Evaluation of Soil Phosphate Residues by Plant Uptake and Extractable Phosphorus[1]

S. R. Olsen, F. S. Watanabe* and R. A. Bowman[2]

ABSTRACT

Residual phosphate from fertilizer P or manure seemed to accumulate mainly as octocalcium phosphate in 23 alkaline and calcareous soils of eastern Colorado. These soils contained 37 to 162 ppm $NaHCO_3$-soluble P. Phosphorus removed by cropping varied between 58 and 275 ppm with 5 to 8 crops before P deficiency reappeared. Phosphorus uptake was highly correlated with $NaHCO_3$-soluble P (four successive extracts), resin-extractable P, and labile P by ^{32}P isotopic dilution. All the OCP dissolved during cropping. This material seems to have a very high availability coefficient for plants. Accumulation of fertilizer P residues in this form would appear to be beneficial since this P is potentially all available to crops. Therefore, methods for estimating the amount of OCP in soils should be useful.

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When phosphate fertilization of soil exceeds plant P removal, the P residues gradually increase and P concentration in the soil solution usually increases. If P concentration increases above saturation levels for precipitation of crystalline solid-phase phosphates, these new phases will form and subsequently control the P concentration in solution at levels characteristic of the solid-phase phosphates and soil pH. When this condition appears in soils, we need to evaluate the plant P availability of the soil P residues and to determine the performance of soil tests to estimate the amount of P that crops can remove before the available P decreases to a level where crops will respond to added P fertilizer. A method of predicting the amount of residual P available to crops is important economically to a farmer and useful for advisory service in planning fertilizer practices.

In this paper we describe the results of experiments designed to measure plant P uptake and its relationship to various parameters of soil P availability. We evaluated soil properties, such as pH, $CaCO_3$ and clay contents, as they affected the relationship between P uptake and soil parameters of P availability. These parameters were: soluble P in solution, $NaHCO_3$-soluble P, resin extractable P, and labile P by isotopic dilution with ^{32}P. This study included 23 alkaline, calcareous soils.

Methods

Greenhouse experiments: We collected 23 soils from irrigated fields in eastern Colorado. These soils were selected from fields showing high levels of available P. The $NaHCO_3$-soluble P ranged from 37 to 162 ppm P (Watanabe and Olsen, 1965). None of these soils would be expected to respond to added P fertilizer in the field or greenhouse. We assumed these soils might contain octocalcium phosphate (OCP) in varying amounts and that essentially all the OCP would dissolve with time of cropping. Therefore, we continued cropping until the available soil P decreased to levels where we expected a response to added P (i.e. $NaHCO_3$-P levels < 15 ppm). The number of crops harvested varied from 5 to 8. Total P uptake was summed for 5 to 8 crops. Total P in the roots was also measured because the roots had to be removed in order to continue cropping and the designed level of available soil P would be reached sooner by the procedure.

Two kg samples of the soils were placed in two-liter containers. Nitrogen as $(NH_4)_2SO_4$ was added at 100 ppm initially and 100 ppm 3 weeks later as KNO_3. Iron was added to all soils at 10 ppm as chelate-138. This general procedure was followed for subsequent crops. Sudan grass (Sorghum sudanenses Stapt.) was the first crop. Three cuttings were taken. The roots were separated and harvested for dry weight and total P content after the third cut. Sorghum (Sorghum bicolor L. Moench.) was the fourth crop and barley (Hordeum vulgare, var. Moravian) the fifth and sixth crop. Roots were separated, dry weight and P content determined for sorghum and barley and for each succeeding crop. After the fifth crop, $NaHCO_3$-soluble P was < 12 ppm in soil numbers 3, 7, 10, 11, 12, and 17, so cropping was discontinued. The last two crops were sorghum. After the sixth crop, $NaHCO_3$-soluble P levels were < 12 ppm in soil numbers 1, 4, 6, 8, 14, 16, 20, 21, and 22. After the seventh crop, $NaHCO_3$-soluble P levels were < 12 ppm in all samples except numbers 9, 19, and 23. Another crop of sorghum was grown on these three soils.

Following these 5 to 8 crops, two of the four replicates of each soil sample was fertilized with 50 ppm of P as concentrated superphosphate. Another crop of barley was grown and the dry matter yield and P content was measured.

Laboratory experiments:

Water-soluble P - This fraction of soil P was measured in .01 M $CaCl_2$ extracts with a 1-hour shaking period. Soil to solution ratios were 20:50 and 10:50. The difference in P concentration between these two extractions was added to the higher P concentration (20:50) (Aslyng, 1954). Soil pH and (Ca + Mg) concentration was measured in each extract solution. The monocalcium phosphate potential ($.5pCa + pH_2PO_4$) and lime potential ($pH - .5\ p\ Ca$) was calculated from these data using the Debye-Huckel equation to obtain activity coefficients, pH and pK_2 (7.20) to obtain the ratio of $H_2PO_4^-$ to $HPO_4^=$, and the method of Larsen (1965) to correct for the $CaHPO_4^o$ complex ion formation.

Solubility diagrams were constructed for hydroxyapatite (HA, $pK_{sp} = 113.7$), octocalcium phosphate (OCP, $pK_{sp} = 46.91$), and dicalcium phosphate dihydrate (DCPD, $pK_{sp} = 6.56$) (Adams, 1971; Lindsay and Moreno, 1960).

NaHCO$_3$-soluble P - The method of Watanabe and Olsen (1965) was used with a 1:20 soil to solution ratio and a 30-minute shaking period. With four successive extracts, the same soil sample was extracted four times by the standard procedure and the amounts extracted were summed.

Resin-extractable P - The amount of P extracted from the soil was measured using 2 g of Dowex-2 resin to 1 g soil in 100 ml water and a shaking time of 24 hours (Amer et al. 1955).

Labile P by ^{32}P exchange - The amount of P in the soil that undergoes isotopic dilution with ^{32}P was measured using 5 g soil per 100 ml of water and a 24-hour reaction period (Olsen and Watanabe, 1963).

Results

Some physical and chemical properties of the soils are listed in Table 1. All the soils were calcareous (0.05 to 7.96% $CaCO_3$) with a pH > 7 in .01 M $CaCl_2$. Four soils, however, contained < 0.12% $CaCO_3$ and these same four soils showed the lowest pH. Soil texture ranged from a fine sandy loam to a clay loam with clay contents between 19.0 and 44.0%. Organic matter ranged from 1.02 to 2.83% and it generally increased as clay content increased. The electrical conductivity values (EC) fell within the range considered as normal for good growth with respect to salt levels. Sulfate-S appeared adequate for crop growth. Extractable Fe and Zn levels (DTPA) were 7 to 39 ppm and 1.3 to 52 ppm, respectively. These levels are adequate for crop growth.

<u>Monocalcium phosphate potential</u> - Figure 1 shows these values and the lime potential for the 23 soils in relation to the solubility isotherms for HA, OCP, and DCPD. These data suggest that OCP is present in most of these samples but solubility is the only criterion indicating its possible presence as a solid-phase calcium phosphate. Soil numbers are shown by each point to identify the sample with data in Table 1. Ten soils appeared to be somewhat supersaturated with respect to OCP, 12 soils showed solubility points very near the OCP line, and one soil appeared to be undersaturated with respect to OCP. The latter soil contained the lowest amount of $NaHCO_3$-soluble P. The spread of data points along the OCP isotherm is related to pH variation among the soils.

