

BASIC REACTIONS OF PHOSPHATE RETENTION
AND REMOVAL FROM SOIL

By

LANNY OLEN ASHLOCK

Bachelor of Science
University of Arkansas
Fayetteville, Arkansas
1965

Master of Science
University of Arkansas
Fayetteville, Arkansas
1967

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Thesis Approved:

J. Morrill

Thesis Adviser

Leroy D. Cray

Lester Reed

Billy B. Tucker

Eddie Basler

Norman N. Dunham

Dean of the Graduate College

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CHAPTER I

INTRODUCTION

The chemistry of phosphorus in the soil and the effect of various soil constituents on the availability of phosphorus to plants is critical to soil fertility and the solution of associated problems. "Soil phosphorus" has been the subject of intensive research effort over the last 30 years. The development of phosphorus fractionation procedures in soils has played an important role in demonstrating that aluminum, iron and calcium phosphates are formed and that relative amounts of these compounds can influence the chemical nature of the phosphate reaction products in soils. The solubility of the compounds dictate, to a large extent, the portion of soil phosphates that can be made available to plants. Amount of clay, clay types, iron and aluminum compounds, calcium carbonate content, surface area, pH, organic matter content and probably other soil factors such as water content, temperature and aeration can affect the solubility of phosphates in soils.

Some soils have a large capacity for sorbing or retaining phosphates, and in some instances they are used as filtering agents for polluted water and sediments. It is apparent that there is a danger of saturating the phosphate retention capacities of the soils, subsequently, these soils could release phosphates to ground-waters for an extended time period. Phosphates applied in lesser amounts can

be useful agriculturally without detrimental consequences.

Fifteen Oklahoma benchmark soils were investigated in this study with the purpose of studying soil factors which influence sorption and desorption of phosphates with implications on beneficial agricultural use without detrimental effects from several waste sources. The specific objectives of this study were: (1) to determine the role of certain physical, chemical and mineralogical characteristics of soils as they relate to phosphate sorption, (2) to study the effect of time and phosphorus application rates on phosphorus desorption characteristics as it relates to Bray extractable phosphorus, (3) and utilization of a phosphorus fractionation procedure to determine chemical change of phosphates with time and the soil fraction sources of phosphates extracted with repeated Bray extractions.

CHAPTER II

REVIEW OF LITERATURE

Phosphorus Retention in Soils

Some of the earliest research that showed that the aluminum (Al) content of clay minerals was responsible for phosphate (P) retention was conducted by Coleman (1944). The work of many other soil scientists have substantiated this view. Kittrick and Jackson (1956) demonstrated that in kaolinite-variscite ($\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$) systems, the solubility product of variscite is unaltered and that kaolinite will decompose in the presence of rather high P concentrations to form variscite.

P retention in soils has been defined in many different ways. Wild (1950) summarizes the varied definitions used to explain the phenomena of soils retaining P from an equilibrating solution or the loss of plant availability of applied P to soils. Thomas and Peaslee (1973) indicated that when P is added in dilute solution or in salts of near neutral pH, there appears to be an initial adsorption (or sorption, which would include absorption and/or adsorption) by a number of different solids. They further indicated that in calcareous soils, a surface coat of P can be formed on calcium carbonate (CaCO_3) and in neutral or acid soils P is more likely to be sorbed on hydrated iron (Fe) and Al oxides, or on the edges of clay minerals.

Low and Black (1947) were among the first to demonstrate that

absorbed P can rather suddenly be precipitated. In a reaction of P with kaolinite clay, the clay began to dissolve after 4 days, giving new products instead of adsorbed P. This process is now commonly referred to as P fixation or P precipitation.

Thomas and Peaslee (1973) also pointed out that in many instances there may be little chemical differences between the products formed by precipitation or adsorption. For example the mineral variscite is identical in composition with dihydrogen phosphate (H_2PO_4^-) adsorbed on dihydroxy aluminum. The important factor is that soluble P reacts with soil and clay minerals to form less soluble products almost immediately and with time these products became even more insoluble. This process is generally referred to as P retention, fixation or sorption, depending on the conditions used in the study.

Hemwall (1957) hypothesized that P retention by clay minerals is due to soluble Al which originated from the exchange sites or from structure decomposition of the clay mineral. His work indicated that Al saturated kaolinite and montmorillonite retained a greater amount of P in comparison to the same clays saturated with sodium (Na). Kaolinite, regardless of whether it was Na or Al saturated, fixed a greater amount of P than did montmorillonite. The rate of fixation was found to be dependent upon the rate Al is replenished in the soil solution. The work of Coleman and others also indicated that 1:1 type clays retain P to a greater extent than do 2:1 type clay minerals. These workers concluded that the retention of P is largely dependent upon the Al and Fe content of clays.

The work by Hsu and Jackson (1960) suggest that P retention in soils is generally in the form of calcium (Ca), Al and Fe-P. They

summarize that the solubility of Ca, Al, and Fe-P compounds is a function of pH, and that the solubility constants are approximately equal in the pH range of 6.0 - 7.0. They further state that below pH 6.0, Al and Fe-P reaction products predominate and above 7.0, Ca-P compounds predominate. They concluded that the transformation of P in the soil is mainly controlled by pH.

The effect of pH on P sorption in soils was studied by Hernandez and Burnham (1974). They found that the correlation between pH and P retention was not significant for a group of mixed soils, but a group of pedologically similar soils differing mainly in pH gave a highly significant decrease in retention with an increase in pH.

A review of some of the earlier research work indicated that P retention at pH values around 4.0 was due, primarily, to the presence of hydrous iron oxide (Fe_2O_3); at pH value 6.0 P retention was strongly influenced by the presence of free aluminum oxide (Al_2O_3). Wild (1950) further stated that both Fe and Al can react with P in the soil and that these ions can come from clay minerals or from free hydrous oxides.

The text authored by Tisdale and Nelson (1966) states that at pH values below 5.5 P availability decreases, while fixation of P increases. The increase in P fixation results largely from an increase in concentration of available Fe and Al and their hydrous oxides. They further stated that above 7.0, P availability decreases due to the ions of Ca and magnesium (Mg) as well as the carbonates of these ions, causing a precipitation of P.

Hemwall (1957) concluded that in calcareous and alkaline soils, the fixation of P is due to the formation of a whole series of insoluble Ca-P compounds. These compounds are heterogenous and

difficult to characterise chemically.

It has long been considered that the addition of organic matter (O.M.) will increase the solubility of soil and applied P. Research work by Dalton et al. (1952) and Stanford and Pierre (1953) would tend to support this statement. Although the evidence is scarce, the effect may be due, in part, to an increased carbon dioxide production from the decomposition of fresh O.M., which, in the presence of water, produces carbonic acid that can solubilize rather insoluble P compounds in soils.

The effect of O.M. on P fixation in soils was studied by Doughty (1935). His work indicated that natural and synthetic humus did not fix P and that oxidation of the O.M. with hydrogen peroxide decreased the power of soils to fix added P. This loss in "fixing power" was attributed to the saturation of the fixing materials with P which was liberated from the organic compounds by oxidation. Doughty concluded that soil O.M. as such has only a minor role, if any, in the fixation of P in an unavailable form when soluble P fertilizers are applied to soils. He further attributed nearly all the P fixation occurring in soils to be due to Fe, Al and Ca Compounds. These findings were substantiated by Fox and Kamprath (1971) and Wild (1950).

Recent work conducted by Vigayochandran and Harter (1975) over a broad selection of soil types indicated that Al and O.M. in the soil are primarily responsible for P adsorption. They felt that due to a lack of any significant correlation between the carbon and extractable Fe and Al, the little Fe or Al is actually chelated by O.M. These workers felt that anion adsorption sites on the O.M.

itself were responsible for the correlation between organic carbon and P sorption. They theorized that only a portion of the soil O.M. is effective in the initial P adsorption step, while another portion of the O.M. is in a "non-reactive" form, perhaps consisting of resistant lignin type compounds.

The significance of the ability of Al and Fe to fix P cannot be over emphasized. When there are large amounts of exchangeable Al and Fe present in the soil, fixation of applied P is significantly increased. But conversely, if over a period of time of applying P to a soil the ratio of Fe and Al to P becomes small, then the amount of P fixed from an application of P to the soil decreased. Work by Shelton and Coleman (1968) indicated that this type of reaction does occur. Their work indicated that the P fixation capacity can to some extent, be saturated. This results in a much slower rate of decline in available P and a long residual value from heavy P application. They found that soil test P values were found to be positively correlated with the Al-P levels.

Research conducted by Yuan and Breland (1969) and Franklin and Risenauer (1960) has shown that active Al and Fe sorb P but that Al is more active than Fe in P sorption.

The correlation coefficients for the amounts of free Fe_2O_3 and Ca-P decreased significantly when evaluated with P sorption maximum (b_1), which was based on 10 ug P/ml and with P sorption maximum (b_5) which was based on 100 ug P/ml (Peaslee and Balleux, 1975). The reverse situation occurred when O.M. was correlated with the b_1 and b_5 values. The results from this study indicated that Ca and Fe compounds react with P and play a dominant role in P retention. Once the Ca and Fe

compounds are saturated with P, then the soil O.M. fraction may become an important agent in P sorption.

Hernandez and Burnham (1974) found that % O.M. correlated well with P sorption on poorly drained British and Tropical soils when the sorption capacity was measured using a high P concentration in the equilibrating solution.

Phosphorus Sorption Isotherms

Considerable amount of research work has been conducted in an attempt to measure the relationship between various chemical and physical soil properties and P sorption. The construction of P sorption isotherms is commonly used to depict P sorption characteristics in soil.

The Freundlich equation was derived to represent the adsorption of a gas on a solid and has been utilized by many soil scientists to depict the sorption of P in soils. The equation can be presented in the following form:

$$x/m = k_1 c^{k_2} \quad (1)$$

where x/m = the amount of P sorbed per unit mass of soil, k_1 and k_2 = constants and c = the P concentration in solution after equilibration.

Olsen and Watnabe (1957) found that the sorption of P by soils from dilute solutions showed a closer agreement with the Langmuir isotherm than with the Freundlich isotherm. The Langmuir equation has the additional advantage of predicting maximum sorption capacity of a soil. The equation proposed by Langmuir (1918) was:

$$x/m = k_1 c / (1 + k_2 c) \quad (2)$$

where x/m and c had the same meaning as in the Freundlich equation with

k_1 and k_2 being constants. Olsen and Watnable presented the Langmuir equation in the linear form of:

$$c/(x/m) = 1/kb + c/b \quad (3)$$

where b = the sorption maximum, k = constant related to the bonding energy of the absorbent to the absorbate. They found that the sorption maximum calculated from the Langmuir isotherm was closely related with the surface area of soils. Acid soils retained more P per unit of surface area, and also held the P with a greater bonding energy, than alkaline soils.

Rennie and McKertcher (1959) utilized the Langmuir equation described by Olsen in calculating the P adsorption maximum for four Saskatchewan soils. They concluded that the Langmuir isotherm depicted the sorption of P when the final P solution concentrations were less than 20 ug P/ml. In this study, O.M. was as important as the inorganic colloids in determining P sorption capacity in soil. Exchangeable Ca was not closely related to the sorption maximum.

Weir and Soper (1961) reported that P sorption follows the Langmuir equation up to a concentration of about 25 to 30 ug P/ml remaining in solution. They also suggested that a second reaction, which obeys the Langmuir adsorption equation, is operative at higher final concentrations. Adsorption maxima calculated from these adsorption isotherms at higher concentrations were found to be considerably higher than those obtained from the initial adsorption reaction.

Many workers, among them Weir (1961), Syers, (1973), Peaslee, (1975), Robarge (1975), and Holford (1974) et al. have observed a curvature of the P sorption isotherm at relatively high P

equilibrating concentrations. Holford, et al. (1974) used a Langmuir two-surface equation as a model for P sorption on soils. They resolved that in a complex soil system all the absorbing components would not have the same bonding energy. Therefore if the total surface consists of two or more components with surfaces of different bonding energies, the Langmuir transformation of the isotherm to a linear form will produce a curve because adsorption should occur simultaneously on all surfaces, although somewhat proportional to the bonding energy of the unoccupied sites.

Holford et al. (1974) felt that the excellent fit of the two-surface Langmuir equation to the adsorption data over a wide range of soils confirmed that P is sorbed on two types of surfaces of contrasting bonding energy. The two surfaces were referred to as a low-energy (high capacity) surfaces and a high-energy (lower capacity) surfaces.

Syers et al. (1973) attempted to measure the sorption capacity of 3 soils which vary considerably in their ability to sorb P. When the sorption data was plotted according to the conventional Langmuir equation (Equation 3), two linear relationships were obtained, indicating the presence of two populations of sites which have a widely differing affinity for P. Plots of the sorption data were also made using a rearranged form of the Langmuir equation:

$$x/m = b - (x/m)/kc \quad (4)$$

This equation produced a curve which could not be resolved satisfactorily into two-straight line components, suggesting the existence of three populations of sites.

Recent work by Fritter and Sutton (1975) has shown that the Freundlich equation is adequate for describing P sorption if the

native labile P is first added to the sorption data and this sum plotted against intensity. They felt that their equation was much less cumbersome for most purposes when compared to the two-component Langmuir equations used by Syers et al. (1973) and Holford (1974) et al. The exponent from the Freundlich isotherm was closely related to exchangeable Al (in acid soils) and exchangeable Ca (in neutral and calcareous soils) with a mole ratio of one P to 6 Al or Ca.

Rabarge (1975) recently determined sorption isotherms for both P and K for several Brazilian soils utilizing a multiparametric curve fitting computer program which allowed the P and K sorption isotherms to be separated into individual isotherms through the use of multiple linear regression analysis. This approach was based on the assumption that several definable populations of sites with different binding energies for P and K may exist and that the observed P or K sorption isotherm is simply the summation of the isotherms for the individual populations. With this program the number of different populations of sorption sites, their sorption maximum, and the Langmuir constants for P were estimated. The computer analysis of P sorption isotherms for the soils used in their study suggested two to three distinct population sites having Langmuir constants ranging from 0.12 to 380 ml/ug. Rabarge stated that the relative contribution of each population to the total sorption maximum varies among soils.

Phosphorus Desorption in Soils

From an agronomic view point factors that affect the quality of P in the soil solution that can be utilized by the plant is of utmost importance. Many researchers have studied the desorption or release

mechanism in soils and attempts have been made to evaluate sorption and desorption of P.

Fried and Shapiro (1956), in discussing soil-plant relations and P uptake, stated that equilibrium desorption of P from four low P-fixing soils could be described by a Langmuir isotherm. Their work also indicated that there were two forms of soil P based on rate of release: (1) a rapidly released form which quickly diminishes with time, and (2) a more slowly released form which is relatively constant with time. Fried and Shapiro also conducted a P sorption study in conjunction with the release study of P in soils. The P sorption study indicated at least two forms of soil P, one form tightly held and one relatively loosely held.

Research conducted by Williams et al. (1970) measuring P sorption and desorption by lake sediments indicated that sediments which retain the most P during sorption tended to release the least P during subsequent desorption at all levels of added P. This observation was also noted by Shapiro and Fried (1959).

There have been attempts to construct desorption isotherms to assist in the understanding of the adsorption mechanisms that are involved in replenishing P in the soil solution. Hernandez (1974) constructed P desorption isotherms using five soils with different chemical properties. In moderate P sorbing soils, fairly reasonable desorption isotherms were obtained with 0.0025 M citric acid. An almost linear isotherm was obtained when 0.1 M citric acid was used as an extractant.

Phosphorus desorption isotherms were determined by Brewster et al. (1975) using 0.01 M CaCl_2 plus different amounts of anion

exchange resin. From their work they concluded that resin desorption isotherms predict P buffering power 1.5 to 2 times greater than solution desorption isotherms. They also concluded that the applicability of these isotherms to the transport of P around roots may need modification.

Daughtrey et al. (1972) characterized 16 organic soils based on their desorption patterns. The patterns were obtained by extracting each soil with 12 successive equilibrations with water. Soils that had desorption patterns that were increasing, yet small in total amount desorbed, were classified as relatively infertile with respect to P. The second group of soils which consisted primarily of muck soils, exhibited a decreasing amount of P desorbed with successive equilibrations but the total amount of P released was large. This group was classified as soils that supply adequate P initially, but could not continue to supply sufficient P. Crops grown on these soils would respond to P fertilization. The third group of soils, composed primarily of red bed and intergrade soils, had either an increasing amount of P desorbed with successive equilibrations and/or a relative high amount of total P desorbed. This third group should supply adequate P for plant growth throughout the growing season. No real explanation of mechanisms was offered by the authors.

Fox and Kemprath (1971) determined desorption isotherms for Georgeville soils after they were allowed to equilibrate for 11 days after 250 and 500 ug/ml P were added, respectively. After extracting the P from the equilibrated sample a total of 33 times in a 0.01 M CaCl_2 solution, they concluded that P solubility is greater when P is being added to the system than when it is being withdrawn. Their data

suggested that the concentration of P in solution is the overriding factor in P nutrition of plants and their review of literature indicated that most plants attain near maximum growth at around 0.2 ppm P.

Phosphorus Fractionation

The fractionation of the P in soils into the chemical forms of P aids in (1) determining what chemical forms are involved in replenishing P to the soil solution, (2) determining end products from the addition of P to soils, and (3) predicting amounts of P needed to saturate the sorbing complex.

Chang and Jackson (1957) developed a fractionation procedure for inorganic P in soils. The fractionated P was placed into four main groups: Ca-P, Al-P, Fe-P and the reductant soluble P. These groups are determined based on the solubility of these P groups in different extractants. The original procedure consisted of the following steps: (1) removal of loosely bound P by extraction with 1 N NH_4Cl for 30 minutes, (2) removal of Al-P by extraction with 1 N NH_4F for one hour, (3) removal of Fe-P by extraction in 0.1 N NaOH for 17 hours, and (4) removal of Ca-P by extraction with 0.5 N H_2SO_4 for one hour. Their procedure also determined occluded-P and reductant-soluble P. Many workers disregard these forms since they are thought to be formed over many years and these forms of P are not considered to be available to plants.

There have been many criticisms and modifications of the original procedure developed by Chang and Jackson. The main criticism concerns the use of NH_4F to accurately assess the Al-P fraction in soils. Chang and Jackson admitted that NH_4F could dissolve some Fe-P and

suggested subtracting 10% of the Al-P and adding it to the Fe-P fraction. An excellent discussion concerning the merits and criticism of Chang and Jackson's P fractionation procedure is presented by Norwood (1972).

Petersen and Corey (1966) developed a slightly modified Chang and Jackson procedure for routine fractionation of inorganic P. The primary difference was in the order of the extraction and the pH of the NH_4F solution which was increased to 8.2 in order to decrease Fe-P solubilization. Broomfield (1967) indicated that NH_4F discriminated rather poorly between Al- and Fe-P and that di-calcium phosphate was soluble in NH_4Cl and NH_4F extracts. Chu and Chang (1966) found surface bonded Ca-P compounds to dissolve almost completely in the NH_4F and NaOH extractants. Fife (1959) evaluated NH_4F as a selective extractant for Al bound soil P and found that by increasing the pH of 0.5 M NH_4F extractant to 8.5, a decrease in the solubilization of Fe-P compounds resulted. This increase in pH of the NH_4F resulted in an increase in the separation of Al-P from other forms of soil-P.

Rajendran and Sutton (1970) measured the re-sorption of soil P during fractionation utilizing ^{32}P . Their data from six soil types indicated that considerable re-sorption of P occurs during the Chang and Jackson fractionation procedure. Their findings indicate that the Chang and Jackson procedure underestimates the NH_4Cl -P (loosely bound P) and over estimates the occluded-P.

Williams, Syers and Walker (1967) developed a fractionation procedure for soil inorganic P by a modification of the Chang and Jackson procedure in an attempt to more accurately characterize native P. In addition to the forms obtained by the Jackson procedure they

included a second NaOH, and a second HCl extraction, a residual organic P and a residual inorganic P fraction. By incorporating these modifications into the Chang and Jackson procedure they were able to make mutually compensating corrections to the $\text{NH}_4\text{F-P}$ and the 1st NaOH-P fractions.

CHAPTER III

MATERIAL AND METHODS

Fifteen soil types representing some of the major soil types in Oklahoma were selected for study and were collected in the summer and fall of 1973. The soil at each site had previously classified by the Soil Conservation Service and Oklahoma State University (Gray et al., 1976). Each soil was sampled to a depth of approximately 15 cm depth from one site. Approximately 332 kilograms was obtained for each soil and was air-dried and sieved through a one quarter inch screen. The samples were stored in plastic-lined barrels. Representative sub-samples were then removed and ground to pass through a #20 mesh sieve and were stored in covered paper containers in the lab. Various physical, chemical and mineralogical analysis were made on these sub-samples prior to the P sorption, P desorption and P fractionation studies.

Textural and Mineralogical Data

The textural and mineralogical data are presented in Table I. The texture was determined by the hydrometer method developed by Day (1956) in a constant temperature room. Fifty grams of soil were weighed and transferred into a 1000 ml sedimentation cylinder with sodium carbonate added as a dispersing agent.

The clay fraction of each soil was separated using the method

TABLE I
TEXTURAL AND MINERALOGICAL DATA FOR
FIFTEEN OKLAHOMA SOILS

Soil Type	Order	Percent Composition			Course Clay	Fine Clay
		Sand	Silt	Clay		
Summit CL	Mollisol	26	40	34	M-V,I,K,Q,C	M-V,k
Ulysses L	Mollisol	34	46	20	I,K,Q	M-V,I,k
Richfield L	Mollisol	36	48	16	I,K,Q	M-V,i,k
Renfrow SiL	Mollisol	32	50	18	M-V,I,K,Q	M-V,I
Kingfisher SiL	Mollisol	34	52	14	M-V,I,k,Q	M-V,I
Dill LS	Inceptisol	82	12	6	M-V,I,K,Q	M-V,i,Q
Grandfield SL	Alfisol	78	12	10	M-V,I,K,Q	M-V
Parson SiCL	Alfisol	18	54	28	m-v,i,K,Q	M-V,k,Q
Tipton L	Mollisol	44	44	12	m-v,I,K,Q	M-V,i
Hollister L	Mollisol	32	44	24	m-v,I,K,Q	M-V,I,q
Bates SiL	Mollisol	30	60	10	m-v,i,K,Q	M-V,q
Miller SiC	Mollisol	18	40	42	M-V,I,K,Q,C	M-V,i,k,c
Bowie SL	Ultisol	58	36	6	M-V,K,Q	M-V,k
Foard CL	Mollisol	28	44	28	m-v,I,K,Q	M-V,i,k
Zaneis L	Mollisol	50	38	12	m-v,I,K,Q	M-V,i,k

Capital letters = medium - strong peaks

Lower case letters = weak - medium peaks

M = montmorillonite

Q = quartz

I = illite

M-V = montmorillonite - vermiculite interstratification

K = kaolinite

C = chlorite

proposed by Jackson (1973) for mineralogical determination. A Sharples steam turbine centrifuge was used to separate the fine clay (<.2 μ) from the coarse clay (2 - .2 μ). X-ray examination of each of the clay fractions for each soil was completed by coating ceramic slides with a respective clay film. Slides were prepared with the clay fraction: Ca^{2+} saturated and ethyleneglycol solvated; K^{+} saturated; and K^{+} saturated and heated to 500 $^{\circ}$ C for 4 hours. These procedures were followed to assist in identifying the various clay minerals present in the clay fraction of each soil. The above treatments were particularly useful in differentiating between expanding and non-expanding 2:1 clay minerals, and between kaolinite and other minerals with similar diffraction properties. The x-ray analysis were performed using a General Electric XRD 6 X-Ray Diffractometer with Ni-filtered $\text{CuK}\delta$ radiation.

