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Phosphate Sorption Isotherms for Evaluating the Phosphate Requirements of Soils[1]

R. L. Fox and E. J. Kamprath[2]

ABSTRACT

Phosphorus sorption isotherms were constructed for soils which varied in mineralogy, texture, and past history of phosphate fertilization. Equilibrating conditions were: 25C, 0.01*M* $CaCl_2$, and 6 days. Effects of heavy phosphate fertilization of soils with high phosphate sorption capacities were evident in phosphate sorption isotherms 10 years later. The sorption curves were used as a basis for fertilizing soils in pots so that phosphate in soil solutions varied from about 0.01 to 1.8 ppm P. Millet (*Pennesitum typhoides*, var. Gahi-1), was grown for 4 weeks. Yields approached 95% maximum when phosphate in soil solutions was adjusted to 0.2 ppm. The phosphate concentrations at which near maximum yields were attained were little influenced by soil texture or past fertilizer treatments, but absolute yields of millet growing in the sandy Norfolk soil (low phosphate buffering capacity) was greatest if the soil had been previously phosphate fertilized.

Additional Key Words for Indexing: P fixation, P solubility, soil solution.

While soil phosphate tests, properly calibrated, may predict whether or not fertilizer phosphorus is needed, it is frequently difficult to relate test values to the quantity of P required. In highly weathered soils especially, extractable phosphate is usually low, but amounts of fertilizer P which the soils immobilize vary greatly (5).

Several factors determine the flux of P to plant roots. Williams (16) has discussed these as intensity, quantity, capacity, and mobility factors. In its simplest form the intensity factor can be represented as P concentration in the soil solution. Plants vary in the concentration of P required in solution. For some plants 0.03 ppm P continuously supplied in nutrient solutions will sustain maximum growth (1). For other plants, concentrations 25 times greater were required. A value of 0.2 ppm has been suggested as one at which most plants attain near maximum growth (4). In soils a value of 0.3 ppm P has been used as a standard value for establishing fertilizer rates for wheat (12). However, it is recognized that the value will vary with soil moisture, since soil moisture content influences phosphate diffusion to roots. (10, 11).

It is becoming increasingly clear that phosphate moves to the roots of plants by diffusion (3, 9, 10, 17). Thus the concentration of phosphate in soil solutions is vital, since the soil solution must contain sufficient phosphorus to provide the concentration gradient necessary for net movement to the root.

One measure of the quantity factor is the amount of labile P in soils. The solid phase must have sufficient phosphate to maintain concentration during depletion. A capacity factor, as it applies to P, is the quantity of P retained at specified conditions of intensity. It indicates the phosphate buffering capacity of soils and the ability of soils to maintain intensity during P depletion. Mobility includes a number of rate factors involved in the dissolution of phosphate associated with the solid phase, transport of P to roots, and uptake of P by plants.

Two or more of these factors may be related but frequently they are not, which makes evaluation of the P status of an array of soils difficult. A system used for predicting the amounts of phosphorus fertilizer to bring soils to various levels of adequacy for crop production should consider capacity and intensity factors.

An approach to this problem has been suggested by Beckwith (4) who measured sorbed phosphate at standard supernatant concentrations of P as an estimate of the phosphate needs of soils. The standard value chosen was 0.2 ppm based on the assumption that successful growth of plants in soils would require a P concentration of approximately this magnitude in the soil solution. Beckwith recognized that the critical concentration would almost certainly vary somewhat among soils, as well as for different crops.

Many factors of soil mineralogy, chemistry, and management are integrated in a measurement of the kind proposed by Beckwith. When values for phosphate sorbed are plotted against log P remaining in the equilibrium soil solution, approximately straight-line curves are obtained. The slope of these curves gives information about the phosphate buffering capacity of the soil (12). The intercept at zero phosphate sorption is an estimate of phosphate in the soil solution, a value which seems to be better related to plant growth than phosphate potential (14). Amounts of phosphate required to attain desired levels of P in the equilibrium solution can be read directly from the graph.

