RELATIONSHIPS BETWEEN AVAILABLE SOIL P FORMS AND THEIR ROLE IN WATER QUALITY MODELING

Abstract

Surface samples (0-10 cm) of 66 soils from throughout the USA and volcanic ash from the 1980 eruption of Mt. St. Helens were collected. Physical and chemical properties of the soils were determined, including available P as measured by several procedures (Bray, double acid, Olsen, and water extractants) currently used by state soil testing laboratories. In addition, parameters describing sorption and desorption characteristics were obtained.

Amounts of available P as measured by the different procedures were not closely correlated. Thus, it is not possible to estimate the available P content of a soil as measured by one procedure from another. Available P measured by Bray-I, Olsen, and water extractants were related (significant at the 0.001 level) to labile P content as determined by isotopic exchange (correlation coefficients of 0.656, 0.834, and 0.523, respectively).

The constants of 2 equations describing the kinetics of P desorption were not closely related to individual soil properties associated with P desorption (Al, Fe, Ca, clay, and organic carbon content), however, multiple regression of these properties explained from 10 to 78 % of the variation in the constants. The use of these equations in predicting the loss of soluble P in runoff is evaluated.

Phosphate sorption index and buffer capacity of the soils were closely related to the Fe and Ca contents of acidic and alkaline soils, respectively. The importance of these results to water quality models is discussed.

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Relationships Between Available Soil P Forms and Their Role in Water Quality Modeling

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Introduction

The transport of phosphorus (P) in runoff from agricultural land is one of the major factors in accelerating the biological productivity of natural waters (Loehr, 1974; Schindler, 1975; Vollenweider, 1975). Due to the high cost and long time needed to obtain reliable data on nutrient loss in runoff, increasing efforts are being made to model the processes associated with the transport of P in runoff, in conjunction with the existing models for hydrologic and sediment loss (Bruce et al., 1975; Frere et al., 1975; Donigian et al., 1977; Williams and Haan, 1978; Knisel, 1980).

These models incorporate physically based descriptions of the various processes where possible. For example, in the CREAMS (Chemicals, Runoff, and Erosion from Agricultural Management Systems) model (Knisel, 1980), the amount of total P (TP) transported is calculated from the enrichment of soil P in runoff sediment. The P enrichment ratio (PER) for a given event is calculated from a linear logarithmic relationship between PER and sediment discharge obtained for both simulated rainfall-runoff (Sharpley, 1980) and field data (Massey and Jackson, 1952; Menzel, 1980).

In the case of soluble P transport, amounts of runoff (ROP) are calculated from the P extraction coefficient (EXK) of a given soil, using the following equation:

$$ROP = P_A * EXK * Q \qquad [1]$$

where P_A is the available soil P content of surface soil (top 1 cm) prior to runoff, and Q the total volume of runoff. The coefficient is a number reflecting the extraction of soil P by rainfall-runoff and partitioning between solid and solution phases. This coefficient has been determined empirically from the relationship between the soluble P concentration of runoff and the available P content of surface soil (Romkens and Nelson, 1974; Sharpley et al., 1978; Frere et al., 1980; McDowell et al., 1980). Limited field tests of these models, however, have shown that the prediction of P transport is the weakest part of the model (Donigian et al., 1977; Davis and Donigian, 1979; Frere et al., 1980; Leonard and Wauchope, 1980). One of the major problems at the moment is the input of available P content, which can change dramatically due to fertilizer P addition (Romkens and Nelson, 1974; Sharpley et al., 1978), plant wash-off (Gburek and Broyan, 1974; McDowell et al., 1980; Sharpley, 1981), release from decaying plant residues (Timmons et al., 1968; Burwell et al., 1975), mineralization of soil

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organic P (Halm et al., 1972; Cole et al., 1977), plant uptake, and sorption (Sharpley, 1982). Consequently, the available P content of surface soil must be measured at regular intervals.

The representation of available P in water quality models, for use on a national basis, is further complicated by a variance from state to state in methodology used to measure available P. In 1951, the 50 state soil testing laboratories used 28 different extractions for determining available P (Nelson et al., 1953), most of which were locally developed. In a 1973 study of the same laboratories, Jones (1973) found that essentially three extraction methods were used to determine available P (Bray-I, double acid, and Olsen). Although the number of extractants used in the last twenty years has decreased dramatically, there is still considerable variance in the techniques. For example, Bray-I is determined at solution:soil ratios varying from 6.7:1 to 10:1 and shaking times from 40 sec to 5 min (Jones, 1980). A standardization of procedures used to measure available P is, therefore, needed.

As certain procedures are more applicable to certain soil types, it may be necessary for soil test laboratories to measure available P by two procedures. One value for use by farm advisors (the existing procedure) and one for use in water quality models. For the latter estimate, a water extraction at solution:soil ratios of 100:1 for 1 hour may be most suitable (Sharpley et al., 1982). If the wealth of existing available P data is to be used, however, an extraction coefficient for each available P procedure has to be included in the model or relationships between the various procedures developed so that available P as measured by one procedure can be estimated from another. If significant correlations exist between available P, as measured by the different procedures, they could be very useful in comparing available P values from state to state, where different extractants are used.

For a more detailed description of P release from surface soil to runoff during a single event, models describing the kinetics of soil P release may be used (Donigian and Crawford, 1976; Ahuja et al., 1981; Sharpley et al., 1981a). One such model is the modified Elovich equation (Chien and Clayton, 1980);

$$P = (1/a)\ln (ba) + (1/a) \ln t \qquad [2]$$

where P is the amount of soil P desorbed in time t, and a and b are constants. According to Eq. [2], a plot of P versus log of time should yield a straight line. More recently, Sharpley et al. (1981b) suggested the following simplified model for the release of P to water;

$$P = KP_0 \, t^{\alpha} \, W^{\beta} \qquad [3]$$

where W is the solution:soil ratio of the system where P is desorbed, P_0, the initial amount of soil P that can be readily released to solution, and K, α, and β constants for a given soil. The model was found to give a reasonably good description of P desorption at different P_0 values ranging from 5 to 200 μg P/g soil and W values ranging from 10:1 to 1000:1. The essential features of Eq. [3] are that straight lines should result from a plot of log of P desorbed versus log of t for a given soil at a given value of W and P_0, and from log of P desorbed versus log of W at a given value of t and P_0. It should be noted that the amount of desorbable P in the soil initially (P_0), as measured by water, Bray-I, or Olsen extractions (Sharpley et al., 1981b), is not an absolute measure of this soil P fraction. It was evident from P release data obtained (Sharpley et al., 1981b), however, that P_0 so determined represents a reasonable estimate of the amount of soil

P that can be released to water during times (up to 3 hours) and solution:soil ratios (10:1 to 1000:1) to which the model can be applied. Equation [3] differs from Eq. [2] in that the effect of initial soil-P level and solution:soil ratio on P desorption can be accounted for. This is an advantage for application to the dynamic surface soil-runoff environment.

At the moment application of the equations is restrictive, due to the fact that the constants have to be determined for a given soil prior to their use. It may be possible, however, to estimate values of the model constants from soil physical or chemical properties. Although Chien et al. (1981) observed that constants a and b of Eq. [2], were related to the reactive Al content of several acid Columbian soils, no information is available for neutral or alkaline soils or for constants K, α, and β (Eq. [3]).

During the transport of P in stream flow, exchange between solution and sediment bound forms can occur. These transformations are accentuated by the selective transport of fine material, which has a greater capacity to sorb or desorb P. In order to model the amounts of soluble and sediment P entering lakes and impoundments, these exchanges have to be accounted for. The direction of the exchange between soluble and sediment P will depend upon their concentration in stream flow and equilibrium P concentration (EPC_0) of the sediment material contacted, which will include suspended sediment, streambank, and bottom material. The EPC_0 is defined as the soluble P concentration that is supported by a solid sample at which no net sorption or desorption takes place (White and Beckett, 1964; Taylor and Kunishi, 1971). Consequently, if the soluble P concentration of runoff or stream flow falls below the EPC_0 of the suspended or streambank material contacted, P will be desorbed from the material in an attempt to raise the soluble P concentration to the EPC_0. If, however, the soluble P concentration increased above the EPC_0, P may be sorbed by the suspended or streambank material contacted. These initial changes in soluble P concentration of stream flow may occur with an increased contribution to stream flow from subsurface runoff of low soluble P concentration, or from surface runoff having a high concentration.

The above processes assume that sufficient desorbable P is present on the sediment for the EPC_0 to be reached and that the rate of desorption or contact time is sufficient for equilibrium to occur during runoff. If the sediment concentration of stream flow is high, then equilibrium may be attained due to rapid P desorption quickly reaching the soluble P concentration in equilibrium with sediment (Kunishi et al., 1972; Schuman et al., 1973; McColl et al., 1975). The input of sediment from heavily P fertilized soils may increase the soluble P concentration of stream flow dramatically (Taylor and Kunishi, 1971). If, however, the sediment concentration of stream flow is low, the factors limiting the attainment of the EPC_0 will be the rate of P desorption and capacity of the desorbable P pool of the sediment contacted. In this case, the reaction mainly occurs with streambank and bottom material that the stream contacts on its way to the watershed outlet. Streambank material is usually P deficient and has a high P sorption capacity. A decrease in the soluble P concentration during base stream flow where the sediment concentration was low has been observed by Taylor and Kunishi (1971), Gburek and Heald (1974), Johnson et al., (1976), and Sharpley and Syers (1979). Soluble P concentrations of 0.10 to 0.13 mg/1 of runoff from a fertilized field were reduced to 0.009 mg/1 by sorption during movement downstream (Kunishi et al., 1972).

The extent of this exchange will depend on the labile P content of the sediment material contacted during stream flow and rate of flow. Knowledge of the EPC_0 and

labile P content of lake sediment is also important in evaluating the contribution of deposited sediment material to the P loading of a lake. The measurement of EPC_0 and labile P content by standard methods using sorption isotherms and ^{32}P, respectively, is time consuming and costly. Consequently, estimation of these values by simpler methods or correlation with other soil properties would aid the application of P transport models.

The behaviour of labile P in soil is mainly affected by it buffer capacity. Because buffering is controlled in most soils by sorption-desorption processes, it is usually measured from the slope of an adsorption isotherm (White and Beckett, 1964; Barrow, 1967; Holford, 1977). The P buffer capacity refers to the ability of the soil solution concentration to resist change when P is added or removed from the pool of labile P (Holford and Mattingly, 1976). It is thus, an important P property of the soil, as it characterizes the dynamic change between solid and solution phase labile P.

This report presents an investigation of the relationships between a) available soil P content as measured by several soil test procedures currently used in the USA, b) constants of models describing the kinetics of soil P desorption and various soil chemical and physical properties, and c) several soil P desorption and sorption parameters and various soil properties for a large number of soils (66) from 19 states, and ash from the 1980 volcanic eruption of Mount St. Helens.

Experimental Procedure

Materials

Surface samples (0-10 cm) of 66 soils were collected from throughout the USA, encompassing all the soil groups except histosols and oxisols. The location, soil family, and subgroup of the selected soils are given in Table A of the appendix. Volcanic ash from the May 19, 1980, eruption of Mount St. Helens was collected from a 1/2″ thick deposit. The soils were air dried, sieved (2 mm), and stored until analysis.

Methods

General Chemistry. The particle size distribution of the soils was determined by pipet analysis (Day, 1965), following dispersion of the samples with sodium hexametaphosphate. Soil pH was measured with a glass electrode using a 5:1 water:soil ratio (weight:weight). Organic carbon was determined by the dichromate-wet combustion method (Raveh and Avnimelech, 1972) and $CaCO_3$ equivalent by the gravimetric method for loss of carbon dioxide (Allison and Moodie, 1965). Exchangeable Ca and Al content was measured by atomic adsorption on filtered extracts following end-over-end shaking of l g of soil for 2 hours with IN KCL (Black, 1965). Similarly, extractable Fe and Al was determined by atomic adsorption of filtered extracts after 10 g of soil was allowed to stand in 100 ml of 1N $NH_4 OAc$ (adjusted to pH $4·8$) for 2 hours (Black, 1965).

Available phosphorus. Several soil test procedures, currently used in the USA, to estimate the amount of soil P available for plant uptake (plant available P) were carried out on the soils. These were the double acid (North Carolina) procedure, where 5 g of soil were shaken with 20 ml of 0.05 N HCL and 0.025N H_2SO_4 for 5 min (Sabbe and Breland, 1974); the Bray-I procedure, where 2 g of soil were shaken in 20 ml of

0.03N NH₄F and 0.025N HCL for 5 min (Bray and Kurtz, 1945); the Olsen bicarbonate procedure, where 1 g of soil was extracted with 20 ml of 0.5M NaHCO₃ (pH 8·5) for 30 min (Olsen et al., 1954); and the water procedure, where 1 g of soil was shaken with 2 ml of water for 5 min (Olsen and Dean, 1965). In all cases, the samples were end-over-end shaken at 25°C, centrifuged (27,160 g), and filtered (0.45 μm), with P being determined on the filtrate.

