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SOME FACTORS AFFECTING THE UTILIZATION OF PHOSPHORIC ACID IN SOILS BY PLANTS IN POT EXPERIMENTS

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The relations between the quantities of phosphoric acid removed by corn and milo or kafir and the composition and other characteristics of Texas soils was ascertained from the data of 375 pot experiments.

The average quantities of phosphoric acid removed per crop increased with the phosphoric acid soluble in 0.2 N nitric acid (active phosphoric acid) when the soils had a basicity of less than 2%. When the basicity was over 2%, the quantities of phosphoric acid removed by the crops increased with the total phosphoric acid of the soil. The quantities of phosphoric acid removed per crop from surface soils which contained similar quantities of active phosphoric acid were greater than those removed from subsoils. With similar quantities of active phosphoric acid, the quantities of phosphoric acid removed by the crops increased with increases in total phosphoric acid, in total nitrogen and in active potash. Phosphoric acid came either directly or indirectly from soil compounds in which the phosphoric acid was insoluble in 0.2 N nitric acid, since the quantities of active phosphoric acid in some soils were practically the same before and after cropping. Soils varied widely with respect to the availability of their total phosphoric acid. The availability of the total phosphoric acid in some soils was higher than in rock phosphate, but not as high as in superphosphate. Availability of total phosphoric acid was higher in calcareous than in noncalcareous soils. A crop of corn recovered from 20% to 30% of the phosphoric acid fixed from solution by different soils, which means that the phosphoric acid fixed in these soils was highly available.

This work shows that the quantities of phosphoric acid which a soil will furnish to a crop is related not only to the active phosphoric acid or total phosphoric acid contained in the soil, but also to its basicity, content of total phosphoric acid, nitrogen, active potash, and whether it is a surface soil or a subsoil.

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SOME FACTORS AFFECTING THE UTILIZATION OF PHOSPHORIC ACID IN SOILS BY PLANTS IN POT EXPERIMENTS

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The relation of the chemical composition of soils to the production of crops and possible deficiencies is an important field for research work. The subject is very complex, because the yields of crops are influenced not only by the quantities and forms of combination of various elements in the soil, such as phosphoric acid, potash, nitrogen, calcium, magnesium, iron, manganese, boron, and zinc, but also by the amount and distribution of rain, the capacity of the soil to receive and hold water, the depth of the soil suitable for root growth, length of day, intensity of light, temperature, kind and variety of plants grown, and perhaps by other factors. In such a complexity of factors, it is usually necessary to study one factor at a time, keeping all the others constant so far as possible, except those whose effects upon the factor being studied are varied in order to ascertain the effects of such variations.

Phosphoric acid (P_2O_5), because of its economic and its scientific importance, is one of the factors which has been given considerable attention at the Texas Agricultural Experiment Station. Pot experiments were used in much of the work, because it is possible, in pot experiments, to mix the soil to secure uniformity and to keep constant some of the other factors which affect plant growth. The results of pot experiments cannot always be applied directly to farm practice, but need confirmation by field experiments.

Previous work has shown definite relations between the quantities of active phosphoric acid in the soils and the amounts of phosphoric acid withdrawn by crops in pot experiments (4, 5, 6, 7, 8, 9, 10, 11, 14, 18, 22, 24). When the soils are divided into groups according to their content of active phosphoric acid, within each group there are considerable variations from the average amount of phosphoric acid removed. It is important to know what factors cause differences in the use by plants of the phosphoric acid in different soils. Larger amounts of phosphoric acid were removed by plants from soils containing the same amounts of active phosphoric acid when the soils had a higher content of nitrogen or of total phosphoric acid than the average, and from surface soils as compared with subsoils.

The object of this publication is to present the results of additional studies on these relations.