Chemical and Physical Properties

The chemical properties of the soils used in this study are presented in Table II. The pH and Bray-P measurements were conducted by routine procedures used in the Soil Testing Laboratory at Oklahoma State University. The cation exchange capacity (C.E.C.) values were determined by a method developed by Reed (1974). Ten grams of soil were shaken with 50 ml 1N calcium chloride (CaCl_2) for 4 hours or longer. The soil-salt mixture was filtered on a 10 cm Buchner funnel and rinsed three times with 50 ml portions of 1 N CaCl_2 . The samples were then rinsed with de-ionized water, and leached 3 additional times with 50 ml aliquots of 1 N sodium nitrate (NaNO_3). The NaNO_3 leachate was analyzed for Ca by ethylenediamine tetraacetic acid (EDTA) titration.

TABLE II
CHEMICAL AND SELECTED PHYSICAL PROPERTIES
FOR FIFTEEN OKLAHOMA SOILS

Soil Type	pH (1:1)	C.E.C. ¹	P.P.M. P		Surface area m ² /g soil		Ex ² Al	% CaCO ₃	% Fe ₂ O ₃	% OM	% ³ Al
			Bray	Total	23°C	500°C*					
Summit CL	6.4	27.36	2.5	432	150	54	0.00	1.75	2.54	6.55	0.12
Ulysses L	7.9	19.30	6	316	138	49	0.00	1.81	0.70	1.55	0.05
Richfield L	7.3	17.50	15	350	128	61	0.00	1.43	1.49	1.69	0.05
Renfrow SiL	6.0	10.75	23	205	65	22	0.14	0.63	0.86	1.06	0.05
Kingfisher SiL	5.2	7.71	27	204	51	10	0.28	0.53	1.14	0.85	0.06
Dill LS	7.8	5.93	33	160	12	5	0.00	2.23	0.72	0.47	0.03
Grandfield	6.6	6.24	10	108	31	5	0.51	0.56	0.73	0.39	0.05
Parson SiCl	5.1	10.12	23	256	75	20	0.35	0.83	1.39	1.73	0.07
Tipton L	8.1	13.11	37	253	61	19	0.25	1.84	0.42	0.89	0.03
Hollister L	6.4	17.47	60	250	79	47	0.00	1.05	0.76	1.27	0.07
Bates SiL	5.2	7.28	45	301	42	13	0.00	0.26	1.44	1.76	0.09
Miller SiC	7.1	28.89	102	626	136	58	0.00	1.97	1.65	2.44	0.05
Bowie SL	5.2	3.44	9	80	10	2	3.95	0.07	0.35	2.58	0.11
Foard CL	6.7	19.45	18	168	109	33	0.00	0.82	0.34	0.85	0.05
Zaneis L	7.2	11.65	3	177	36	8	0.00	0.64	1.28	2.79	0.07

¹ C.E.C. = expresses in me/100g.

² ExAl = exchangeable Al expressed in me/100g.

³ % Al was determined by extracting Al by the Na-citrate procedure of Frink (1965).

* Determined after saturation with K⁺ and heated at 500°C for 4 hours.

The chloride in the NaNO_3 leachate was determined by the Mohr titration as presented by Day and Underwood (1974). Values presented in Table II are averages of 2 determinations.

The surface area (SA) of the soil was determined by the ethylene glycol monoethyl ether (EGME) method developed by Carter, et al. (1965). Approximately 1 g of each soil sample, saturated with Ca^{2+} was placed in a weighing pan and dried in a vacuum desiccator for 48 hours in a constant temperature room. The weighing pan and the contents were then re-weighed and the weights of the dried samples recorded.

Solvation with EGME followed allowing 2 hours for an equilibrium. The sample was then returned to the desiccator and dried in a vacuum over CaCl_2 repeatedly, until a constant weight was obtained.

An additional amount of Ca^{2+} saturated sample representing each soil type was then heated in a muffle furnace at 500°C for 4 hours. After the samples had cooled to room temperature in a desiccator, a total of 4 replicates were weighed and then equilibrated with EGME and weighing process repeated. The surface area obtained after heating is also listed in Table II. Each surface area value listed is the mean of 4 observations.

Extractable Al was determined by the method described by Frink (1965) utilizing sodium citrate (Na-citrate) as the extracting solution. Twenty ml of 1M Na-citrate was added to 1 g of each soil in a 50 ml centrifuge tube. The tubes were then placed in a water bath at 85°C for a period of one hour, the tubes were then cooled and centrifuged at 2000 rpm for 20 minutes. The supernatant was then removed and increased to a volume of 25 ml with de-ionized water. The

determination of Na-citrate extractable Al was accomplished using a Perkin-Elmer 403 Atomic Absorption Spectrometer and a nitrous oxide flame.

Total P was determined after digestion with nitric and perchloric acid according to Reed (1974). P was determined colorimetrically using the hydrazine sulfate procedure described by Shelton and Harper(1941).

The CaCO_3 percentage present in the soils was determined according to a acid-neutralization procedure outlined in the test edited by Black et al. (1965). The value for CaCO_3 included in Table II is the mean of 2 replications.

Free Fe_2O_3 percentage was determined by a method described by Jackson (1973). Sodium dithionite was used as the reducing agent and o-phenanthroline as the complexing agent. The means of 2 replicates are listed on Table II.

Organic matter determinations were made according to the Walkley and Black procedure as described by Jackson (1958). The means of 2 replicates are listed in Table II.

Exchangeable Al was determined by leaching 2 replicated samples of each soil with 1 N KCl according to the procedure developed by Pratt and Bair (1961). The Al in the leachate was determined by a method developed by Britchard (1967) which utilized xylenol orange as a complexing agent with Al and ethylenedinitrilotetracetate disodium salt to eliminate Fe interference.

Phosphorus Sorption Study

In order to determine the sorption capacity of each soil used in this study 1 g samples (replicated 4 times) were weighed into 50 ml

centrifuge tubes and equilibrated with 25 ml. of one of seven P concentrations (treatments) for 24 hours on a horizontal shaker. The treatments used were 0,50,250,500,1000,2000, and 4000 ug P/g of soil. All treatment solutions were adjusted to pH 7.0 with 4 N KOH. Following the equilibration period, samples were centrifuged at 15000 rpm for 30 minutes and the supernatant removed. The soil sample in the centrifuge tube was then re-suspended with 25 ml of saturated NaCl and then centrifuged at 2500 rpm for 15 minutes. This supernatant was then combined with the original treatment supernatant and analyzed for P concentration on the Busch and Lomb colorimeter by Murphy and Riley's (1962) procedure. This procedure was used for all P analysis unless otherwise stated.

Phosphorus Desorption Study

Immediately following the P sorption study the soil samples remaining in the bottom of the centrifuge tubes were subjected to a series of desorption washes with 20 ml of Bray's (1945) #1 solution (0.03 N NH_4F in 0.025 N HCl). After adding Bray's #1 solution the suspension was then mixed for 4 minutes on a horizontal shaker, followed by 10 minutes of centrifugation at 2000 rpm. The supernatant was removed and the soil sample resuspended in 25 ml of saturated NaCl and again centrifuged at the same speed and time and the supernatant combined with the Bray solution. The combined supernatants were designated as a Bray extraction and P analyses were conducted for each Bray extraction. The decision for using the Bray #1 extractant under the condition just described was based on the concept that the information obtained could be evaluated in lieu of work done by Norwood(1969), which indicates

that P extracted under these conditions correlates well with sorghum yields and was best suited for measuring the available P from all the soils in his study as a group. The Bray extraction procedure is presently being used for available P determination by the Soil Test Laboratory at Oklahoma State University, also. The P concentration for each extraction was determined and used in the analysis of the P release characteristics for the various soils used in this study.

The pattern used for the entire study (includes P sorption, P desorption and P fractionation) is shown in Table III. The original 4 replicates initiated in the P sorption study were separated during the P desorption study. Duplicate samples of the various treatments were systematically removed from the desorption study and placed in the deep freeze and stored at approximately -18°C . By separating duplicate samples for each soil and treatment level and then fractionating these samples, significant differences between the chemical forms of P (obtained by fractionation) could be attributed to the amount of P removed by the additional Bray extractions.

Phosphorus Fractionation Study

All the soil samples initiated in the P sorption study were subjected to the P fractionation procedure developed by Williams et al. (1967, see Table III). This procedure was a modification of the procedure developed by Chang and Jackson (1957).

The fractionation scheme as proposed by Williams et al., with the exception of the use of $2\text{N H}_2\text{SO}_4$ to remove any additional residual inorganic P, is shown in Table IV. The remaining concentration of P was classified as residual-P and determined by nitric-perchloric acid

TABLE III

PHOSPHORUS SORPTION, DESORPTION AND FRACTIONATION
PLAN UTILIZED IN THE STUDY FOR EACH SOIL.

P Sorption Study		P Remaining Solution	P Desorption Study									P Fractionation Study								
P Treatment Code	Replication or Sample		Bray Extractions (ugP/ml)					Ex-6	Ex-7	Ex-8	Ex-9	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	CDB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ -P	Residual-P
			Ex-1*	Ex-2	Ex-3	Ex-4	Ex-5													
1	A	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	B	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	C	X	X																	
	D	X	X																	
2	A	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	B	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	C	X	X																	
	D	X	X																	
3	A	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	B	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	C	X	X	X	X	X														
	D	X	X	X	X	X														
4	A	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	B	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	C	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	

* Extractions 1-9 were made on the following days after P sorption, respectively,
1,2,4,7,14,21,28,35, and 70.

TABLE III (CONTINUED)

P Sorption Study			P Desorption Study										P Fractionation Study							
P Treatment Code	Replication or Sample	P Remaining Solution	Bray Extractions (ugP/ml)					Ex-6	Ex-7	Ex-8	Ex-9	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	CDB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ -P	Residual-P
			Ex-1	Ex-2	Ex-3	Ex-4	Ex-5													
5	A	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	B	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	C	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
6	A	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	B	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	C	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
7	A	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	B	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	C	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	D	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

TABLE IV
PROCEDURE AND NOMENCLATURE USED IN THE
FRACTIONATION OF SOIL PHOSPHATE.

Stage No.	Extractant	Soil:Solution Ratio	Shaking Time	Nomenclature
1.	0.5M NH_4Cl ¹	1:25	30 min.	$\text{NH}_4\text{Cl-P}$ ¹
2.	0.5M NH_4F ¹ (pH 8.2) ⁴	1:25	24 hr.	$\text{NH}_4\text{F-P}$ ¹ (Al-P) ²
3.	0.1N NaOH + 1M NaCl ¹	1:25	17 hr.	1-NaOH-P ¹ (Fe-P) ²
4.	0.3M Na-Citrate ^{1,2,3} + 1.0 M $\text{NaHCO}_3 + \text{Na}_2\text{S}_2\text{O}_4$	1:32.5	-----	reductant-soluble P ^{1,2}
5.	1M NaOH ¹	1:25	17 hr.	2-NaOH-P ¹ (occluded-P) ²
6.	0.5 N HCl ¹	1:25	1 hr.	1-HCl-P (Ca-P) ²
7.	1.0 N HCl ¹	1:25	4 hr.	2-HCl-P ¹
8.	1.0 N H_2SO_4	1:25	16 hr.	$\text{H}_2\text{SO}_4\text{-P}$ (Residual Inorganic P)
9.	HClO_4 ⁴	-----	-----	Residual-P

¹Williams et al (1967)

³P determined by Pons and Guthrie; described by Watnabe and Olsen(1961)

²Jackson (1958)

⁴P determined by the procedure developed by Shelton and Harper(1941)

digestion procedure by Shelton and Harper (1941).

Methods of Data Evaluation

The data obtained from this study was subjected to normal statistical analysis utilizing an IBM 370/158 Computing System with the Statistical Analysis System (SAS) program. Analysis of variance procedures were used to determine if treatment effects were significant at the .05 level of probability for the three studies (P sorption, P desorption and P fractionation). The comparison of means was accomplished using the protected least significant difference (LSD) procedure. This procedure implies that the "F" value for treatment effects must be significant before the means of the various treatments will be compared by the conventional LSD procedure.

Regression analysis was conducted on the data when it seemed justified. Regression coefficients (R^2) were shown with accompanying Observation Significance Levels (OSL). Correlation coefficients (r) were also obtained to represent relationships between various independent variables or soil characteristics.

CHAPTER IV

RESULTS AND DISCUSSION

Phosphorus Sorption Study

The amount of P sorbed for each soil and treatment is shown in Table V. Generally, P sorbed for treatment levels within each soil were significantly different. There were certain soils (Richfield, Dill, Grandfield, Tipton and Foard) which did not have a significant difference between successive P treatments but did show a significant difference between low and high levels of P.

The Summit soil sorbed the greatest amount of P at all treatment levels. The Dill and Tipton soils, sorbed the least amount of P for all treatments except at the highest level (4000 ugP/g), but at this high level the Dill soil sorbed more than the Hollister, Bowie, Foard, and Zaneis. The Tipton, Hollister, Bates, Foard, and Zaneis samples did not show a significant difference between treatments 6 and 7 (.05 level), which may suggest that sorption maximum had been reached. The calculation of the P sorption maximum by the Langmuir equation appears to verify this observation.

A regression analysis was performed to relate P sorption to increases in P concentrations (i.e. P treatments). The regression coefficient (R^2) and the coefficient of variation are also included in Table V. In general, the R^2 values are greater than 0.90, indicating that P sorption is dependent on the P concentration in the equilibrating

TABLE V

AMOUNT OF P SORBED (UG/G OF SOIL) IN THE P SORPTION STUDY											
Soil Type	Treatments for P Sorption(ug/g) ³							Analysis of Variance		Regression Analysis	
	#1 0 ³	#2 50	#3 250	#4 500	#5 1000	#6 2000	#7 4000	F Value ²	LSD .05	R ²	CV ⁴
Summitt	0.0	45.8	167.9	270.0	408.1	646.6	1003.0	1313.4	28.8	0.997	4.58
Ulysses	0.0	27.1	84.2	128.2	205.6	410.4	800.5	1672.0	20.9	0.998	4.97
Richfield	-2.4 ¹	26.1	64.2	113.6	151.6	275.4	375.3	52.2	56.0	0.937	26.54
Renfrow	-4.5 ¹	23.7	76.1	122.5	201.1	265.3	449.5	242.7	29.9	0.986	12.56
Kingfisher	-2.8 ¹	27.1	75.3	95.0	216.8	346.3	510.3	156.3	44.3	0.978	16.64
Dill	-4.3 ¹	7.7	28.3	44.8	90.8	123.5	266.8	28.4	44.8	0.890	41.17
Grandfield	-1.6 ¹	21.9	65.3	93.4	142.6	302.4	463.0	63.2	62.4	0.948	27.34
Parson	-1.4 ¹	41.1	131.2	187.3	270.8	417.1	618.3	341.5	34.9	0.990	9.97
Tipton	-5.0 ¹	11.3	31.3	43.2	79.6	93.1	112.0	4.0	64.1	0.535	83.48
Hollister	-9.9 ¹	14.2	59.9	84.5	138.1	187.6	199.8	25.4	47.8	0.879	33.78
Bates	-2.2 ¹	42.4	132.6	172.0	219.1	332.8	348.3	73.4	46.0	0.954	17.58
Miller	-14.6 ¹	12.5	70.2	101.5	169.6	214.6	274.0	84.0	34.1	0.960	19.58
Bowie	-1.4 ¹	34.1	89.1	113.6	169.6	214.6	247.0	117.1	24.9	0.971	13.70
Foard	-3.0 ¹	27.6	81.0	111.2	210.1	194.4	199.8	32.7	44.6	0.903	25.58
Zaneis	0.0	30.8	76.7	107.2	169.6	170.8	193.0	71.5	22.3	0.952	12.06

1 Negative values arise because P was present in the supernant, when no P was applied.

2 All F values were significant at 0.01 level with the exception of the Tipton soil.

3 The following sequence was used in the P Sorption Study:

Treatment No.	ug P/ml	No. of ml	Total Mg P/g of soil
1	0	25	0
2	2	25	50
3	10	25	250
4	20	25	500
5	40	25	1000
6	80	25	2000
7	160	25	4000

4 CV refers to the coefficient of variation.

solution. The exception is the Tipton soil for which the sorption maximum was reached at a relative low P level and, therefore, P sorption did not increase appreciably with increasing P concentration. The coefficient of variation (CV) indicated the amount of variation between the four observations at each treatment level. One major contributor to an increase in the CV values was the adoption of a tipet pitet into the procedure beginning with soil number 3(Richfield) and was used through the remainder of the soils. The second major contribution to the relatively high CV was from the large dilution factors for treatments 6 and 7, which were 1350 to 2700, respectively.

In an attempt to relate P sorption to some of the chemical and physical characteristics of each soil studies, P sorption isotherms were constructed for each soil and are depicted in figures 1-5. In general, these isotherms were not linear at high P concentrations. This phenomena has been observed by many workers including Peaslee, et al. (1975) and Syers, et al. (1975). Due to the curvilinear isotherm obtained, treatments 2, 3, and 4 (50,250, and 500 ug P/g of soil, respectively) were plotted according to a re-arranged Langmuir equation (equation 4*) proposed by Syers, et al. This enables a sorption maxima and binding energy constant (b_1 and k_1 , respectively) to be calculated for region 1 (P treatments 2,3,4). A second plot was made for treatments 5,6,and 7 (region 2), and b_2 and k_2 values calculated for this segment of the isotherm. Syers, et al. have indicated that these constants relate to different sorption sites for P. The b_1 and k_1 constants relating to those sorption sites operative in relative low P concentrations with b_2 and k_2 constants relating to sorption sites operative at higher P levels. Figure 6 depicts the P

* See pages 8,9,and 10 in Literature Review.

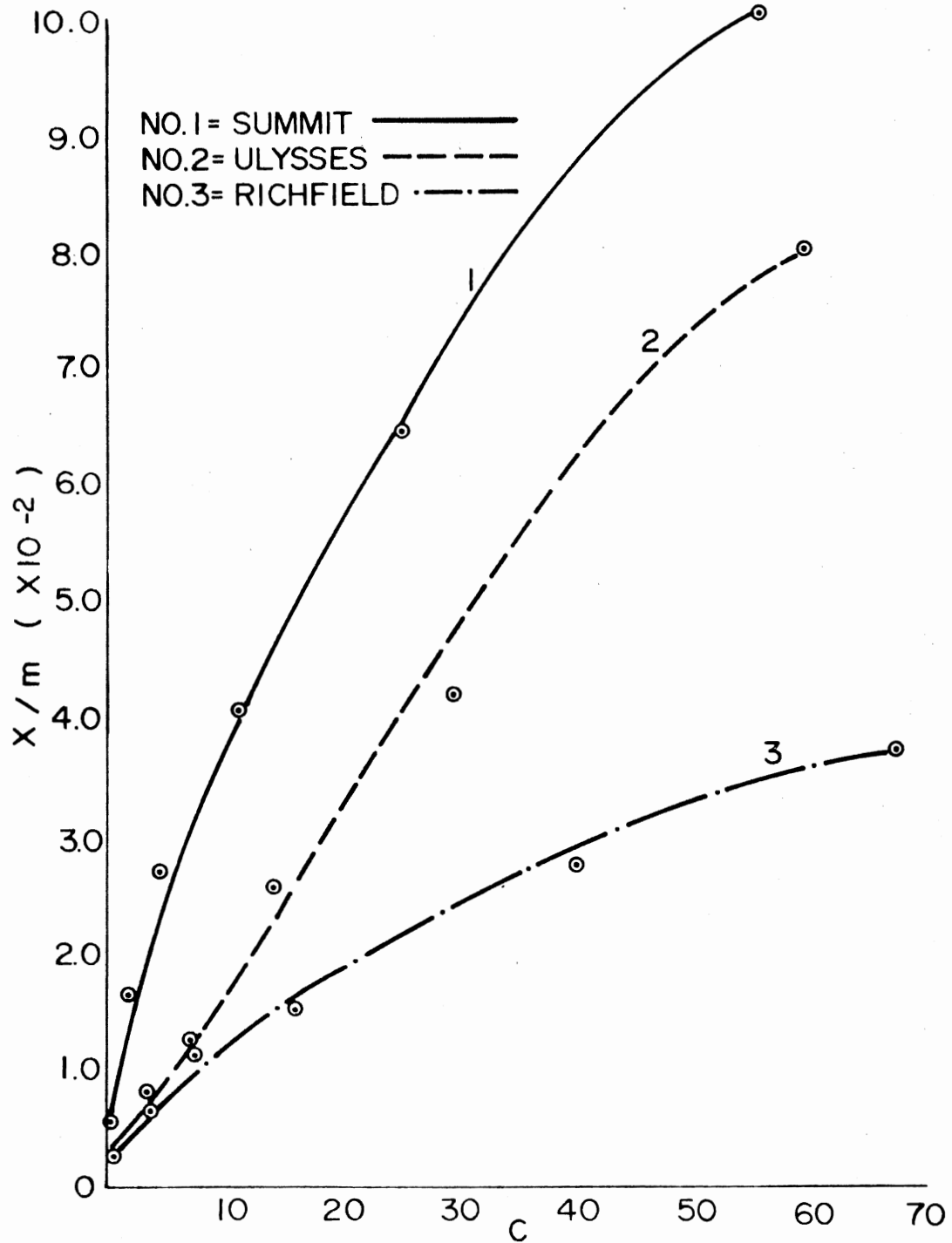


Figure 1. Phosphate Sorption Isotherms for Summit, Ulysses, and Richfield Soils.

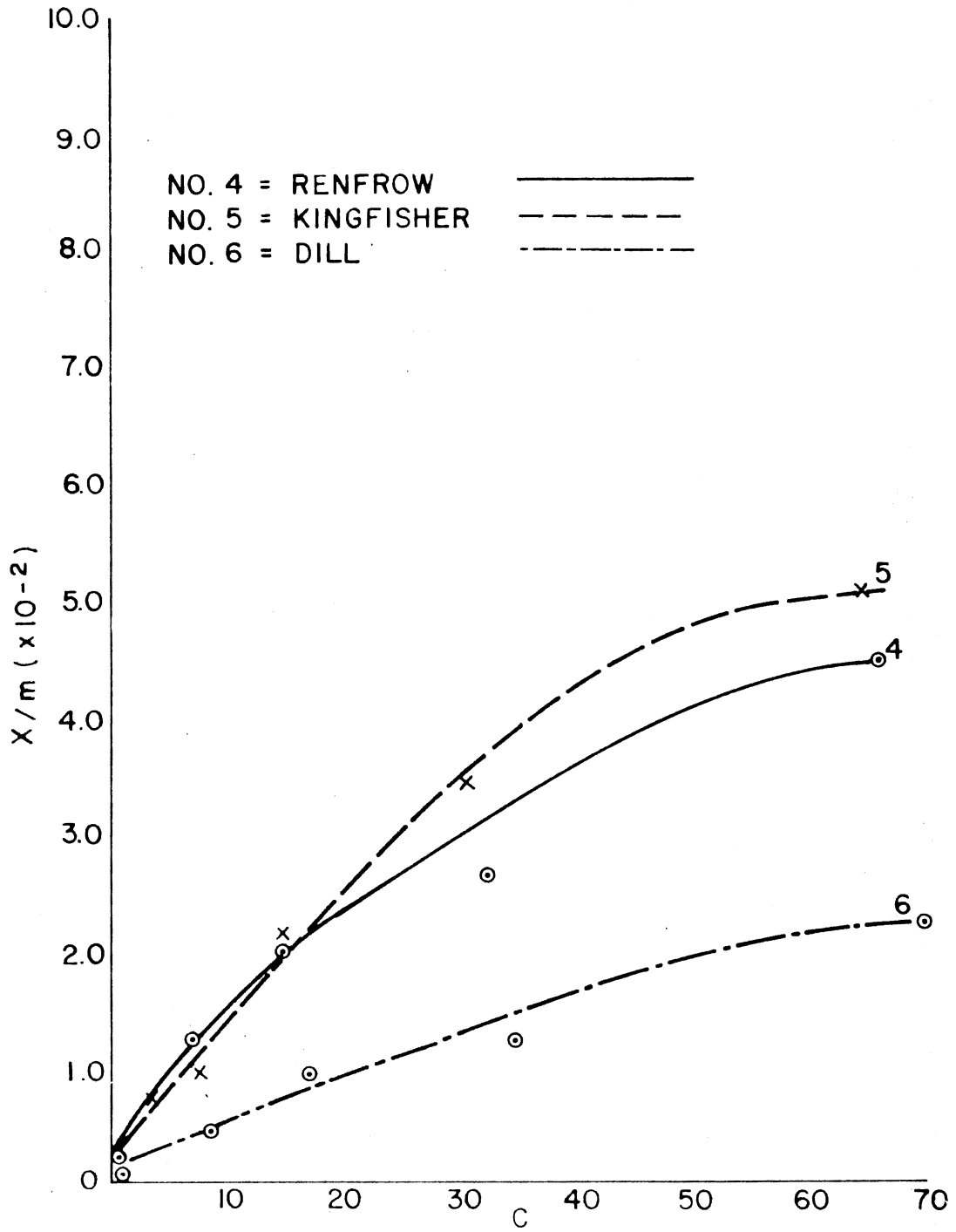


Figure 2. Phosphate Sorption Isotherms for Renfrow, Kingfisher, and Dill Soils.