The labile P content, or amount of solid-phase P that is in equilibrium with solution-phase P, was determined by isotopic dilution using ^{32}P. One g of soil was shaken with 39 ml of water and 2 drops of toluene, to inhibit microbial activity, for 24 hours on an end-over-end shaker at 25°C. At this time a 1 ml aliquot of ^{32}P solution (containing approximately 2μci) was added and the solution shaken for a further 24 hours. The solution was then centrifuged (27,160 g) and filtered (0.45 μm) and the concentrations of ^{31}P and ^{32}P determined. The activity of ^{32}P in the filtrate was counted with a Hamner scaler-counter, on 2 ml aliquots of the filtrate evaporated to dryness on metal planchets. The amount of sorbed ^{31}P which is labile was calculated from isotopic dilution theory (Olsen and Dean, 1965). The total and inorganic P contents of the selected soils were determined by extraction of ignited and nonignited samples, respectively, with 0.5 M H₂SO₄ (Walker and Adams, 1958), organic P being calculated by difference.

Phosphorus desorption. Desorption of P from the soils was investigated by incubating 25 g of soil with various amounts of P (0-200 μg P/g of soil, added as a solution of K₂HPO₄) at 25°C for 4 weeks. The soils were wetted to field capacity and allowed to dry slowly. The soils were rewetted with de-ionized water when dry. At the end of the incubation period the dry soils were seived (2 mm). The amounts of P desorbed by distilled water at water:soil ratios of 10:1, 40:1, 100:1, 200:1, 400:1, and 1000:1, on an end-over-end shaker at 25°C for 5 min to 180 min, were determined. The constants of the semi-logarithmic Eq. [1] (a and b) were determined from the slope (1/a) and intercept ((1/a) ln (ab) of the linear relationship between P desorbed and logarithm of time (Chien and Clayton, 1980). The constants of the logarithmic Eq. [2] (K, α, and β) were determined from the slope of the linear relationships between logarithm of P desorbed and logarithm of time (slope = α) and logarithm of water:soil ratio (slope = β). Constant K was calculated from the slope of a linear relationship between amount of P desorbed and initial desorbable soil P, represented by labile P (Sharpley et al., 1981).

Phosphorus sorption. The sorption of P by the soils was investigated by shaking 1-g samples of soil with 40 ml of distilled water containing various amounts of P (0 to 1.0 mg P /1, added as K₂HPO₄) and 2 drops of toluene. The soil samples were shaken on an end-over-end shaker at 25°C for 40 hours. The samples were then centrifuged (27,160 g), filtered (0.45μm), and the concentration of P in the filtrate determined. The amount of P sorbed was calculated by difference and a P sorption isotherm restricted to low solution P concentrations, subsequently constructed (Fig. 1). The equilibrium P concentration (EPC$_0$) supported by the soil (White and Beckett, 1964) was obtained from the isotherm (Fig. 1). The slope of the isotherm at this point was taken as equivalent to the P buffer capacity at EPC$_0$ (Beckett and White, 1964; Barrow, 1967; Bache and Williams, 1971). The labile P content was also estimated as the intercept of the isotherm extrapolated to zero equilibrium P concentration (Fig. 1) (Taylor and Kunishi, 1977; McDowell et al., 1980).
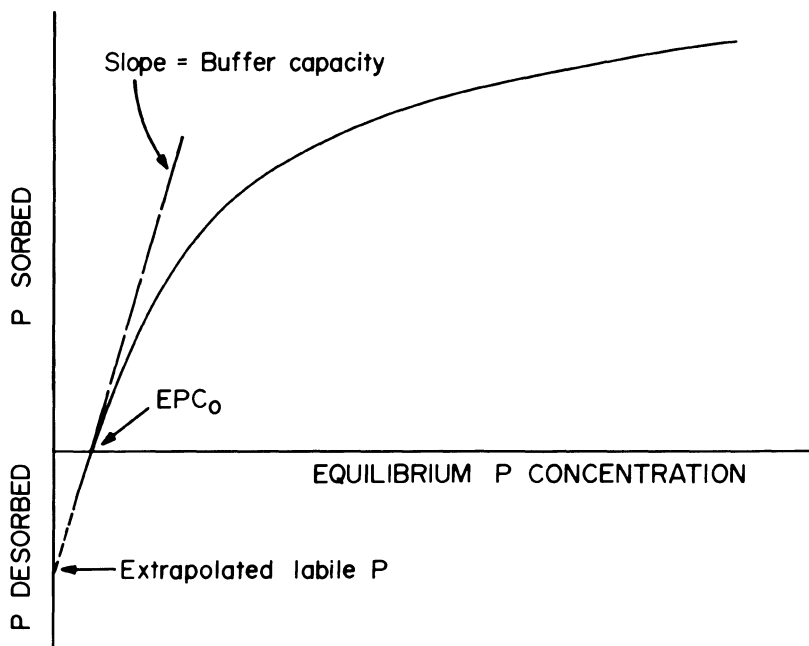
Figure 1. Diagramatic representation of P sorption isotherm showing sorption-desorption characteristics determined.

The amount of P sorbed, x (μg/g) from one addition of 150 mg P/100 g soil (added as K_2HPO_4) after end-over-end shaking for 40 hours at a water:soil ratio of 100:1 was determined. The P sorption capacity was calculated using the quotient x/log C, where C is the solution P concentration (mg/1) (Bache and Williams, 1971).

For all samples, the concentration of P was determined colorimetrically on filtered samples by the molybdenum-blue method (Murphy and Riley, 1962). Acid or alkali filtrates were neutralized prior to P determination.

Results and Discussion

Several chemical and physical properties of the soils are given in Table B of the appendix. The range, mean, and standard deviation of the measurements are shown in Table 1. A wide range in properties was evident, with soil texture for example, ranging from the Superstition sand (6% clay content) to Wyarno clay loam (53% clay content). The available, inorganic, organic, and total P contents of the soils are listed in Table C of the appendix. The range, mean, and standard deviation of these contents are summarized in Table 2. the EPC_0, buffer capacity, and labile P contents calculated from the sorption isotherm are given in Table D of the appendix, along with the constants of the P desorption equations.

Table 1. Range, means, and standard deviations of several physical and chemical properties of the soils.

Parameter	Range	Mean	Standard deviation
$CaCO_3$, %	0 – 21.10	3.30	5.10
Clay, %	6 – 53	23	10
Exchangeable Al, mg/g	0.2 – 2.4	0.9	0.4
Exchangeable Ca, mg/g	0.1 – 9.4	1.7	1.5
Extractable Al, mg/g	0.9 – 14.8	5.5	1.8
Extractable Fe, mg/g	2.0 – 38.0	10.0	6.3
Organic C, %	0.07 – 4.93	1.16	0.74
pH	5.1 – 9.1	6.8	0.9

Table 2. Range, means, and standard deviations of the phosphorus properties of the soils.

Soil property	Range	Mean	Standard deviation
	———————————$\mu g/g$———————————		
Double acid	3.3 – 274.6	65.3	61.8
Water	0.14 – 6.06	1.62	1.33
Bray I	2.7 – 92.6	26.8	19.6
Olsen bicarbonate	1.4 – 272.4	17.8	33.0
Total P	63 – 1062	467	212
Total inorganic P	9 – 987	306	198
Total organic P	16 – 487	156	111
Labile P	3.0 – 278.7	37.3	38.5
EPC ($\mu g/ml$)	0.021 – 1.952	0.503	0.437
Buffer capacity (ml/g)	6 – 360	83.5	76.7
Sorption index	57 – 1070	518	182

Correlations Between Available Soil P Tests

Simple linear regressions were run between the available P contents of the soils as measured by the different soil test methods (Fig. 2). The closest correlation was between Bray-I P and water P (Fig. 3), indicating that these methods are measuring available P extracted from similar fractions of soil P. Even so, each method extracted different amounts of P (Table 2), with a general increase in the order; water, Olsen, Bray-I, and double acid. All four available P methods were related to the labile P content of the soil as determined by isotopic exchange (Fig. 2). Consequently, each available P method was extracting a proportion of labile P from the soil, although slightly more P was extracted by the double-acid method than was present as labile P for several soils (Table C).

The soils were then grouped according to pH and texture and the regressions rerun. The following pH classifications were used; 5.5 to 6.0, strongly acidic; 6.0 to 7.0, acidic; 7.0 to 8.0, alkaline; and above 8.0 strongly alkaline. The correlations obtained are presented in Figs. A, B, C, and D (appendix). For soils of pH below 5.0 no significant
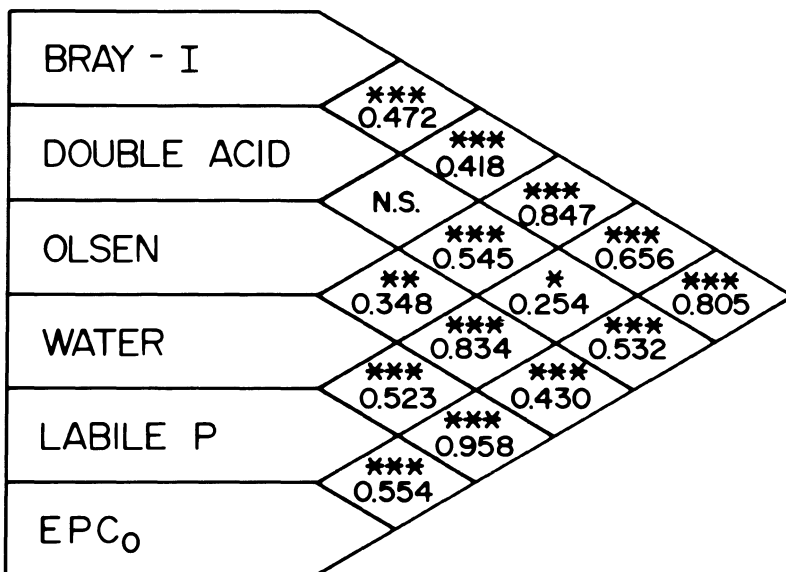
Figure 2. Correlation of available soil P determined by several methods for the soils. ***,**,* designate significance (n = 67) at the $p < 0.001$, < 0.01 and 0.1 levels, respectively.

correlations were obtained (Fig. A of the appendix). The correlation coefficients between water P, double acid P, and Bray-I P increased with an increase in soil pH. For example, correlation coefficients for water P and double acid P for soils of pH 5.5 to 6.0, 6.0 to 7.0, 7.0 to 8.0, and >8.0 were not significant, 0.434, 0.717, and 0.864, respectively. Although Olsen and double acid P were related to labile P content for all the soils, no significant relationships were obtained when the soils were split into the pH groups.

In contrast, an increase in correlation coefficient between Bray-I and labile P was obtained with an increase in pH. An increase in the correlation between available P content as measured by acidic extractants would be expected with an increase in soil pH, due to an increasing predominance of P associated with Ca in increasingly alkaline soils, which will be acid soluble. No trends in correlation coefficients were observed when the soils were partitioned according to clay content (Figs. D, E, F, G, and H of the appendix).