The fertilizer history for these soils is known in some cases. For example, soil No. 8 has received farmyard manure only for 30 years prior to sampling. Soil numbers 1, 2, 3, 4, 5, 6, 13, 19, and 23 have received P mainly as farmyard manure. In general, the farmers have applied 13 to 17 ppm P per year as concentrated superphosphate or farmyard manure for 20 to 30 years.

Crop removal of P - Table 2 shows the P removal by cropping from the soils in the tops, roots, and tops plus roots. Phosphorus removal ranged from 58 to 275 ppm. These amounts indicate the available soil P from present levels to lower levels where a yield response was observed from added fertilizer P. This variation in P uptake seems likely due to different amounts of OCP (and other available residual P forms) that have accumulated in the soils. Eight crops were grown on three soils and five crops on all soils before P deficiency occurred.

Extractable and soluble P - Table 2 shows the amounts of extractable P by anion resin and in four successive extractions by the $NaHCO_3$ method. Labile P by isotopic dilution with ^{32}P and soluble P in .01 M $CaCl_2$ extract are also shown in Table 2. Resin-extractable P ranged from 64 to 226 ppm. With the resin, 1, 2, and 3 g resin per g of soil were compared and the mean amounts extracted were 124, 128, and 130 ppm P respectively. Four extractions with $NaHCO_3$ gave values between 61 and 239 ppm. The fourth extract showed values between 5 and 17 ppm with 16 soils showing < 10 ppm. Thus, in the fourth extract, P levels were similar to unfertilized soils. Mean values for the first, second, third, and fourth extracts were 74.6, 26.1, 12.1, and 8.8 ppm P, respectively. The labile P (by isotopic dilution with ^{32}P) ranged from

67 to 232 ppm with a mean value of 133 ppm. Similar amounts of P were measured by these three methods in these 23 soils and the average value was 13% less than P removal by the crops.

Soluble P in .01 M $CaCl_2$ solution ranged from 12.7 to 107.8 μM. Variations in pH seem to be the major cause of differences in soluble P since OCP mainly controlled the solution P concentration in these soils.

Correlation of P uptake with soluble P - Table 3 shows the correlation coefficients and multiple regression coefficients for the relationship between P uptake by crops and soluble P. Multiple regression included soil pH and clay content. Phosphorus uptake correlated significantly with initial P concentration but it accounted for only 47.6% of the variation in uptake. The correlation increased when uptake was related with the calcium phosphate potential, $0.5\ pCa + pH_2PO_4$, or with log soluble P, but these increases are due partly to the conversion to a log parameter, and the increase in the coefficient, r, was not significant. Uptake of P also correlated significantly with soil pH, probably because P concentration increased as soil pH decreased. When pH was included with soluble P in a multiple regression, the effect of pH was not significant. When % clay was included with soluble P in a multiple regression, the correlation with P uptake increased significantly. Inclusion of pH in this latter multiple regression did not increase the correlation significantly.

Figure 2 shows P uptake in relation to P concentration ($r = .690$ and $y = 1.473X + 88.9$). The soil numbers are shown by each data point. To obtain a better understanding of the point spread from the regression line, various soil pairs were selected based on their position above or below the regression line. Soil pairs were selected for approximately equal P concentrations and for pairs where the soil below the regression line had a higher P concentration but a lower P uptake than a mate above the line. Table 4 lists these soil pairs with respect to P uptake, P concentration, extractable resin-P, and various soil parameters. The higher P uptake (points above the regression line) is shown first for each pair.

The higher P uptake of each soil pair in Table 4 is correlated best with clay content and resin-P. Table 3 shows, from multiple regression analysis, that % clay increased the correlation between P uptake and soluble P. This increase in correlation seems to occur because P uptake is larger in soils with higher clay contents in comparisons (soil pairs) where soluble P is approximately equal, or even greater for the soil with less clay. Additional information concerning the effect of clay content on P uptake is shown in Figure 3. The soils were separated into two groups. One group (11 soils) contained over 30% clay, as shown by the upper regression line, $y = 2.82X + 71.4$ with $r = .739$. The second group (12 soils) contained less than 30% clay, as shown by the lower regression line, $y = 1.74X + 54.9$ with $r = .868$. Both correlation coefficients are significant ($P = .01$).

Two soils (3 and 9) showed a poor fit with the regression lines in Figure 3. Soil 3 contains the largest $CaCO_3$ content (7.96%), it has a high pH (7.68) and is probably well buffered against pH changes during crop growth. Soil 9 has a trace of $CaCO_3$ (0.05%), a low pH (7.07) and it is probably poorly buffered against pH changes during crop growth. These factors could account for the poor fit of these two soils.

The effect on P uptake of small or large amounts of $CaCO_3$ in the soils was examined by dividing the 23 soils into two groups, one with $< 1.0\%$ $CaCO_3$ and another with $> 1.0\%$ $CaCO_3$. This approach indicated 5 of 8 soils in group one and 5 of 15 soils in group two plotted above the regression line in Figure 2. This result indicates a moderate tendency for the plants to extract more P, from residual forms with similar, initial soluble P levels, from soils containing less $CaCO_3$.

Correlation of P uptake with quantity parameters - Table 3 shows the percentage of P uptake variation accounted for and the correlation coefficients of P uptake with resin-P, $NaHCO_3$-P (1 and 4 extracts, and with addition of organic P extracted by the $NaHCO_3$ method), and labile P (by ^{32}P isotopic dilution). The correlation coefficients are higher for all these quantity parameters compared with soluble P in .01 M $CaCl_2$ (intensity parameter). A multiple regression analysis including % clay with resin-P or $NaHCO_3$-P (4) did not increase the correlation coefficients, in contrast with an increase when % clay was included with soluble P in .01 M $CaCl_2$.

Figure 4 shows the relationship between P uptake and resin-P. The individual soils are indicated to assist in identifying soil properties with deviations above and below the regression line. None of the soil properties in Table 1 showed a consistent relationship with these deviations. Soils 2, 13, and 23 account for most of the deviation above the regression line. Two of these soils (2 and 23) had soluble P values above the mean of soluble P and this factor could account partly for their position above the regression line. The resin-P accounted for 87.2% of the variation in P uptake and the mean value of the resin-P was 14% less than the mean uptake.

Figure 5 shows the relationship between P uptake and $NaHCO_3$-P (4 extracts). The individual soils are shown to aid in identifying soil properties with deviations above and below the regression line. Eight soils contained < 1.0% $CaCO_3$. Five of these plotted above the regression line and none below it. This result suggests a tendency for the plants to absorb relatively more P from soils with < 1.0% $CaCO_3$ than the P extracted in the $NaHCO_3$ solution. However, four of these five soils plotting above the regression line also had soluble P values (in .01 M $CaCl_2$) above the mean soluble P. Thus, the soil properties do not clearly indicate a relationship with deviations of points above or below the regression line, but a low $CaCO_3$ content may favor an increased P uptake with respect to the $NaHCO_3$-soluble P. The $NaHCO_3$-P(4) accounted for 87% of the variation in P uptake and the mean value for $NaHCO_3$-P(4) was 17% less than the mean for P uptake.

