Burnham, 1974), and negatively correlated with BS (Brown and Loewenstein, 1978).

Due to a lack of published data, the relationships used to predict F_l could not be tested.

SUMMARY

The paper presents equations which can be used to initialize labile P, organic P, and fertilizer P availability index for the simplified soil P model described in Jones et al. (1984a). Surface soil samples and chemical characteristics of 78 soils from the continental U.S. and Puerto Rico were obtained from the SCS National

Soil Survey Lab. Labile P (anion exchange resin P), Bray P, Olsen P, and double acid P were measured. The relationships between labile P and soil test extractable P were determined for the following soil groups: calcareous, slightly weathered (noncalcareous), and highly weathered (noncalcareous). For all soil groups, at least two of the three extractants accounted for over 70% of the variation in labile P. Organic P was found to be a linear function of total N for all soils.

Separate regression equations were developed to estimate F_i for each soil group. Equations with one or three independent variables accounted for over 70% of the variation in F_i in each soil group.

A third paper in this series (Jones et al., 1984b) describes preliminary testing of the simplified soil P model using these relationships.

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