Ozanne and Shaw (12) have used phosphate sorption curves to estimate the amount of P required for wheat. The relationship between predicted and actual values was close ($r = 0.96$) and linear. When buffering capacity was included as a variable, the multiple coefficient of correlation was slightly higher.

Phosphate sorption isotherms have been used by Fox et al. (6) to estimate phosphate requirement of Hawaiian latosols. The values obtained were consistent with observed needs. Kurtz and Quirk (8) and Fox et al. (6) used P sorption isotherms to evaluate the residual effects of phosphate fertilizers. Kurtz and Quirk found little or no reductions in adsorption maxima as a result of past fertilization of a red-brown earth from South Australia, but there were residual effects in a brunizem soil and a lateritic soil. Phosphate which had been applied nine years earlier was still effectively decreasing the phosphate requirement of a Humic Ferruginous Latosol (Gibbsihumox) in Hawaii.

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When allowance was made for the removal of P by crops, the measured residual efficiency of phosphate from the fertilizer was 64 to 80%.

The objectives of this investigation were to study (*i*) the feasibility of using phosphate sorption isotherms for determining P fertilizer needs of soils, and (*ii*) the effects of soil texture and past P fertilization on P concentrations required for maximum growth.

MATERIALS AND METHODS

Soil samples were collected from field plots being used to evaluate long term effects of P fertilization in Central and Eastern North Carolina. The soils represented a wide range of texture and past phosphate treatments. The soils were:

Georgeville Clay Loam (Typic Hapludult)—A Piedmont soil high in kaolin with moderate amounts of 2:1–2:2 lattice clay minerals and small amounts of gibbsite and goethite. It contains about 5% free iron oxide (13). Plots from fertilizer treatments of 0, 175, 350, and 700 kg P/ha applied 10 years before were sampled. Some results from these plots have been published (7).

Portsmouth Sandy Loam (Typic Umbraquult)—This is a lower Coastal Plains soil. It is younger and, thus, has a lower P requirement than the more highly weathered soils of the upper Coastal Plain. The clay fraction is predominantly kaolin but with considerable amounts of expanding lattice clays. One sample represented plots which have not been P-fertilized recently and another sample represented small maintenance applications of P.

Norfolk Sand (Typic Paleudult)—Three samples were collected from plots which had been fertilized with 0, 50, or 100 kg P/ha 2 years before. The clay fraction is of the kaolin and 2:1 and 2:2 types.

St. Johns Sand—A poorly drained soil from the Coastal Plains area was sampled from a recently cleared, unfertilized area in a commercial blueberry field. The soil contained 10% organic matter and 90% quartz sand.

Histosol—Three samples of peaty muck, representing three levels of P, were collected from a commercial farm. This soil contained almost no mineral colloids.

Adsorption Isotherm—Data for plotting phosphate sorption isotherms were obtained by equilibrating 3-g samples of soil for 6 days at 25C in 30 ml of 0.01*M* $CaCl_2$ containing various amounts of $Ca(H_2PO_4)_2$. Two drops toluene were added per sample. Equilibration was carried out in 50-ml plastic centrifuge tubes. These were shaken longitudinally in a reciprocal shaker for a 30-minute period twice daily. After centrifugation in a super-speed centrifuge, P was determined in the supernatant. Phosphorus which disappeared from solution was considered to have been sorbed. Phosphorus sorbed was plotted against P in the supernatant solution.

Desorption Isotherm—Phosphorus was added to unfertilized Georgeville soil at 250 and 500 ppm. After equilibration for 11 days under the conditions described above, 28 ml of the supernatant solution was replaced with 0.01*M* $CaCl_2$ and the soil again resuspended for 4 to 8 hours. The sample was again centrifuged, 28 ml of supernatant removed for P analysis, and the cycle repeated 33 times. In calculating P desorbed, allowance was made for the 2 ml of supernatant carried over from each cycle.