Figure 6 shows the relationship between P uptake and $NaHCO_3$-P (1 extract). Correlations of this relationship with soil properties showed similar results with those described for Figure 5. The $NaHCO_3$-P (1) accounted for 78.7% of the variation in P uptake and the mean value for $NaHCO_3$-P(1) was 51% less than the mean for P uptake.

Labile P (by ^{32}P isotopic dilution) showed a correlation with P uptake similar to the relationship with resin-P as shown in Figure 5.

Calcium phosphate potential changes with cropping - Values of this potential after cropping were plotted in Figure 7 and identified by soil number. These results are directly comparable with data in Figure 1 showing the initial potentials. Phosphorus removal by cropping caused all potentials to move below the OCP isotherm, which suggests that all the OCP dissolved and became available to plants in these soils. Values for three soils (9, 16, 23) are missing from Figure 7, but the low $NaHCO_3$-P for these soils after the eight crop indicates the potentials would plot near the other soils below the OCP isotherm.

Discussion

Evidence of OCP in soils - When a soil sample tests higher than 22 ppm $NaHCO_3$-soluble P, we consider this field as high in available P and nonresponsive to fertilizer P additions. Twenty-three soils in this study ranged from 37 to 162 ppm $NaHCO_3$-soluble P. Solubility criteria indicated 22 soils probably contained OCP and that the P in solution was mainly controlled presently by this solid-phase calcium phosphate. However, the amount of OCP was variable as suggested by the range in $NaHCO_3$-soluble P and by P uptake variations of 58 to 275 ppm with 5 to 8 crops. A common, yearly fertilizer P addition is about 13 to 17 ppm, so the available P in residues constitutes an important reserve.

We found that all the OCP dissolved during cropping. This material seems to have a very high availability coefficient for plants. Accumulation of fertilizer P residues in this form would appear to be beneficial, since this P is potentially all available to crops. Therefore, methods for estimating the amount of OCP in soils should be useful.

Long-term applications of manure or superphosphate produced OCP in Hoosfield and Broadbalk plots at Rothamsted (Aslyng, 1954; Warren and Johnston, 1967). In the Hoosfield plots both treatments caused formation of a solid-phase phosphate in equilibrium with OCP. In the Broadbalk plots the manure treatment yielded OCP but the superphosphate treatment produced a less soluble phosphate. At the Barnfield plots, manure plus superphosphate brought about OCP but a less soluble phosphate formed with the separate treatments (Warren and Johnston, 1962). All these soils were calcareous.

Olsen and Flowerday (1971) reviewed the evidence for OCP in soils. OCP has been observed under three contrasting conditions (i) by hydrolysis of DCPD in neutral and alkaline soils (ii) by liming acid soils that have a high available P status initially and (iii) as a result of long-term applications of manure to calcareous soils. These conditions seem to be related to the stability of OCP in alkaline soils. Initially, DCPD forms when monocalcium phosphate (MCP) dissolves and when the fertilizer solution reacts with the soil. Hydrolysis of DCPD produces OCP. Alkaline conditions and a high level of soluble P (also produced from manure applications) apparently favor persistence of OCP. A high rate of adsorption of P on hydrous oxides and clay minerals could limit or prevent OCP formation with low rates of MCP or DCPD application. In general, as P fertilization continues in soils with pH > 6.5 and phosphate reaction products accumulate, the conditions to form OCP become more favorable.

Correlation of P uptake with soluble P - In soils containing OCP, soluble P levels indicate an ample P supply for plants, but we could not adequately predict how much P plants could remove, apparently because soluble P in solution represents only 1 to 3% of the plant P uptake or resin-P. By including % clay with soluble P in multiple regression, the combined variables accounted for 62.9% of the variation in P uptake, an increase from 47.6% with soluble P. In other short-term experiments, we have shown that P uptake by roots was greater, as % clay increased, from soil solutions with equal P concentrations

(Olsen and Watanabe, 1970). This effect was attributed to diffusion and buffer capacity, since both factors increased with clay content. The regression lines in Figure 3 indicate that plants absorbed more P, at equal conentrations of soluble P (initial levels), from soils containing higher clay contents.

Although P uptake was highly correlated with resin-P, the mean resin-P was 131 ppm for one group (clay > 30%) and 124 ppm for the other group (clay < 30%) in Figure 3. This result implied that the amount of OCP in the soils was not correlated with clay content. Therefore, we assume that clay content improves the correlation between soluble P and P uptake because of its effect on diffusion and buffer capacity.

TABLE 1. Physical and Chemical Properties of Soils

Soil Type	Soil No.	pH	Organic Matter	$CaCO_3$	Clay	EC	NO_3-N	SO_4-S	$NaHCO_3$-P
			%	%	%	mmhos/cm	ppm	ppm	ppm
Weld cl l	1	7.54	2.33	2.34	34.5	1.46	38	24	77
Weld cl l	2	7.55	2.43	2.59	38.3	1.58	59	22	91
Weld cl l	3	7.68	1.93	7.96	38.0	1.62	26	31	45
Nunn cl l	4	7.44	2.83	0.53	44.0	1.89	36	16	66
Cass cl l	5	7.43	2.04	0.48	31.0	2.40	53	46	96
Greeley sa cl l	6	7.75	1.89	4.24	26.5	4.57	52	95	73
Greeley l	7	7.69	1.20	1.05	26.5	2.57	24	43	61
Gilcrest sa cl l	8	7.64	2.02	3.52	28.6	1.95	26	36	83
Gilcrest sa cl l	9	7.07	1.71	0.05	24.8	3.73	43	27	86
Terry si cl l	10	7.46	2.36	3.79	35.8	1.10	41	5	37
Weld l	11	7.78	1.35	5.91	27.0	2.98	49	19	38
Weld l	12	7.71	1.02	3.76	26.8	1.78	24	19	39
Fort Collins cl l	13	7.58	2.57	4.37	36.1	0.75	27	8	81
Fort Collins cl l	14	7.67	1.95	5.22	32.5	0.96	19	13	58
Greeley l	15	7.53	1.83	0.44	24.4	1.82	38	27	82
Cass l	16	7.20	2.13	0.40	21.9	2.55	46	21	93
Weld l	17	7.65	1.35	4.55	27.4	1.50	27	28	49
Gilcrest sa cl l	18	7.32	2.06	0.11	34.7	1.41	26	19	61
Nunn sa cl l	19	7.10	2.39	0.05	31.7	2.43	49	38	107
Weld sa cl l	20	7.48	1.86	1.17	32.2	1.78	36	19	65
Greeley f sa l	21	7.48	1.76	2.70	26.0	2.01	38	27	91
Greeley f sa l	22	7.04	1.43	0.07	19.0	0.85	23	8	72
Greeley f sa l	23	7.48	1.79	6.20	24.7	1.61	50	21	162

TABLE 2. Phosphorus Removal by Crops, Soluble and Extractable P.