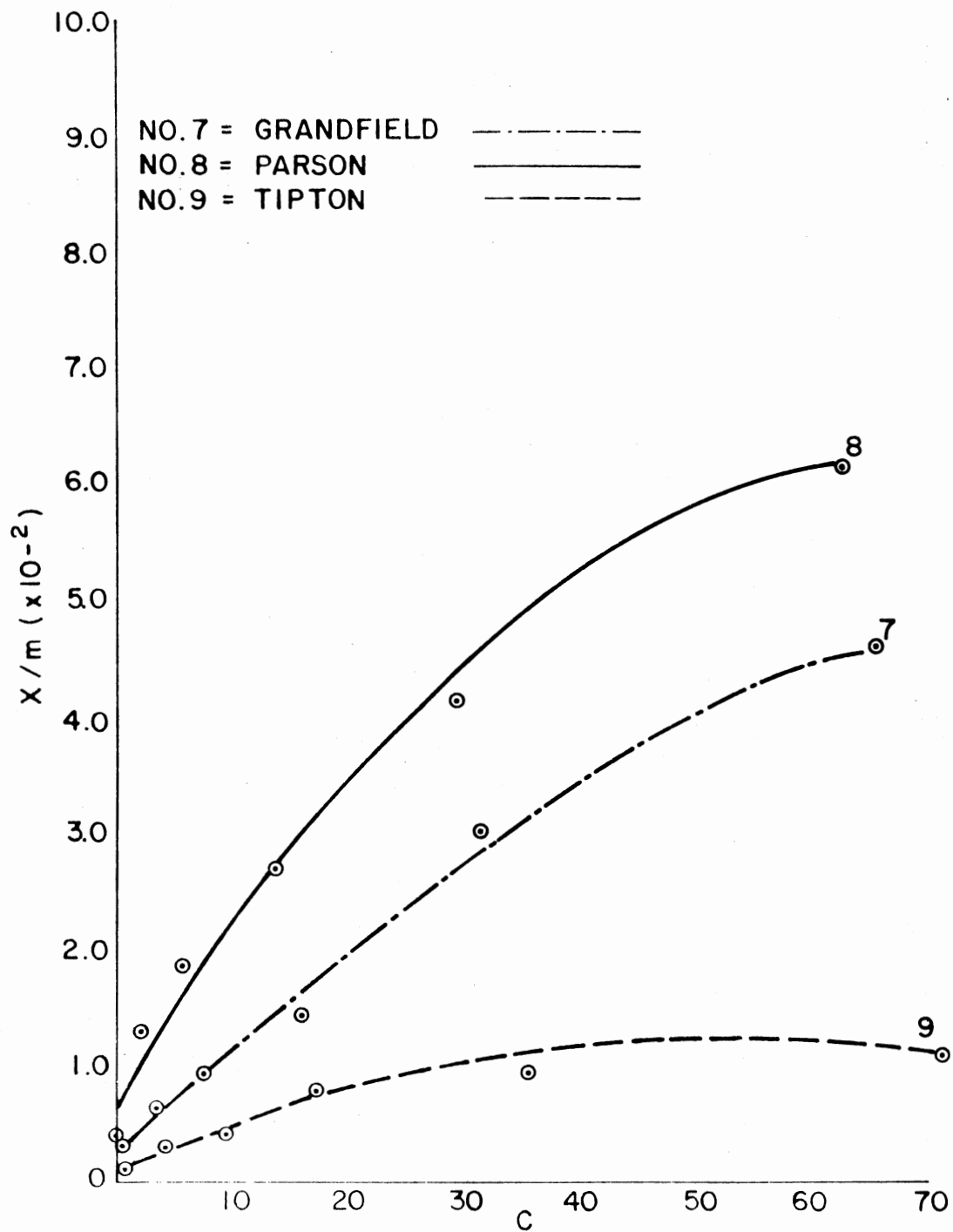


Figure 3. Phosphate Sorption Isotherms for Grandfield, Parson, and Tipton Soils.

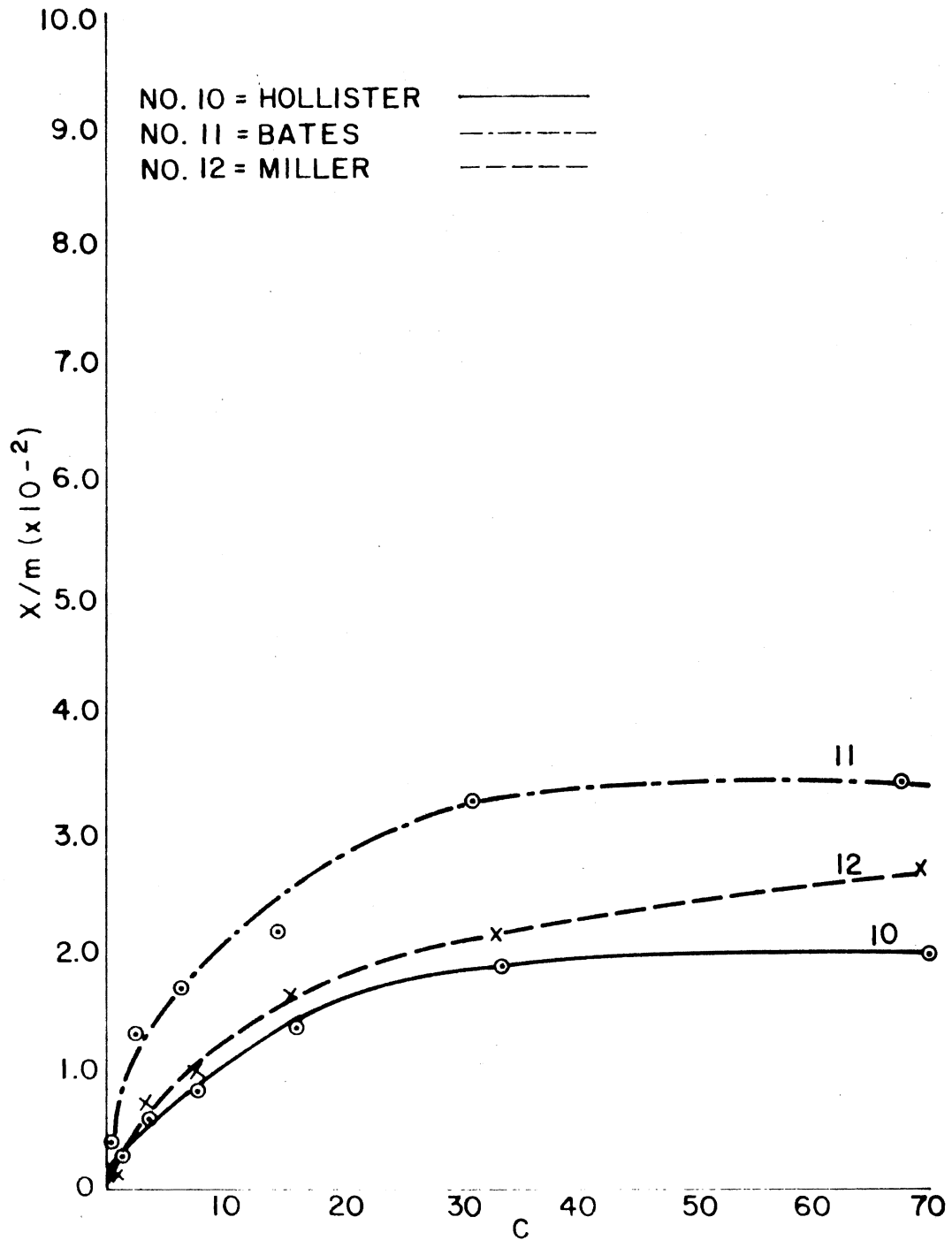


Figure 4. Phosphate Sorption Isotherms for Hollister, Bates, and Miller Soils.

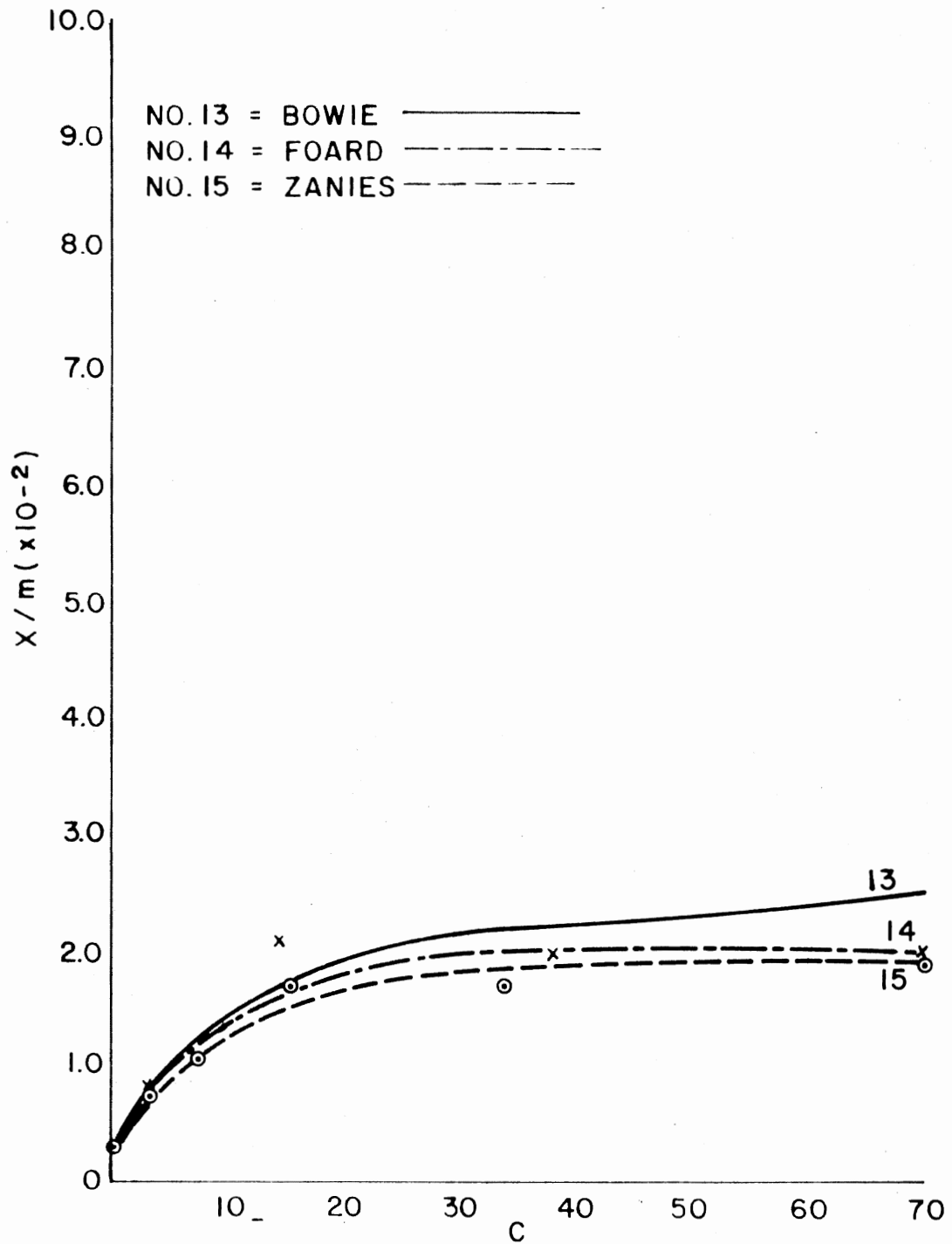


Figure 5. Phosphate Sorption Isotherms for Bowie, Foard, and Zaneis Soils.

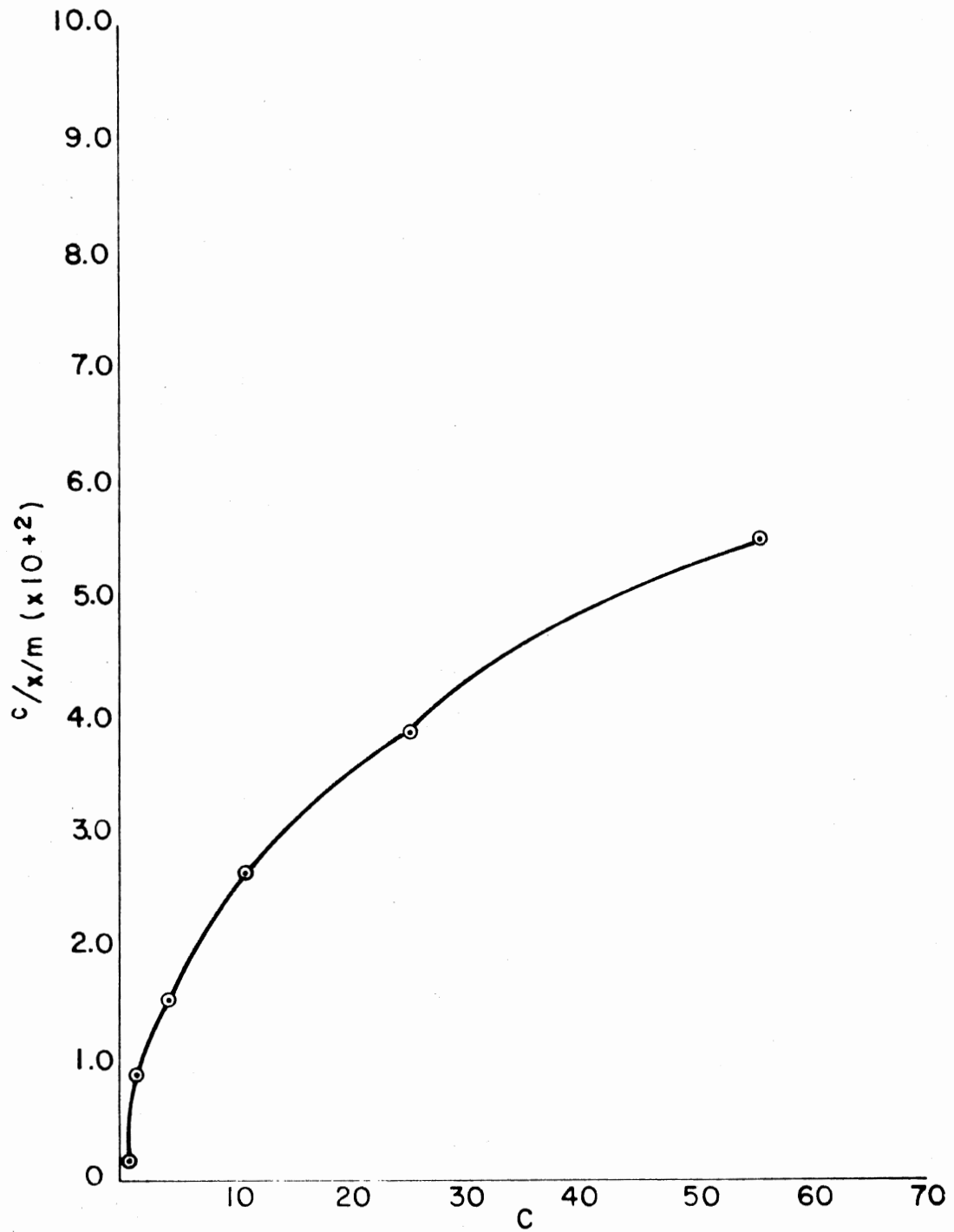


Figure 6. Phosphate Sorption Isotherm for the Summit Soil
Using the Conventional Langmuir Equation.

sorption isotherms using the conventional Langmuir equation (equation 3). Figure 7 represents the P sorption isotherm obtained by using the re-arranged Langmuir equation (equation 4). Also shown in figure 7 is the method by which P sorption parameters ($b_1, k_1, b_2,$ and k_2) were obtained.

These P sorption parameters ($b_1, k_1, b_2,$ and k_2) are useful in approximating the sorption capacity of soils. This procedure is better than trying to force the curvilinear isotherm into one straight line which tends to under estimate b and k constants at high P concentrations and over estimate the same parameters at low P concentrations. The data in Table VI supports this reasoning. The indices of bonding energy (k) values were consistently greater in region 1 than in region 2 or when the conventional isotherm (equation 3) is compared to the re-arranged equation (equation 4). The bonding energy determination is questionable, since the isotherm is not level or constant. It appears that more confidence can be placed in the sorption maximums obtained for the various soils than the bonding energy constants. The k_2 values for the Dill, Grandfield and the Hollister soils appear to reflect the large variations for the treatments 6 and 7 which contain high P concentrations.

Correlation coefficients for the means of the various chemical determinations and the means of calculated P sorption characteristics are depicted in Table VII. Percent O.M., % Fe_2O_3 , surface area, and extractable Al have a significant affect on P sorption. O.M. has a significant positive correlation with the Langmuir constants except for the binding energy constant in region two. This is probably due to the amount of variation in measuring the binding energy at these

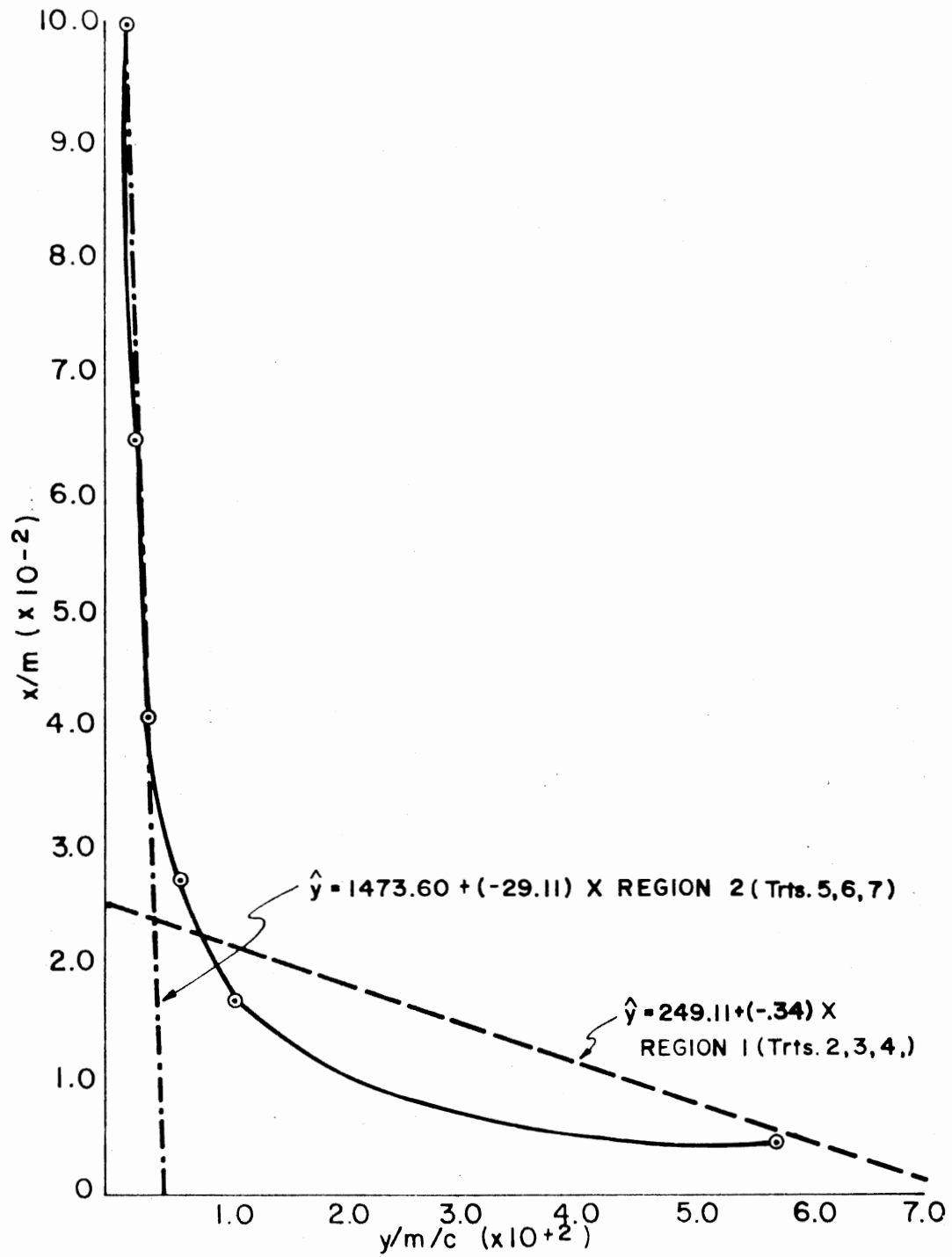


Figure 7. Phosphate Sorption Isotherm Using the Rearranged Langmuir Equation with the Curved Isotherm Fitted into Two Straight Lines.

TABLE VI

P SORPTION MAXIMA AND BONDING ENERGY CONSTANTS DETERMINED BY
THE CONVENTIONAL AND REARRANGED LANGMUIR EQUATION

Soil Type	Sorption Maxima's*			Index of Bonding Energy**		
	b	b ₁	b ₂	k	k ₁	k ₂
Summit	560	249	1474	1.05	2.94	0.03
Ulysses	514	154	1517	0.11	0.49	0.01
Richfield	241	104	393	0.27	0.91	0.06
Renfrow	344	159	560	0.13	0.35	0.04
Kingfisher	336	109	652	0.18	0.77	0.04
Dill	177	55	152	0.06	0.26	0.77
Grandfield	306	112	303	0.13	0.47	8.29
Parson	375	187	870	0.66	1.69	0.03
Tipton	94	53	54	0.19	0.39	0.07
Hollister	218	157	185	0.11	0.16	0.59
Bates	263	171	378	1.28	2.36	0.13
Miller	307	141	299	0.08	0.22	0.09
Bowie	191	119	269	0.66	1.35	0.12
Foard	197	128	180	0.37	0.65	0.36
Zaneis	166	110	187	0.59	1.08	0.65

* All b values expressed in ug P/g soil.

** All k values expressed in ml/ug of P.

TABLE VII

RELATIONSHIP OF SELECTED SOIL CHEMICAL PROPERTIES TO P SORPTION,
P SORPTION MAXIMUM AND BINDING ENERGY CONSTANTS UTILIZING
SIMPLE CORRELATION COEFFICIENTS.