In a similar study, Malik and Sarwar (1976) obtained close correlations for Bray-I and water P with Olsen P (r = 0.83 and 0.75, respectively) for 12 Pakistani soils. They concluded that use of the three procedures to measure available P content were interchangeable, with a considerable degree of reliability. As a small number of alkaline soils (lowest pH was 7.60) were used in the study, this interchangeability must be treated with caution.
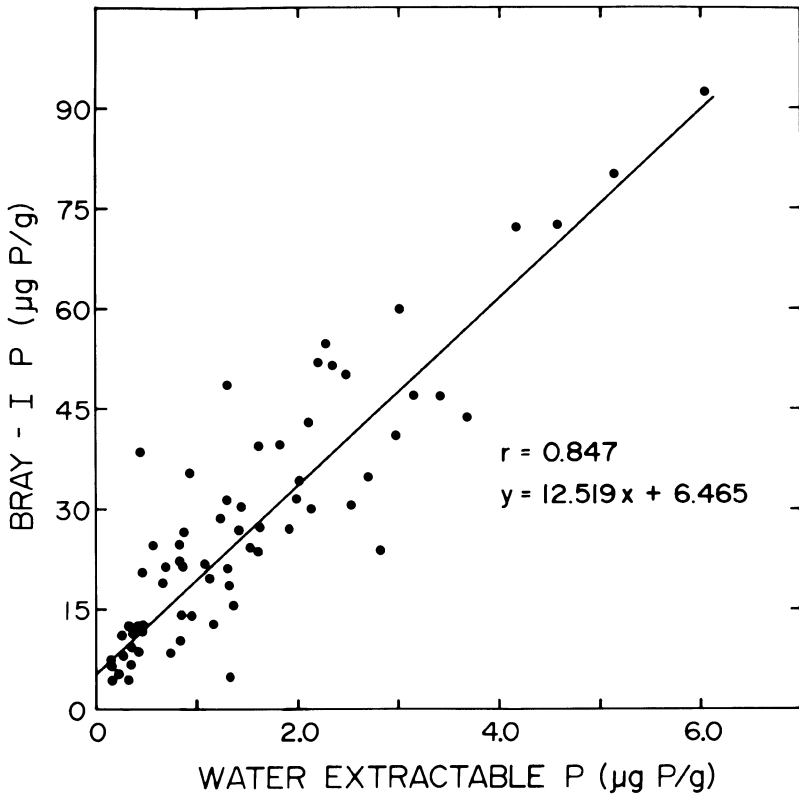
Figure 3. Relationships between available P content as measured by water and Bray-I extractions, for the soils.

No significant correlation was obtained between available P and soil properties associated with P sorption and desorption (extractable Al and Fe, exchangeable Al and Ca, organic carbon, and clay content). Available P was related to the total and inorganic P content of the soils (Table 3). However, the correlation coefficients were low, such that at the most only 38% of the variation in available P content (double acid) was accounted for by total inorganic P content. The presence of a major proportion of inorganic P in unavailable forms (averaged for all the soils 79, 99.5, 91, and 94% of the inorganic P content was unavailable as measured by the double acid, water, Bray-I, and Olsen reagents, respectively) is the reason for the low correlation coefficients (Table 3).

As available P content measured by each procedure were not closely related (Fig. 2), it is not possible to extrapolate the available P content as measured by one soil test procedure from another for a given soil. Consequently, algorithms developed to predict

Table 3. Correlation of available soil P as measured by several soil P test methods.

Soil P test	Total P content	Total inorganic P content
Bray-I	0.405***	0.409**
Double acid	0.522***	0.615***
Olsen	0.416***	0.449***
Water	0.316**	0.410**
Labile P	0.482***	0.484**

+ Total inorganic P content.
*, **, *** designate significance (n = 67) at p < 0.05, < 0.01, and < 0.001 levels, respectively.

the soluble P concentration of runoff from available P content of the surface soil (Eq. [1]), must have the capacity to use available P content measured by several different methods. This will be important if existing data is to be used from several states, where different available P test procedures are employed. As the soluble P concentration of runoff is related to the available P content of surface soil measured by several procedures (Sharpley et al., 1981a), an extraction coefficient relating soluble P concentration and available P content for each procedure can be included in water quality models. The present data suggests that water quality models should be oriented towards using Bray-I or water P as inputs of available P content.

Soil P Desorption Kinetics

The range and means of the constants of Eq. [2] and [3] describing the kinetics of P desorption for the soils are given in Table 4. The constants were not highly correlated to any single soil property associated with P sorption and desorption, such as Al, Fe, Ca, organic carbon, or clay content (Table 5). When all the soil properties were used in a multiple regression with the constants, however, an improvement in the correlation was obtained (Table 6). As would be expected the highest correlation was obtained when all the properties associated with P sorption and desorption were used.

Table 4. Range, means, and standard deviations of the constants of the kinetic models for the soils.

Constant	Range	Mean	Standard deviation
P_d/log t − Eq. [2]			
$a(h^{-1})$	0.02 − 5.73	1.02	1.27
$b(\mu g\ P/g/hr)$	10.8 − 552.2	140.3	115.8
log P_d/log t − Eq. [3]			
K	0.021 − 0.302	0.127	0.064
α	0.045 − 0.319	0.166	0.060
β	0.204 − 0.850	0.544	0.155

Table 5. Correlation of several soil properties and constants of the kinetic equations [1] (a and b) and [2] (K, α, and β) for the soils.

Soil property	P desorption constants				
	a	b	K	α	β
Exchangeable Al	N.S.	N.S.	N.S.	N.S.	N.S.
Extractable Al	N.S.	N.S.	N.S.	N.S.	N.S.
Extractable Fe	N.S.	N.S.	N.S.	N.S.	N.S.
Exchangeable Ca	N.S.	N.S.	N.S.	N.S.	N.S.
Percent Clay	N.S.	N.S.	0.357**	0.336**	0.386***
Organic carbon	N.S.	N.S.	0.621***	0.567***	0.511***

*, **, *** designate significance (n = 67) at p < 0.05, < 0.01, and < 0.001 levels, respectively.
N.S. Not significant.

Table 6. Multiple regression of several soil properties and constants of the kinetic equations [1] (a and b) and [2] (K, α, and β) for the soils.

Soil property	Constants				
	a	b	K	α	β
Ext Al^{+}, Ext Fe	N.S.	N.S.	N.S.	N.S.	N.S.
Ext Al, Exch Al^{++}	N.S.	N.S.	N.S.	N.S.	N.S.
Clay[†], O.C.[††]	0.358**	N.S.	0.868***	0.801***	0.786***
Ext Al, Exch Al, Ext Fe, Clay, O.C., Exch Ca	0.436***	0.314**	0.884***	0.820***	0.828***

+ Ext represents extractable.
++ Exch represents exchangeable.
† Clay represents percent clay.
†† O.C. represents organic carbon.
*,**,*** designate significance (n = 67) at p < 0.05, < 0.01, and < 0.001 levels, respectively.
N.S. Not significant.

Table 7. Correlation between available P content as measured by several soil P test methods and constants a and b of Eq. [1] for the soils.

Soil Property	Constant			b
	a			
	Linear	Exponential	Power form	Linear
Bray-I	0.468***	0.603***	0.621***	0.706***
Double acid	0.289**	0.311**	0.425***	0.345**
Olsen	N.S.	0.433***	0.406***	0.317**
Water	0.353**	0.459***	0.450***	0.540***
Labile P	0.349**	0.585***	0.720***	0.635***
EPC	0.334**	0.462***	0.486***	0.485***

*, **, *** designate significance (n = 67) at p < 0.05, < 0.01, and < 0.001 levels, respectively.
N.S. Not significant.

The constants a and b of Eq. [1] were significantly correlated with available P content (Table 7). The correlation coefficient of the linear regression between available P content and constant a was lower than for constant b. An increase in the correlation coefficient was obtained when the logarithm of available P was used (Table 7). The highest correlation was obtained with a power-form equation, an example of which is given in Fig. 4, for Bray-I P. The variation in Bray-I P explained 39% of the variation in constant a. In the case of constant b, a significant linear correlation with available P content was obtained (Table 7), which for Bray-I, water, and labile P explained 50, 29, and 40% of the variation in constant b, respectively. The relationship between Bray-I P and constant b is given as an example in Fig. 5.

The constants a and b of Eq. [1] will be a function of reaction rate of P desorption, such that a is related to the rate of change of reaction rate and b to the initial reaction rate. A decrease in a or an increase in b should enhance the reaction rate (Chien and Clayton, 1980). This is consistent with the data obtained, where an increase in available P content results in a decrease in a (Fig. 4) and increase in b (Fig. 5). Due to the close correlation between constants a and b and available P content, it may be possible to predict these constants from available P content, using the following relationships;

$$a = 8.046 \text{ Bray-I P}^{-0.890}$$
$$b = 4.174 \text{ Bray-I P} + 28.507$$

instead of obtaining them by more time consuming experimentation.
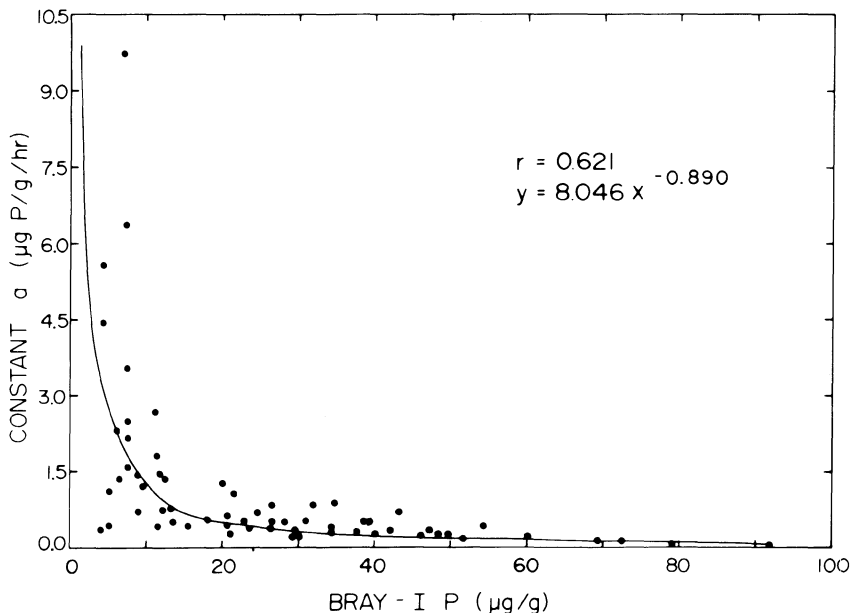
Figure 4. Relationship between Bray-I-P and constant a of Eq. [2] for the soils.
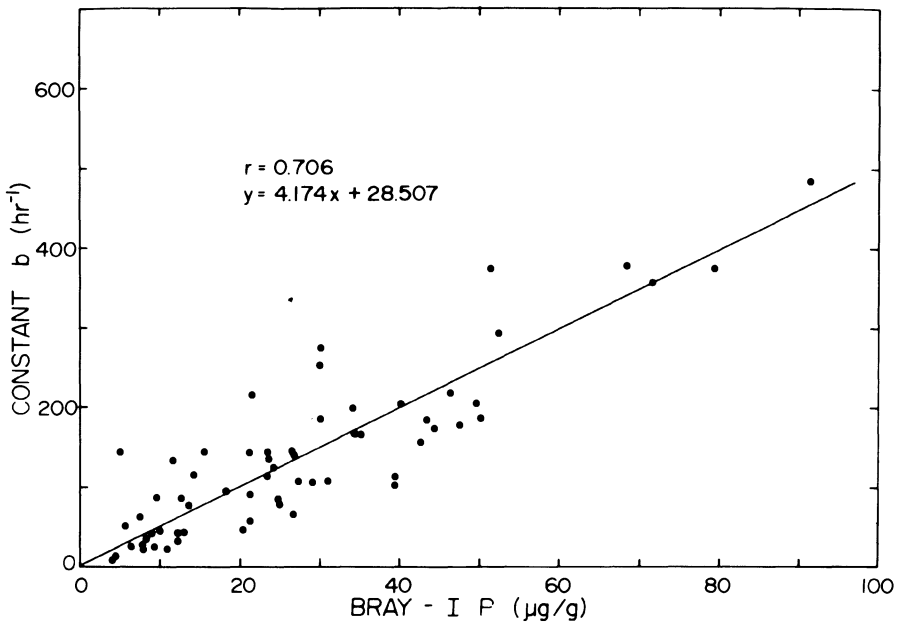
Figure 5. Relationship between Bray-I-P and constant b of Eq. [2] for the soils.
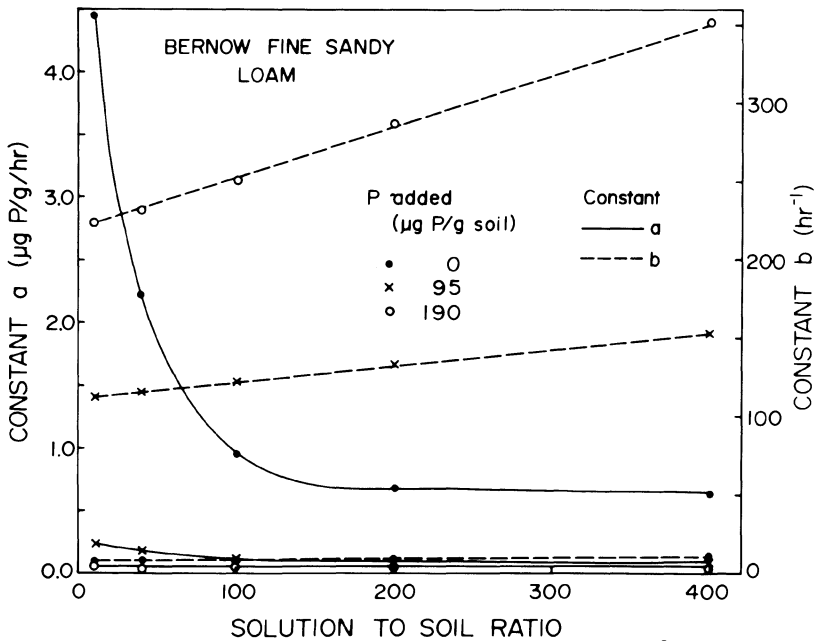
Figure 6. Constants a and b of Eq. [2] as a function of solution:soil ratio and soil P addition for Bernow fine sandy loam.
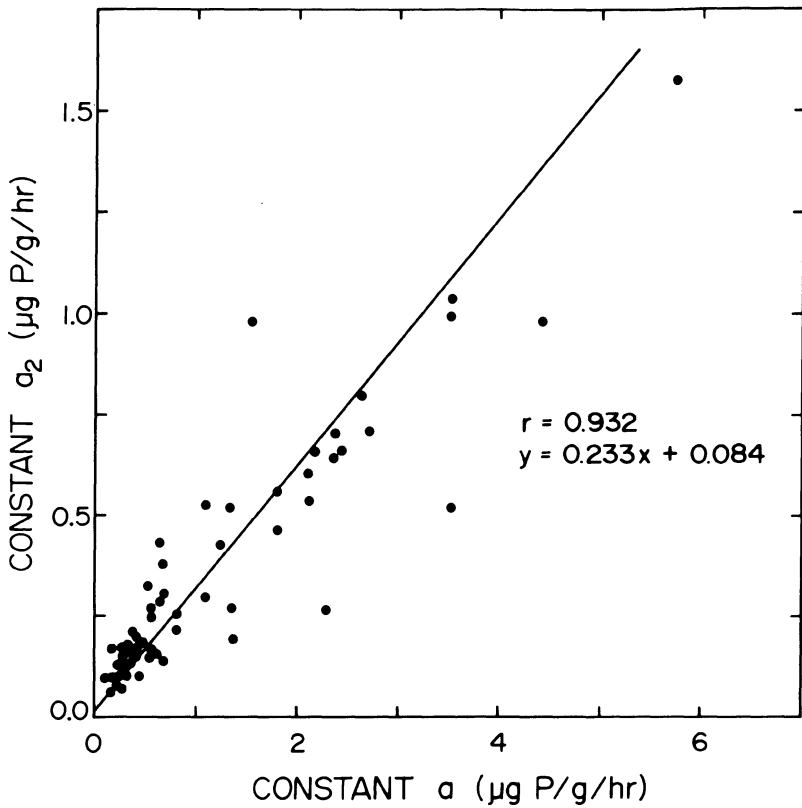
Figure 7. Relationship between the value of constant a (Eq. [2]) measured at a solution:soil ratio of 40:1 (a) and 400:1 (a_2) for the soils.