	P Uptake			Extractable P		Labile P	Soluble P
Soil No.	Tops	Roots	Tops & Roots	Resin	$NaHCO_3$(4)	^{32}P	.01M $CaCl_2$
	- - - - - -	- - - - - -	mg/kg	- - - - - -	- - - - - -	- - - - - -	µM
1	82	49	131	120	135	120	25.0
2	120	83	203	159	153	166	52.0
3	54	48	102	85	89	94	30.0
4	88	52	140	115	110	142	19.4
5	128	74	202	207	160	181	39.5
6	66	39	105	112	112	108	27.3
7	50	37	87	94	94	83	17.2
8	78	56	134	118	128	110	40.2
9	141	82	223	211	150	169	51.9
10	52	35	87	64	61	80	12.7
11	36	22	58	68	69	68	13.8
12	42	31	73	69	67	67	13.6
13	115	71	186	128	137	144	20.7
14	83	45	128	101	99	115	19.3
15	89	75	164	143	127	134	59.2
16	94	68	162	139	139	162	84.7
17	51	37	88	80	84	84	21.8
18	99	54	153	133	106	152	25.1
19	148	94	243	226	192	232	48.0
20	82	46	128	109	108	128	34.2
21	90	57	147	134	132	170	64.1
22	91	74	165	128	108	136	84.2
23	155	120	275	195	239	214	107.8
Mean	88.4	58.6	147.1	127.7	121.7	133.0	39.6

TABLE 3. Correlation Coefficients and Percentage of Variation in P Uptake Accounted for by Soil Parameters

Factors Correlated	Coefficients		Variation Accounted For, %	
	r	R	r^2	R^2
Uptake vs soluble P	.690**	-	47.6	-
Uptake vs (0.5 p Ca + p H_2PO_4)	-.793**	-	62.9	-
Uptake vs pH	-.624**	-	38.9	-
Uptake vs log soluble P	-.724**	-	52.4	-
Uptake vs soluble P plus pH	-	.750	-	56.3
Uptake vs soluble P plus % clay	-	.792	-	62.7
Uptake vs soluble P + % clay + pH	-	.830	-	68.9
Uptake vs resin - P	.934**	-	87.2	-
Uptake vs resin - P + pH	-	.934	-	87.3
Uptake vs resin - P + % clay	-	.936	-	87.6
Uptake vs $NaHCO_3$ - P(4)	.933**	-	87.0	-
Uptake vs $NaHCO_3$ - P(4) + % clay	-	.934	-	87.2
Uptake vs $NaHCO_3$ - P(1)	.887**	-	78.7	-
Uptake vs $NaHCO_3$ - P(1) + organic P	.919**	-	84.5	-
Uptake vs $NaHCO_3$ - P(4) + organic P	.962**	-	92.5	-
Uptake vs Labile - P (^{32}P)	.943**	-	88.9	-

** (P = .01)

TABLE 4. Comparisons of Soil Pairs, Selected from Above and Below Regression Line in Figure 1, in Relation to Various Soil Parameters

Soil Pair and No.	P Uptake	P Concentration	pH	$CaCO_3$	Clay	Resin-P
	mg/kg	μ*M*		%	%	*mg/kg*
2	203	52.0	7.55	2.59	38.3	159
22	165	84.2	7.04	0.07	19.0	128
4	140	19.4	7.44	0.53	44.0	115
17	88	21.8	7.65	4.55	27.4	80
5	202	39.5	7.43	0.48	31.0	207
8	134	40.2	7.64	3.52	28.6	118
5	202	39.5	7.43	0.48	31.0	207
21	147	64.1	7.48	2.70	26.0	134
5	202	39.5	7.43	0.48	31.0	207
15	164	59.2	7.53	0.44	24.4	143
9	223	51.9	7.07	0.05	24.8	211
16	162	84.7	7.20	0.40	21.9	139
13	186	20.7	7.58	4.37	36.1	128
6	105	27.3	7.75	4.24	26.5	112
13	186	20.7	7.58	4.37	36.1	128
8	134	40.2	7.64	3.52	28.6	118
14	128	19.3	7.67	5.22	32.5	101
11	58	13.8	7.78	5.91	27.0	68
19	243	48.0	7.10	0.05	31.7	226
22	165	84.2	7.04	0.07	19.0	128
18	153	25.1	7.32	0.11	34.7	133
3	102	30.0	7.68	7.96	38.0	85

FIGURE LEGENDS

Figure 1. Monocalcium phosphate potentials of 23 soils in relation to solubility isotherms of HA, OCP, and DCPD.

Figure 2. Phosphorus uptake by crops in relation to soluble P in .01 M $CaCl_2$ extracts.

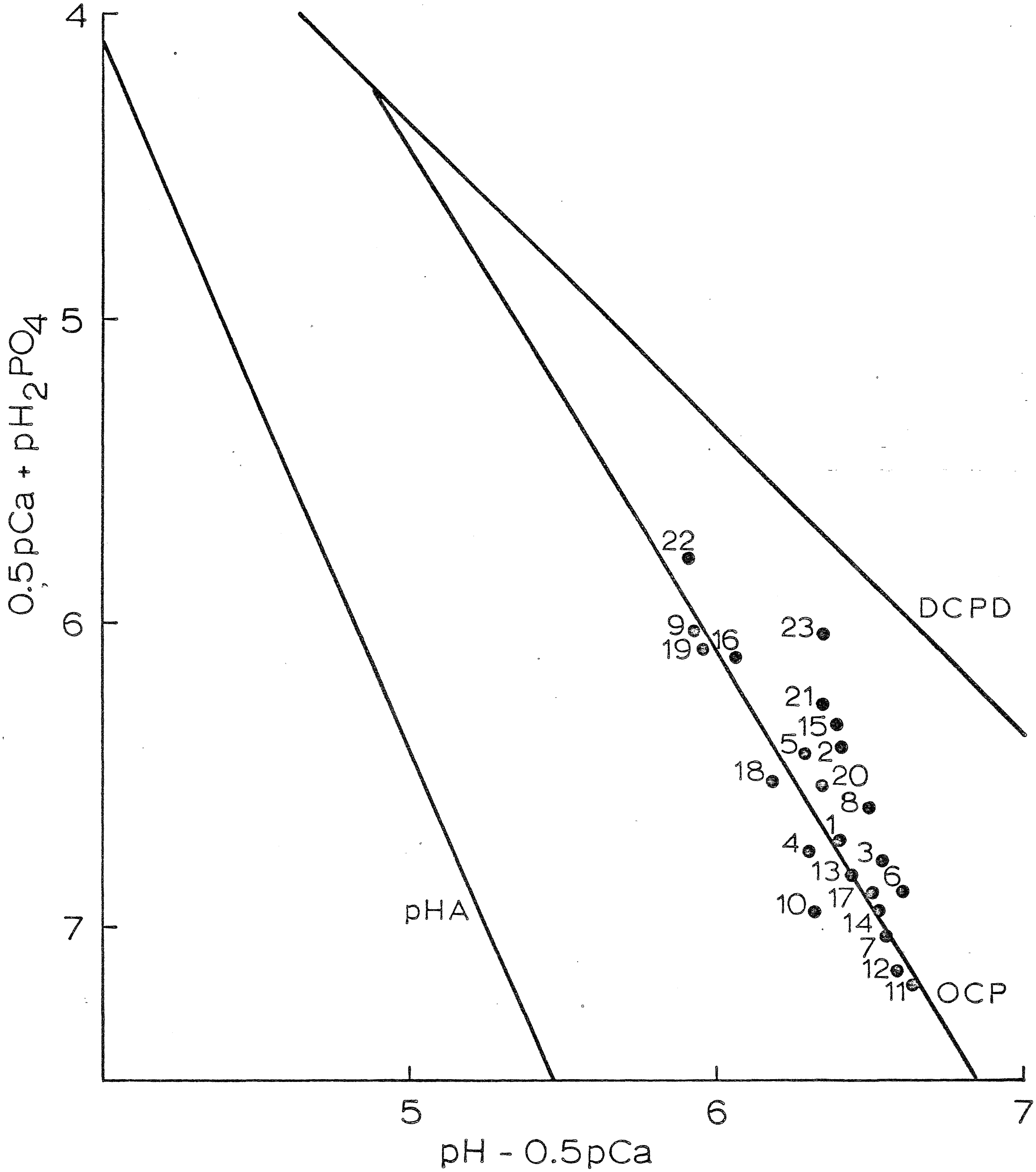
Figure 3. Effect of clay content on the relation between P uptake and soluble P in solution.