Soil Properties	P Sorption	b	b ₁	b ₂	k	k ₁	k ₂
% O.M.	0.72**	0.51*	0.68**	0.54*	0.61*	0.73**	-0.28
Ex. Al ¹	-0.12	-0.20	-0.11	-0.15	0.16	0.12	0.02
% Fe ₂ O ₃	0.72**	0.63**	0.72**	0.55*	0.53*	0.66**	-0.15
S.A. ²	0.51*	0.56*	0.50	0.55*	-0.03	0.11	-0.31
H.S.A. ³	0.37	0.45	0.42	0.42	-0.13	0.00	-0.33
C.E.C.	0.38	0.42	0.45	0.37	-0.05	0.05	-0.29
% CaCO ₃	0.07	0.15	-0.14	0.21	-0.38	-0.24	-0.20
Ext. Al ⁴	0.56*	0.35	0.70**	0.35	0.79**	0.81**	-0.16
pH	-0.24	-0.18	-0.47	-0.09	-0.52*	-0.49	0.05
% Clay	0.40	0.48	0.60*	0.37	0.00	0.10	-0.25

* Significant at 0.05 level

** Significant at 0.01 level

1 Refers to exchangeable Al determined by the Pratt and Bair(1961) procedure.

2 S.A. = Surface area measurement at 23^oC.

3 H.S.A. = Surface area measurements made after heating to 500^oC.

4 Refers to extractable Al determined by the Frink(1965) procedure.

high P levels or is due to some other soil component being involved in P sorption at these P concentrations. O.M., Fe_2O_3 , and extractable aluminum appeared to play a dominant role in the binding of P in soils.

There are some distinct advantages to segmenting the Langmuir isotherm and calculating theoretical P sorption maxima (such as b_1 , b_2 , etc). The primary advantage is the opportunity to determine which variables are responsible for P sorption in a particular P concentrations range. Extractable Al and the % clay were significant contributors to P sorption in region 1 but were not significant in region 2. From this data it appears that % O.M., % Fe_2O_3 and surface area are the primary variables involved in the sorption of P at the relatively high levels used in this study.

Regression equations using only the soil properties that were significantly correlated with P sorption, b , b_1 , and b_2 were calculated and the results from these calculations were listed in Table VIII. The equations used produced F values significant at the .05 level except in the case of the b_2 parameter. From a practical viewpoint, equations such as these may prove useful for predicting various P sorption parameters.

One difficulty in trying to relate various chemical properties to P sorption parameters is that in many instances the chemical properties themselves are correlated to each other. Table IX depicts the correlation between the various chemical properties determined from the 15 soils included in this study. Since % Fe_2O_3 and Na-citrate extractable Al are significantly correlated with % O.M., there may be Al and Fe compounds associated with the O.M. that are responsible for

TABLE VIII

RELATIONSHIP OF P SORPTION MEASUREMENTS
WITH SIGNIFICATION SOIL PROPERTIES

Source	F	Prob>F	R ²	C.V.	Regression Equation
P sorption (Avg. over treatments)	4.99	0.02	0.67	38.57	$\hat{Y} = -45.85 + -4.99(\%OM) + 68.66(\%Fe_2O_3) + 0.73(SA)^* + 0.15(Ext.A1)**$
P Maximum (b)	3.94	0.04	0.52	35.04	$\hat{Y} = 100.51 + -6.00(\%OM) + 117.87(\%Fe_2O_3) + 1.03(SA)$
P maximum (b ₁) Region 1	5.31	0.02	0.59	26.80	$\hat{Y} = 64.38 + 8.09(\%OM) + 37.70(\%Fe_2O_3) + 0.23(SA)$
P maximum (b ₂) Region 2	2.92	0.08	0.44	77.22	$\hat{Y} = -78.53 + 46.78(\%OM) + 218.54(\%Fe_2O_3) + 3.64(SA)$

* SA - surface area determined

** Ext. Al - Na-citrate extractable Al

TABLE IX

RELATIONSHIP BETWEEN VARIOUS CHEMICAL AND PHYSICAL
MEASUREMENTS IN FIFTEEN OKLAHOMA SOILS
DETERMINED BY CORRELATION COEFFICIENTS

	%OM	Ex. Al ¹	%Fe ₂ O ₃	SA ²	HSA ³	CEC	%CaCO ₃	Ext. Al ⁴	pH	%Clay
%OM	1.00									
Ex. Al ¹	0.08	1.00								
%Fe ₂ O ₃	0.78**	-0.34	1.00							
SA ²	0.44	-0.44	0.40	1.00						
HSA ³	0.38	-0.41	0.35	0.94**	1.00					
CEC	0.52*	-0.44	0.48	0.92**	0.89**	1.00				
%CaCO ₃	0.14	-0.46	0.18	0.52*	0.53*	0.58*	1.00			
Ext. Al ⁴	0.74**	0.48	0.50	0.01	-0.01	0.03	-0.47	1.00		
pH	-0.12	-0.40	-0.22	0.31	0.29	0.38	0.78**	-0.65**	1.00	
%Clay	0.44	-0.36	0.54*	0.80**	0.74**	0.87**	0.36	0.12	0.01	1.00

* Indicates significance at the .05 level.

** Indicates significance at the .01 level.

1 Ex. Al = exchangeable aluminum in 1N KCl

2 SA = surface area

3 HSA = heated surface area - Surface area measurements made after heating to 500°C.

4 Ext. Al = Na-citrate extractable aluminum

some P sorption. This data is in conflict with that reported by Vijayachandran and Harter (1975), who found no significant correlation between Fe or Al and O.M.

Phosphorus Desorption Study

Immediately following the P sorption study all samples were initiated into the P desorption study. The data obtained from the P desorption study is included in Table X. Generally, repeated extractions of the different soils with the Bray #1 extractant (0.03 N NH_4F in 0.025 N HCl) removed the entire amount of P sorbed in the P sorption study. There were no significant differences between treatments after the fifth or sixth extraction for most soils. There were two notable exceptions, the data for Summit and Bates soils indicated that there were significant differences between treatments through all extractions. The P desorption curve for the Summit soil is depicted in Figure 8. Figure 9 is the desorption curve obtained from plotting the data from the Renfrow soil and typifies many of the soils used in the study. A statistical evaluation of the data indicate that for certain soils (Renfrow, Grandfield, Parson, Bowie and Zaneis), a significant difference between treatments occurred after the 35 day equilibration period had elapsed (between extraction 8 and 9). It appears that a portion of the sorbed P is in a non-extractable form, by the Bray #1 extractant, and with time a new equilibrium is established in which an increased amount of the non-extractable P becomes extractable.

This type of an equilibrium was apparent with the majority of the soils in this study. The amount of P removed is reduced as consecutive

TABLE X

THE AMOUNT OF P REMOVED BY SUCCESSIVE EXTRACTIONS WITH 20 ml ALIQUOTS OF BRAY #1 EXTRACTANT (ug P/g OF SOIL).

Soil Type	Initial P* Treatments	Extraction Number									Sum of all Extractions	Total** P Sorbed
		1	2	3	4	5	6	7	8	9		
Summit	0	6.54	4.63	5.45	4.36	4.20	5.59	5.45	4.91	1.14	42.26	0.00
	50	25.37	10.36	9.27	6.68	6.68	6.46	6.27	5.45	1.64	78.15	45.82
	250	97.28	23.57	16.62	11.17	10.76	10.63	8.99	7.36	3.27	189.66	167.92
	500	130.53	31.94	24.53	15.94	13.08	11.31	10.90	9.27	5.45	252.93	269.96
	1000	207.10	46.87	32.43	17.99	15.94	11.99	11.31	10.63	5.59	359.84	408.13
	2000	297.57	68.13	41.97	20.71	20.71	13.76	14.58	12.26	7.49	497.18	646.63
	4000	465.98	87.61	63.49	30.11	24.12	17.58	16.21	12.40	9.27	726.77	1003.00
	F Value	1220.05	996.08	49.91	64.55	148.39	115.38	128.07	170.30	101.63		
	OSL***	0.0001	0.0001	0.0002	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001		
LSD (.05)	15.61	3.23	0.61	3.67	1.98	1.28	1.18	0.79	0.99			
Ullyses	0	6.54	9.27	12.54	15.26	13.76	17.99	19.67	14.31	13.63	122.95	0.00
	50	27.74	12.40	16.90	16.62	14.31	18.80	19.73	18.07	14.17	158.73	27.05
	250	96.19	16.90	16.90	16.35	15.26	19.89	22.21	15.21	15.67	234.49	84.22
	500	130.66	19.35	16.90	13.76	20.03	21.26	19.73	14.17	15.12	270.97	128.21
	1000	209.28	25.62	18.53	17.03	19.48	21.39	20.17	18.53	14.99	365.56	250.60
	2000	296.75	35.42	21.26	17.03	19.62	22.75	21.80	17.03	15.94	467.61	410.38
	4000	466.30	44.42	25.07	19.08	19.62	21.80	21.55	18.80	16.90	653.54	800.50
	F Value	1128.25	68.01	92.08	29.18	36.28	6.86	6.86	10.94	2.79		
	OSL	0.0001	0.0001	0.0001	0.0004	0.0003	0.0124	0.0121	0.0037	0.1030		
LSD	16.21	5.16	1.38	1.02	1.58	2.19	1.39	2.03	2.20			
Richfield	0	21.80	13.22	18.26	16.35	23.98	23.60	17.58	23.57	21.80	180.15	-2.43
	50	40.74	14.72	17.31	16.40	22.48	23.44	20.03	24.80	20.71	200.61	26.11
	250	71.67	18.26	19.02	17.99	24.12	23.44	17.39	25.48	20.30	236.65	64.24
	500	104.37	20.17	18.61	18.61	25.34	24.66	17.85	23.17	21.26	274.03	113.63
	1000	137.89	24.66	20.85	19.89	23.00	16.62	18.67	26.30	19.76	307.63	151.58
	2000	156.96	42.78	35.15	28.89	31.34	28.20	27.25	30.66	27.39	408.61	275.38
	4000	199.47	37.06	28.61	23.44	25.34	19.70	24.12	24.25	22.75	404.74	375.25
	F Value	67.82	4.01	2.01	2.12	0.66	1.28	1.96	0.78	0.86		
	OSL	0.0001	0.0463	0.1906	0.1733	0.6835	0.3715	0.1985	0.6108	9.57		
LSD (.05)	26.14	18.96	15.89	10.37	12.14	10.90	9.11	9.58	0.29			
Renfrow	0	19.21	5.50	6.68	8.59	8.04	6.00	7.09	9.67	6.27	77.12	
	50	42.92	9.13	8.86	8.45	8.61	6.68	7.90	10.08	6.27	108.89	-4.46
	250	76.57	10.90	11.17	9.40	9.84	6.27	8.04	10.36	6.54	149.08	23.68
	500	100.83	14.99	12.81	11.45	11.09	7.63	6.13	9.95	8.18	183.04	76.12
	1000	128.08	18.53	16.87	14.17	9.97	5.72	7.09	10.22	7.36	218.00	122.54
	2000	147.97	24.25	19.24	18.12	11.39	6.13	6.46	10.27	8.18	252.01	201.09
	4000	372.78	34.74	22.18	18.39	11.31	7.33	7.09	10.41	8.58	492.82	449.50
	F Value	1998.99	110.51	30.74	17.33	5.04	4.92	3.71	1.29	4.80		
	OSL	0.0001	0.0001	0.0004	0.0012	0.0266	0.0282	0.0555	0.3690	0.0299		
LSD (.05)	8.78	3.19	3.41	3.46	1.98	1.07	1.20	0.76	1.51			

* Total P added/g of soil in 25 ml of equilibrating solution.

** Total P sorbed from the P sorption study.

*** OSL - Observation Significance Level.

TABLE X: (CONTINUED)

Soil Type	Initial P Treatments	Extraction Number									Sum of all Extractions	Total P Sorbed
		1	2	3	4	5	6	7	8	9		
Kingfisher	0	20.49	6.95	4.36	6.68	5.59	7.36	6.00	4.11	5.18	66.71	-2.83
	50	37.47	10.90	6.00	6.95	5.45	7.22	5.78	4.11	5.64	89.52	27.05
	250	68.94	19.67	7.82	7.49	6.27	7.49	6.81	4.91	5.64	135.05	75.31
	500	88.97	23.44	11.83	8.50	6.54	8.18	7.41	4.63	6.10	165.60	95.00
	1000	258.88	15.94	12.53	9.10	9.40	7.22	5.72	6.13	6.10	331.03	216.84
	2000	279.18	17.99	15.12	11.36	10.08	6.81	6.27	5.72	6.10	358.64	346.25
	4000	579.61	32.97	18.80	11.99	9.67	8.18	6.65	5.61	6.10	679.59	510.25
	F Value	4574.14	119.42	55.54	23.37	144.42	1.46	2.61	7.71	2.17		
	OSL	0.0001	0.0001	0.0001	0.0006	0.0001	0.3127	0.1176	0.0090	0.1674		
	LSD (.05)	9.92	2.60	2.32	1.45	0.57	1.41	1.28	0.97	0.83		
Dill	0	32.84	8.04	4.77	4.36	4.36	3.41	3.27	0.00	3.00	64.04	-4.32
	50	56.00	11.85	2.73	4.09	4.09	3.27	2.89	3.27	2.18	90.36	7.75
	250	65.40	11.58	2.78	4.36	3.68	3.24	1.64	2.86	2.18	97.80	28.33
	500	66.76	10.55	3.60	4.52	4.09	3.27	1.36	2.86	2.18	99.19	44.78
	1000	69.49	12.26	4.36	4.80	4.09	3.87	1.91	3.82	1.64	106.22	90.82
	2000	75.54	12.70	4.36	4.80	3.82	3.82	1.91	3.27	2.18	112.38	123.50
	4000	91.56	13.49	4.96	4.80	4.36	3.54	1.36	3.37	2.04	129.38	226.75
	F Value	121.65	8.95	6.37	3.66	0.97	0.14	4.14	17.62	1.16		
	OSL	0.0001	0.0061	0.0147	0.0571	0.5051	0.9841	0.0429	0.0012	0.4184		
	LSD (.05)	5.47	1.99	1.21	0.49	0.86	2.25	1.23	1.00	1.25		
Grandfield	0	8.99	3.13	4.63	5.04	6.00	6.54	6.00	3.82	3.82	47.96	-1.62
	50	26.71	4.91	4.63	5.04	5.59	5.45	4.63	4.77	3.68	65.40	21.92
	250	48.64	6.54	4.63	5.45	5.59	5.59	4.36	4.09	3.82	88.70	65.32
	500	66.76	6.54	5.72	5.04	6.40	6.51	5.70	6.00	6.00	114.67	93.38
	1000	152.87	6.68	6.54	5.75	6.00	6.27	5.59	4.22	6.81	200.72	142.57
	2000	294.30	10.22	6.95	5.86	6.68	6.27	6.54	4.22	8.18	349.21	302.38
	4000	706.32	12.26	7.49	8.04	7.09	7.22	6.54	4.96	8.18	768.10	463.00
	F Value	10000.00	21.20	12.07	9.55	2.28	1.38	16.24	3.09	4.35		
	OSL	0.0001	0.0008	0.0029	0.0052	0.1523	0.3386	0.0014	0.0831	0.0380		
	LSD (.05)	4.89	2.25	1.17	1.16	1.24	1.71	1.71	1.40	3.25		
Parson	0	28.48	18.12	14.58	14.17	12.81	6.70	8.18	6.54	2.18	111.75	-1.35
	50	56.14	26.57	10.62	15.53	12.13	7.52	8.58	6.00	6.10	149.19	41.09
	250	129.17	37.61	17.03	17.44	13.22	8.09	10.08	6.95	6.10	245.69	131.20
	500	170.18	42.78	15.67	18.80	13.63	10.90	10.49	6.81	6.10	295.36	187.34
	1000	233.81	41.97	19.76	19.70	13.63	11.31	10.76	6.95	6.10	363.98	270.85
	2000	332.72	54.50	27.80	21.85	15.12	11.72	10.90	6.95	7.90	489.46	417.13
	4000	404.57	63.22	27.25	23.03	15.81	12.81	16.49	6.68	7.90	582.74	618.25
	F Value	1401.11	491.23	57.90	153.16	10.60	33.56	1.83	2.27	343.32		
	OSL	0.0001	0.0001	0.0001	0.0001	0.0040	0.0003	0.2239	0.1542	0.0001		
	LSD (.05)	12.55	2.32	2.84	0.87	1.32	1.37	6.76	0.77	0.34		

TABLE X: (CONTINUED)

Soil Type	Total P Treatments	Extraction Number									Sum of all Extractions	Total P Sorbed
		1	2	3	4	5	6	7	8	9		
Tipton	0	43.06	36.65	12.67	14.03	17.85	14.85	15.26	7.49	8.18	170.04	-5.00
	50	52.46	36.10	16.35	14.17	18.67	14.85	16.21	7.77	8.58	185.16	11.26
	250	69.62	38.42	17.99	14.17	18.53	15.26	17.44	8.18	9.54	209.14	31.30
	500	84.61	45.24	17.82	13.63	23.17	13.63	16.95	7.90	8.18	231.65	43.16
	1000	103.82	45.37	18.80	13.63	28.34	15.81	17.03	8.04	8.99	259.83	79.56
	2000	131.62	49.05	18.12	13.79	25.07	14.58	18.26	7.90	8.31	286.70	93.13
	4000	139.79	54.64	23.16	13.49	24.12	14.09	17.71	8.99	8.26	304.25	112.00
	F Value	329.07	13.18	71.22	1.09	73.19	4.29	6.42	1.33	1.22		
	OSL	0.0001	0.0023	0.0001	0.4523	0.0001	0.0394	0.0144	0.3514	0.3931		
	LSD(.05)	6.92	6.39	1.24	0.90	1.57	1.16	1.31	1.37	1.55		
Hollister	0	47.55	14.44	13.22	13.08	15.26	11.85	16.08	5.31	9.59	146.39	-9.86
	50	64.04	17.44	14.72	13.63	15.94	14.85	15.67	7.36	9.56	173.20	14.22
	250	93.74	26.30	18.53	15.53	17.03	14.50	17.30	8.04	9.59	220.56	59.92
	500	130.53	29.57	17.44	15.40	18.26	16.21	20.17	8.86	9.70	266.12	84.47
	1000	165.68	34.88	25.34	15.53	15.53	15.26	16.08	7.63	9.54	305.47	138.08
	2000	224.40	35.15	23.44	16.62	17.66	16.35	16.08	7.77	16.40	363.95	187.63
	4000	357.51	39.79	26.30	18.80	19.21	16.76	17.44	8.72	10.63	415.15	199.75
	F Value	146.02	96.55	61.52	3.34	13.48	7.25	1.87	3.26	1.77		
	OSL	0.0001	0.0001	0.0001	0.0700	0.0022	0.0105	0.2145	0.0739	0.2357		
	LSD(.05)	22.06	3.22	2.22	3.47	1.35	2.06	3.81	2.18	6.46		
Bates	0	50.96	28.20	14.06	11.99	10.49	7.77	1.64	4.63	5.80	135.54	-2.16
	50	80.66	38.15	18.26	16.49	11.85	8.18	1.91	5.45	6.00	186.94	44.44
	250	147.72	51.23	19.25	18.12	13.63	9.81	2.23	5.86	6.16	273.81	132.55
	500	178.49	54.50	23.98	19.08	14.85	10.63	3.13	8.72	6.16	314.53	171.95
	1000	214.46	61.99	24.80	22.35	17.85	10.08	3.27	11.04	7.90	373.73	219.09
	2000	277.54	70.31	33.52	28.84	19.48	10.36	3.82	9.67	8.07	462.05	332.75
	4000	353.16	71.26	31.20	25.07	16.76	9.81	3.00	8.18	6.95	525.38	348.75
	F Value	4807.76	744.26	112.38	19.25	79.77	11.18	7.07	25.85	11.01		
	OSL	0.0001	0.0001	0.0001	0.0010	0.0001	0.0035	0.0112	0.0005	0.0036		
	LSD(.05)	5.12	1.97	2.21	4.29	1.25	1.10	1.00	1.57	0.94		
Miller	0	123.44	76.90	51.37	40.33	33.25	28.24	24.25	18.39	20.44	416.71	-14.58
	50	147.42	77.94	52.27	42.92	33.25	30.11	24.39	17.99	14.44	440.71	12.47
	250	200.83	80.93	55.86	45.78	34.88	30.38	23.44	18.39	13.49	503.99	70.18
	500	226.45	88.02	64.56	41.15	34.20	32.43	24.93	19.89	14.31	545.93	101.48
	1000	264.87	93.88	68.13	42.93	34.61	32.70	23.71	20.44	14.63	595.88	169.58
	2000	327.41	104.64	70.09	46.33	38.50	34.34	24.93	20.57	15.12	681.99	214.63
	4000	387.50	115.00	78.21	50.96	41.28	37.20	25.89	21.26	15.40	772.67	274.00
	F Value	793.29	179.35	29.61	7.94	11.22	34.65	1.26	4.26	7.09		
	OSL	0.0001	0.0001	0.0004	0.0083	0.0035	0.0003	0.3819	0.0398	0.0112		
	LSD(.05)	11.25	3.60	6.20	4.34	3.04	1.68	2.48	2.09	2.89		

TABLE X: (CONTINUED)

Soil Type	Initial P Treatments	Extraction Number									Sum of all Extractions	Total P Sorbed
		1	2	3	4	5	6	7	8	9		
Bowie	0	6.27	2.45	2.45	0.00	1.50	1.09	1.09	1.63	0.55	17.03	-1.35
	50	37.61	4.36	4.91	0.68	2.18	1.23	1.36	1.36	1.09	54.77	34.07
	250	92.11	6.13	4.91	0.68	2.73	1.91	1.09	1.36	1.42	112.32	89.08
	500	128.08	6.68	5.72	1.23	2.73	1.69	1.36	1.91	0.55	149.88	113.63
	1000	168.95	6.95	5.18	1.23	2.73	1.09	1.09	1.91	1.36	190.48	169.58
	2000	237.08	8.45	5.18	1.91	2.73	1.23	1.91	1.64	0.82	260.92	214.63
	4000	310.65	8.31	4.91	1.91	2.18	0.82	1.96	1.31	1.36	333.40	247.00
	F Value	3523.17	21.78	8.72	4.55	2.54	1.96	6.65	1.32	4.66		
	OSL	0.0001	0.0007	0.0066	0.0002	0.1247	0.1990	0.0131	0.3601	0.0322		
	LSD (.05)	6.09	1.54	1.19	0.34	0.99	0.88	0.49	0.74	0.60		
Foard	0	18.80	7.90	6.00	5.80	7.90	4.91	4.22	4.11	4.50	64.15	-2.97
	50	41.97	9.81	6.40	6.27	8.72	6.00	3.21	4.14	6.13	93.14	27.59
	250	90.06	14.44	9.40	9.27	8.72	6.40	3.73	4.09	6.73	152.85	80.98
	500	123.44	21.26	13.90	9.81	9.13	6.13	4.82	4.11	6.18	199.42	111.20
	1000	159.69	27.93	15.12	12.54	9.67	7.22	5.04	4.69	5.18	247.08	210.09
	2000	224.81	26.30	13.08	11.85	8.99	8.04	3.73	4.11	6.81	307.73	194.38
	4000	282.86	42.24	18.12	14.17	10.08	8.13	4.85	6.27	5.18	392.07	199.75
	F Value	857.20	76.20	65.76	53.78	2.54	42.49	2.10	18.52	2.61		
	OSL	0.0061	0.0001	0.0001	0.0001	0.1238	0.0002	0.1772	0.0011	0.1174		
	LSD (.05)	10.92	4.60	1.89	1.43	1.48	0.62	1.37	0.63	1.97		
Zaneis	0	5.86	2.73	2.73	3.00	2.18	1.64	1.23	1.36	2.18	22.89	0.00
	50	23.98	4.36	4.36	4.36	2.45	2.02	2.18	1.36	2.18	47.25	30.83
	250	55.45	9.27	6.68	5.04	3.27	2.02	3.54	1.96	3.95	91.18	76.66
	500	78.07	12.40	7.77	5.86	3.19	2.45	3.13	1.42	3.27	117.56	107.15
	1000	109.82	14.17	8.04	6.40	3.73	3.27	3.27	0.60	3.54	152.85	169.58
	2000	152.46	18.94	10.36	6.54	4.36	3.82	3.54	1.36	3.68	205.05	170.75
	4000	188.84	24.80	14.17	11.31	5.72	4.50	3.95	2.45	3.82	259.56	193.00
	F Value	1638.63	427.88	491.21	32.40	21.42	20.60	9.70	0.52	15.12		
	OSL	0.0001	0.0001	0.0001	0.0003	0.0008	0.0008	0.0050	0.7813	0.0017		
	LSD (.05)	5.52	1.27	0.57	1.54	0.87	0.79	1.02	2.68	0.64		