The values of constants a and b given in Figs. 4 and 5 are calculated from P desorbed at a solution:soil ratio of 40:1 and P addition of 100 μg/g. With an increase in solution:soil ratio and soil P addition, a decrease in the value of a and increase in b was calculated from the amounts of P desorbed (Fig. 6). Bernow fine sandy loam is given as an example, with the other soils behaving similarly. It was apparent, however, that at any given solution:soil ratio and P addition the values of constants a and b were linearly related (Figs. 7 and 8, respectively). The constants a_2 and b_2 of Figs. 7 and 8, were calculated from P desorption at a solution:soil ratio of 400:1 and P addition of 100 μg/g.

The effect of solution:soil ratio and P addition on P desorption must be accounted for in water quality models, as the solution:soil ratio can change rapidly during interaction between the surface soil and runoff, and fertilizer P applications will change soil P status.
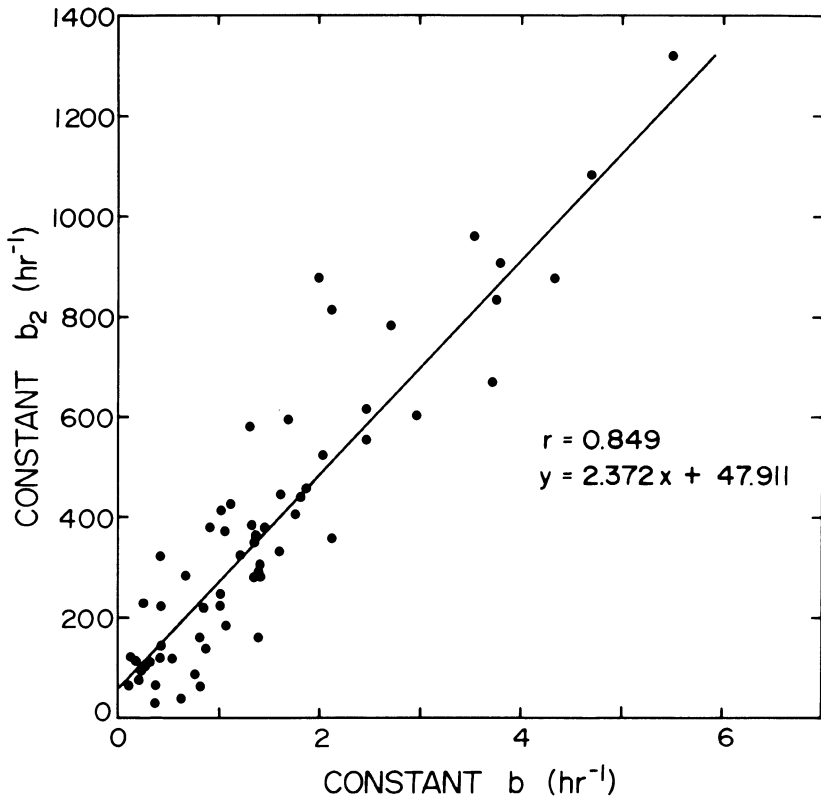
Figure 8. Relationship between the value of constant b (Eq. [2]) measured at a solution:soil ratio of 40:1 (b) and 400:1 (b_2) for the soils.

Consequently, use of the modified Elovich equation (Eq. [2]) is impractical for describing soil P desorption to runoff, due to the effect of solution:soil ratio and P addition, unless these two parameters are included. Use of the log-log equation (Eq. [3]) suggested by Sharpley et al. (1981b) to describe soil P desorption by runoff water is thus preferred as the effect of solution:soil ratio and P addition on P desorption are accounted for, and the constants K, α, and β are unaffected. For practical field application, these constants can be predicted from percent clay and organic carbon content using the following relationships;

$$K = -0.0042 \text{ percent clay} + 0.073 \text{ organic carbon} + 0.138$$
$$\alpha = -0.0036 \text{ percent clay} + 0.063 \text{ organic carbon} + 0.177$$
$$\beta = -0.0098 \text{ percent clay} - 0.152 \text{ organic carbon} + 0.493$$

Table 8. Regression of several soil properties and P sorption and desorption properties for the soils.

Soil Property	Buffer capacity	Equilibrium P concentration	Labile P	Sorption index
		μg/ml	μg/g	
Exch Al^{+}	0.312**	N.S.	N.S.	0.327**
Ext Al^{++}	0.294*	N.S.	N.S.	0.354**
Ext Fe	0.474***	N.S.	N.S.	0.585***
Exch Ca	N.S.	N.S.	N.S.	N.S.
Clay#	0.487***	N.S.	N.S.	0.432***
O.C.##	0.410***	N.S.	N.S.	0.312**
Ext Al, Ext Fe	0.477***	0.274*	N.S.	0.588***
Clay, O.C.	0.551***	0.296*	N.S.	0.466***
Ext Al, Exch Al, Ext Fe, Clay, O.C., Exch Ca	0.710***	0.460***	0.291*	0.711***

+   Exch represents exchangeable.
+ + Ext represents extractable.
#   Clay represents percent clay.
O.C. represents organic carbon.
*, **, *** designate significance (n = 67) at p < 0.05, < 0.01, and < 0.001 levels, respectively.
N.S. Not significant.

Soil P Desorption Capacity

As discussed in the introduction, the P buffer capacity of a soil, as calculated from its P sorption isotherm, represents the capacity of a soil to respond to changes in solution P concentration. The buffer capacity of the soils was related to properties controlling the sorption and desorption of P (Table 8). The highest correlation coefficient was obtained with a multiple regression of all the properties associated with P reaction and P buffer capacity. When the soils were grouped into acidic (pH < 7.0) and alkaline soils (pH > 7.0), highly significant correlations were obtained between P buffer capacity and extractable Fe (Fig. 9) and exchangeable Ca (Fig. 10), respectively. Extractable Al was similarly related to P buffer capacity of the acidic soils, although the correlation coefficient was not as high (r = 0.677) as for extractable Fe (r = 0.891). Holford (1977) also observed a close correlation between Fe content and the P buffer capacity of several calcareous soils from England. It is suggested that the P buffer capacity will be useful in water quality modeling in terms of expressing the extent to which soil material can modify the solution P concentration of runoff, when used in conjunction with the EPC$_O$ and labile P content of the soil.

Both EPC$_O$ and labile P content were significantly correlated with available P content of the soils as measured by Bray-I, double acid, Olsen, and water extractions (Fig. 2). For EPC$_O$ the highest correlation coefficient was obtained with water extractable P (Fig. 11), which accounted for 92% of the variation in EPC$_O$. This correlation is expected as the two methods are similar. Although the value of the EPC$_O$ for a given soil will be affected by solution:soil ratio and time of shaking the relative magnitude
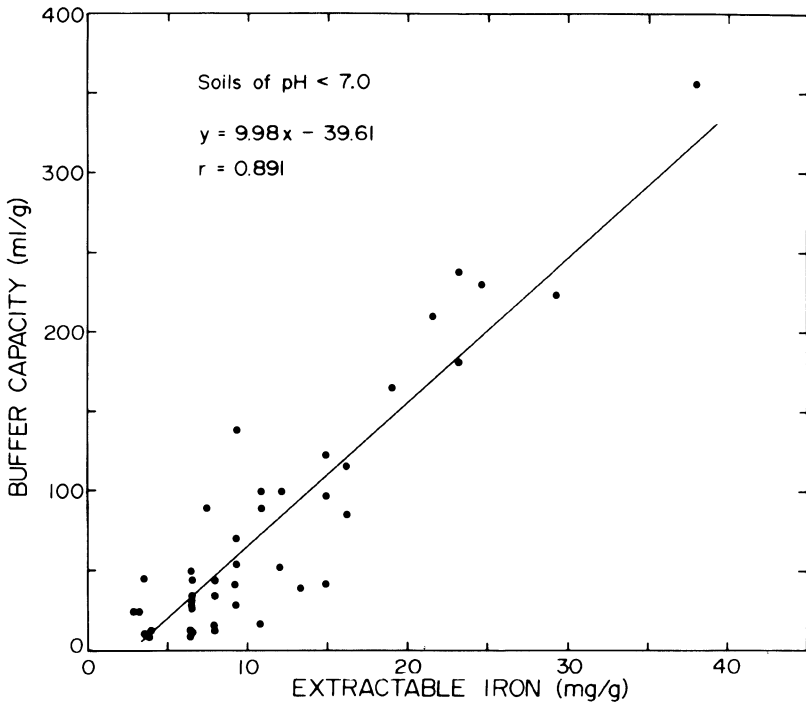
Figure 9. Relationship between extractable Fe content and P buffer capacity of the soils with a pH < 7.0.
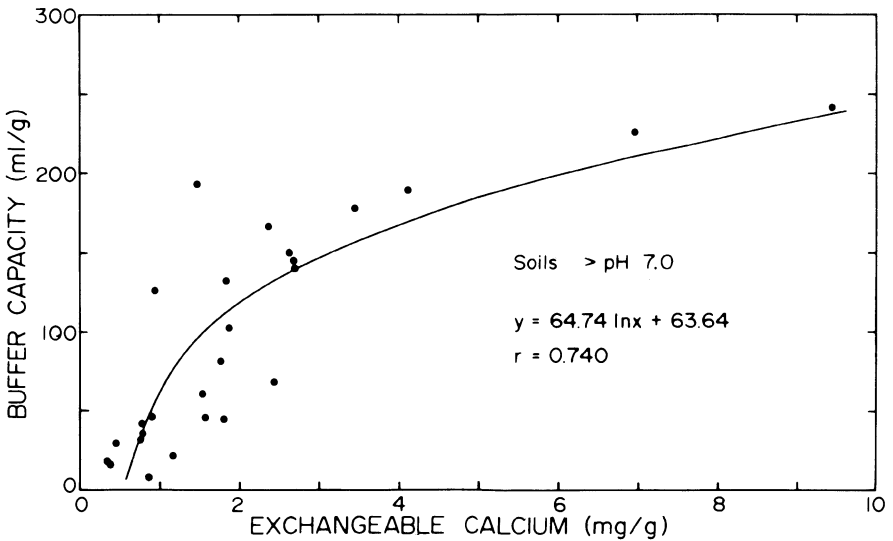
Figure 10. Relationship between exchangeable Ca content and P buffer capacity of the soils with a pH > 7.0.
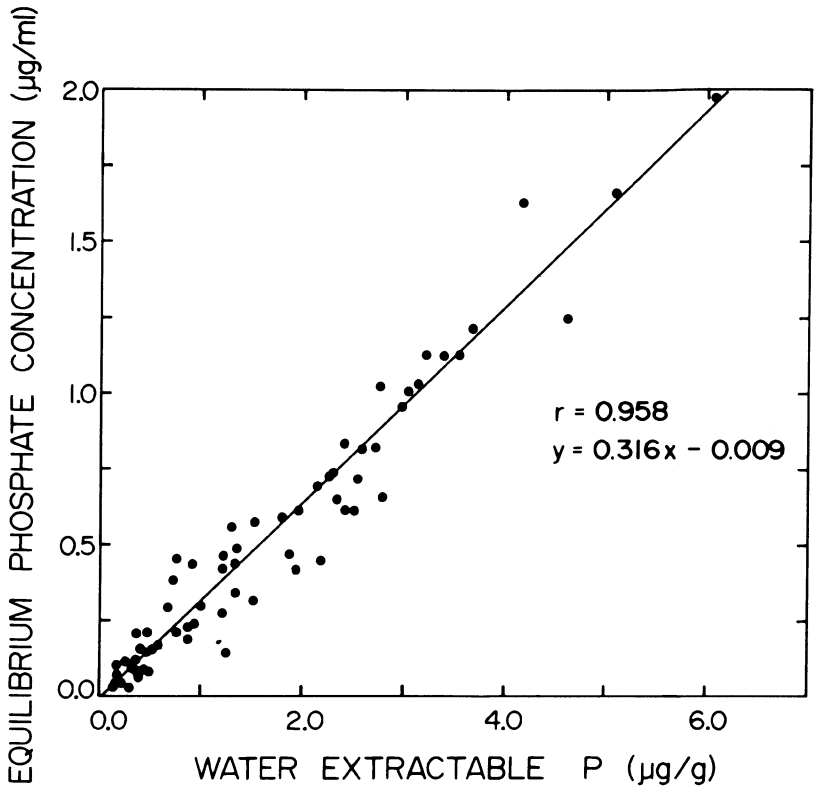
Figure 11. Relationship between water extractable P (solution:soil ratio of 20:1 for 5 min) and equilibrium P concentration of the soils.