Figure 4. Phosphorus uptake by crops in relation to resin-extractable P.

Figure 5. Phosphorus uptake by crops in relation to $NaHCO_3$-soluble P (4 extracts).

Figure 6. Phosphorus uptake by crops in relation to $NaHCO_3$-soluble P (1 extract).

Figure 7. Monocalcium phosphate potentials of 23 soils after cropping in relation to solubility isotherms of HA, OCP, and DCPD.


4
5
6
7
0.5pCa + pH$_2$PO$_4$
5
6
7
pH - 0.5pCa
pHA
OCP
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22
23
9
16
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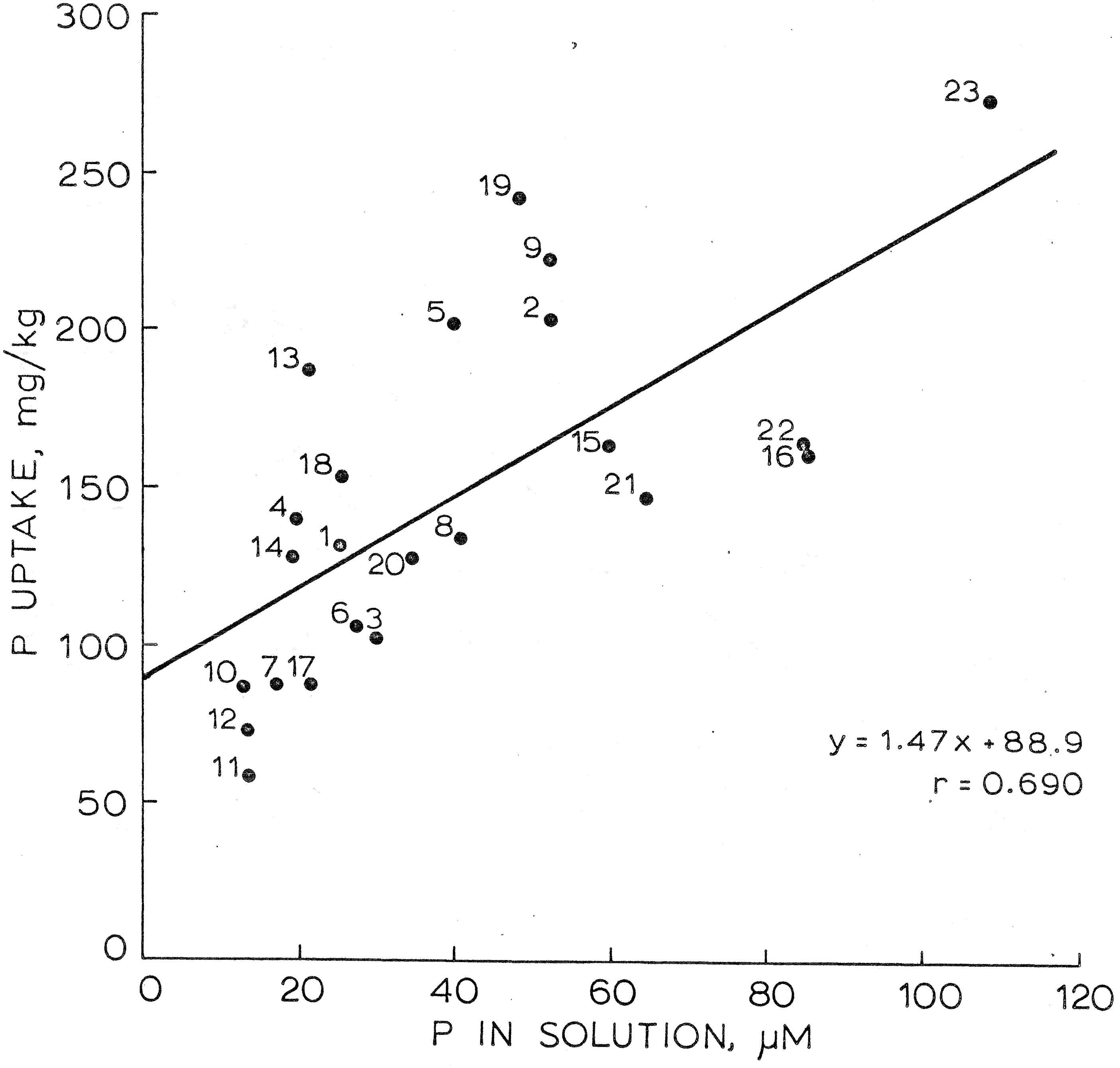