Greenhouse Procedures—The 12 soil materials were limed with fine dolomite equivalent to 1.5 times exchangeable $H^+ + Al^{3+}$. After 2 weeks equilibration, five levels of P were established in the soil by adding P as indicated by the appropriate sorption curve to give soil solution concentrations of 0.022, 0.066, 0.2, 0.6, and 1.8 ppm P. There were also check treatments for which no P was added. Phosphorus added as a solution of $Ca(H_2PO_4)_2$ was mixed with the soil after which soil water was adjusted to field capacity and equilibrated for 6 days with occasional mixing. Finally, blanket treatments of N, K, S, and micronutrients were mixed with the soil and the soil was placed in 1-gallon pots and planted to pearl millet (*Pennesitum typhoides*, var. Gahi-1).

Soil moisture was maintained by frequently adjusting pots to field capacity by weighing. Plants were harvested 4 weeks after planting to minimize interception of roots by pot walls.

RESULTS AND DISCUSSION

Equilibrating conditions influence phosphate sorption by soils. Beckwith (4) washed and equilibrated soils with phosphate in 0.1*M* sodium acetate at pH 5.2, while Ozanne and Shaw (12) equilibrated in 0.1*M* $CaCl_2$. Ozanne, Shaw, and Beckwith equilibrated soils with phosphate for about 16 hours, but this has been found to be insufficient time for equilibrating highly weathered soils of Hawaii (6). A preliminary investigation of the effect of equilibrating conditions on phosphate sorption using the Georgeville soil demonstrated that reasonably stable levels of P in solution could not be expected during the first 6 days of equilibration (Fig. 1) and that sorption isotherms shift rapidly

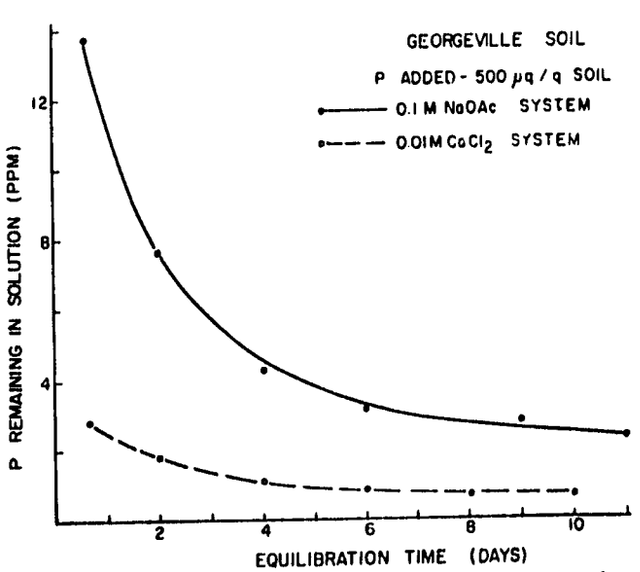

Fig. 1—Phosphorus remaining in equilibrating solutions in relation to time.

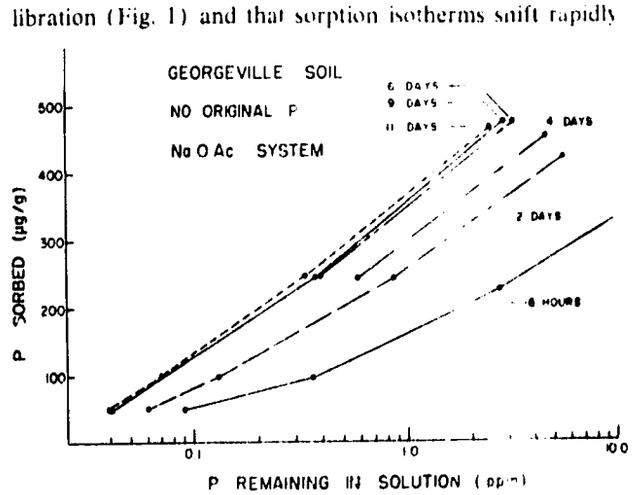

Fig. 2—Phosphate sorption isotherms constructed for various equilibration times.

during the first several days of equilibration (Fig. 2). Phosphate remaining in solution was always greater in the sodium acetate system of Beckwith than in 0.01*M* $CaCl_2$ (Fig. 1). This has some analytical advantages but the prevalence of calcium in most agricultural soils, the importance of approximating field pH during equilibration, and the ease of obtaining clear extracts led us to equilibrate soils in 0.01*M* $CaCl_2$.