can be predicted from a simple and rapid water available P test. This would eliminate the construction of a P adsorption isotherm in order to determine EPC_0. However, soils of similar EPC_0 values can have widely differing P buffer capacities. For example, Hoytville, Sacramento, and Wyarno soils had similar EPC values (0.073, 0.08, and 0.077 mg/1, respectively) but had P buffer capacities of 226, 360, and 137 ml/g, respectively. Thus, use of the correlation between EPC_0 and available P content should be limited to a common group of soils. Furthermore, the relationship should be calibrated for a certain locality and not applied to another area without recalibration and testing.

Labile P can be estimated from the P sorption isotherm (Fig. 1). This may be an approximate value, however, due to the nonlinearity of the desorption curve. For the collected soils, labile P measured using ^{32}P was significantly related to the value estimated, from the desorption curve (r = 0.951 significant at the 0.001 level, Fig. 12). Consequently, deviation from linearity on the desorption part of the curve is small. The relationship between estimated and extrapolated labile P is close to 1:1 (slope of the relationship is 0.944). The slope of this relationship may vary if different extracting mediums and solution:soil ratios are used to construct the P sorption isotherm from which labile P is estimated.
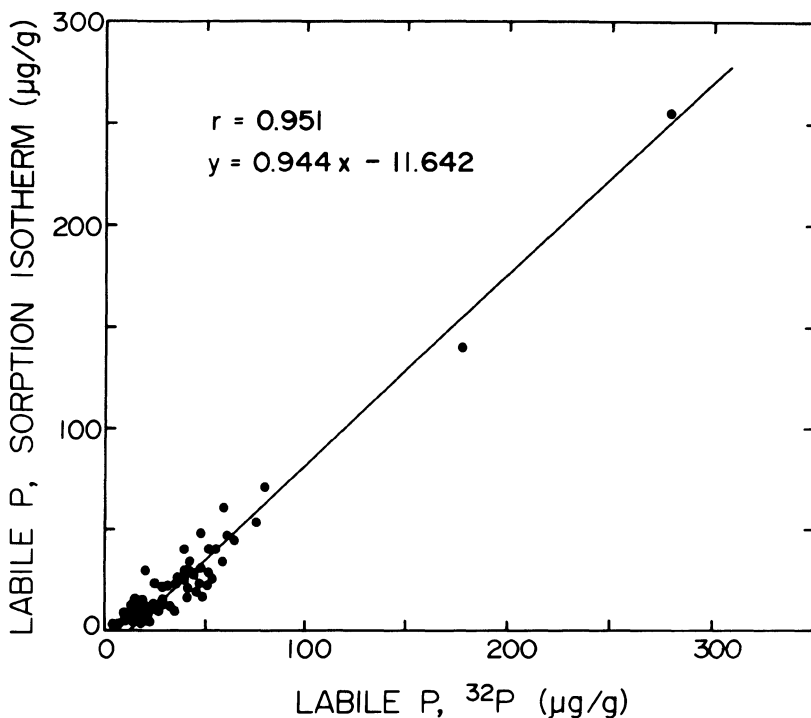
Figure 12. Relationship between labile P measured by isotopic dilution and by extrapolation from desorption isotherms for the soils.

Soil P Sorption Index

A large range in P sorption index, as measured by the method of Bache and Williams (1971), was observed (Table 2). The P sorption index was most closely related to clay content of the soils, such that as clay content increased, sorption index increased (Table 8). Several other soil components associated with P sorption (Fe, Al, and Ca), were not closely related to P sorption index, with extractable Al only explaining 34% of the variation in P sorption. Multiple regression of all these components resulted in a larger correlation coefficient with P sorption index (Table 8).

The soils were then grouped as acidic (<pH 7.0) and alkaline (>pH 7.0) and the correlations rerun. The P sorption index of the acidic soils was most closely correlated to extractable Fe content ($r = 0.894$, significant at the 0.001 level, Fig. 13). Although extractable Al was similarly related to P sorption index, the correlation coefficient was not as high ($r = 0.494$, significant at the 0.01 level). The P sorption index of alkaline soils was closely correlated with the exchangeable Ca content ($r = 0.895$, significant at the 0.001 level, Fig. 14). The close correlations shown in Figs. 13 and 14 are consistent with the dominance of Fe and Al, and Ca in P sorption processes in acidic
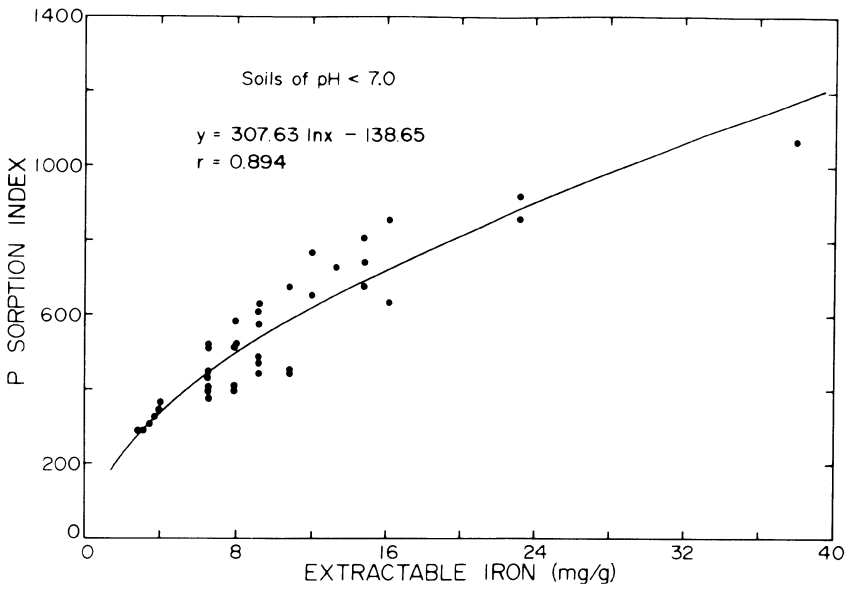
Figure 13. Relationship between extractable Fe content and P sorption index of the soils with a pH < 7.0.
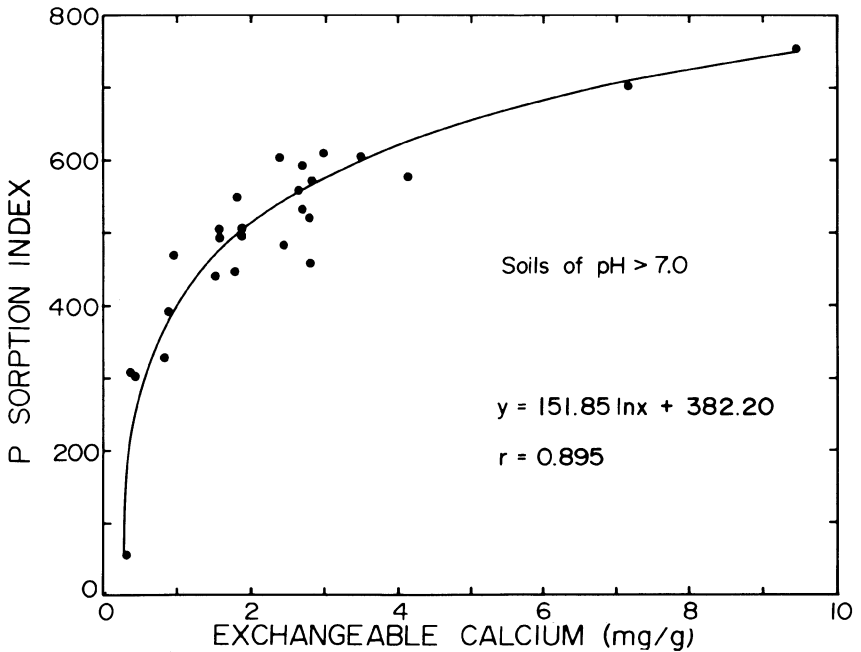
Figure 14. Relationship between the exchangeable Ca content and P sorption index of the soils with a pH > 7.0.

and alkaline soils, respectively. A similar significant correlation for extractable Fe and Ca with P sorption for acid and alkaline soils, respectively, was obtained by Larsen and Widdowson (1970), Williams et al., (1971), Fitter and Sutton (1975), and Singh and Tabatabai (1977).

Conclusions and Recommendations

The following conclusions and recommendations for obtaining field measurements to model P transport in runoff, can be made from the data presented;

a. Available soil P tests measured different amounts of P from the same soil, with a general increase in the following order, water, Olsen, Bray-I, and double acid P. Only Bray-I and water P were highly correlated ($r = 0.85$). Although available P contents as measured by other procedures were related, the coefficient of determination was no more than 30%. It is not possible, therefore, to estimate available P content as measured by one procedure from another, for a given soil. Consequently, for application on a national scale, water quality models must have the capacity to use available P content measured by several different procedures.

b. The constants (a and b) of the modified Elovich equation (Eq. [2]), describing soil P release were significantly related to the available P content. For constant a, the highest correlation was obtained with a power form equation. For constant b, a highly significant linear correlation was obtained with available P content. It is suggested, therefore, that the constants of Eq. [2] for a given soil may be estimated from available P content using the following relationships,

$$a = 8.046 \text{ Bray-I P}^{-0.890}$$
$$b = 4.174 \text{ Bray-I P} + 28.507$$

The constants a and b, however, vary with the solution:soil ratio of the extracting medium in which they were determined and amount of P added. Consequently, the use of Eq. [2] in modeling P transport in runoff is limited due to the rapid changes in solution:soil ratio, which can occur during a runoff event.

c. The constants (K, α, and β) of Eq. [3] were closely related to soil properties associated with P sorption and desorption. For practical field application, the constants of Eq. [3] can be predicted from percent clay and organic carbon content of a given soil using the following relationships,

$$K = -0.0042 \text{ percent clay} + 0.073 \text{ organic carbon} + 0.138$$
$$\alpha = -0.0036 \text{ percent clay} + 0.063 \text{ organic carbon} + 0.177$$
$$\beta = 0.0098 \text{ percent clay} - 0.152 \text{ organic carbon} + 0.493$$

As the effect of solution:soil ratio and soil P status on P release can be accounted for in Eq. [3], its use in water quality models is recommended over Eq. [2].

d. The EPC_0 and labile P content of the surface soil were related to available P content. The use of these relationships to estimate EPC_0 or labile P, however, should be limited to a common group of soils.

e. The P sorption index and buffer capacity of the soils were closely related to the amount of soil constituents associated with adsorption processes. This was Fe and Ca for the acid ($< pH$ 7.0) and alkaline soils ($> pH$ 7.0), respectively.

f. Although the number of procedures used by state soil testing laboratories to measure available P content has decreased dramatically over the past 20 years, there is still a need for further standardization. This is necessary for comparison of available P values from state-to-state, where different procedures are used and for water quality model implementation.