P UPTAKE, mg/kg
300
250
200
150
100
50
0
P IN SOLUTION, µM
0
20
40
60
80
100
120
1
2
3
4
5
6
7
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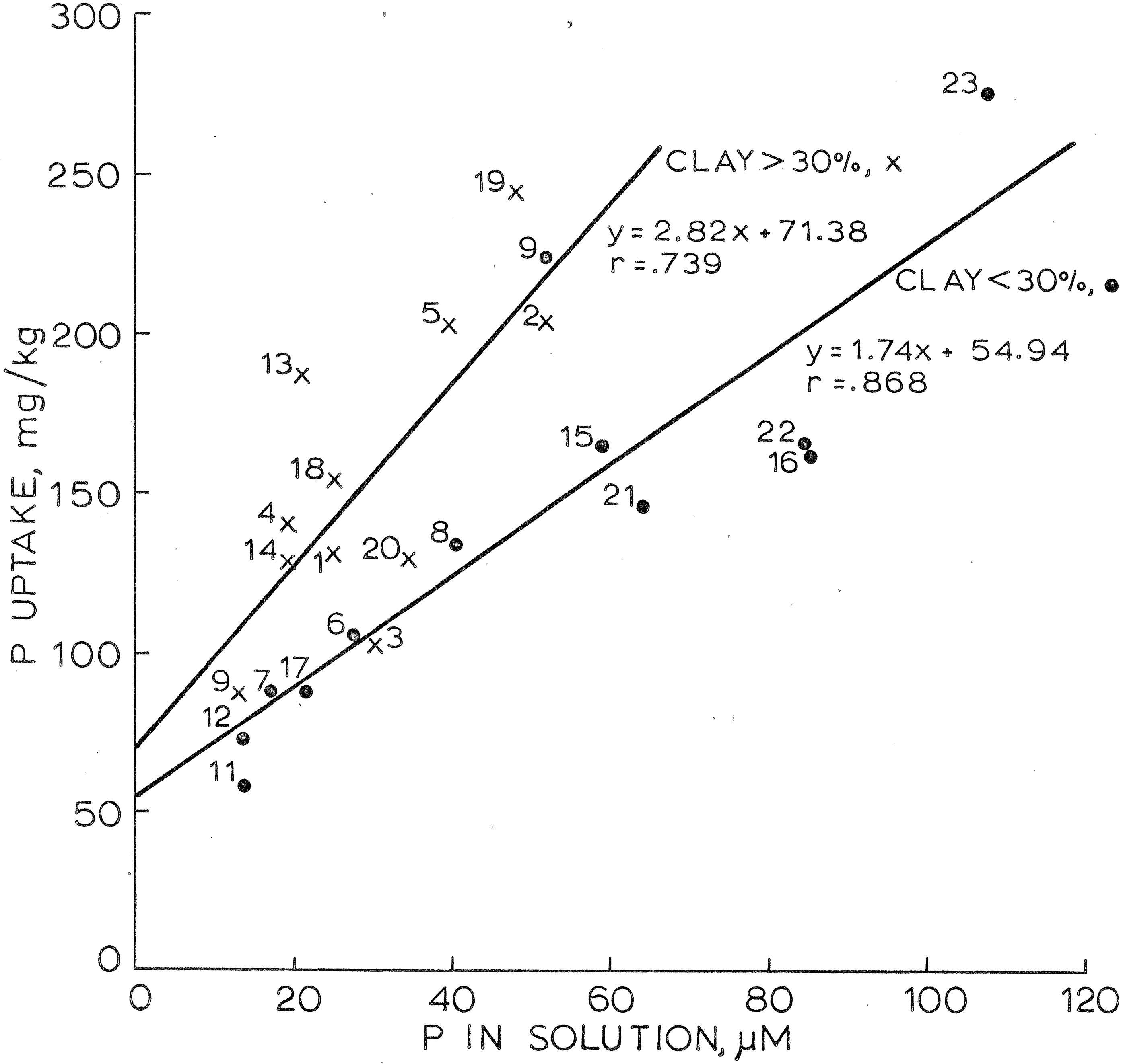
10
11
12
13
14
15
16
17
18
19
20
21
22
23
y = 1.47 x + 88.9
r = 0.690

Fig 3



300
250
200
150
100
50
0
P UPTAKE, mg/kg
0
20
40
60
80
100
120
P IN SOLUTION, μM
CLAY > 30%, x
y = 2.82x + 71.38
r = .739
CLAY < 30%, ●
y = 1.74x + 54.94
r = .868
23
19
9
5
2
13
15
22
16
18
21
4
14
1
20
8
6
3
9
7
17
12
11