Phosphate sorption isotherms constructed for four diverse North Carolina soils are presented in Fig. 3 and 4. The slopes of the curves represent the buffering capacity with respect to P and reflect, in a general way, the clay content of the soil; although it can be seen from the clay contents given that phosphate adsorption per gram of clay increases with decreasing clay content. For the Georgeville, Portsmouth, and Norfolk soil the calculated values are 700, 910, and 2,160 μg/g clay, respectively. This suggests easier access of phosphate to clay surfaces when the clay is dispersed through media like sand. Probably much of the clay in iron oxide-cemented peds is positionally inactive. Also colloidal material in sands may be very reactive as the result of intense weathering resulting from leaching.

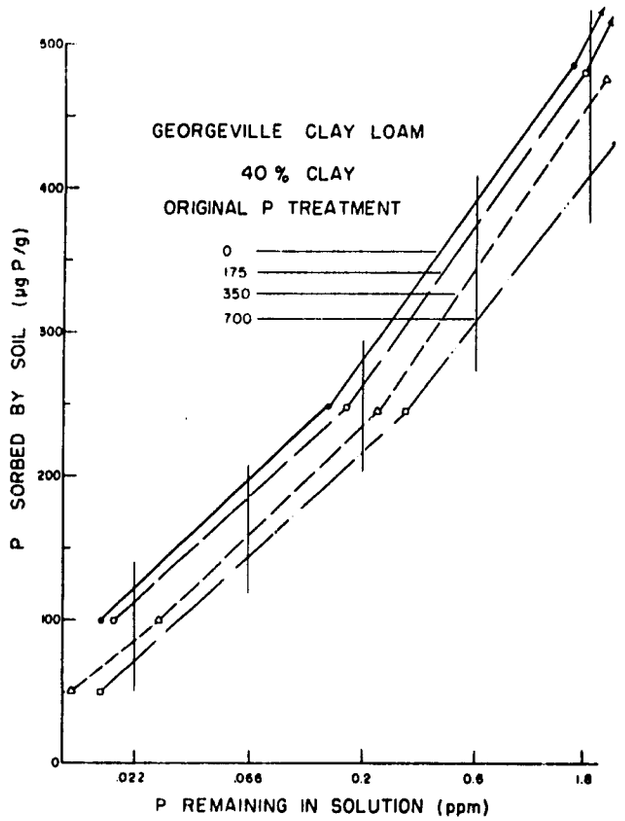

Fig. 3—Phosphate sorption by Georgeville clay loam which had been fertilized with different amounts of P 10 years before.

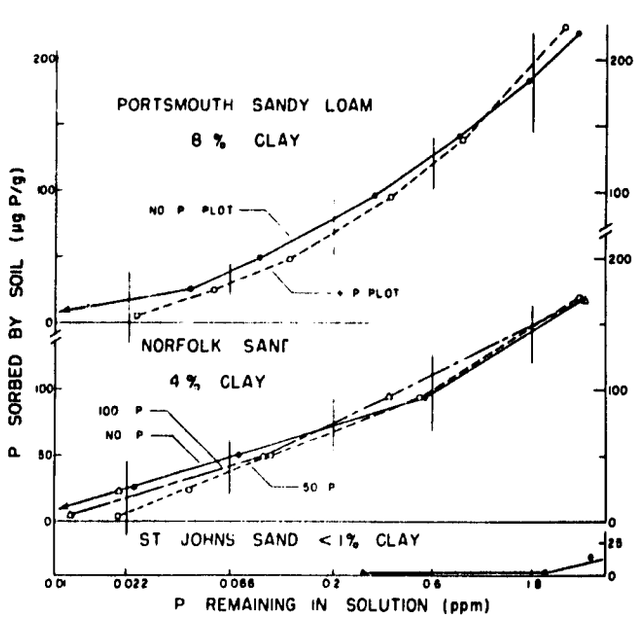

Fig. 4—Phosphate sorption by Portsmouth, Norfolk, and St. Johns soils.