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Appendix

Table A. Location and classification of the soils

Soil series	Location	Family	Subgroup
Aastad c.l.	MN	Fine-loamy, mixed	Pachic Udic Haploborolls
Amarillo f.s.l.	TX	Fine-loamy, mixed thermic	Aridic Paleustalfs
Archerson f.s.l.	WY	Fine-loamy, mixed, mesic	Aridic Argiustolls
Ascabon f.s.l.	CO	Fine-loamy, mixed, mesic	Aridic Argiustolls
Athena si.l.	WA	Fine-silty, mixed, mesic	Pachic Haploxerolls
Bagdad, si.l.	WA	Fine-silty, mixed, mesic	Calcic Argixerolls
Bernow, f.s.l.	OK	Fine-loamy, siliceous, thermic	Fragic Palendults
Blount si.l.	IN	Fine, illitic, mesic	Aeric Ochraqualfs
Canover si.l.	MI		
Canyon f.s.l.	CO	Loamy, mixed, mesic, shallow	Ustic Torriorthents
Chalmers si.l.	IN	Fine-loamy, mixed, mesic	Typic Argiaquolls
Chama si.l.	MT	Fine-silty, mixed	Typic Haploborolls
Clarion l.	IA	Fine-loamy, mixed, mesic	Typic Hapludolls
Colby si.l.	CO	Fine-silty, mixed, mesic	Ustic Torriorthents
Comoro s.l.	AZ	Coarse-loamy, mixed, thermic	Cumulic Haplustolls
Devona f.s.l.	CO		
Durant l.	OK	Fine, montmorillonitic, thermic	Vertic Argiustolls
Ft. Collins s.l.	CO	Fine-loamy, mixed, mesic	Ustollic Haplargids
Goshen l.	CO	Fine-silty, mixed, mesic	Pachic Argiustolls
Greenfield s.l.	CA	Coarse-loamy, mixed, mesic	Typic Haploxeralfs
Greenville si.l.	AL	Clayey, kaolinitic, thermic	Rhodic Paleudults
Guest c.l.	AZ	Fine, mixed, thermic	Cumulic Haplustolls

Table A. Location and classification of the soils (cont.)

Soil series	Location	Family	Subgroup
Hanford f.s.l.	CA	Coarse-loamy, mixed, thermic	Typic Xerorthents
Haxton f.s.l.	CO	Fine-loamy, mixed, mesic	Pachic Argiustolls
Houston Black c.	TX	Fine, montmorillonitic, thermic	Udic Pellusterts
Hoytville c.l.	IH	Fine, illitic, mesic	Mollic Ochraqualfs
Keith l.	CO	Fine-silty, mixed, mesic	Aridic Argiustolls
Kirkland si.l.	OK	Fine, mixed, thermic	Udertic Paleustolls
Kranzburg si.l.	SD	Fine-silty, mixed	Udic Haploborolls
Kuma l.	CO	Fine-silty, mixed, mesic	Pachic Argiustolls
Laveen l.	AZ	Coarse-loamy, mixed, hyperthermic	Typic Calciorthids
Locke s.l.	MI	Coarse-loamy, mixed, mesic	Aquollic Hapludalfs
Mansker f.s.l.	CO	Fine-loamy, carbonatic, thermic	Calciorthidic Paleustolls
McLain si.l.	OK	Fine, mixed, thermic	Pachic Argiustolls
Mt. St. Helens ash	WA		
Myakka f.s.	FL	Sandy, siliceous, hyperthermic	Aeric Haplaquods
Nicollet c.l.	IA	Fine-loamy, mixed, mesic	Aquic Hapludolls
Norka l.	CO	Fine-silty, mixed, mesic	Aridic Argiustolls
Orangeburg f.sd.	FL	Fine-loamy, siliceous, thermic	Typic Paleudults
Palouse si.l.	WA	Fine-silty, mixed, mesic	Pachic Ultic Haploxerolls
Panoche c.l.	CA	Fine-loamy, mixed, thermic	Typic Torriorthents
Pima si.c.	AZ	Fine-silty, mixed, thermic	Cumulic Haplustolls
Platner l.	CO	Fine, montmorillonitic, mesic	Aridic Paleustolls
Port si.l.	OK	Fine-silty, mixed, thermic	Cumulic Haplustolls

Table A. Location and classification of the soils (cont.)

Soil series	Location	Family	Subgroup
Pullman c.l.	TX	Fine, mixed, thermic	Torrertic Paleustolls
Quincy si.l.	OR	Mixed, mesic	Xeric Torripsamments
Rago si.l.	CO	Fine, montmorillonitic, mesic	Pachic Argiustolls
Ramona f.s.l.	CA	Fine-loamy, mixed, thermic	Typic Haploxeralfs
Renfrow si.l.	OK	Fine, mixed, thermic	Udertic Palerrstolls
Renslow si.l.	WA	Coarse-silty, mixed, mesic	Aridic Calcic Argixerolls
Ritzville si.l.	WA	Coarse-silty, mixed, mesic	Calclorthidic Haploxerolls
Rossmoyne si.l.	OH	Fine-silty, mixed, mesic	Aquic Fragiudalfs
Ruston f.s.l.	OK	Fine-loamy, siliceous, thermic	Typic Paleudults
Sacramento c.l.	CA	Very-fine, montmorillonitic, thermic	Vertic Haplaquolls
Scott l.	CO	Fine, montmorillonitic, mesic	Typic Argialbolls
Shano si.l.	WA	Coarse-silty, mixed, mesic	Xerollic Camborthids
Sharpsburg si.l.	IA	Fine, montmorillonitic, mesic	Typic Argiudolls
Stoneham l.	CO	Fine-loamy, mixed, mesic	Ustollic Haplargids
Superstition s.	AZ	Sandy, mixed, hyperthermic	Typic Torriorthents
Temvik si.l.	ND	Fine-silty, mixed	Typic Haploborolls
Vinton s.l.	AZ	Sandy, mixed, thermic	Typic Torrifluvents
Vista s.l.	CA	Coarse-loamy, mixed, thermic	Typic Xerochrepts
Weld si.l.	CO	Fine, montmorillonitic, mesic	Aridic Paleustolls
Williams l.	MT	Fine-loamy, mixed	Typic Argiborolls
Woodward l.	OK	Coarse-silty, mixed, thermic	Typic Ustochrepts
Wyarno c.l.	WY	Fine, montmorillonitic, mesic	Ustollic Haplargids
Yolo l.	CA	Fine-silty, mixed, thermic	Typic Xerochrepts

Table B. Physical and chemical properties of the soils

Soil	Clay content	pH	Organic C	CaCo₃	Exchangeable Ca	Exchangeable Al	Extractable Al	Extractable Fe
	%		--------%--------		--------------mg/g soil--------------			
Aastad	27	6.1	2.89	---	3.4	1.2	4.8	6.5
Amarillo	15	6.8	0.79	---	0.8	1.0	6.2	6.5
Archerson	19	8.0	2.05	8.50	4.1	0.2	1.0	9.3
Ascabon	17	6.6	0.78	---	0.9	0.6	5.9	6.5
Athena	17	6.0	1.79	---	1.7	0.8	5.4	10.7
Bagdad	23	5.8	0.80	---	1.5	0.4	3.4	7.9
Bernow	8	6.3	0.71	---	0.4	0.6	5.3	3.5
Blount	23	6.4	1.00	---	1.2	0.6	6.8	16.4
Canover	23	6.7	1.65	---	1.2	0.8	3.1	10.7
Canyon	15	7.7	1.05	1.25	2.4	1.0	3.8	5.1
Chalmers	25	6.5	2.31	---	2.2	1.2	5.1	9.3
Chama	28	6.9	1.44	---	1.7	0.6	3.8	3.7
Clarion	27	6.0	1.05	---	1.4	1.4	5.7	13.4
Colby	21	7.7	0.91	1.05	1.6	1.2	4.0	5.1
Comoro	14	7.1	0.54	---	0.4	0.8	5.1	5.1
Devona	17	6.6	0.71	---	1.1	0.6	5.2	6.5
Durant	27	7.1	0.37	---	1.0	1.0	5.6	16.2
Ft. Collins	16	8.2	0.43	4.28	1.6	0.4	3.9	10.7
Goshen	27	7.5	1.19	0.48	1.5	0.6	4.4	6.5
Greenfield	17	6.8	0.56	---	1.8	0.8	4.7	6.5
Greenville	21	5.9	0.93	---	0.4	0.6	9.0	9.3
Guest	41	8.7	1.08	2.30	1.9	0.4	5.9	5.1

Table B. Physical and chemical properties of the soils (Cont.)

Soil	Clay content	pH	Organic C	CaCo₃	Exchangeable Ca	Exchangeable Al	Extractable Al	Extractable Fe
	%		--------%---------		--------------------mg/g soil----------------			
Hanford	11	7.1	0.62	---	0.4	1.2	4.3	12.0
Haxton	10	6.2	1.13	---	1.2	0.8	5.5	6.5
Houston	50	7.9	2.17	21.10	9.4	1.2	0.9	9.3
Hoytville	38	7.3	2.06	1.78	7.0	1.4	3.7	10.4
Keith	27	6.3	1.14	---	1.5	0.6	5.0	6.5
Kirkland	13	6.0	2.02	---	1.6	0.8	5.8	3.9
Kranzburg	24	6.3	2.17	---	2.9	0.8	5.8	7.9
Kuma	25	6.9	0.91	---	1.1	0.4	5.4	6.5
Laveen	19	8.2·	0.51	8.80	1.9	1.2	3.7	9.3
Locke	14	5.6	1.53	---	0.7	0.8	6.6	23.2
Mansker	19	7.7	0.95	1.31	2.7	0.6	5.7	6.5
McLain	29	7.5	0.67	---	1.8	1.0	5.3	6.5
Mt. St. Helens	19	6.8	0.07	---	0.3	0.6	6.3	24.5
Myakka	9	5.6	1.06	---	0.4	0.6	5.8	7.9
Nicollet	46	7.0	1.44	---	2.2	0.8	7.0	14.8
Norka	27	7.6	1.00	0.81	2.6	0.6	7.1	6.5
Orangeburg	14	5.6	0.73	---	0.1	2.4	8.8	23.2
Palouse	19	5.6	2.18	---	2.1	1.8	6.2	10.7
Panoche	41	7.7	0.55	2.30	3.5	0.8	6.9	14.8
Pima	36	9.1	0.89	1.16	2.7	0.8	5.7	5.1
Platner	26	6.5	0.86	---	1.2	1.2	4.8	6.5
Port	32	7.3	1.20	---	2.4	1.0	5.9	5.1

Table B. Physical and chemical properties of the soils (Cont.)