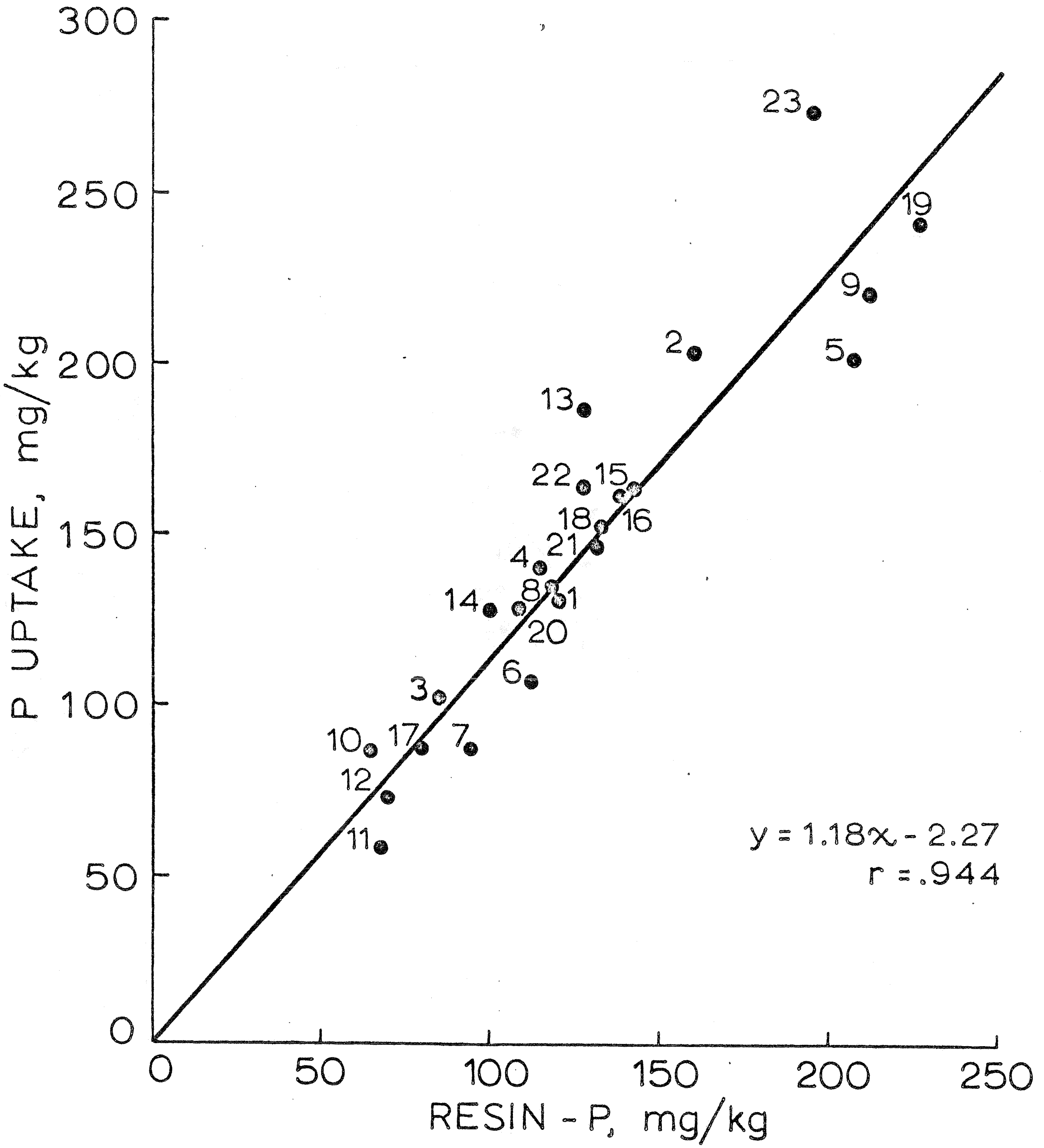
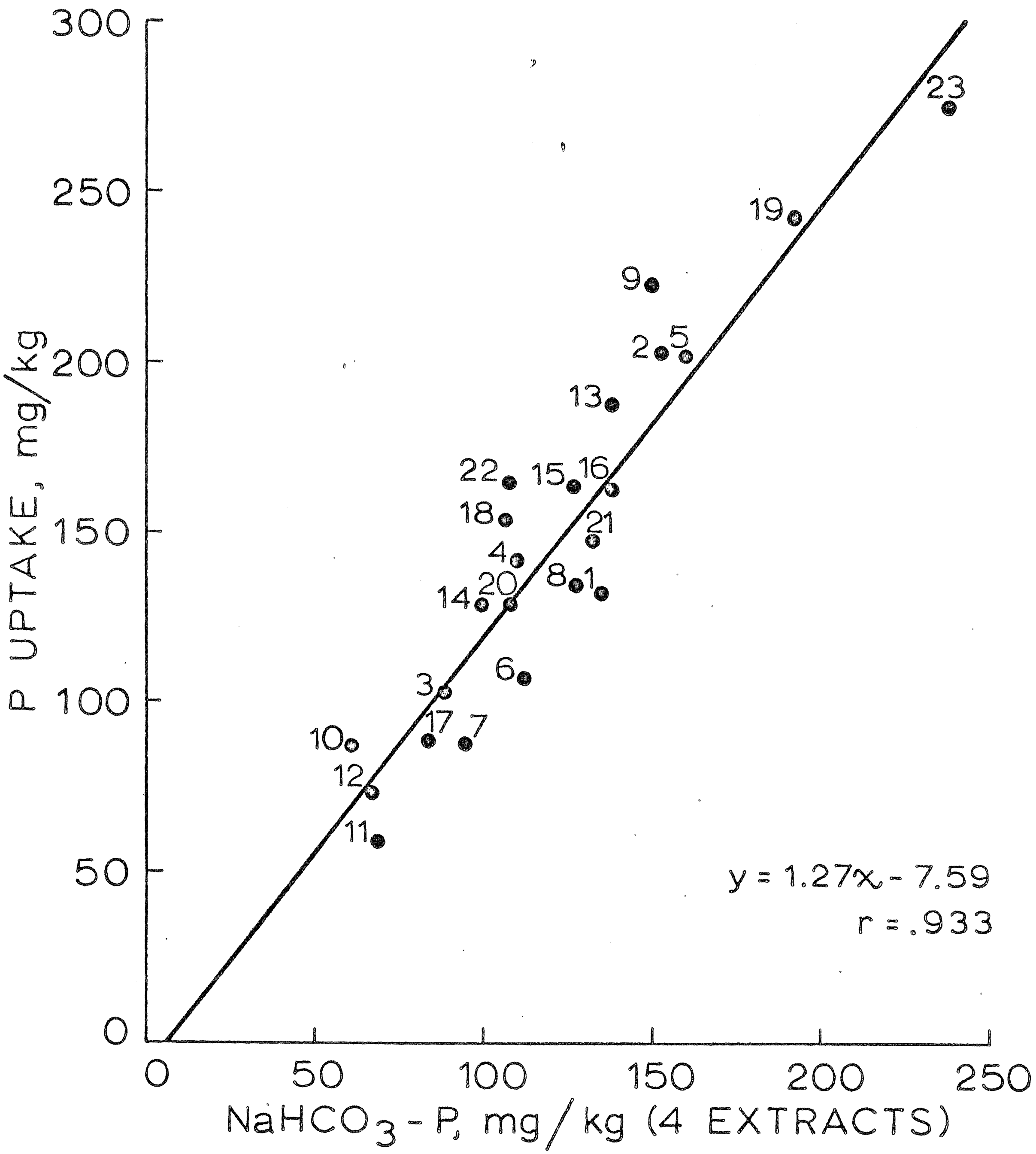
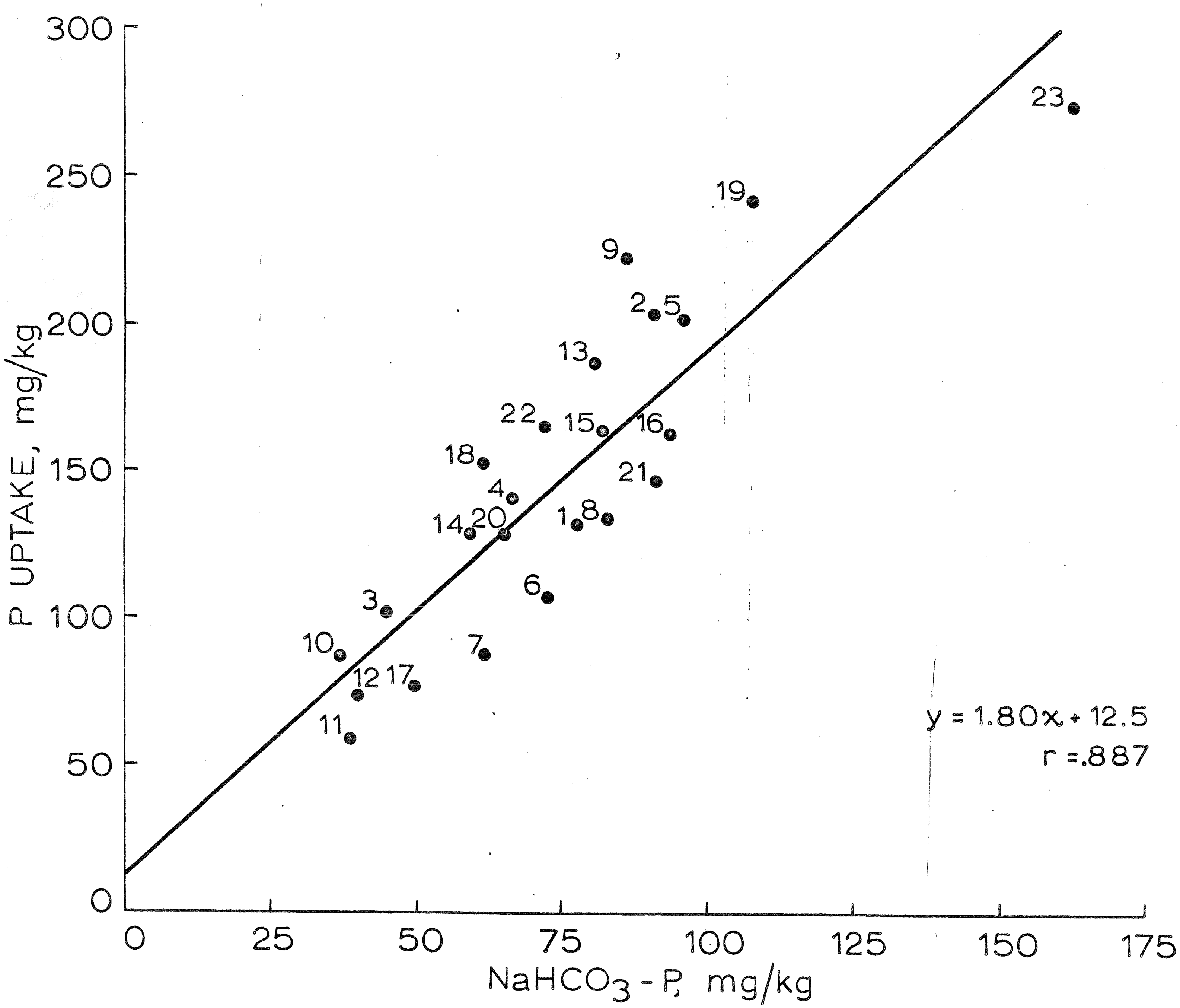