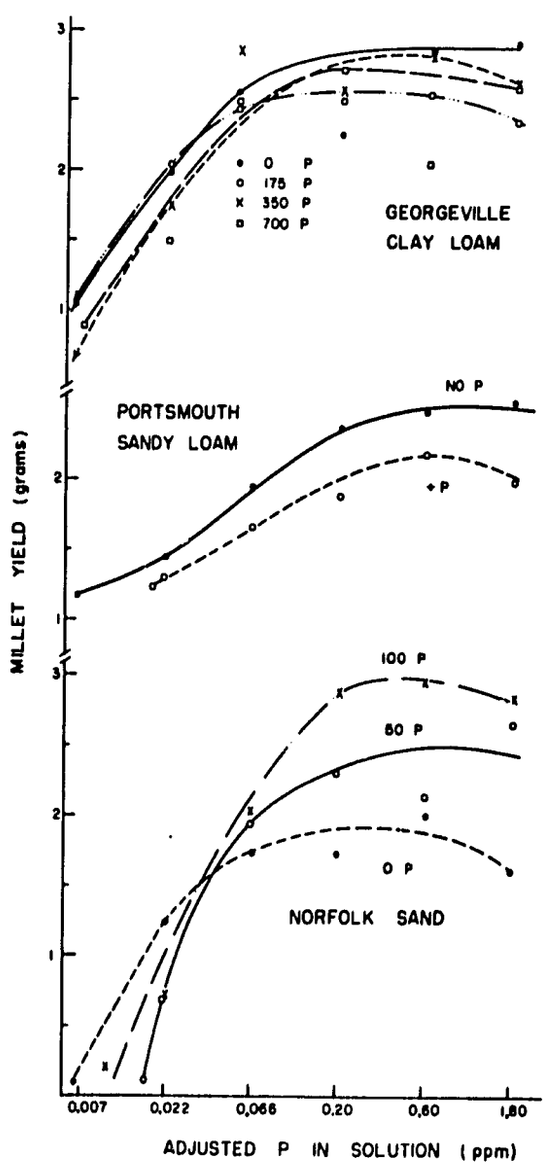

Fig. 5—Yield of millet in relation to adjusted levels of P in soil solutions for several soils and levels of prior P fertilization.

Table 1—The phosphorus percentage of millet grown in Georgeville soil in relation to adjusted levels of P and fertilizer P applied 10 years earlier

Original P treatment	Adjusted P level, ppm					
	No P applied	0.022	0.066	0.2	0.6	1.8
kg/ha						
0	0.17	0.38	0.47	0.60	0.62	0.76
175	0.33	0.36	0.47	0.50	0.67	0.72
350	0.36	0.38	0.44	0.52	0.66	0.77
700	0.29	0.36	0.44	0.56	0.68	0.71

The residual effects of phosphate fertilizer treatments are clearly seen in the Georgeville soil by the spread among curves corresponding to four rates of P applied 10 years earlier. The effects of previous P treatments were not so obvious in the sandy Portsmouth and Norfolk soils. Vertical bars in Fig. 3 represent selected P levels which were established for growing millet in pots.

Yields of millet in relation to adjusted levels of P in soil solutions are presented in Fig. 5. Yields were 92 to 99% of maximum at 0.2 ppm P in the adjusted solution for all soils and all previous P treatments. This does not necessarily indicate that 0.2 ppm in solution is the optimum concentration for plant nutrition. This value has been suggested by Beckwith (4) as a standard for comparative purposes, since it seems to be a reasonable value for a number of plant species growing in solutions.

The P content of millet within an adjusted level of the P in the Georgeville soil was remarkably uniform (Table 1). Previous P fertilization had some effect on yields, particularly on the sandy Norfolk soil. The low P sorption capacity of the Norfolk soil indicates a limited capacity to continuously renew the soil solution with P. Woodruff and Kamprath (18) found that soils with a low adsorption capacity required a higher saturation of the adsorption capacity and a higher equilibrium solution concentration for maximum growth. Thus, the previous phosphorus treatments probably helped to maintain the soil solution concentration for a longer period of time.