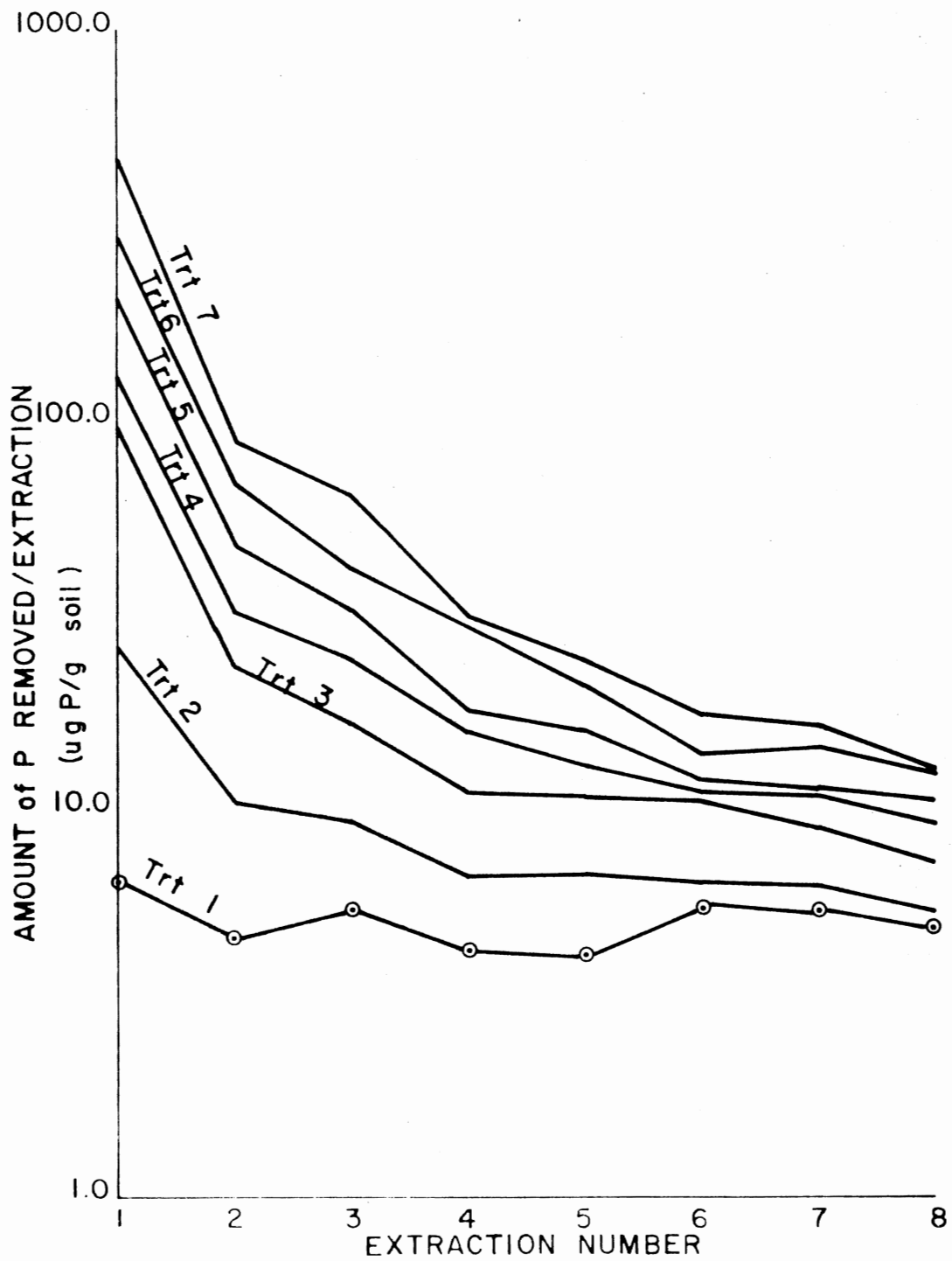


Figure 8. P Extracted by Repeated Equilibrations with the Bray #1 Extractant from the Summit Soil.

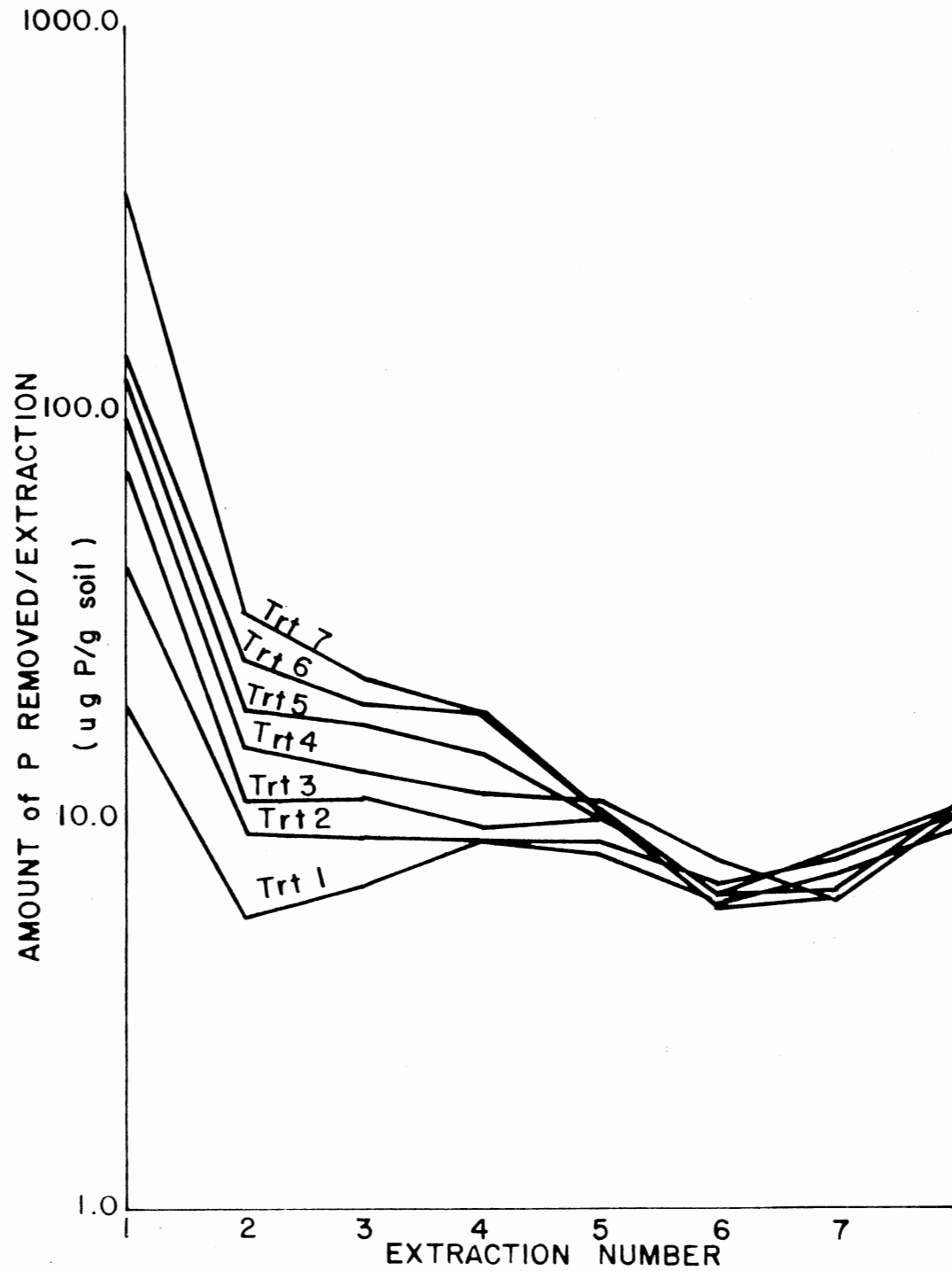


Figure 9. P Extracted by Repeated Equilibration with the Bray #1 Extractant from the Renfrow Soil.

extractions proceed, but if several days elapsed, between consecutive extractions the amount of P removed often remains constant or increases. Figures 10, 11, and 12 depict the amount of P removed per extraction averaged over all the original P treatments. Each data point on the graph is the mean of 14 observations.

The simple correlation coefficients used to measure the relationship between the P fractions removed with sequential Bray extractions, and the various chemical properties determined for each soil are shown in Table XI. The majority of all P extracted was obtained in the first and second Bray extraction. In the first Bray extraction, % clay was the only statistically significant soil characteristic, although % Fe_2O_3 approached significance at the 0.05 level. Percent Fe_2O_3 was correlated with removed P in the two following Bray extractions (2 and 3) and then became less significant with continued Bray extraction (4 thru 9). The reverse situation appeared with measurements of soil surface area on heated and non-heated soil samples. The values obtained from the measurements of "heated" and "non-heated" soil surface areas increased in statistical correlation with the P removed with each additional Bray extraction.

Some of the chemical and physical properties (O.M., % Fe_2O_3 , and % clay) decreased in statistical correlation with continued Bray extraction and other properties (soil surface areas, heated and non-heated, and CEC) became better correlated with an increase Bray extraction. This is confirming evidence that P is sorbed by the least two mechanism as suggested by Holford, et al. (1974) Syers, et al. (1973), Fritter and Suttén (1975), and others.

Correlation coefficients were calculated to evaluate the relation-

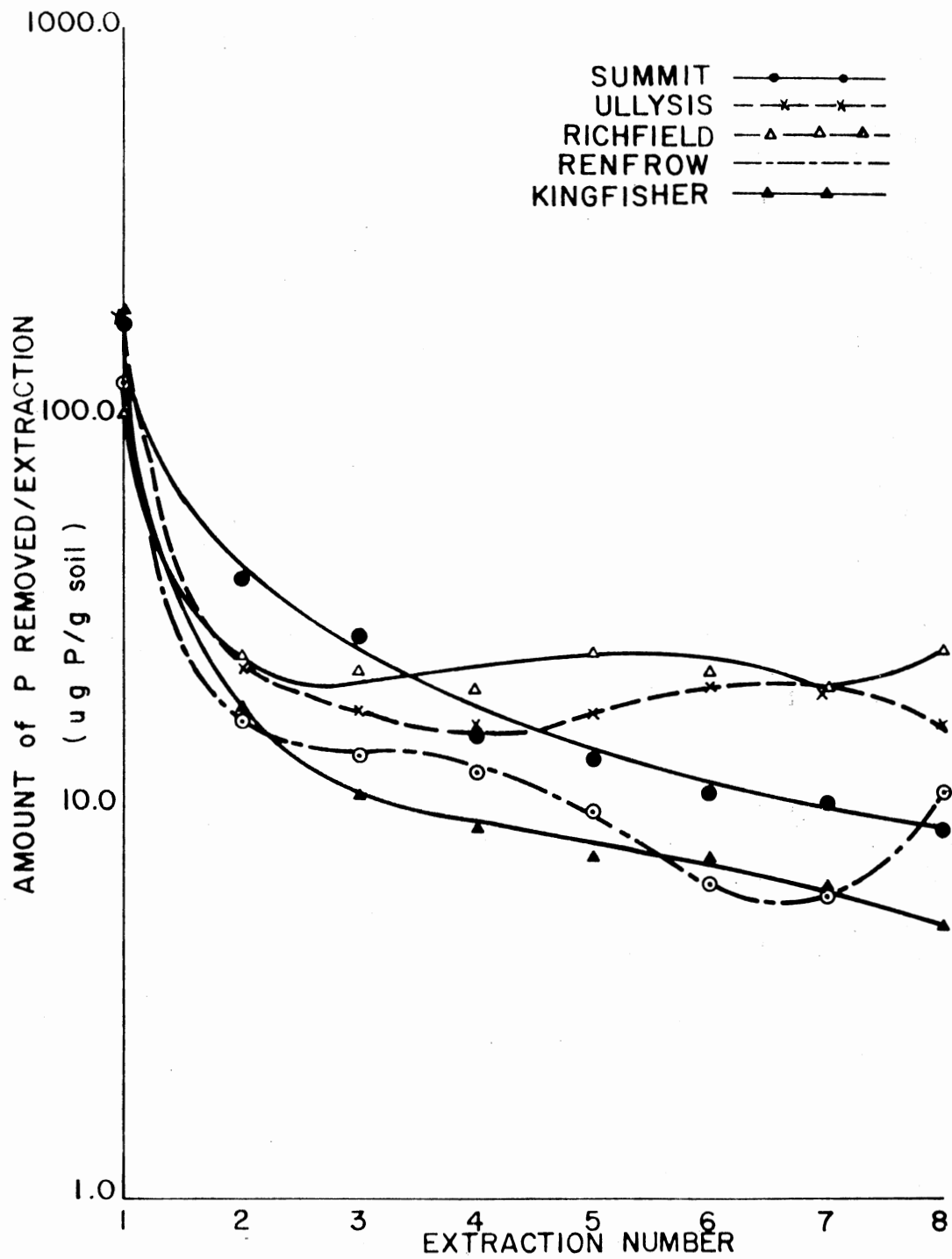


Figure 10. Desorption Patterns Obtained by Extracting Various Soils with the Bray #1 Extractant.

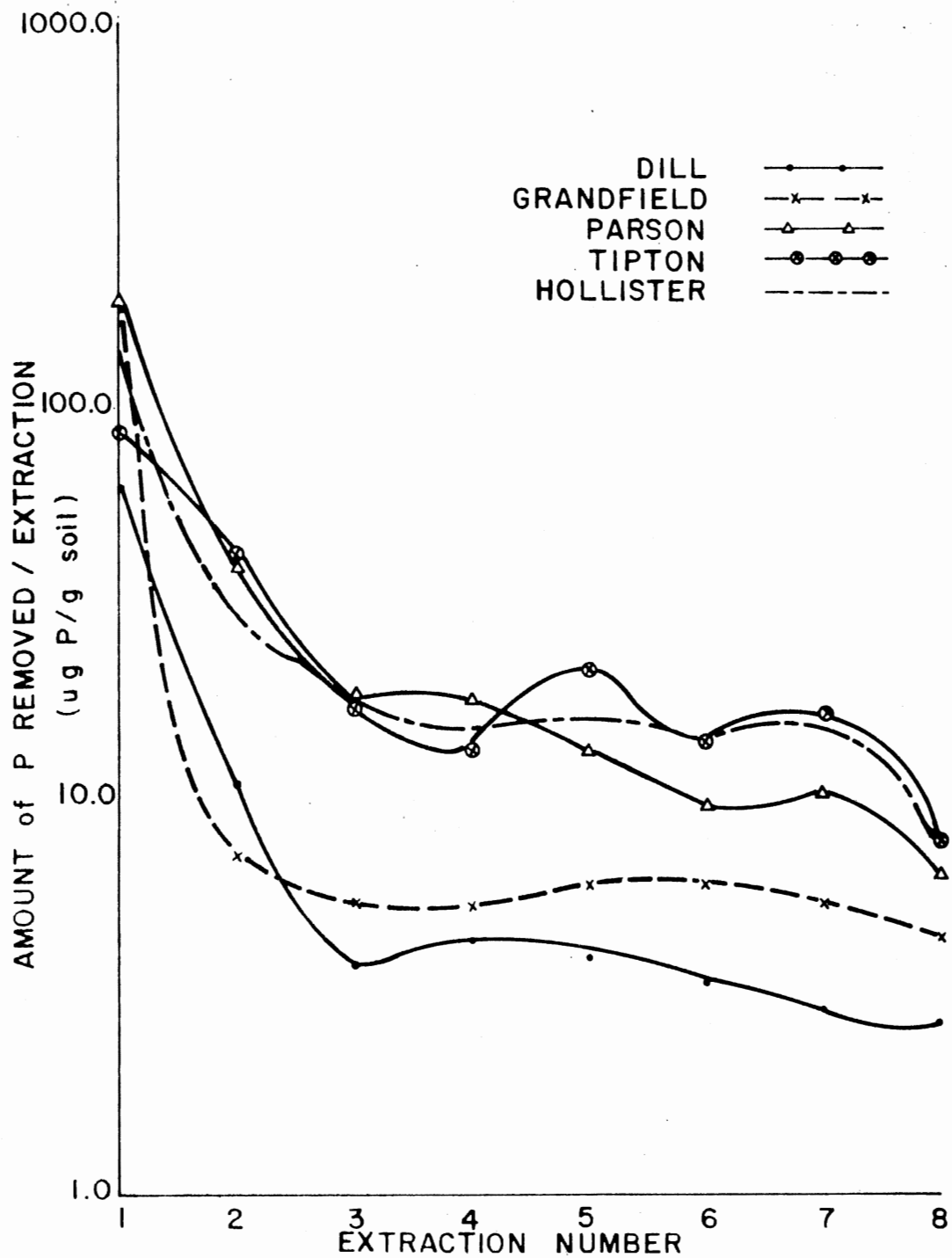


Figure 11: Desorption Patterns Obtained by Extracting Various Soils with the Bray #1 Extractant.

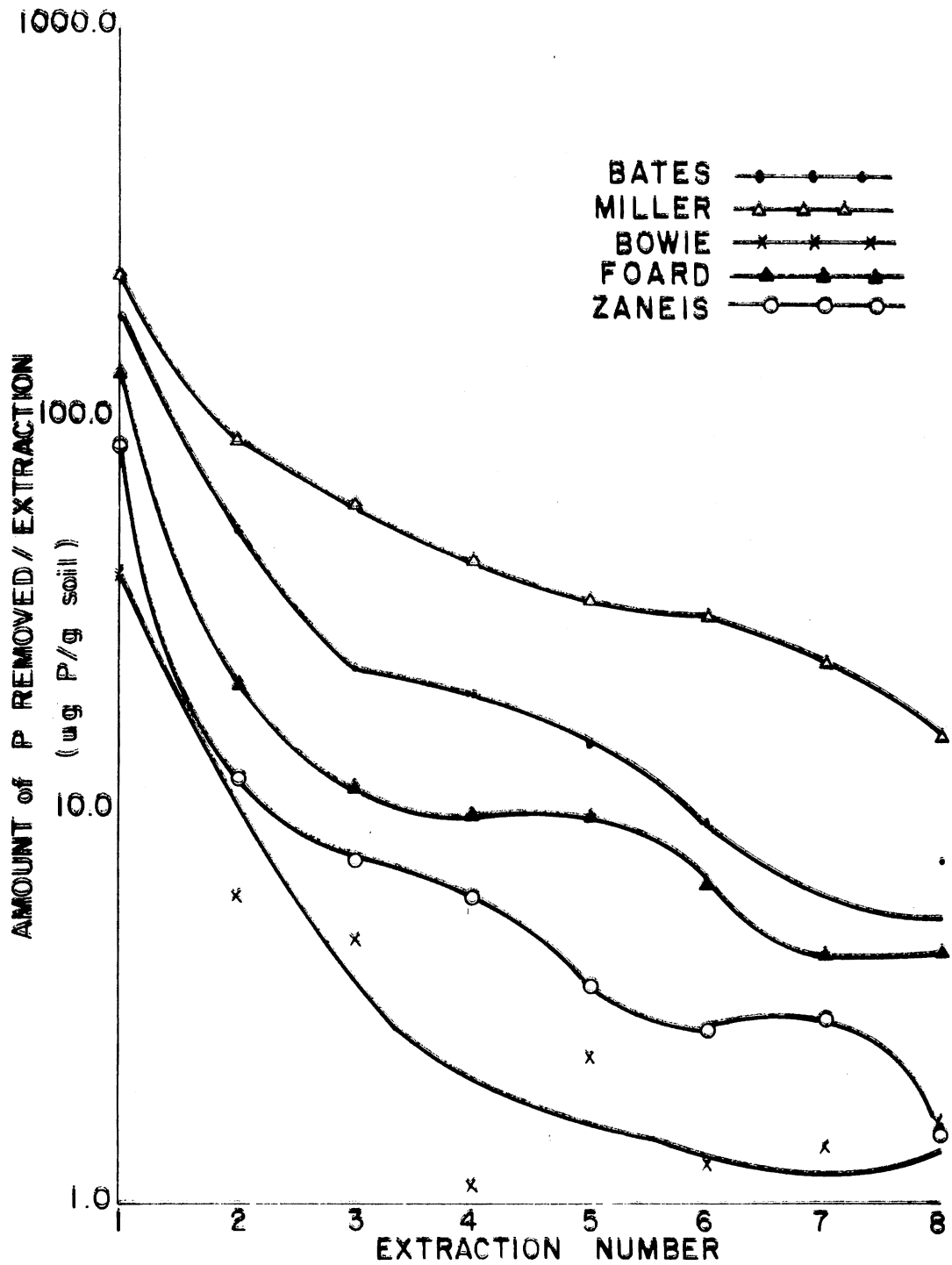


Figure 12. Desorption Patterns Obtained by Extracting Various Soils with the Bray #1 Extractant.

TABLE XI
CORRELATION COEFFICIENTS BETWEEN THE VARIOUS BRAY EXTRACTIONS
AND CHEMICAL PROPERTIES AVERAGED
OVER FIFTEEN OKLAHOMA SOILS

Extraction Number	Days After P Sorption	Chemical and Physical Properties									
		% OM	Ex Al ¹	% Fe ₂ O ₃	SA ²	HSA ³	CEC	% CaCO ₃	Ext Al ⁴	pH	% Clay
1	1	0.21	-0.01	0.49	0.35	0.30	0.31	-0.15	0.33	0.47	0.56
2	2	0.26	-0.32	0.50*	0.50*	0.50*	0.60*	0.37	0.01	-0.03	0.67**
3	4	0.34	-0.30	0.53**	0.66**	0.70**	0.76**	0.43	0.02	0.10	0.77**
4	7	0.18	-0.39	0.44	0.65**	0.69**	0.69**	0.41	-0.01	0.11	0.73**
5	14	0.10	-0.37	0.23	0.70**	0.76**	0.69**	0.53*	-0.23	0.32	0.61*
6	21	0.09	-0.37	0.21	0.75**	0.83**	0.73**	0.57*	-0.26	0.38	0.61*
7	28	0.07	-0.34	0.12	0.75**	0.82**	0.70**	0.61*	-0.30	0.45	0.51*
8	35	0.09	-0.33	0.14	0.74**	0.82**	0.60*	0.46	-0.24	0.34	0.43
9	70	-0.09	-0.38	-0.02	0.69**	0.79**	0.55*	0.41	-0.35	0.39	0.36
Sum of all Extractions		0.23	-0.27	0.48	0.66**	0.67**	0.65**	0.28	-0.05	0.05	0.74

* Indicates significance at the 0.05 level.

** Indicates significance at the 0.01 level.

1 Ex Al refers to exchangeable Al by the Pratt and Bair (1961) procedure.

2 SA refers to surface area measurements at 23°C.

3 HSA refers to surface area measurements after heating to 500°C.

4 Ext Al refers to extractable Al by the Frink (1965) procedure.

ship between P sorption and the various Bray extractions and the relationship between Bray extractions. The data comparisons are shown in Table XII. P sorption and the P removed in Bray extraction 1 are well correlated but with each succeeding Bray extraction the correlation between subsequent extractions and P sorption is reduced. This is further evidence of a relationship between the P being removed by Bray extraction and the actual P sorbed during the P sorption study.