P UPTAKE, mg/kg
300
250
200
150
100
50
0
0
50
100
150
200
250
RESIN - P, mg/kg
23
19
9
2
5
13
22
15
18
16
21
4
8
1
14
20
6
3
10
17
7
12
11
y = 1.18x - 2.27
r = .944

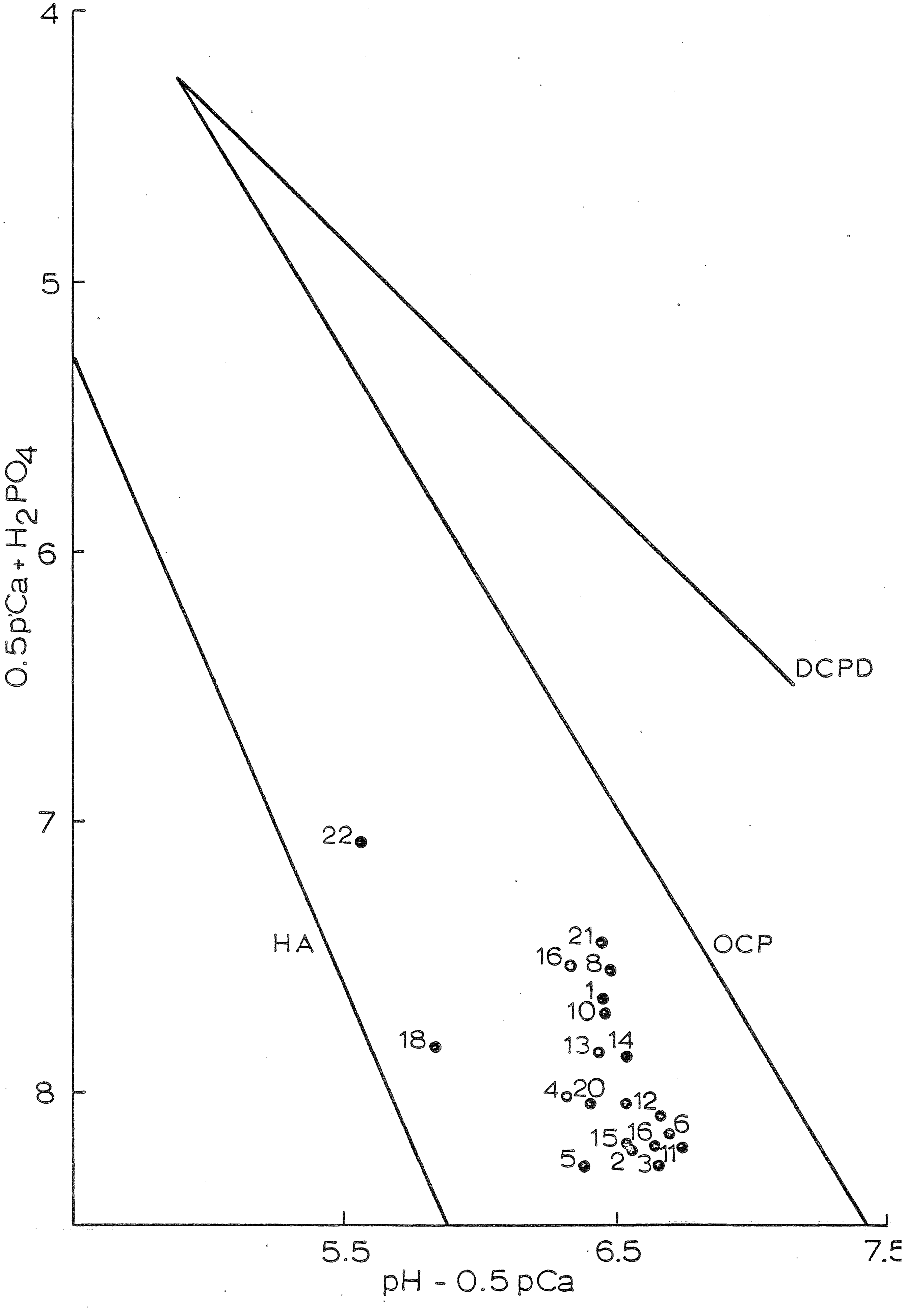
Fig 5



P UPTAKE, mg/kg
300
250
200
150
100
50
0
NaHCO3 - P, mg/kg (4 EXTRACTS)
0
50
100
150
200
250
23
19
9
2
5
13
22
15
16
18
21
4
8
1
20
14
6
3
17
7
10
12
11
y = 1.27x - 7.59
r = .933

Fig 5


300
250
200
150
100
50
0
P UPTAKE, mg/kg
0
25
50
75
100
125
150
175
NaHCO3 - P, mg/kg
23
19
9
2
5
13
22
15
16
18
21
4
1
8
14
20
6
3
10
7
12
17
11
y = 1.80x + 12.5
r = .887


4
5
6
7
8
0.5pCa + H2PO4
DCPD
OCP
HA
22
21
16
8
1
10
18
13
14
4
20
12
6
15
16
5
2
3
11
5.5
6.5
7.5
pH - 0.5 pCa

REFERENCES

1. Adams, F. 1971. Ionic concentrations and activities in soil solutions. SSSA Proc. 35:420-426

2. Amer, F., D. R. Bouldin, C. A. Black, and F. R. Duke. 1955. Characterization of soil phosphorus by anion exchange resin adsorption and P^{32} equilibration. Plant & Soil 6:391-408.

3. Aslyng, H. C. 1954. The lime and phosphate potential of soils: The solubility and availability of phosphates. Roy. Vet. and Agric. College, Copenhagen, Den. Yearbook, pp. 1-50.

4. Larsen, S. 1965. The influence of calcium chloride concentration on the determination of lime and phosphate potentials of soil. J. Soil Sci. 16:275-278.

5. Lindsay, W. L. and E. C. Moreno. 1960. Phosphate equilibria in soils. SSSA Proc. 24:177-182.

6. Olsen, S. R. and F. S. Watanabe. 1963. Diffusion of phosphorus as related to soil texture and plant uptake. SSSA Proc. 27:648-653.

7. Olsen, S. R. and F. S. Watanabe. 1965. Test of an ascorbic acid method for determining phosphorus in water and $NaHCO_3$ extracts from soil. SSSA Proc. 29:677-678.

8. Olsen, S. R. and F. S. Watanabe. 1970. Diffusive supply of phosphorus in relation to soil textural variations. Soil Sci. 110:318-327.

9. Olsen, S. R. and A. D. Flowerday. 1971. Fertilizer phosphorus interactions in alkaline soils, pp. 153-185 IN Fertilizer Technology and use, 2nd ed. Soil Sci. Soc. Am., Madison, Wis.

10. Warren, R. G., and A. E. Johnston. 1962. Barnfield Rept. Rothamsted Expt. Sta. for 1961. Harpenden, pp. 227-247.

11. Warren, R. G. and A. E. Johnston. 1967. Hoosfield Continuous Barley. Rept. Rothamsted Expt. Sta. for 1966. Harpenden. pp. 320-338.