Although yields in all soils approached maxima as adjusted P levels were increased to 0.2 ppm, there were indications that soil texture was directly or indirectly influencing P supply patterns. A comparison of three soils in Table 2 demonstrates that P percentage of, and P uptake by millet decreased with decreasing clay content of the soils. This effect became less pronounced with increasing levels of adjusted P. Effects of this type can be explained as depletion of P from the immediate vicinity of roots, thus increased distance over which diffusion must move P to the root, thus a lower concentration gradient and lower P flux —this effect being accelerated as harvest approached so that yields were little affected even though plant P had fallen below the critical concentration (about 0.48% for 95% yield).

Table 2—The P percentage and yield of P in millet grown on three soils in relation to adjusted levels of P in solution. Values are means of the various original P treatments

Soil	Adjusted P level, ppm											
	No P applied		0.022		0.066		0.2		0.6		1.8	
	%	mg	%	mg	%	mg	%	mg	%	mg	%	mg
Georgeville cl	0.29	1.4	0.37	6.8	0.46	11.3	0.55	13.7	0.66	16.9	0.72	19.5
Portsmouth sl	0.32	3.8	0.33	4.4	0.40	7.2	0.45	9.6	0.51	11.9	0.69	15.7
Norfolk s	0.30	0.5	0.25	2.3	0.31	6.2	0.39	9.2	0.51	14.2	0.61	17.0

This train of events is favored in pot culture, especially with sandy soils, by the tendency of roots to "pile up" against the walls and bottoms of pots. Essentially, this removes many roots from the soil environment. Diffusion of phosphate to these roots becomes increasingly unlikely, as the outer layer of soil in the pots adjacent to these roots becomes depleted of P and water. The low phosphate sorption capacity of sandy soils would hasten P depletion in this situation and the effect will not be overcome by simply using very large pots, as has been demonstrated by Baker and Woodruff (2). The existence and significance of this "barrier effect" in plant nutrition should merit further investigation, not only as it affects plant nutrition in pots, but also, plants growing on soils with stones, pans, or other barriers to root penetration.

Soils which have no capacity to sorb P require very high concentrations of P in solution to compensate for lack of total available P in the system. An example is the muck soil presented in Fig. 6.

The foregoing results reported here agree with data from Hawaii in which Kikuyu grass (*Pennesitum clandestinum*) was grown on several volcanic ash soils (Fox, R. L. Fertilization of volcanic ash soils of Hawaii. Panel on Soils Derived from Volcanic Ash of Latin America. Turrialba, Costa Rica. 1969.). The Hawaiian soils' capacity to adsorb P at standard concentration (0.2 ppm) during 6 days in a NaOAc system, varied from 70 to 3,000 μgP/g dry soil. Combined yields (two cuttings) of the Kikuyu grass was 95% maximum at 0.3 to 0.4 ppm P for soils which adsorbed 220–3,000 μgP/g soil, but was greater than 1 ppm for the soil which sorbed only 70 μg P.

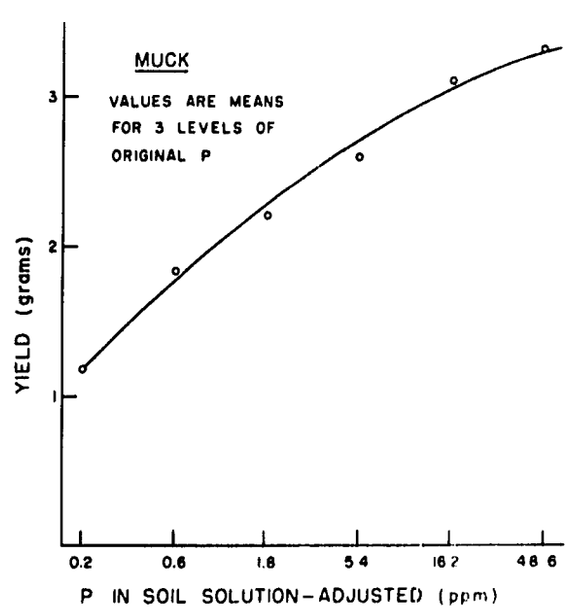

Fig. 6—Yield of millet in relation to adjusted levels of P in soil solutions of muck. P response was due to initial growth differences. The organic soils mineralized copious amounts of P shortly after planting. Even at the lowest level of P applied, all plants were about 1% P when harvested.