Also evidenced in Table XII are the sequential relationships between Bray extractions. In general, there is good correlation between Bray extractions in sequence except for extractions 1 and 2. This suggests that the amount of P removed in the first Bray extraction is primarily the P sorbed in the sorption study, while the P removed by later Bray extractions is controlled to a large extent by the soil physical and chemical characteristics or P-chemical equilibrium reactions.

The data in Table XI indicated that surface area measurements are significantly correlated to all Bray extractions except for 1 and 2. Since these Bray extractions are within themselves significantly correlated (Table XII), the Bray #1 extractant appears to be extracting P associated with the exposed surfaces.

Regression analysis was conducted to relate the total P extracted by numerous Bray extractions to the amount of P sorbed. This data is shown in Table XIII. With two exceptions (Tipton and Foard), the data indicate that the total P removed by the Bray extractions is highly dependent upon the amount of P sorbed during the P sorption study.

The reason for relatively low R^2 values with the Tipton soil probably

TABLE XII
CORRELATION COEFFICIENTS BETWEEN THE VARIOUS BRAY
EXTRACTIONS AND PHOSPHATE SORPTION
IN FIFTEEN OKLAHOMA SOILS¹

	P Sorbed	Extraction Number								
		1	2	3	4	5	6	7	8	9
P Sorbed ²	1.00									
Extraction 1	0.79	1.00								
Extraction 2	0.40	0.47	1.00							
Extraction 3	0.39	0.44	0.93	1.00						
Extraction 4	0.29	0.38	0.91	0.95	1.00					
Extraction 5	0.19	0.26	0.81	0.86	0.90	1.00				
Extraction 6	0.15	0.23	0.71	0.82	0.86	0.94	1.00			
Extraction 7	0.16	0.18	0.56	0.68	0.72	0.88	0.92	1.00		
Extraction 8	0.20	0.15	0.48	0.64	0.71	0.82	0.86	0.82	1.00	
Extraction 9	0.18	0.17	0.40	0.54	0.63	0.78	0.84	0.84	0.92	1.00
Sum of Extractions	0.72	0.90	0.76	0.76	0.72	0.63	0.60	0.51	0.47	0.46

1 All correlation coefficients 0.70 were significant at the 0.01 level.

2 P sorbed refers to the amount of P sorbed during the P sorption study averaged over 7 treatments for each soil.

TABLE XIII

RELATIONSHIP OF THE SUM OF THE BRAY
EXTRACTIONS TO PHOSPHATE SORPTION

Soil Type	F Value	OSL *	R ²	CV
Summit	1010.36	0.0001	0.99	6.59
Ulysses	407.63	0.0001	0.98	7.77
Richfield	71.93	0.0001	0.88	10.66
Renfrow	91.98	0.0001	0.90	18.26
Kingfisher	265.01	0.0001	0.96	14.18
Dill	1778.26	0.0001	0.92	3.72
Grandfield	57.10	0.0001	0.85	39.05
Parson	407.19	0.0001	0.98	6.99
Tipton	2.03	0.1841	0.17	17.02
Hollister	156.06	0.0001	0.94	7.70
Bates	735.48	0.0001	0.99	4.20
Miller	126.52	0.0001	0.93	5.56
Bowie	186.65	0.0001	0.95	12.44
Foard	17.76	0.0018	0.64	27.95
Zaneis	56.19	0.0001	0.85	20.69

* OSL - Observation Significance Level

relate to the relatively high amount of P extracted compared to lesser amounts of P sorbed during the P sorption study. This would indicate that a large percentage of the soil sorption capacity was satisfied or occupied prior to the P sorption study. Furthermore, Tipon and Foard had rather high C.V. values in the P sorption study and could account for low R^2 values compared to other soils used in the study.

Phosphorus Fractionation Study

Determination of the Amounts and Chemical Forms of Phos- phates at the Completion of the Phosphorus Desorption Study

P fractionation procedures, according to Williams, et al. (1967), were applied to all samples introduced into the P sorption study. Each P treatment level of each soil was replicated four times. Two of these replicates (A and B) were carried through the entire P desorption study, while the other two samples were placed into a deep freeze according to the pattern depicted in Table III. After the desorption study was completed for all soils, the A and B replicates for each treatment level of each soil were fractionated. The analysis of variance for replicates A and B is included in Table XIV.

Ammonium Chloride Phosphate Fraction.

There was a significant difference (.01 level) between P treatments and the amount of P removed in the NH_4Cl fraction for the Summit soil. Kingfisher, Bates, and Foard soils showed significant differences

TABLE XIV

TOTAL AMOUNT OF P OBTAINED PER FRACTION
BY TREATMENT AND SOIL.

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	DCB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ P ₂	Residual P	Sum of all Fractions
Summit	0	0.25	4.20	47.13	10.00	16.76	4.38	8.00	7.50	98.50	196.70
	50	0.30	4.95	51.75	8.50	17.00	2.00	3.00	4.88	94.75	187.13
	250	1.50	6.60	60.25	7.00	20.18	2.13	3.00	5.63	100.00	206.28
	500	1.93	7.05	64.75	12.50	19.30	3.28	4.25	6.95	88.50	208.50
	1000	1.55	8.50	71.50	17.75	18.75	3.00	2.63	8.80	20.00	152.38
	2000	1.60	7.80	74.75	12.00	19.50	2.90	7.38	4.40	31.00	161.33
	4000	1.88	9.75	82.00	14.75	20.25	2.63	5.15	4.38	44.00	184.78
	F Value	13.46	34.10	48.58	1.32	3.13	2.60	1.62	2.57	36.42	
	OSL*	0.0022	0.0003	0.0002	0.3576	0.0807	0.12	0.27	0.1211	0.0003	
LSD(.05)	0.65	1.11	6.01	10.73	2.69	1.65	5.73	3.57	19.38		
Ulysses	0	10.00	6.25	28.25	17.00	20.75	18.00	6.25	6.00	20.00	132.50
	50	8.88	5.60	26.63	18.25	21.38	21.50	6.85	6.50	21.00	136.58
	250	9.00	5.08	26.60	14.75	18.00	15.25	6.20	6.50	56.00	156.78
	500	9.00	6.00	27.25	29.25	25.00	28.50	6.50	6.90	57.00	195.40
	1000	8.63	4.80	23.50	22.50	22.38	15.75	5.63	5.50	45.00	153.68
	2000	9.50	5.60	27.50	23.00	21.38	15.00	6.23	5.75	48.50	162.45
	4000	9.95	5.78	28.25	12.00	21.50	14.75	8.00	5.50	53.00	158.73
	F Value	1.57	0.94	2.22	3.21	1.59	0.95	6.27	11.43	784.11	
	OSL	0.28	0.52	0.1600	0.08	0.28	0.52	0.02	0.0033	0.0001	
LSD(.05)	1.45	1.74	3.72	10.85	5.51	17.39	1.00	0.54	1.90		

* OSL - Observation Significance Level

TABLE XIV: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	l-NaOH-P	DCB-P	l-NaOH-P	l-HCl-P	2-HCl-P	H ₂ SO ₄ -P ²	Residual P	Sum of All Fractions
Richfield	0	12.00	23.03	35.38	21.50	17.38	20.38	8.63	7.00	85.00	230.75
	50	11.55	21.23	36.28	16.00	17.00	19.13	9.00	10.00	61.75	201.93
	250	11.98	24.00	37.23	10.00	18.75	17.50	8.20	10.63	56.50	194.78
	500	11.50	23.25	38.50	19.50	17.00	20.00	7.88	8.55	32.50	178.68
	1000	12.30	23.25	38.75	13.50	18.25	20.13	8.63	8.63	36.50	179.93
	2000	12.93	21.00	55.25	14.00	25.25	48.75	16.25	12.00	74.60	280.03
	4000	11.75	19.43	39.80	16.50	17.98	18.43	11.25	8.88	61.00	205.00
	F Value	0.79	0.59	1.09	2.03	0.97	1.08	0.88	0.44	5.61	
	OSL	0.6042	0.7301	0.4515	0.1873	0.5067	0.4529	0.5530	0.8323	0.0203	
	LSD(.05)	1.85	7.14	21.88	9.03	9.91	35.96	10.60	8.73	26.68	
Renfrow	0	2.25	3.30	29.00	12.40	19.75	5.25	5.13	2.38	36.50	115.95
	50	2.48	2.75	25.00	12.30	28.18	39.13	9.63	2.33	42.75	164.53
	250	3.25	2.80	17.70	13.65	24.00	27.75	8.75	2.00	48.50	148.40
	500	2.45	3.00	23.00	14.05	27.00	52.25	4.00	3.25	37.00	166.00
	1000	3.28	3.30	20.90	10.30	30.00	26.25	4.00	2.25	43.00	143.28
	2000	4.25	4.15	21.33	12.25	25.75	34.00	3.63	3.15	56.00	164.50
	4000	3.80	3.75	21.43	16.65	34.70	18.43	4.65	3.70	54.50	161.60
	F Value	2.87	1.64	3.51	1.06	1.25	6.73	1.60	8.79	1.75	
	OSL	0.0973	0.2659	0.0630	0.4659	0.3843	0.0128	0.2750	0.0064	0.2396	
	LSD(.05)	1.49	1.34	6.39	6.44	14.07	19.36	6.50	0.72	19.78	

TABLE XIV: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	DCB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ -P ²	Residual P	Sum of All Fractions	
Kingfisher	0	0.50	8.38	20.13	12.25	17.75	2.75	3.63	11.50	38.50	115.38	
	50	0.05	6.05	20.63	12.25	21.25	2.38	3.38	2.78	23.00	92.18	
	250	1.13	6.88	21.00	15.25	12.88	3.00	9.25	2.00	32.00	103.38	
	500	1.33	7.63	17.38	11.50	13.75	2.68	8.50	3.00	29.00	94.75	
	1000	2.80	9.25	19.43	6.00	18.00	1.85	16.13	2.15	31.50	107.10	
	2000	1.90	7.75	18.05	7.50	15.63	2.38	6.25	1.98	19.50	80.93	
	4000	2.13	6.63	17.20	9.75	16.00	1.50	15.38	13.13	18.25	99.95	
	F Value	6.37	2.02	0.85	23.08	1.73	1.30	5.79	1.07	1.25		
	OSL	0.0147	0.1894	0.5687	0.0007	0.2431	0.3646	0.0187	0.4588	0.3826		
	LSD(.05)	1.14	2.56	5.68	2.19	7.19	1.54	7.17	15.79	22.12		
Dill	0	0.25	1.00	1.50	9.75	6.25	47.25	6.58	2.43	35.15	110.15	
	50	0.73	1.75	0.63	8.00	4.38	47.00	3.65	3.33	35.00	104.45	
	250	0.05	1.78	2.13	8.00	6.00	42.25	3.75	3.50	47.50	114.95	
	500	0.05	2.13	1.75	8.25	3.25	48.38	3.50	2.05	37.50	106.85	
	1000	1.13	1.75	2.25	5.00	6.75	46.63	3.00	2.88	33.75	99.13	
	2000	0.03	1.78	4.75	7.25	3.25	41.38	3.13	3.18	53.75	118.48	
	4000	0.38	3.25	1.88	10.50	5.75	47.88	2.75	3.20	42.50	118.08	
	F Value	1.51	1.09	7.35	1.73	2.03	0.58	1.30	1.86	1.10		
	OSL	0.2994	0.4506	0.0102	0.2432	0.1876	0.7417	0.3673	0.2183	0.4461		
	LSD(.05)	1.13	2.17	1.57	4.50	3.41	13.30	3.79	1.20	24.07		

TABLE XIV: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	DCB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ -P ²	Residual P	Sum of all Fractions	
Hollister	0	4.50	10.25	20.88	15.25	9.75	3.33	3.33	4.00	113.00	184.28	
	50	4.03	9.55	19.63	16.00	10.50	3.33	3.20	3.88	85.50	155.60	
	250	5.38	10.75	21.55	15.00	10.13	3.63	3.45	3.88	156.00	229.75	
	500	6.38	11.00	26.88	17.50	9.38	3.50	3.88	4.88	169.00	252.38	
	1000	2.75	7.25	9.50	14.25	10.88	2.55	2.38	3.13	70.50	123.18	
	2000	9.88	18.25	39.50	28.75	16.88	11.20	6.83	15.63	139.00	285.90	
	4000	4.25	12.63	23.38	15.50	8.95	3.58	3.83	4.13	81.00	157.23	
	F Value	1.00	1.02	1.78	4.49	2.04	1.03	1.01	7.22	1.47		
	OSL	0.4908	0.4803	0.2341	0.0352	0.1863	0.4797	0.4863	0.0106	0.3116		
	LSD(.05)	7.71	11.36	22.62	8.01	6.34	9.91	4.68	5.51	107.97		
Bates	0	0.63	10.50	32.75	28.50	9.25	0.65	2.00	2.55	55.00	141.83	
	50	1.38	10.38	30.50	25.75	8.75	0.35	0.35	1.63	59.00	138.08	
	250	1.25	11.38	34.25	29.15	9.13	0.95	0.25	2.00	109.50	197.85	
	500	1.60	11.88	35.75	26.00	8.63	0.88	0.75	1.75	55.00	142.23	
	1000	1.38	12.50	35.70	30.50	9.38	0.48	1.68	2.50	55.00	149.10	
	2000	1.95	13.50	36.13	29.50	9.63	0.13	0.88	2.08	58.50	152.28	
	4000	1.13	12.13	37.50	33.50	8.38	0.20	1.18	2.00	53.50	149.50	
	F Value	4.05	2.33	6.38	1.74	0.08	0.88	1.04	0.86	0.92		
	OSL	0.0451	0.1461	0.0146	0.2410	0.9956	0.5562	0.4733	0.5661	0.5339		
	LSD(.05)	0.68	2.43	3.12	6.75	5.30	1.15	2.14	1.26	70.96		

TABLE XIV: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	DCB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ P ₂	Residual P	Sum of all Fractions	
Miller	0	7.75	14.13	25.88	29.00	11.38	12.25	4.25	5.63	64.00	174.25	
	50	8.38	16.00	25.13	32.35	12.13	9.25	4.00	5.45	126.00	238.58	
	250	8.38	16.13	25.83	30.25	11.88	9.50	5.13	5.63	148.50	261.20	
	500	8.50	17.00	26.68	38.50	11.25	9.68	4.25	6.00	125.50	247.35	
	1000	8.45	15.68	26.88	35.50	12.38	9.38	4.13	4.88	129.00	247.25	
	2000	8.55	15.80	26.90	29.00	11.00	10.25	4.88	4.45	110.00	220.83	
	4000	9.00	14.63	27.88	33.50	10.75	9.63	4.38	4.83	117.00	231.58	
	F Value	0.27	3.30	2.58	1.68	0.33	4.32	3.83	2.62	0.94		
	OSL	0.9346	0.0721	0.1207	0.2545	0.9019	0.0386	0.0513	0.1166	0.5345		
LSD(.05)	2.38	1.77	2.19	9.15	3.52	1.68	0.71	1.14	90.90			
Grandfield	0	2.63	3.88	7.13	19.50	9.00	6.00	3.13	1.88	29.00	82.13	
	50	2.13	3.50	8.13	9.50	6.88	5.63	3.38	2.25	34.00	75.38	
	250	2.20	3.75	7.88	22.00	8.88	5.38	4.00	2.20	36.00	92.28	
	500	2.13	3.25	6.48	14.50	6.38	3.75	3.00	1.70	21.25	62.43	
	1000	2.55	3.30	6.95	19.75	7.63	5.38	3.25	1.90	26.00	76.70	
	2000	3.13	3.58	6.50	14.00	7.38	5.00	3.25	1.25	25.50	69.60	
	4000	2.25	3.10	6.00	14.50	5.50	5.50	3.88	1.70	29.25	71.68	
	F Value	0.59	1.75	1.32	2.13	2.03	1.39	0.97	1.17	1.26		
	OSL	0.7316	0.2388	0.3569	0.1719	0.1873	0.3354	0.5092	0.4141	0.3797		
LSD(.05)	1.60	0.71	2.42	9.92	2.99	2.04	1.29	1.95	15.12			

TABLE XIV: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	DCB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ P ₂	Residual P	Sum of all Fractions	
Parson	0	1.63	6.00	22.38	26.99	9.95	3.13	1.28	1.75	58.50	130.60	
	50	1.58	7.25	23.18	23.00	10.00	2.00	1.60	1.25	65.00	134.85	
	250	0.75	7.00	25.13	26.00	10.33	2.25	1.55	1.50	79.00	154.50	
	500	2.50	6.38	26.25	28.50	9.38	1.80	0.50	1.65	54.10	131.05	
	1000	1.38	7.63	27.25	25.00	10.23	1.50	0.25	0.63	46.00	119.85	
	2000	1.13	7.70	27.50	23.00	10.13	3.25	0.70	1.63	53.50	128.53	
	4000	1.25	8.25	29.38	30.00	9.75	1.50	0.83	1.63	72.50	155.18	
	F Value	0.85	2.20	6.68	2.86	0.04	21.79	4.29	1.13	1.31		
	OSL	0.5700	0.1631	0.0130	0.0900	0.9989	0.0007	0.0394	0.4339	0.3617		
LSD(.05)	1.98	1.77	3.21	5.25	5.30	0.52	0.84	1.32	33.87			
Tipton	0	3.25	5.20	10.75	19.25	7.00	1.88	1.88	1.25	63.00	113.45	
	50	2.75	5.15	11.38	13.00	7.88	1.75	2.00	1.20	104.50	149.60	
	250	4.50	6.88	12.05	12.25	8.25	2.63	1.75	0.25	79.50	128.05	
	500	2.75	5.70	10.43	19.25	5.50	2.88	0.63	0.88	100.00	148.00	
	1000	3.63	5.38	10.93	17.75	4.63	2.38	7.08	0.13	114.00	165.88	
	2000	3.00	4.63	11.68	23.50	6.38	2.63	1.00	1.00	91.50	145.30	
	4000	3.88	4.25	12.05	12.25	6.75	2.38	1.88	0.13	58.00	101.55	
	F Value	1.77	6.16	1.96	4.85	1.15	2.52	1.10	0.91	0.85		
	OSL	0.24	0.0160	0.1994	0.0291	0.4256	0.1260	0.4443	0.5390	0.5684		
LSD(.05)	1.63	1.13	1.54	6.61	3.97	0.87	6.88	1.78	76.71			

TABLE XIV: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	DCB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ P ₂	Residual P	Sum of all Fractions	
Bowie	0	0.25	3.13	5.50	6.50	3.63	1.88	1.30	0.13	20.75	43.05	
	50	1.00	3.25	6.58	9.00	5.05	0.58	1.45	1.20	21.35	49.45	
	250	0.80	3.45	6.95	2.00	5.38	1.38	1.20	1.00	19.40	41.55	
	500	0.25	2.95	6.33	10.50	1.03	1.18	1.70	0.83	21.35	46.10	
	1000	2.00	2.75	6.00	8.50	5.03	1.55	1.88	0.78	21.10	49.58	
	2000	1.00	2.63	6.50	8.50	4.63	1.75	1.45	1.20	21.70	49.35	
	4000	0.73	2.63	5.73	1.00	4.50	1.50	1.33	1.38	21.35	40.13	
	F Value	0.88	0.43	1.49	8.56	8.30	2.44	2.22	1.87	1.03		
	OSL	0.5515	0.8397	0.3034	0.0069	0.0075	0.1346	0.1598	0.2148	0.4773		
	LSD(.05)	2.11	1.64	1.40	4.19	1.74	0.92	0.53	1.01	2.51		
Foard	0	2.50	5.68	11.13	13.20	7.30	1.75	2.50	3.75	36.25	84.05	
	50	1.75	5.68	11.13	14.60	7.75	2.05	3.63	3.93	46.50	97.00	
	250	2.70	6.34	11.00	13.65	6.30	1.75	3.13	3.75	40.50	89.20	
	500	2.70	5.63	10.63	14.15	7.50	1.93	2.75	4.30	42.50	92.08	
	1000	2.13	6.43	11.45	21.45	7.50	2.05	2.18	3.13	55.25	111.55	
	2000	1.50	6.75	1.63	19.55	6.25	1.63	2.25	3.38	44.00	96.93	
	4000	1.75	6.58	13.13	17.00	6.60	1.50	4.00	3.25	47.50	101.30	
	F Value	5.15	2.73	1.28	8.12	0.61	1.76	3.21	5.29	2.90		
	OSL	0.0241	0.1078	0.3728	0.0079	0.7215	0.2376	0.0766	0.0235	0.0949		
	LSD(.05)	0.729	0.98	2.39	3.76	2.69	0.53	1.30	0.60	11.80		

TABLE XIV: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P ₄	NH ₄ F-P ₄	1-NaOH-P	DCB-P	2-NaOH-P	1-HCl-P	2-HCl-P	H ₂ SO ₄ -P ₂	Residual P	Sum of all Fractions	
Zaneis	0	0.13	1.80	6.38	12.80	4.75	2.55	1.93	2.18	38.75	71.25	
	50	0.25	2.45	7.15	8.75	5.00	0.88	1.75	3.28	39.00	68.50	
	250	1.20	5.23	8.80	17.20	5.50	1.43	1.48	2.08	31.85	74.03	
	500	1.55	3.25	8.88	17.60	6.18	1.28	2.53	1.63	41.85	84.73	
	1000	0.63	2.75	9.88	16.85	4.13	0.35	1.28	1.80	43.75	81.50	
	2000	1.05	3.70	10.13	22.50	6.25	0.38	1.80	2.08	40.00	87.88	
	4000	1.00	3.75	8.93	20.45	4.95	0.50	2.00	1.10	43.50	86.18	
	F Value	1.28	12.27	6.47	29.68	1.71	3.59	0.97	1.37	2.46		
	OSL	0.3817	0.0028	0.0141	0.0004	0.2488	0.0598	0.5071	0.3404	0.1323		
LSD(.05)	1.53	1.06	1.81	2.83	1.98	1.39	1.36	1.89	8.64			

at the 0.05 level. This confirms earlier data (Table X) which showed that the amount of P retained at the conclusion of the P desorption study were significantly different by P treatment for the Summit and Bates soils, though such was not the case for the Kingfisher soil. There were no consistent patterns which indicate statistical differences in the Foard soil were due to P treatments, rather, differences appear to be related to higher initial P content. There were no significant differences in the $\text{NH}_4\text{Cl-P}$ fractions for the remaining 11 soils.

Aluminum Phosphate Fraction.

Since most workers accept Chang and Jackson's (1957) nomenclature in P fractionation procedures, the NH_4F fraction is referred to as the Al-P fraction. The Al-P fraction of the Summit soil had significant differences due to P treatments at the .01 level, while the Tipton and Zaneis soils showed significance at the .05 level. Of these three soils only the Al-P fraction of the Summit and Zaneis soils related to the original P treatments. There were no consistent patterns among consecutive P treatments with the Al-P fraction of the Tipton soil.

An analysis of the Al-P content of the remaining 12 soils used in the study did not exhibit significant differences at the .05 level.

Iron Phosphate Fraction.

The 1-NaOH-P fraction was obtained by equilibrating the soil with 0.1 N NaOH and 1 M NaCl (Table IV). This fraction is usually referred to as the Fe-P fraction (Jackson, (1958), Syer, et al, (1973), and others). The Summit soil had a statistical difference due to P treatment at the .01 level for the Fe-P fraction, while the Fe-P fraction for Dill,

Parson, Bates and Zaneis were significant at the .05 level. The Summit, Parson, Bates and Zaneis soils reflected the P treatments in the Fe-P fraction, indicating that a portion of the sorbed P was present in this fraction.

The Fe-P fraction present in the Dill soil did not reflect consecutive differences due to P treatments. Apparently, other Fe-P compounds were initially present in the samples, and were responsible for the statistical significance.

An analysis of the Fe-P fractions from the remaining 10 soils in the study did not show statistical differences at the .05 level.

Reductant Soluble Phosphate Fraction.