Soil	Clay content	pH	Organic C	CaCo₃	Exchangeable		Extractable	
					Ca	Al	Al	Fe
	%		--------%---------		---------------mg/g soil---------------			
Pullman	30	6.8	0.83	---	2.3	1.2	6.9	14.8
Quincy	14	6.8	1.40	---	0.9	1.2	5.0	2.9
Rago	23	7.0	1.23	0.81	2.8	0.4	5.8	6.5
Ramona	16	6.0	0.80	---	0.3	0.8	5.3	23.2
Renfrow	23	6.5	0.50	---	1.0	0.8	5.9	9.3
Renslow	22	5.2	1.07	---	0.9	1.0	5.0	14.8
Ritzville	20	5.7	0.83	---	1.0	1.2	5.2	9.3
Rossmoyne	24	5.7	1.60	---	1.2	1.0	6.7	12.0
Ruston	13	5.6	1.41	---	0.5	1.0	6.6	2.0
Sacramento	45	5.1	4.93	---	0.7	2.0	14.8	38.0
Scott	29	6.3	0.97	---	1.6	0.4	4.1	7.9
Shano	22	6.0	0.68	---	0.8	1.2	5.3	12.0
Sharpsburg	28	6.0	1.85	---	2.3	1.2	4.5	16.2
Stoneham	26	7.6	1.05	0.68	0.8	0.4	6.6	5.1
Superstition	6	8.3	0.17	---	0.4	0.6	5.6	21.8
Temvik	21	6.5	2.25	---	1.6	1.0	5.0	6.5
Vinton	8	8.5	0.38	0.83	0.9	1.0	3.9	5.1
Vista	11	6.0	0.53	---	0.7	0.6	5.3	16.2
Weld	17	7.7	0.86	0.81	2.8	0.8	7.2	6.5
Williams	23	6.4	0.93	---	2.8	1.0	5.1	7.9
Woodward	32	7.9	1.02	1.12	1.8	0.8	5.8	10.7
Wyarno	53	6.4	0.77	---	2.2	0.6	5.4	9.3
Yolo	23	7.0	0.82	---	0.9	0.4	5.2	6.5

Table C. Total, inorganic, and available P contents of the soils

| Soil | P Content | | | Available P | | | | Labile | Sorption |
	Total	Inorg.	Organic	Double acid	Bray PI	Olsen	Water	P	index
				------ugP/g soil------					
Aastad	550	182	368	42.2	14.3	15.9	0.88	45.8	515
Amarillo	188	137	51	7.6	8.3	4.6	0.45	12.7	379
Archerson	589	422	167	8.2	31.2	30.0	1.31	46.0	588
Ascabon	259	147	112	42.0	11.8	6.7	1.39	18.1	403
Athena	820	604	216	87.7	28.7	23.8	1.23	33.5	677
Bagdad	570	490	80	22.0	27.0	13.2	2.64	27.3	389
Bernow	144	67	77	12.3	18.7	16.9	0.98	17.7	318
Blount	551	331	200	38.0	25.0	15.7	0.59	49.7	511
Canover	518	141	377	30.8	12.0	10.1	0.47	42.3	454
Canyon	183	144	39	15.4	9.5	6.8	0.38	15.3	603
Chalmers	585	243	342	50.5	30.6	24.3	1.45	58.4	466
Chama	618	403	215	53.0	10.1	5.8	0.87	15.3	329
Clarion	386	178	208	42.4	50.9	42.2	2.33	53.6	724
Colby	372	256	116	51.3	13.0	7.3	0.51	14.8	496
Comoro	639	554	85	20.4	21.2	8.3	1.31	20.0	307
Devona	271	182	89	49.6	26.8	11.7	1.42	29.5	393
Durant	165	57	108	9.0	7.5	6.1	0.17	18.9	470
Ft. Collins	573	530	43	3.3	8.2	7.3	0.28	16.0	506
Goshen	532	389	143	139.0	60.3	39.5	3.02	176.2	441
Greenfield	276	171	105	46.2	34.5	19.6	2.70	41.4	379
Greenville	139	114	25	29.0	45.7	12.5	1.32	36.3	472
Guest	680	594	86	46.0	30.3	10.4	2.01	21.5	506

Table C. Total, inorganic, and available P contents of the soils (Cont.)

Soil	P Content			Available P				Labile	Sorption
	Total	Inorg.	Organic	Double acid	Bray PI	Olsen	Water	P	index
	--ugP/g soil--								
Hanford	805	318	487	173.7	71.9	12.8	4.17	30.4	308
Haxton	371	213	158	62.6	42.8	13.7	3.14	36.7	427
Houston	477	255	222	9.2	9.7	1.8	0.57	35.8	755
Hoytville	763	438	325	93.1	20.9	14.3	0.48	47.3	613
Keith	418	251	167	88.9	54.3	23.2	2.77	51.9	375
Kirkland	303	137	166	10.5	8.1	19.2	1.76	18.6	364
Kranzburg	651	221	430	40.9	21.8	13.0	0.87	40.4	514
Kuma	376	292	84	100.5	39.3	5.2	1.61	35.7	449
Laveen	1062	987	75	86.4	79.7	272.4	5.14	278.7	496
Locke	267	114	153	35.5	26.8	12.1	1.92	23.2	857
Mansker	358	203	155	9.6	12.8	3.0	0.35	21.6	596
McLain	541	419	122	91.7	92.6	11.8	6.06	79.3	422·
Mt. St. Helens	360	344	16	19.7	5.8	1.4	0.25	3.0	933
Myakka	77	33	44	24.9	18.4	8.7	2.35	10.9	349
Nicollet	394	82	312	8.6	6.6	4.5	0.17	23.8	805
Norka	353	234	119	30.0	12.2	3.7	0.45	14.2	562
Orangeburg	63	9	54	8.7	2.7	18.7	0.21	11.5	922
Palouse	757	546	211	104.3	51.8	28.1	2.21	60.6	442
Panoche	437	406	31	181.2	18.7	8.0	0.67	16.8	606
Pima	727	614	113	274.6	53.7	7.6	3.42	74.2	532
Platner	305	189	116	50.8	26.8	21.0	2.49	26.1	379
Port	366	139	147	51.7	29.7	13.4	2.14	46.0	480

Table C. Total, inorganic, and available P contents of the soils (Cont.)

Soil	P Content			Available P				Labile	Sorption
	Total	Inorg.	Organic	Double acid	Bray Pl	Olsen	Water	P	index
-----ugP/g soil-----									
Pullman	636	337	299	65.4	24.9	21.0	0.86	30.7	745
Quincy	711	644	67	230.0	23.7	9.8	2.84	20.8	285
Rago	426	291	135	68.4	21.5	16.9	0.90	29.5	514
Ramona	147	68	79	12.3	12.7	2.7	1.19	10.6	281
Renfrow	177	42	135	5.7	4.4	12.5	0.14	16.9	438
Renslow	649	542	107	119.5	34.5	21.2	2.03	39.1	675
Ritzville	685	603	82	170.4	29.7	17.6	2.56	31.9	575
Rossmoyne	633	168	465	9.9	11.2	6.3	0.29	26.8	766
Ruston	327	86	231	37.6	46.4	5.4	3.17	25.3	204
Sacramento	762	475	287	42.1	38.3	29.0	0.43	58.1	1070
Scott	361	327	34	91.0	72.4	4.1	4.60	66.0	580
Shano	734	650	84	182.6	41.1	24.0	2.97	54.1	652
Sharpsburg	484	173	311	30.2	35.1	19.0	0.92	52.2	632
Stoneham	315	211	104	47.4	9.2	20.9	0.40	19.0	571
Superstition	201	157	44	68.8	15.9	6.0	2.40	11.3	57
Temvik	597	323	274	100.4	23.8	14.9	3.56	38.5	407
Vinton	697	634	63	270.8	43.4	7.4	3.69	11.8	328
Vista	677	599	78	106.8	4.5	13.4	1.36	24.1	850
Weld	637	277	90	71.8	21.4	52.0	0.71	28.1	456
Williams	295	152	143	38.1	6.8	4.0	0.36	12.7	520
Woodward	346	182	164	12.6	4.4	8.5	0.35	8.8	550
Wyarno	508	375	133	65.6	12.5	8.8	0.48	26.7	630
Yolo	480	415	65	122.6	23.7	13.1	1.60	38.4	393

Table D. Equilibrium P concentration, buffer capacity, and labile P contents calculated from P sorption isotherm and constants of equations [1] and [2] describing P desorption kinetics for the soils.

Soil	EPC$_0$	Buffer capacity	Labile P	Constants				
				a	b	K	α	β
	mg/l	mg/g	μg/g	1/hr	mg/1/hr			
Aastad	0.208	210	43.8	0.52	115.6	0.218	0.188	0.484
Amarillo	0.141	29	4.1	2.16	27.8	0.129	0.136	0.536
Archerson	0.419	189	29.1	0.55	109.5	0.243	0.301	0.329
Ascabon	0.555	12	4.4	0.68	22.4	0.112	0.177	0.542
Athena	0.135	87	11.7	0.56	107.1	0.302	0.277	0.330
Bagdad	0.812	13	10.4	0.56	107.1	0.083	0.133	0.607
Bernow	0.289	45	13.0	0.77	77.8	0.193	0.223	0.362
Blount	0.169	73	23.3	0.77	198.2	0.100	0.148	0.530
Canover	0.204	100	20.5	0.45	134.5	0.154	0.196	0.643
Canyon	0.056	167	15.0	2.43	24.7	0.191	0.185	0.376
Chalmers	0.484	70	33.9	0.24	251.0	0.228	0.231	0.385
Chama	0.451	10	4.7	1.24	48.6	0.139	0.138	0.511
Clarion	0.727	37	26.7	0.32	185.2	0.082	0.145	0.670
Colby	0.147	61	9.0	1.39	43.2	0.116	0.144	0.566
Comoro	0.462	28	13.0	0.81	65.3	0.093	0.164	0.624
Devona	0.431	50	21.4	0.41	145.6	0.131	0.174	0.579
Durant	0.035	126	4.5	5.73	21.7	0.038	0.094	0.794
Ft. Collins	0.101	44	4.4	3.54	17.0	0.060	0.088	0.739
Goshen	0.953	193	140.3	0.29	464.1	0.109	0.153	0.611
Greenfield	1.020	28	28.1	0.30	200.0	0.069	0.150	0.333
Greenville	0.334	27	4.4	0.34	174.9	0.147	0.132	0.562
Guest	0.415	103	42.7	0.42	144.6	0.073	0.121	0.680

Soil	EPC$_0$	Buffer capacity	Labile P	Constants				
				a	b	K	α	β
	mg/1	mg/g	μg/g	1/hr	mg/1/hr			
Hanford	1.624	16	25.6	0.17	77.1	0.140	0.251	0.466
Haxton	1.119	12	13.7	0.38	158.3	0.267	0.306	0.276
Houston	0.162	242	29.5	0.71	84.9	0.098	0.206	0.527
Hoytville	0.073	226	16.5	0.39	43.2	0.143	0.139	0.617
Keith	0.816	34	27.6	0.47	127.1	0.115	0.128	0.475
Kirkland	0.582	7	4.1	1.59	37.8	0.261	0.319	0.240
Kranzburg	0.181	89	16.2	0.27	155.9	0.220	0.206	0.536
Kuma	0.572	31	17.9	0.55	109.9	0.087	0.119	0.535
Laveen	1.952	132	283.5	0.02	375.0	0.074	0.140	0.652
Locke	0.603	237	16.3	0.43	139.9	0.212	0.198	0.272
Mansker	0.112	144	5.0	0.12	181.2	0.131	0.121	0.584
McLain	1.655	44	72.8	0.09	552.2	0.054	0.097	0.750
Mt. St. Helens	0.107	230	1.8	5.14	12.4	0.021	0.045	0.850
Myakka	0.732	12	8.5	3.63	95.2	0.191	0.264	0.204
Nicollet	0.062	122	1.4	0.18	106.8	0.082	0.140	0.737
Norka	0.089	150	13.3	1.88	32.0	0.088	0.140	0.509
Orangeburg	0.037	181	3.0	2.54	86.9	0.120	0.164	0.548
Palouse	0.690	16	26.6	0.29	375.0	0.245	0.232	0.386
Panoche	0.287	175	7.3	0.13	357.1	0.033	0.073	0.827
Pima	1.120	140	22.8	0.24	336.1	0.075	0.108	0.709
Platner	0.709	9	6.1	0.87	68.6	0.076	0.148	0.571
Port	0.441	69	30.4	0.22	174.0	0.084	0.140	0.598
Pullman	0.220	96	21.0	0.74	81.0	0.073	0.105	0.702