Table 3—Residual efficiency of P added to field plots of Georgeville soil 10 years before. The plots were annually cropped to wheat or corn

Original P treatment	Estimated* fertilizer P remaining	P sorbed† at 0.2 ppm	Residual efficiency of‡ fertilizer P	
	kg/ha			%
0	0	630	--	--
175	105	580	50	48
350	220	520	110	50
700	540	490	150	28

* Based on phosphorus removed by corn during the 7th year.
† 6 days equilibration in 0.01M $CaCl_2$.
‡ A determination of residual efficiency based on 6 days equilibration in a NaOAc system gave identical results. Absolute values for residual efficiency (column 4) are decreases in phosphate sorption (column 3) associated with increasing rates of P fertilizer originally applied (column 1).

$$\text{Residual efficiency of Fertilizer P (as percent)} = \frac{\text{Residual efficiency of Fertilizer P}}{\text{Estimated Fertilizer P remaining}} \cdot 100.$$

The residual effectiveness of old phosphate applications, as measured by displacement of adsorption isotherms was less for the Georgeville soil (Table 3) than has been reported for a bauxitic soil of Hawaii (64 to 80%) (6). Nevertheless, a substantial residual effect is indicated which agrees with field data from these plots (7).

An important difference between the management of the North Carolina and Hawaii plots is this: the North Carolina site has grown annual crops (wheat or corn) for 10 years since it was last phosphate fertilized, while the Hawaii location had grown a grass-legume mixture continuously for 9 years (19). Thus, the Hawaii soil has not been mixed since it was first fertilized.

The data presented in Fig 7 demonstrate that for a given level of P in the Georgeville soil, P solubility is greater when P is being added to the system than when it is being withdrawn. For some soils it may be necessary to construct separate desorption isotherms in order to make predictions about P solubility after large amounts of P have been extracted by plants.

It is not surprising that concentration of P in soil solutions gives useful information about P nutrition, since concentration gradients provide the driving force for moving P to roots and, in addition, since P uptake by roots is concentration dependent. Other variables influence the flux of P to roots also (11), but these data suggest that concentration of P in solution is the overriding factor since, by adjusting soil solution concentration to a standard level,

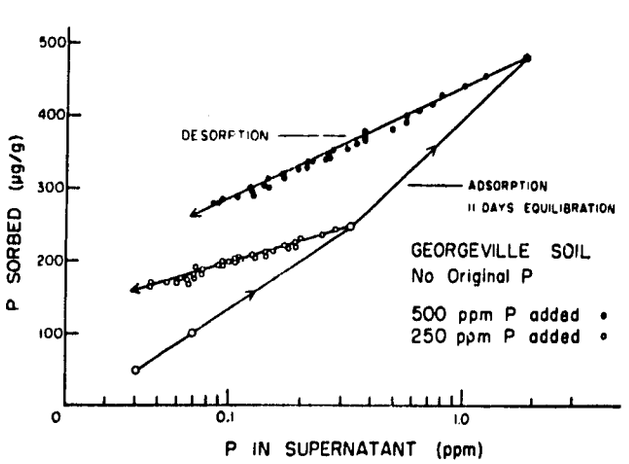

Fig. 7—Desorption of P during 33 extractions with 0.01M $CaCl_2$.

P nutrition of an indicator plant was reasonably constant. The same cannot be said for soils which have a very low capacity to sorb P, or perhaps for very intense P extraction from soils with high capacity, because hysteresis effects, such as those illustrated in Fig. 7, become excessive.