The P solubilized in the citrate-dithionite-bicarbonate (CDB) procedure developed by Chang and Jackson (1957) is often referred to as the reductant soluble-P. The CDB-P is considered by Jackson and others as an Fe_2O_3 precipitate formed on the surface of Fe and Al-P particles during weathering by hydrolysis of Fe^{3+} salts. Kingfisher, Bowie, Foard, and Zaneis soils differed significantly in CDB-P content at the .01 level, and the Tipton and Hollister soils were significant at the .05 level when the CDB-P extract was analyzed (Table XIV). Only the Foard and Zaneis soils appeared to have differences due to P treatments, however, in the Kingfisher, Tipton, Hollister, and Bowie, soils the differences appear to be due to sampling or initial CDB-P content instead of P treatments. The other 9 soils in the study did not show statistical differences at .05 level for the CDB-P fractions.

Occluded Phosphate Fraction.

The remaining Fe and Al-P was extracted with 1 N NaOH (Williams, et al. 1967). This strong alkali solution dissolves any remaining Fe oxides and releases any Fe and Al-P compounds occluded within the oxides. Occluded phosphates (Occ-P) are thought to be accumulated over long periods of time, therefore, the conditions of this study should have been prohibitive to any significant change of Occ-P.

The Bowie soil was the only soil which had statistical (.05 level) differences in the Occ-P fraction. Upon examination of the data, treatment 4 had an extremely low reading which was responsible for the observed difference. From the survey of the data it seems safe to assume that there were no real differences found in the Occ-P fractions in any of the soils used in this study.

Calcium Phosphate Fraction.

Determination of Ca-P was accomplished by extracting the soil samples with 0.1 N HCl and then with 1 N HCl for any further Ca-P, according to the procedure of Williams et al. 1967. The analysis of variance for Ca-P fraction by P treatment for the Renfrow, Parson, and Miller soils indicated that there were significant differences between treatments in the .1 N HCl (1-HCl-P) fraction. A close examination of the data indicated that the differences between treatments did not reflect differences between P treatments but instead reflected differences between samples or observations (initial soil differences). The data obtained on the Ulysses, Kingfisher, and Parson soils indicated significant differences at the .05 level in Table XIV for the 1 N HCl

(2-HCl-P) fraction. Of these three soils only the Kingfisher soil appeared to respond to the original P treatments. The Ulysses and Parson soil reflected differences due to native Ca-P compounds present in the soil prior to sampling.

There were no statistically significant differences (.05 level) in Ca-P content in the remaining 10 soils that were used in this study.

Residual Inorganic Phosphate Fraction.

In a final attempt to remove any additional inorganic P from the soil, the samples were extracted with 1N H_2SO_4 . Table XIV indicates that the Ulysses, Renfrow, Hollister and Foard soils showed significant differences in residual inorganic P removed at the .05 level. An examination of the data revealed that these differences were apparently due to differences in amounts of H_2SO_4 soluble P compounds present prior to the P sorption study.

An analysis of the H_2SO_4 -P fraction of the remaining 11 soils did not indicate any statistical differences at the .05 level.

Residual Phosphate Fraction.

At the conclusion of fractionation procedure the soil samples were digested in HNO_3 and $HClO_4$ acids according to Reed (1974). This fraction consisted of organic-P, since the inorganic-P had been removed in the previous fractions. An analysis of variance for the Summit and Ulysses soils produced a highly significant F value (.01 level) indicating that the P treatments did have an effect on the residual (organic) P measured. In the Summit soil, increasing P concentrations

(treatments), resulted in decreasing amounts of P in the residual-P fraction. The reverse situation occurred with the Ulysses soil.

It is difficult to explain why the Summit and Ulysses soils react differently under the same conditions, unless it results from the type of organic compounds present in each soil. There is also the possibility of an incomplete digestion of the soil samples.

The residual P fraction of the Richfield soil had a statistical difference at the .05 level. The statistical difference was not related to the P sorption treatments, rather the differences appeared to be related to initial P differences. There were no significant differences between the residual P fraction after the P treatments in the remaining 12 soils used in the study.

An overall evaluation of Table XIV indicates that for the majority of soils there were no significant differences between different chemical forms of P after 9 Bray extractions (P desorption study). There were some exceptions depending on the soil and the P fraction.

The Summit, Kingfisher and Bates soils had a significant amount of P from the P sorption study present in the NH_4Cl fraction. An examination of the Al-P fraction indicates that P sorption differences due to P treatments were present in the Summit and Zaneis soils. The Summit, Parson, Bates and Zaneis soils reflected P sorption affects in the Fe-P fraction. The Zaneis and Foard soils had significant differences due to the P sorption study in the CDB-P fraction. The analysis of the Occ-P fraction did not reflect P sorption affects with any of the 15 soils used in the study. A review of the Ca-P determinations indicated that only 1 soil (Kingfisher) reflected Ca-P compounds present due to the P sorption study. The evaluation of the data for measuring the effect on

residual inorganic and organic-P were inconclusive in relating the P present in these fractions to P sorption treatments.

Evaluation of the Chemical

Forms of Phosphorus Removed

With Successive Extr-

actions Using the Bray #1

Extractant

According to the pattern depicted in Table III, one set of duplicate samples (C and D) were placed in cold storage (-18°C) at different time intervals to evaluate the chemical forms of P being extracted by the Bray #1 extractant. Table XV presents the data obtained for P treatments 1, 2, and 5 after one extraction with the Bray #1 extractant. Table XVI included the data from P treatments 3 and 6 after 4 Bray extractions and Table XVII is comprised of data from P treatments 4 and 7 after 7 Bray extractions. The $\text{NH}_4\text{Cl-P}$, $\text{NH}_4\text{F-P(Al-P)}$, 1-NaOH-P(Fe-P) , and 1-HCl-P(Ca-P) were the fractions presented in Table XV, XVI, XVII. These were the fractions accounting for almost all of the significant differences (.05 and .01 level) due to initial P sorption treatments.

Ammonium Chloride Phosphate Fraction .

The data in Table XV indicate that there were significant differences between P treatments 1, 2, and 5 (0, 50, and 1000 $\mu\text{g P/g soil}$, respectively) at the .05 level in the $\text{NH}_4\text{Cl-P}$ fraction for all soils with the exception of the Renfrow and Bowie. This indicates that the P extracted in the first Bray extraction reflected the P treatments.

TABLE XV

PHOSPHATE CONCENTRATIONS ($\mu\text{g P/g SOIL}$) PRESENT IN
 CERTAIN FRACTIONS AFTER ONE BRAY #1 EXTRACTION
 IN FIFTEEN OKLAHOMA SOILS EQUILIBRATED WITH
 THREE DIFFERENT PHOSPHORUS LEVELS.

Soil Type	Initial P Treatment ($\mu\text{g P/g}$)	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
	Summit	0	0.25	5.78	45.00
50		3.63	11.78	52.75	18.05
1000		26.98	52.20	91.75	19.00
F Value		4066.68	188.70	449.75	1.97
OSL*		0.0001	0.0008	0.0003	0.2833
LSD(.05)		1.03	8.27	5.32	2.80
Ulysses	0	3.45	1.23	17.25	23.00
	50	8.25	1.00	14.13	16.00
	1000	11.45	4.80	18.63	15.00
	F Value	75.70	19.46	10.41	1.43
	OSL	0.0025	0.0184	0.0443	0.3660
	LSD(.05)	2.08	2.18	4.57	11.21
Richfield	0	13.95	21.00	33.25	102.25
	50	15.38	25.65	26.50	103.25
	1000	17.05	21.38	32.75	99.50
	F Value	13.23	28.47	339.50	0.12
	OSL	0.0319	0.0106	0.0004	0.8929
	LSD(.05)	1.92	2.18	0.92	6.10
Renfrow	0	6.00	4.50	30.50	45.38
	50	6.05	4.20	25.75	48.25
	1000	6.03	4.45	23.70	42.63
	F Value	0.60	1.24	0.42	0.79
	OSL	0.6051	0.4057	0.6910	0.5371
	LSD(.05)	0.15	0.65	24.18	14.25
Kingfisher	0	3.00	9.75	20.00	26.43
	50	4.13	12.13	19.50	25.88
	1000	13.50	21.25	23.37	26.00
	F Value	255.24	51.66	3.91	0.02
	OSL	0.0005	0.0044	0.1465	0.9801
	LSD(.05)	1.62	3.80	4.73	8.74

* OSL - Observation Significance Level

TABLE XV.: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
	(ug P/gl)				
Dill	0	0.75	5.50	5.88	60.25
	50	3.25	13.88	8.25	85.50
	1000	1.75	7.48	8.00	50.50
	F Value	9999.99	3.32	1.07	1.48
	OSL	0.0001	0.1742	0.4464	0.3566
	LSD(.05)	0.00	10.82	5.67	66.75
Grandfield	0	2.63	4.13	7.80	77.00
	50	3.38	5.13	7.00	75.75
	1000	3.93	7.18	8.25	64.25
	F Value	9.33	4.72	1.88	11.08
	OSL	0.0513	0.1189	0.2957	0.0407
	LSD(.05)	0.96	3.22	2.08	9.50
Parson	0	2.13	19.00	3.38	3.38
	50	3.63	14.00	2.50	2.50
	1000	8.50	40.38	2.25	2.25
	F Value	1066.50	9.50	102.91	3.94
	OSL	0.0001	0.0501	0.0017	0.1452
	LSD(.05)	0.46	20.45	4.96	1.34
Tipton	0	2.50	30.75	11.13	86.00
	50	4.25	30.13	10.25	89.88
	1000	8.00	30.00	12.30	87.25
	F Value	9.97	0.01	4.00	1.56
	OSL	0.0469	0.9879	0.1428	0.3431
	LSD(.05)	4.00	15.36	2.31	7.12
Hollister	0	8.03	16.63	21.05	63.38
	50	12.38	19.50	24.50	64.25
	1000	21.50	27.25	27.63	64.75
	F Value	11.57	16.43	13.15	0.64
	OSL	0.0384	0.0235	0.0322	0.5875
	LSD(.05)	9.10	6.10	4.08	3.91
Bates	0	2.63	28.13	66.50	1.58
	50	3.38	25.38	73.00	1.70
	1000	11.50	57.00	96.50	1.48
	F Value	26.13	9.83	186.81	0.26
	OSL	0.0120	0.0479	0.0068	0.7893
	LSD(.05)	4.33	25.15	5.20	1.00

TABLE XV: (CONTINUED)

Soil Type	Initial P Treatment (ug P/g)	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
	Miller	0	36.50	67.00	63.50
50		38.88	69.63	65.75	121.38
1000		49.75	80.50	73.50	129.00
F Value		47.68	11.37	10.83	4.62
OSL		0.0050	0.0393	0.0420	0.1218
LSD(.05)		4.61	9.55	7.18	8.87
Bowie	0	1.13	3.45	7.63	1.80
	50	1.55	3.88	7.08	1.05
	1000	3.00	5.38	7.80	0.93
	F Value	7.38	19.33	1.82	0.84
	OSL	0.0695	0.0186	0.3039	0.5137
	LSD(.05)	1.63	1.04	1.26	2.32
Foard	0	3.25	10.55	13.45	14.75
	50	4.50	12.88	15.38	15.83
	1000	10.18	23.88	19.88	15.75
	F Value	312.82	118.39	205.47	6.72
	OSL	0.0004	0.0014	0.0007	0.0782
	LSD(.05)	0.94	2.94	1.04	3.25
Zaneis	0	0.93	2.28	6.10	14.85
	50	1.88	5.13	9.00	16.40
	1000	8.00	14.98	17.75	18.50
	F Value	119.16	160.14	1765.56	12.82
	OSL	0.0014	0.0009	0.0001	0.0333
	LSD(.05)	1.58	2.37	0.65	1.89

TABLE XVI

PHOSPHATE CONCENTRATIONS (ug P/g SOIL) PRESENT IN
CERTAIN FRACTIONS AFTER FOUR BRAY #1
EXTRACTIONS IN FIFTEEN OKLAHOMA
SOILS EQUILIBRATED WITH TWO
DIFFERENT PHOSPHORUS LEVELS.

Soil Type	Initial P Treatment (ug P/g)	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
Summit	250	2.70	14.33	66.00	10.13
	2000	7.28	36.38	96.00	10.50
	F Value	19.60	13.74	49.32	9.00
	OSL*	0.0445	0.0638	0.0161	0.0949
	LSD(.05)	4.45	25.59	18.38	0.54
Ulysses	250	13.75	7.30	22.63	84.00
	2000	14.38	8.00	24.13	82.50
	F Value	0.41	1.88	4.24	1.00
	OSL	0.5873	0.3041	0.1767	0.4238
	LSD(.05)	4.20	2.19	3.14	6.45
Richfield	250	15.68	26.25	27.38	105.25
	2000	17.18	23.85	34.25	98.75
	F Value	1.05	1.16	336.11	1.45
	OSL	0.4138	0.3954	0.0021	0.3524
	LSD(.05)	6.29	9.59	1.61	23.22
Renfrow	250	5.50	4.50	21.88	35.63
	2000	6.65	4.65	22.25	76.00
	F Value	2.17	1.00	0.02	14.11
	OSL	0.2795	0.4238	0.8968	0.0621
	LSD(.05)	3.36	0.65	11.55	46.24
Kingfisher	250	5.03	10.75	20.75	16.05
	2000	5.00	11.45	20.33	18.88
	F Value	0.01	0.42	0.11	55.76
	OSL	0.9400	0.5829	0.7614	0.0140
	LSD(.05)	1.30	4.64	5.43	1.63
Dill	250	0.00	1.78	2.75	49.63
	2000	0.03	3.25	4.25	46.00
	F Value	1.00	3481.00	7.20	2.33
	OSL	0.4238	0.0004	0.1154	0.2672
	LSD(.05)	0.11	0.11	2.41	10.21

* OSL - Observation Significance Level

TABLE XVI: (CONTINUED)

Soil Type	Initial P Treatment (ug P/g)	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
	Grandfield	250	5.25	5.13	7.55
2000		7.13	5.45	8.38	4.13
F Value		9.00	0.13	1.81	13.88
OSL		0.0949	0.7457	0.3112	0.0600
LSD(.05)		2.70	3.86	2.64	17.02
Parson	250	1.75	15.38	42.75	22.50
	2000	1.25	15.75	47.38	1.50
	F Value	1.00	0.36	47.21	1.00
	OSL	0.4238	0.6086	0.0170	0.5762
	LSD(.05)	2.15	2.69	2.90	3.23
Tipton	250	11.38	8.75	11.88	51.88
	2000	12.38	9.38	11.68	51.38
	F Value	0.49	5.00	0.05	0.07
	OSL	0.5557	0.1556	0.8402	0.8100
	LSD(.05)	6.13	1.20	3.96	8.23
Hollister	250	11.88	15.13	22.63	40.75
	2000	13.13	15.13	23.75	37.13
	F Value	1.11	0.00	1.65	0.10
	OSL	0.4035	0.9955	0.3280	0.7733
	LSD(.05)	5.10	3.80	3.76	1.10
Miller	250	19.00	36.75	42.75	58.50
	2000	22.38	27.50	45.75	62.00
	F Value	17.78	0.18	72.00	2.88
	OSL	0.0492	0.7081	0.0105	0.2325
	LSD(.05)	3.44	7.61	1.52	8.87
Bowie	250	0.50	3.45	5.95	1.25
	2000	0.80	5.50	6.88	1.75
	F Value	0.88	16.64	47.21	2.00
	OSL	0.5511	0.0527	0.0170	0.2933
	LSD(.05)	1.38	2.16	0.58	1.32
Foard	250	4.18	12.38	16.13	6.63
	2000	3.75	12.38	15.75	6.00
	F Value	0.31	0.00	0.22	1.47
	OSL	0.6317	1.0000	0.6832	0.3497
	LSD(.05)	3.28	1.70	3.44	2.22
Zaneis	250	1.68	4.05	11.63	2.05
	2000	1.88	6.63	14.88	0.68
	F Value	1.88	84.87	19.88	121.00
	OSL	0.3043	0.0087	0.0438	0.0059
	LSD(.05)	0.63	1.20	3.14	0.54

TABLE XVII

PHOSPHATE CONCENTRATIONS ($\mu\text{g P/g SOIL}$) PRESENT IN
CERTAIN FRACTIONS AFTER SEVEN BRAY #1
EXTRACTIONS IN FIFTEEN OKLAHOMA
SOILS EQUILIBRATED WITH TWO
DIFFERENT PHOSPHORUS LEVELS.

Soil Type	Initial P Treatment ($\mu\text{g P/g}$)	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
	Summit	500	2.85	9.75	70.50
4000		3.25	15.83	97.00	6.25
F Value		0.64	160.02	112.36	0.35
OSL*		0.51	0.0043	0.0064	0.6149
LSD(.05)		2.15	2.07	10.76	5.48
Ulysses	500	11.43	6.15	26.38	34.50
	4000	14.75	9.18	28.13	35.38
	F Value	118.72	40.11	1.01	1.96
	OSL	0.0060	0.0204	0.4219	0.2971
	LSD(.05)	1.31	2.06	7.49	2.69
Richfield	500	20.88	24.00	35.63	44.50
	4000	20.88	23.25	38.80	42.88
	F Value	0.00	0.07	11.45	6.76
	OSL	1.0000	0.8106	0.0760	0.1218
	LSD(.05)	0.76	12.40	4.04	2.70
Renfrow	500	6.88	4.50	22.93	45.25
	4000	8.20	4.65	25.13	44.13
	F Value	0.93	0.11	1.73	0.00
	OSL	0.5616	0.7636	0.3195	0.9763
	LSD(.05)	5.92	1.94	7.19	150.94
Kingfisher	500	2.90	8.00	19.38	5.30
	4000	6.13	8.88	20.00	5.00
	F Value	63.76	0.67	1.00	1.38
	OSL	0.0120	0.5004	0.4238	0.3612
	LSD(.05)	1.74	4.60	2.69	1.10
Dill	500	0.05	2.88	1.75	49.50
	4000	0.38	1.75	3.00	44.75
	F Value	0.75	9.00	9999.99	2.14
	OSL	0.5231	0.0949	0.0003	0.2820
	LSD(.05)	1.61	1.61	0.00	13.98

* OSL - Observation Significance Level

TABLE XVII: (CONTINUED)

Soil Type	Initial P Treatment	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
	(ug P/g)				
Grandfield	500	5.75	5.50	7.75	11.00
	4000	7.50	5.00	7.75	9.75
	F Value	1.96	4.00	0.00	0.34
	OSL	0.2971	0.1844	0.9955	0.6167
	LSD(.05)	5.38	1.08	3.04	9.19
Parson	500	1.40	9.50	33.00	2.33
	4000	1.00	10.25	37.38	2.08
	F Value	9999.99	2.25	3.39	0.06
	OSL	0.0003	0.2731	0.2077	0.8187
	LSD(.05)	0.00	2.15	10.22	4.33
Tipton	500	11.00	9.50	11.80	7.00
	4000	14.13	9.55	14.13	10.50
	F Value	125.00	0.00	59.50	4.90
	OSL	0.0057	0.9518	0.0130	0.1581
	LSD(.05)	1.20	3.20	1.65	6.80
Hollister	500	9.25	11.38	23.60	8.13
	4000	12.13	12.50	25.05	7.88
	F Value	105.80	0.42	0.59	0.02
	OSL	0.0068	0.5833	0.5222	0.8865
	LSD(.05)	1.20	7.47	8.10	7.01
Bates	500	1.68	13.88	36.38	1.38
	4000	1.50	15.50	39.93	0.78
	F Value	0.45	6.76	1.09	0.86
	OSL	0.5715	0.1218	0.4073	0.5482
	LSD(.05)	1.12	2.69	10.51	2.78
Miller	500	12.38	21.50	31.20	23.88
	4000	14.38	21.88	35.13	25.50
	F Value	128.00	0.31	12.15	9.94
	OSL	0.0055	0.6321	0.07	0.0867
	LSD(.05)	0.76	2.90	4.85	2.22
Bowie	500	0.63	4.08	7.33	1.68
	4000	0.50	3.25	6.88	0.63
	F Value	0.20	1.42	4.38	51.88
	OSL	0.6946	0.3559	0.1724	0.0152
	LSD(.05)	1.20	2.98	0.93	0.63

TABLE XVII: (CONTINUED)

Soil Type	Initial P	NH ₄ Cl-P	NH ₄ F-P	1 NaOH-P	1 HCl-P
	Treatment (ug P/g)				
Foard	500	2.88	8.63	13.58	2.75
	4000	2.95	8.05	13.88	2.25
	F Value	0.31	1.04	1.95	2.00
	OSL	0.6321	0.4164	0.2984	0.2935
	LSD(.05)	0.58	2.43	0.93	1.52
Zaneis	500	1.68	3.55	10.13	1.53
	4000	2.25	5.15	12.13	0.43
	F Value	1.29	39.88	25.60	38.72
	OSL	0.3742	0.0208	0.0335	0.0212
	LSD(.05)	2.18	1.10	1.70	0.76

Tables XVI and XVII are comprised of P fractionation data obtained after 4 and 7 Bray extractions, respectively. After 4 extractions only the $\text{NH}_4\text{Cl-P}$ fractions of the Summit and Miller soils had significant differences between P treatments 3 and 6 (250 and 2000 ug P/g soils, respectively). When the $\text{NH}_4\text{Cl-P}$ fractionation data was evaluated after 7 Bray extractions (Table XVII), the Ulysses, Kingfisher, Tipton, Hollister and Miller soils had statistical differences between P treatments 4 and 7 (500 and 4000 ug P/g soil, respectively). The data for the Parson soil indicated statistical differences, due to P treatments. An examination of the data showed that the differences were due to the zero threatment - (0 ug P/g) variations between duplicate observations.

The data in Tables XV - XVII indicate that the Bray extraction does remove substantial quantities of the P found in NH_4Cl fraction, and the data in Table XIV confirms this statement. The duplicates in Table XIV were subjected to the entire P desorption study and the Summit, Kingfisher and Bates soils were the only soils with statistical differences between P treatments when the NH_4Cl extraction was evaluated.

Aluminum Phosphate Fraction.

The data for the NH_4F fraction (Al-P) was evaluated for statistical differences between P treatments (1,2, and 5) after one Bray extraction. The data in Table XV indicates that Renfrow, Dill, Grandfield, and Tipton soils did not show statistical differences in the Al-P fraction due to P treatments. The $\text{NH}_4\text{F-P}$ fraction for Summit, Kingfisher, Foard, and Zaneis soils were statistically different at the .01 level and the

Ulysses, Richfield, Parson, Hollister, Bates, Miller and Bowie were statistically different at the .05 level.

Table XVI includes the data for the $\text{NH}_4\text{F-P}$ fraction after 4 Bray extractions, these data indicate that the $\text{NH}_4\text{F-P}$ fraction from the Summit, Dill, Bowie, and Zaneis soils were significantly different at the .05 level. The remaining 11 soils did not have statistical differences in the $\text{NH}_4\text{F-P}$ fraction between P treatments 3 and 6.

Table XVII included P treatments 4 and 7 and when the $\text{NH}_4\text{F-P}$ fraction was evaluated statistically the Summit, Ulysses, Dill, Bowie and Zaneis had differences (.05 level) between P treatments. Table XIV, which includes the NH_4F fraction evaluated after 9 Bray extractions, shows that only the Summit and Zaneis soils had statistical differences due to the initial P sorption treatments.

The data presented in Tables, XIV, XV, XVI, and XVII indicates that the Bray #1 extractant is extracting P from the NH_4F fraction.

Iron Phosphate Fraction.