Table D. (continued)

| Soil	EPC$_o$	Buffer capacity	Labile P	Constants				
				a	b	K	α	β
	mg/1	mg/g	μg/g	1/hr	mg/1/hr			
Quincy	0.654	24	15.5	0.43	141.2	0.203	0.178	0.430
Rago	0.430	31	13.5	0.28	15.8	0.093	0.251	0.526
Ramona	0.267	24	6.3	0.74	80.6	0.148	0.194	0.611
Renfrow	0.021	223	4.7	4.45	13.5	0.041	0.148	0.559
Renslow	0.613	42	25.6	0.36	65.3	0.127	0.094	0.700
Ritzville	0.607	40	24.4	0.32	186.3	0.137	0.141	0.575
Rossmoyne	0.021	165	3.5	0.06	357.1	0.153	0.190	0.462
Ruston	1.029	98	42.1	0.28	216.6	0.201	0.195	0.304
Sacramento	0.081	360	61.6	0.16	279.7	0.216	0.281	0.241
Scott	1.243	34	42.4	0.20	294.1	0.076	0.139	0.686
Shano	0.998	52	36.4	0.10	251.6	0.088	0.119	0.638
Sharpsburg	0.232	85	19.8	0.40	266.7	0.118	0.211	0.576
Stoneham	0.148	34	5.1	1.43	42.0	0.089	0.142	0.583
Superstition	0.648	17	11.1	2.42	63.9	0.074	0.117	0.696
Temvik	1.124	10	11.4	0.45	133.3	0.191	0.249	0.329
Vinton	1.210	6	7.4	2.74	81.4	0.105	0.139	0.595
Vista	0.826	15	12.1	0.35	72.9	0.134	0.226	0.558
Weld	0.376	41	15.4	0.67	90.2	0.145	0.168	0.374
Williams	0.220	14	2.7	2.32	25.8	0.071	0.167	0.659
Woodward	0.116	81	9.4	3.56	10.8	0.108	0.088	0.420
Wyarno	0.077	137	10.6	0.42	42.4	0.032	0.056	0.837
Yolo	0.312	44	18.3	0.53	113.0	0.058	0.155	0.705
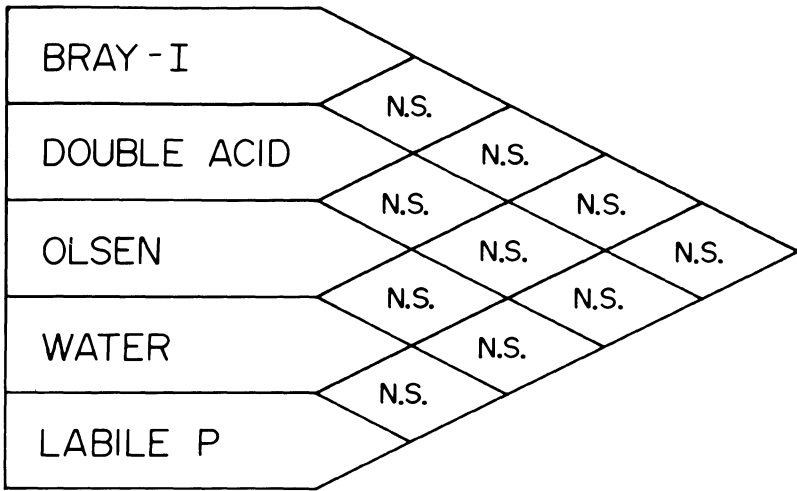
Figure A. Correlation of available soil P determined by several methods for the soils of pH 5.5-6.0.
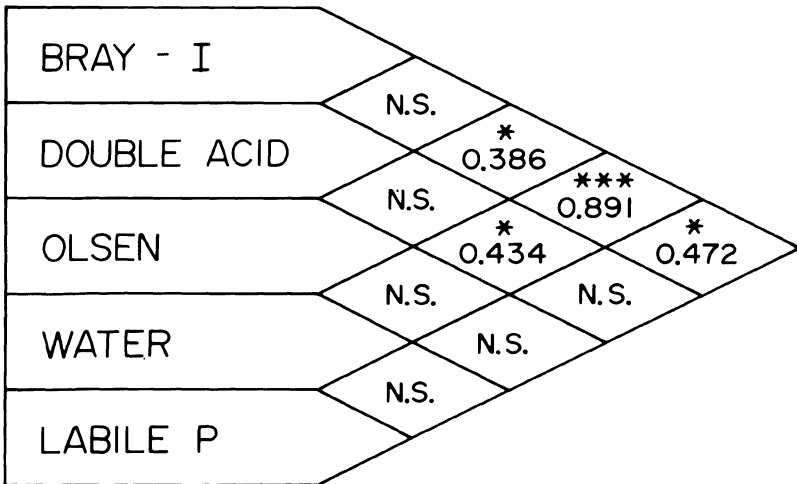

Figure B. Correlation of available soil P determined by several methods for the soils of pH 6.0-7.0.
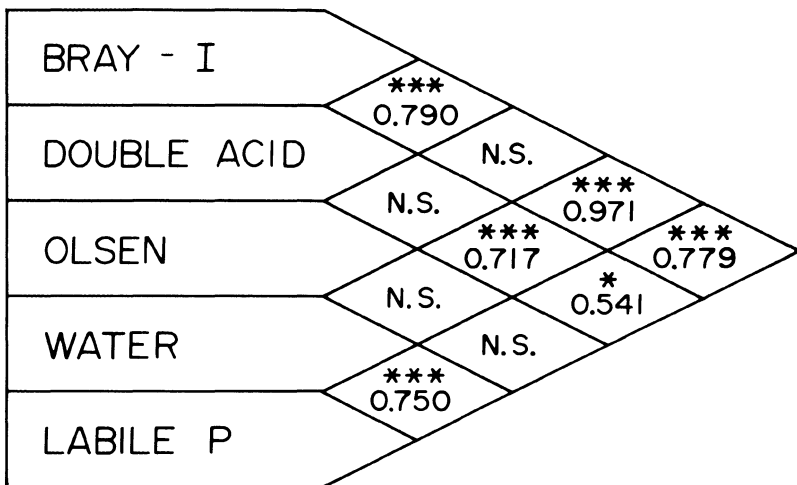***, **, * designate significance (n = 36) at the < 0.001, 0.01, and 0.1 levels, respectively.

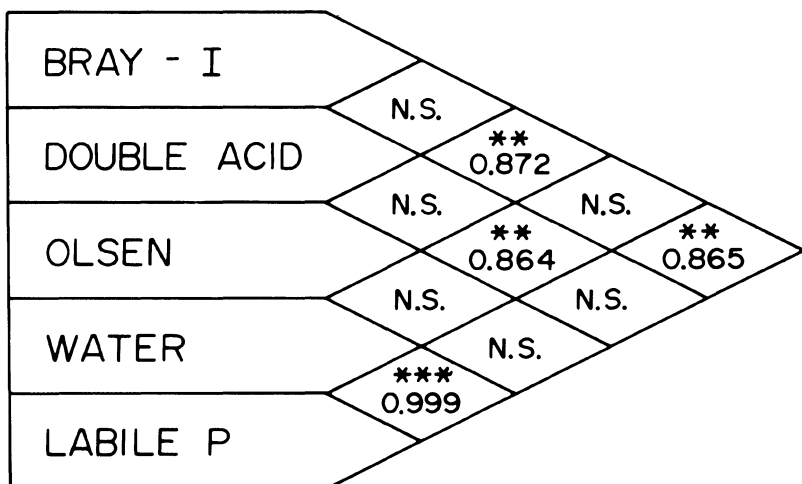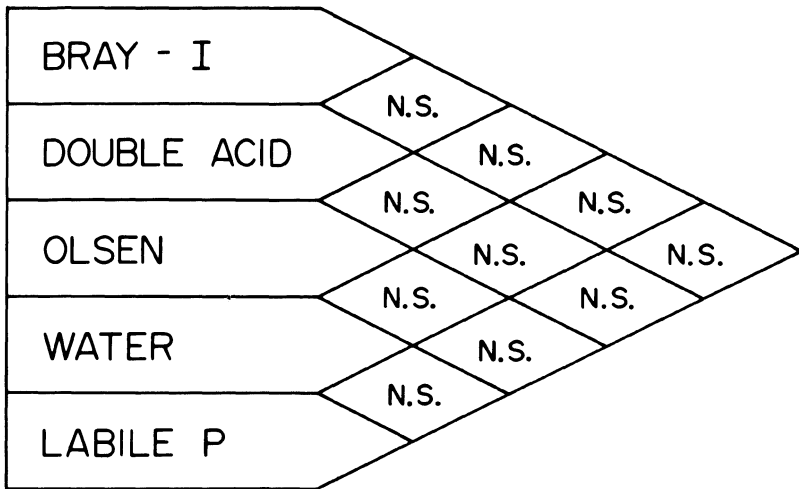Figure C. Correlation of available soil P determined by several methods for the soils of pH 7.0-8.0.
***, **, * designate significance (n = 18) at the p < 0.001, 0.01, and 0.1 levels, respectively.

Figure D. Correlation of available soil P determined by several methods for the soils of pH > 8.0.
***, **, * designate significance (n = 6) at the p < 0.001, 0.01 and 0.1 levels, respectively.

Figure E. Correlation of available soil P determined by several methods for the
soils of clay content > 35%.
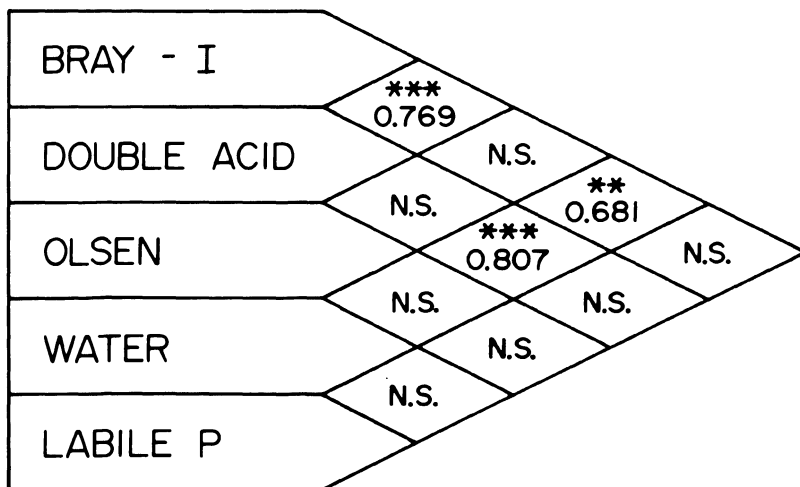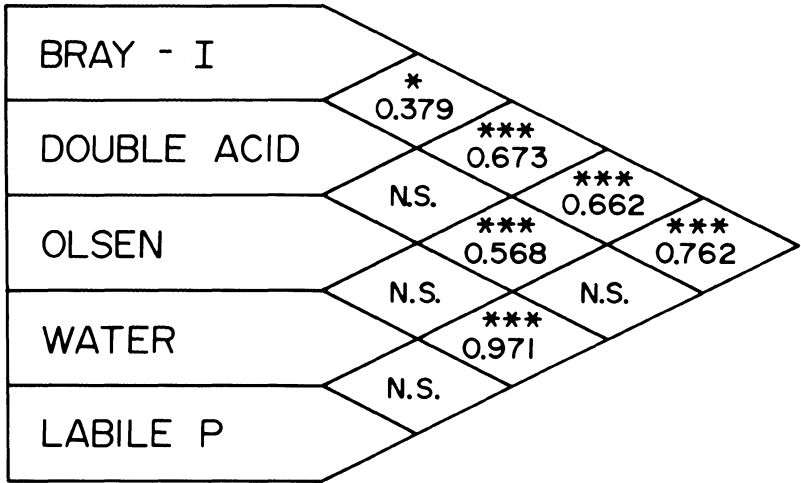***, **, * designate significance (n = 8) at the p < 0.001, 0.01, and 0.1 levels, respectively.

Figure F. Correlation of available soil P determined by several methods for the
soils of clay content 25-35%.
***, **, * designate significance (n = 16) at the p < 0.001, 0.01, and 0.1 levels, respectively.

Figure G. Correlation of available soil P determined by several methods for the soils of clay content 15-25%.
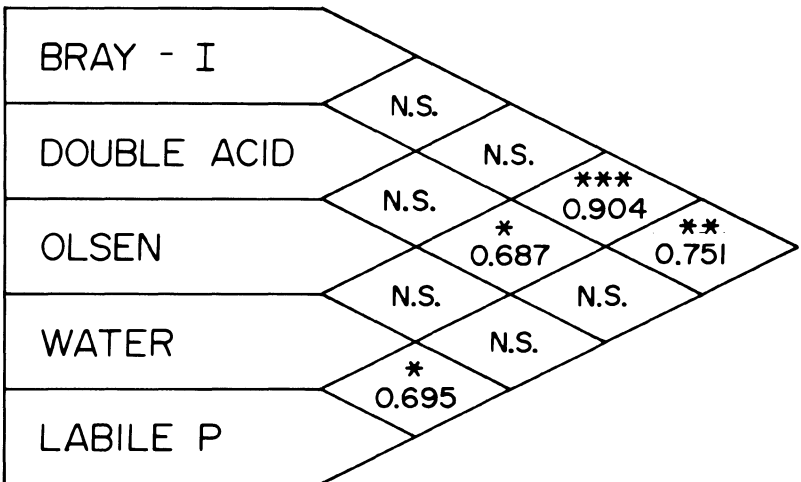*** , ** , * designate significance (n = 31) at the p < 0.001, 0.01, and 0.1 levels, respectively.

Figure H. Correlation of available soil P determined by several methods for the soils of clay content < 15%.
*** , ** , * designate significance (n = 10) at the p < 0.001, 0.01, and 0.1 levels, respectively.