Predicting requirements for P fertilizers on highly weathered soils by use of phosphate sorption isotherms takes into account both intensity and capacity factors. This approach provides a method for studying reactions of P fertilizers which is more closely related to plants than some of the classical studies on solubility of P reaction products. Once P sorption isotherms have been determined, these could be correlated with some of the more traditional soil test methods now in use (15).

LITERATURE CITED

1. Asher, C. J., and J. F. Loneragan. 1967. Response of plants to phosphate concentration in solution culture I. Growth and phosphorus content. Soil Sci. 103:225–233.
2. Baker, D. E., and C. M. Woodruff. 1961. Influence of volume of soil per plant upon growth and uptake of phosphorus by corn from soils treated with different amounts of phosphorus. Soil Sci. 94:409–412.
3. Barber, S. A. 1962. A diffusion and mass flow concept of soil nutrient availability. Soil Sci. 93:39–49.
4. Beckwith, R. S. 1964. Sorbed phosphate at standard supernatant concentration as an estimate of the phosphate needs of soils. Aust. J. Exp. Agr. and An. Hus. 5:52–58.
5. Fox, R. L., S. K. DeDatta, and G. D. Sherman. 1962. Phosphorus solubility and availability to plants and the aluminum status of Hawaiian soils as influenced by liming. Int. Soc. Soil Sci., Trans. Comm. IV, V (Palmerston N., New Zeal.) p. 574–583.
6. Fox, R. L., D. L. Plucknett, and A. S. Whitney. 1968. Phosphate requirements of Hawaiian latosols and residual effects of fertilizer phosphorous. Int. Cong. Soil Sci., Trans. 9th (Adelaide, Aust.) 2:301–310.
7. Kamprath, E. J. 1967. Residual effect of large applications of phosphorus on high phosphorus fixing soils. Agron. J. 59:25–27.
8. Kurtz, L. T., and J. P. Quirk. 1965. Phosphate adsorption and phosphate fractions in field soils of varying histories of phosphate fertilization. Aust. Jour. of Agric. Res. 16: 403–412.
9. Lewis, D. G., and J. P. Quirk. 1967. Phosphate diffusion in soil and uptake by plants. III and IV. Plant and Soil. 26:445–453, 454–468.
10. Olsen, S. R., and F. S. Watanabe. 1963. Diffusion of phosphorus as related to soil texture and plant uptake. Soil Sci. Soc. Amer. Proc. 27:648–653.
11. Olsen, S. R., and F. S. Watanabe. 1966. Effective volume of soil around plant roots determined from phosphorus diffusion. Soil Sci. Soc. Amer. Proc. 30:598–602.
12. Ozanne, P. G., and T. C. Shaw. 1968. Advantages of the recently developed phosphate sorption test over the older extracant methods for soil phosphate. Int. Cong. Soil Sci., Trans. 9th (Adelaide Aust.) 2:273–280.
13. Shelton, J. E. and N. T. Coleman. 1968. Inorganic phosphorus fractions and their relationship to residual value of large applications of phosphorus on high posphorus fixing soils. Soil Sci. Soc. Amer. Proc. 32:91–94.
14. Wild, A. 1967. Soluble phosphate in soil and uptake by plants. Nature, London 203:326–327.
15. Waugh, D. L., and J. W. Fitts. 1966. Soil test interpretation studies: Laboratory and potted plant. Tech. Bul. 3. International Soil Testing Series. North Carolina State Agri. Exp. Sta., Raleigh, N.C.
16. Williams, E. G. 1967. The intensity and quantity aspects of soil phosphate status and laboratory extraction values. Anales de Edafologia y Agrobiologia. 26:525–546.

17. Wilson, A. T. 1968. The chemistry underlying the phosphate problem in Agriculture. Aust. J. Sci. 31:55–61.

18. Woodruff, J. R., and E. J. Kamprath. 1965. Phosphorus adsorption maximum as measured by the Langmuir isotherm and its relationship to phosphorus availability. Soil Sci. Soc. Amer. Proc. 29:148–150.

19. Younge, O. R., and D. L. Plucknett. 1966. Quenching the high phosphorus fixation of Hawaiian latosols. Soil. Sci. Soc. Amer. Proc. 30:653–655.