The 1-NaOH-P fraction (Fe-P) was statistically analyzed for difference between P treatments within soil types and the data is included in Tables XIV, XV, XVI, and XVII. Table XV consists of data from P treatments 1, 2 and 5. The data in Table XV indicate that the Fe-P fraction present in the Summit, Richfield, Parson, Bates, Foard, and Zaneis soils show statistical differences between P treatments at the .01 level after only 1 extraction with the Bray extraction. Table XV also includes data which indicate that the Fe-P fraction from Ulysses, Hollister, and Miller soils were statistically different at the .05 level with respect to P treatments. There were no differences statistically

in the Fe-P fractions present in the Renfrow, Kingfisher, Dill, Grandfield, Tipton, and Bowie soils with respect to P treatments.

When the Fe-P fraction was determined after 4 Bray extractions (Table XVI), the data indicated that Summit, Richfield, Parson, Miller, Bowie, and Zaneis soils had statistical differences between P treatments 3 and 6. The Fe-P fractions in the remaining 9 soils were not statistically different with respect to P treatments 3 and 6.

Table XVII includes data for the 1-NaOH-P (Fe-P) fraction after 7 Bray extractions and includes P treatments 4 and 7. The data in Table XVII indicates that the Fe-P fraction in the Summit, Dill, Tipton, and Zaneis soils were statistically different between P treatments. There were no statistical differences in the Fe-P fractions between P treatments for the remaining 11 soils.

Table XIV includes all of the P sorption treatment data and the soil samples were extracted 9 times with the Bray #1 extractant. The Summit, Dill, Parson, Bates, and Zaneis were the only soils with differences in the Fe-P fraction at the .05 level due to P treatments.

The data presented in these tables show that the Bray #1 extractant does extract some P from the Fe-P fraction.

Calcium Phosphate Fraction.

The data in Table XV which also includes the 1-HCl-P (Ca-P) fraction indicate that of the 15 soils used in this study only the Grandfield, Foard, and Zaneis soils had statistical differences (.05 level) between P treatments 1, 2, and 5 after 1 Bray extraction. After 4 Bray extractions there were statistical differences in the Ca-P fraction between P treatments 2 and 6 in the Kingfisher and Zaneis soils.

The differences in the Ca-P fraction in the Zaneis soil appeared to be related to the initial Ca-P level before P treatments were applied. Table XVII also includes data for the Ca-P fraction and it indicates that there were no soils with significant differences between P treatments due to the P treatments themselves.

The data presented in Tables XV, XVI and XVII show that the soils used in this study did not form much Ca-P due to the added P. The data in Tables XIV includes all 7 P treatments with 9 Bray extractions. This data indicates that the Kingfisher soil was the only soil that reflected significant differences due to the initial P treatments.

In a further attempt to evaluate the relationship of the NH_4Cl , NH_4F , 1-NaOH and 1-HCl extractable P to each other and to selected soil chemical and physical properties, correlation coefficients were determined and included in Tables XVIII, XIX, XX, and XXI.

The NH_4Cl -P fraction was significantly correlated with surface area, surface area after heating (500°C), C.E.C., and % clay as depicted in Tables XVIII-XXI. This indicates that the NH_4Cl -P fraction of P is associated with soil colloid surfaces but not with Al and Fe compounds to any great extent. In some cases (Tables XIX and XX) the NH_4Cl -P fraction is significantly correlated to the $\%\text{CaCO}_3$ content in soils and to the NH_4F -P fraction (Tables XVIII-XXI). The NH_4Cl -P fraction was also correlated to the 1-HCl-P (Ca-P) fraction until the 9th Bray extraction (Table XXI). The decrease in correlation between NH_4Cl -P and Ca-P is probably due to a decrease in extractable Ca-P with continued Bray extractions. There were no statistical correlations between the 1-NaOH-P (Fe-P) fraction and the NH_4Cl -P fraction.

The correlation between the NH_4F -P (Al-P) fraction and various soil

TABLE XVIII

CORRELATION COEFFICIENTS BETWEEN VARIOUS SOIL CHARACTERISTICS
AND SELECTED PHOSPHATE FRACTIONS AVERAGED OVER PHOSPHORUS
RATES OF 0, 50, AND 1000 $\mu\text{g P/g}$ OF SOIL
IN FIFTEEN OKLAHOMA SOILS.

Soil Characteristics	Phosphate Fractions			
	$\text{NH}_4\text{Cl-P}$	$\text{NH}_4\text{F-P}$	1-NaOH-P	1-NCl-P
%Organic Matter	0.20	0.19	0.48	-0.26
Exchangeable Aluminum	-0.25	-0.27	-0.28	-0.31
% Fe_2O_3	0.36	0.43	0.76**	-0.18
Surface Area	0.59*	0.41	0.42	0.45
Heated Surface Area	0.70**	0.46	0.39	0.54*
CEC	0.72**	0.55*	0.41	0.43
% CaCO_3	0.42	0.33	0.04	0.69**
Citrate Extractable Aluminum	-0.10	-0.02	0.42	-0.64**
pH	0.18	0.03	-0.40	0.71**
% Clay	0.72**	0.61*	0.58*	0.20
$\text{NH}_4\text{Cl-P}$	1.00	0.83**	0.49	0.57*
$\text{NH}_4\text{F-P}$	0.83**	1.00	0.71**	0.30
1-NaOH-P	0.49	0.71**	1.00	-0.13
1-HCl-P	0.57*	0.30	-0.13	1.00

* Indicates significance at the 0.05 level.

** Indicates significance at the 0.01 level.

TABLE XIX

CORRELATION COEFFICIENTS BETWEEN VARIOUS SOIL CHARACTERISTICS
AND SELECTED PHOSPHATE FRACTIONS FROM AVERAGED
PHOSPHORUS RATES OF 250 and 2000 $\mu\text{g P/g}$
OF SOIL IN FIFTEEN OKLAHOMA SOILS.

Soil Characteristics	$\text{NH}_4\text{Cl-P}$	$\text{NH}_4\text{F-P}$	l-NaOH-P	l-HCl-P
% Organic Matter	-0.03	0.45	0.76**	-0.25
Exchangeable Aluminum	-0.32	-0.30	-0.30	-0.31
% Fe_2O_3	0.01	0.60*	0.88**	-0.23
Surface Area	0.67**	0.67**	0.62**	0.46
Heated Surface Area	0.78**	0.73**	0.56*	0.57*
CEC	0.66**	0.72**	0.60*	0.34
% CaCO_3	0.51*	0.30	0.18	0.61*
Citrate Extractable Aluminum	-0.36	0.21	0.54*	-0.60*
pH	0.47	-0.06	-0.27	0.64**
% Clay	0.47	0.72**	0.66**	0.07
$\text{NH}_4\text{Cl-P}$	1.00	0.58*	0.16	0.77**
$\text{NH}_4\text{F-P}$	0.58*	1.00	0.75**	0.18
l-NaOH-P	0.16	0.75**	1.00	-0.11
l-HCl-P	0.77**	0.18	-0.11	1.00

* Indicates significance at the 0.05 level.

** Indicates significance at the 0.01 level.

TABLE XX

CORRELATION COEFFICIENTS BETWEEN VARIOUS SOIL CHARACTERISTICS
AND SELECTED PHOSPHATE FRACTIONS FROM AVERAGED
PHOSPHORUS RATES OF 500 AND 4000 $\mu\text{g P/g}$
OF SOILS IN FIFTEEN OKLAHOMA SOILS.

Soil Characteristics	$\text{NH}_4\text{Cl-P}$	$\text{NH}_4\text{F-P}$	1-HaOH-P	1-HCl-P
% Organic Matter	-0.03	0.45	0.80**	-0.25
Exchangeable Aluminum	-0.32	-0.30	-0.29	-0.31
% Fe_2O_3	0.01	0.60*	0.83**	-0.23
Surface Area	0.67**	0.67**	0.68**	0.46
Heated Surface Area	0.78**	0.73**	0.63**	0.57*
CEC	0.66**	0.72**	0.63**	0.34
% CaCO_3	0.51*	0.30	0.22	0.61*
Citrate Extractable Aluminum	-0.36	0.21	0.54*	-0.60*
pH	0.47	-0.05	0.18	0.64**
% Clay	0.47	0.72**	0.60*	0.07
$\text{NH}_4\text{Cl-P}$	1.00	0.58*	0.12	0.77**
$\text{NH}_4\text{F-P}$	0.58*	1.00	0.55*	0.18
1-NaOH-P	0.12	0.55*	1.00	-0.07
1-HCl-P	0.77**	0.18	-0.07	1.00

* Indicates significance at the 0.05 level.

** Indicates significance at the 0.01 level.

TABLE XXI

CORRELATION COEFFICIENTS BETWEEN VARIOUS SOIL CHARACTERISTICS
AND SELECTED PHOSPHATE FRACTIONS AVERAGED OVER
0,50,250,500,1000,2000 and 4000 ug P/g OF
SOIL IN FIFTEEN OKLAHOMA SOILS.

Soil Characteristics	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	1-HCl-P
% Organic Matter	-0.08	0.10	0.72**	-0.29
Exchangeable Aluminum	-0.25	-0.28	-0.32	-0.22
% Fe ₂ O ₃	-0.10	0.20	0.75**	-0.20
Surface Area	0.67**	0.55*	0.71**	-0.03
Heated Surface Area	0.78**	0.71*	0.70**	0.05
CEC	0.54*	0.48	0.61*	-0.08
% CaCO ₃	0.43	0.18	0.22	0.50
Citrate Extractable Aluminum	-0.35	-0.02	0.48	-0.53*
pH	0.45	0.03	-0.15	0.44
% Clay	0.33	0.39	0.56*	-0.20
NH ₄ Cl-P	1.00	0.73**	0.31	0.25
NH ₄ F-P	0.73**	1.00	0.53*	-0.03
1-NaOH-P	0.31	0.53*	1.00	-0.12
1-HCl-P	0.25	-0.03	-0.11	1.00

* Indicates significance at the 0.05 level.

** Indicates significance at the 0.01 level.

factors and other P fractions is also given in Tables XVIII-XXI. In general, factors that relate to soil surfaces such as % clay, C.E.C. surface area, and heated surface area were correlated with the Al-P fraction. Surprisingly, the citrate extractable Al and exchangeable Al (1N KCl) procedure was not significantly correlated to the Al-P fraction, in fact, all of the correlation coefficients between these variables were negative.

For the soils and conditions used in this study it would appear that the NH_4F fraction is not related to the type of Al determinations made, but the $\text{NH}_4\text{F-P}$ fraction is statistically correlated with the $\text{NH}_4\text{Cl-P}$ and 1-NaOH-P fraction.

The 1-NaOH-P fraction (Fe-P) is also evaluated in Tables XVIII - XXI. In all instances the Fe-P fraction is highly correlated to the % Fe_2O_3 present in soils and to % O.M., % clay, surface area measurements, and C.E.C. The Fe-P fraction was also found to be correlated with the $\text{NH}_4\text{F-P}$ fraction but generally was not significantly correlated to the $\text{NH}_4\text{Cl-P}$ fraction nor the 1-HCl-P fraction.

The final P fraction to be evaluated in Tables XVIII - XXI is the 1-HCl-P (Ca-P) fraction. The Ca-P fraction was positively correlated to the % CaCO_3 present in the soils and pH but was negatively correlated to the extractable Al. There was a significant correlation of Ca-P and the heated surface area measurement but not to the non-heated surface area measurement. A good correlation between the Ca-P fraction and the $\text{NH}_4\text{Cl-P}$ fraction is shown in Tables XVIII - XX.

Relationship Between P
Sorption Constants and
Bray #1 Extractions with
Selected P Fractions

Correlation coefficients were used to determine the relationship between P sorption data and P sorption Langmuir constants with selected P fractions from the P fractionation study (Table XXII). The 1-NaOH-P (Fe-P) fraction was found to be significantly correlated with the P sorption maxima for region 1 (b_1) regardless of the number of Bray extractions. The Fe-P fraction was also correlated with the remaining P sorption values (b , b_2 , and P sorbed averaged over all 7 P treatments) for all Bray extractions except for the first Bray extraction. The Fe-P fraction was also significantly correlated with the Langmuir binding energy constants (k , k_1) except for region 2 (k_2). Thus, soils that contain high levels of Fe-P also have large P sorption capacities.

In general, repeated extractions with the Bray #1 extractant resulted in an increase in the correlation between the amount of P sorbed (Langmuir constants) and the amount of P remaining in the Fe-P fraction. This is interpreted to mean that the P being removed by the Bray #1 extractant tended to be other than Fe-P. The data in Table XXIII tends to support this reasoning. The P removed with continued extraction with the Bray #1 extractant becomes increasingly correlated to the $\text{NH}_4\text{Cl-P}$ and the $\text{NH}_4\text{F-P}$ fractions. The Fe-P (1-NaOH-P) and Ca-P (1-HCl-P) fractions are not statistically correlated to the P removed by the Bray #1 extractant. This data supports the work by Norwood (1972), who found that the $\text{NH}_4\text{Cl-P}$ and the $\text{NH}_4\text{F-P}$ were the two forms of P most available to plants. Norwood also concluded that Bray P was well

TABLE XXII

CORRELATION COEFFICIENTS BETWEEN SELECTED P SORPTION
ISOTHERM VALUES AND SOIL P FRACTIONS OBTAINED
AFTER DIFFERING NUMBERS OF
BRAY #1 EXTRACTIONS.

1 Extraction ²	b	b ₁	b ₂	k	k ₁	k ₂	P Sorbed ¹
NH ₄ Cl-P	0.15	0.17	-0.01	-0.23	-0.20	-0.18	-0.03
NH ₄ F-P	-0.03	0.15	-0.15	0.11	0.07	-0.24	-0.09
1-NaOH-P	0.43	0.69**	0.32	0.59*	0.61*	-0.30	0.46
1-HCl-P	0.06	-0.31	0.02	-0.70**	-0.62*	0.13	-0.19
4 Extractions ³							
NH ₄ Cl-P	0.12	-0.03	0.06	-0.47	-0.41	-0.08	-0.08
NH ₄ F-P	0.28	0.45	0.16	0.26	0.31	-0.27	0.27
1-NaOH-P	0.66**	0.84**	0.61**	0.60*	0.73**	-0.30	0.76**
1-HCl-P	0.08	-0.28	0.09	-0.63*	-0.54	-0.09	-0.14

TABLE XXII: (CONTINUED)

7 Extractions ⁴	b	b ₁	b ₂	k	k ₁	k ₂	P Sorbed ¹
NH ₄ Cl-P	0.03	-0.17	0.02	-0.50	-0.43	-0.04	-0.13
NH ₄ F-P	0.13	0.24	0.06	0.11	0.15	-0.25	0.11
1 NaOH-P	0.71**	0.83**	0.68**	0.54*	0.71**	-0.30	0.81**
1-HCl-P	0.11	-0.25	0.09	-0.55*	-0.46	-0.08	-0.10
9 Extractions ⁵							
NH ₄ Cl-P	0.17	-0.03	0.16	-0.42	-0.36	-0.13	-0.01
NH ₄ F-P	0.03	0.14	-0.04	0.03	0.06	-0.23	-0.01
1-NaOH-P	0.69**	0.77**	0.66**	0.48	0.65**	-0.32	0.77**
1-HCl-P	0.01	-0.32	0.00	-0.48	-0.41	-0.07	-0.16

* Indicates significance at the 0.05 level

** Indicates significance at the 0.01 level.

- (1) The P sorbed values represent the average amount of P sorbed by each soil from the P treatments.
- (2) Extraction 1 pertains to P treatments 1,2, and 5 for each soil.
- (3) Extraction 4 pertains to P treatments 3 and 6 for each soil.
- (4) Extraction 7 pertains to P treatments 4 and 7 for each soil.
- (5) Extraction 9 pertains to P treatments 1-7 for each soil with 2 observations per treatment.

TABLE XXIII
 CORRELATION COEFFICIENTS BETWEEN THE
 BRAY #1 EXTRACTIONS AND
 SELECTED P FRACTIONS.

Extraction No.	NH ₄ Cl-P	NH ₄ F-P	1-NaOH-P	1-HCl-P
1	0.14	0.26	0.38	-0.43
2	0.32	0.54*	0.43	-0.21
3	0.52*	0.64**	0.51*	-0.10
4	0.59*	0.70**	0.48	-0.04
5	0.76**	0.76**	0.45	-0.01
6	0.86**	0.75**	0.44	0.07
7	0.86**	0.63**	0.40	0.07
8	0.93**	0.80**	0.28	0.28
9	0.98**	0.82**	0.20	0.20

* Indicates significance at the 0.05 level.

** Indicates significance at the 0.01 level.

correlated with yield on all the soils used in his study.

The data in Table XXII shows that the Ca-P fraction was negatively correlated with the Langmuir binding energy constants. The level of significance of this correlation decreased with continued Bray extractions. This decrease in correlation was probably due to the decrease in the amount of Ca-P present in the soils after 9 Bray extractions (see Tables XVII - XXI).

CHAPTER V

SUMMARY AND CONCLUSION

In an attempt to further the understanding of the P chemistry in Oklahoma soils, 15 important soil series were selected and used in this study. Samples were equilibrated with different P treatments in an attempt to measure the P sorption capacity of each soil type. Soil samples which were treated with different P concentrations were extracted with a series of extractions using the Bray #1 extractant to measure the amount and types of P extracted or desorbed in a sequential P desorption study. The soil samples were subjected to a P fractionation study to measure the chemical forms of P remaining in the soils at the completion of the P sorption study, at different stages in the P desorption study, and at the end of the P desorption study. The following conclusions were reached from the P sorption, P desorption, and P fractionation studies.

Phosphorus Sorption Study

1. Nearly all soils showed significant differences in the amount of P sorbed due to the increasing rates of P added (P treatments). Soils which did not show significant differences between P treatments appear to have had much of their P sorption capacity saturated with P prior to the initiation of this study. An analysis of variance was useful in determining the maximum P sorption capacity. Failure to obtain

significant differences between treatments at high P concentrations was used as an indication that P sorption was at or near the maximum capacity.

2. Phosphate sorption Langmuir isotherms were not linear for the majority of the soils used in this study. This indicates that the conventional Langmuir equation would not adequately predict the amount of P sorbed. The re-arranged Langmuir equation was used to predict P sorption maxima (b values) and indices of bounding energy (k values). The curved P sorption isotherm was fitted by 2 straight lines, one for predicting b_1 and k_1 at lower P rates, and the other for predicting b_2 and k_2 at higher P rates. This method appears to be useful for determining the number or types P sorption reactions.

3. Correlation coefficients (r) were used to measure the relationship of various soil properties to P sorption. Citrate extractable Al and % clay were found to be significantly correlated to P sorption in region 1 (low P concentrations) but were not significantly correlated in region 2 (high P concentrations) of the re-arranged Langmuir isotherm plots. The % O.M., % Fe_2O_3 and surface area were significantly correlated with the sorption of P at the higher levels used in this study. From this data, it is postulated that Al and Fe compounds associated with clay minerals and organic matter are responsible for much of the P sorption in the Oklahoma soils studies. The 15 soils used in this study are representative of the majority of the soils found in the state.

Phosphorus Desorption Study

1. Generally, repeated extractions with Bray #1 extractant did remove all of the P sorbed in the P sorption studies. There

were significant differences in P treatments at the conclusion of 9 Bray extractions in the Summit and Bates soils. These differences appear related to differences in O.M. and Fe content present in the Summit and Bates soils in comparison to the remaining 13 soils.

2. The relationship between the amount of P extracted and %O.M., % Fe_2O_3 , pH and % clay appeared to decrease in significance with continued extraction with the Bray #1 extractant. While the surface area properties were significantly correlated to the P extracted in the latter extractions. This information coupled to the curvilinear isotherms noted in the P sorption study gives further credence to the theory that at least 2 types of P sorption sites are present in soils. These data also indicate that the Bray #1 extractant is especially efficient in extracting P associated with exposed surfaces.

3. Regression analyses indicate that the P present in the Bray extraction solution is dependent upon the amount of P sorbed during the P sorption study. Correlation coefficients were used to relate the various Bray extractions, and the data indicated that there is a significant correlation between P sorbed and the amount of P removed with the first Bray extraction.

Phosphorus Fractionation Study

1. Soil Samples that were carried through the entire P desorption study generally did not have significant differences between chemical forms of P that could be attributed to the P sorption study.

2. Phosphate fractionation data was obtained from soil samples that were extracted with a total of 1, 4, or 7 Bray extractions. The data show that the Bray #1 extractant is especially efficient at

extracting P from the $\text{NH}_4\text{Cl-P}$ and $\text{NH}_4\text{F-P}$ fractions, but it can also extract P from the NaOH-P , and HCl-P fractions. It is possible that some of all of these P fractions may be utilized by plants since Bray #1 extractable P has been significantly correlated to plant response in most Oklahoma soils.

3.(a) The $\text{NH}_4\text{Cl-P}$ fraction was found to be significantly correlated to $\% \text{CaCO}_3$, surface area measurements, C.E.C., and $\% \text{clay}$, but was not correlated to Al and Fe measurements. It was also correlated to the NH_4F and l-HCl-P fractions.

(b) The $\text{NH}_4\text{F-P}$ fraction was not significantly correlated with Al determinations but was correlated to factors that relate to soil surface area measurements and the $\text{NH}_4\text{Cl-P}$ fraction.

(c) The l-NaOH-P fraction was correlated to $\% \text{Fe}_2\text{O}_3$, $\% \text{O.M.}$, $\% \text{clay}$, surface area measurements, and the $\text{NH}_4\text{F-P}$ fraction, but was not correlated to the $\text{NH}_4\text{Cl-P}$ or l-HCl-P fraction.

(d) The l-HCl-P fraction was positively correlated to $\% \text{CaCO}_3$, pH, heated surface area measurement, and the $\text{NH}_4\text{Cl-P}$ fraction and negatively correlated to citrate extractable Al.

4. The Fe-P fraction was significantly correlated with the Langmuir P sorption constants after a total of 1,4,7, and 9 Bray extractions and as the extractions progressed the correlation increased. The $\text{NH}_4\text{Cl-P}$, $\text{NH}_4\text{F-P}$ and the l-HCl-P fractions were not significantly correlated with the Langmuir P sorption constants after a total of 1,4,7, and 9 Bray extractions.

5. The $\text{NH}_4\text{Cl-P}$ and $\text{NH}_4\text{F-P}$ fractions were significantly correlated to the P removed by the Bray #1 extractant. The Fe-P and Ca-P fractions were not significantly correlated to the P extracted by the Bray #1

extractant. The Bray #1 extractant appears to be removing P primarily from $\text{NH}_4\text{Cl-P}$ and $\text{NH}_4\text{F-P}$ fractions which were previously correlated with plant growth response.

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VITA

Lanny Olen Ashlock

Candidate for the Degree of

Doctor of Philosophy

Thesis: BASIC REACTIONS OF PHOSPHATE RETENTION AND REMOVAL FROM SOIL

Major Field: Soil Science

Biographical:

Personal Data: Born in Wagoner, Oklahoma, June 8, 1943, the oldest son of Olen and Dorothy Ashlock. Married the former Bonnie Faye Goodson and am now the father of three sons Rodney Olen, Ricky Lynn and Ronnie Lee.

Education: Graduated from Fourche Valley High School, Briggsville, Arkansas, in 1961; received the Associate of Science degree, with a major in Agriculture, from Arkansas Polytechnic College, Russellville, Arkansas, in 1963; received the Bachelor of Science degree, with a major in Agronomy, from the University of Arkansas, Fayetteville, Arkansas, in 1965; received the Master of Science degree, with a major in Soil Science, from the University of Arkansas, in 1967; completed requirements for the Doctor of Philosophy degree, with a major in Soil Science, at Oklahoma State University, Stillwater, Oklahoma, in 1977.

Professional Experience: Employed as an Assistant County Extension Agent at Harrison, Arkansas, 1967-1969; Associate County Extension Agent at Batesville, Arkansas, 1969-1971; County Extension Director at Waldron, Arkansas, 1971-1973; Research Technician at Oklahoma State University, 1973-1977.

Member: American Society of Agronomy, Soil Science Society of America, Gamma Sigma Delta.