Different Kinds of Phosphates in Soils

Phosphoric acid may be found in soils as inorganic compounds such as apatite or calcium fluophosphate, derived from the original rocks, or as organic compounds derived from plant or animal residues (12, 13). It may be present as tricalcium phosphate, and as various phosphates of aluminum and of iron. If commercial fertilizers containing phosphates are used, monocalcium phosphate and dicalcium phosphate may be found for short periods of time. Calcium phosphate may combine with fluorine to form calcium fluophosphate. Soluble phosphates will form less soluble phosphates of calcium, of aluminum, and of iron (20, 34), or be fixed by kaolinite and some other silicates (2, 30, 32).

Both pot and field experiments have shown that there are decided differences in the quantities of phosphoric acid which plants can remove from different kinds of natural phosphates (16, 19). Tricalcium phosphate has a high availability to plants, while ground rock phosphate (calcium fluophosphate) has a low availability. Phosphates which differ little in solubility in reagents may be quite different in availability to plants (16). Phosphates may also be physically enclosed within soil particles and thus be inaccessible to the roots of plants (10). These particles may be decomposed or dissolved by chemical solvents, so that phosphates which may be physically unavailable to plants are dissolved in the chemical analysis. Even weak acids will dissolve particles of calcium carbonate which may enclose phosphates. Different kinds of plants also differ in their power to utilize phosphates in the soil. This may be due to differences in depth of penetration by the roots, in the solvent powers of the roots, or in the extent to which the fine feeding roots occupy the soil.

It has previously been pointed out (26) that part of the phosphoric acid dissolved by the 0.2 N nitric acid or other weak solvents may be taken out of solution by the fixing power of the soil. The results of the analyses represents the equilibrium between the phosphoric acid dissolved and the fixing power of the soil for phosphoric acid. Further, the phosphoric acid dissolved includes not only that upon the surface of the soil particles and exposed to the roots of the plants, but also that from within such soil particles as are soluble or partly soluble in the solvent and not exposed to the roots of the plants. When a soil contains 10 or less parts per million of active phosphoric acid and has a fixing power of less than 80% and a basicity of less than 1%, the phosphoric acid is probably found as basic phosphates of iron or aluminum, and probably none is found as apatite or calcium phosphates (10). When 10 or less p.p.m. of active phosphoric acid are found and the fixing power for phosphoric acid exceeds 75%, calcium phosphates may or may not be present. The calcium phosphate may go into solution and then part of the phosphoric acid may be removed by fixation. Soils which contain more than 10 p.p.m. of active phosphoric acid probably contain calcium phosphates. Soils which contain more than 100 p.p.m. of active phosphoric acid and have a basicity of less than 2% probably contain considerable amounts of calcium phosphate which is accessible to the roots of plants, although this may not always be the case. If the soil has a basicity of more than 2%, part of the phosphates may be protected from the roots of plants by calcium carbonate.

It is obvious that the determination of the various kinds of phosphates in soils and the relation of these phosphates to crop growth is a task of considerable magnitude. Soils of different origin may differ widely in the kind of phosphates which they contain, and results secured with one kind of crop may be different from those secured with other crops.

Previous Work

The relation of the phosphoric acid of the soil to the phosphoric acid in crops and the effects of fertilization with carriers of phosphoric acid has been the subject of a very large amount of work by many investigators and covers a period of nearly a hundred years. Work done on Texas soils alone by the senior author covers a period of over forty years. It is obviously impracticable to cite all the literature dealing with the results of this vast amount of work; however, certain points dealing particularly with Texas soils are of interest.

The work on the relation of the phosphoric acid of the soil to the phosphoric acid removed by plants in pot experiments has already been mentioned. Soils vary widely in their capacity to fix phosphoric acid from fertilizers, and this affects the availability of phosphates. Fraps (20) found that soils having a fixing power of more than 50%, when treated with superphosphate and subjected to percolation, held practically all of the added phosphoric acid in the upper layers; with most soils having a fixing power of less than 50%, considerable amounts were frequently washed to lower layers of the soil. The action of phosphate fertilization in causing an increase in active phosphoric acid and a downward movement of phosphoric acid in the soil horizon was studied in two sets of field plats. Active phosphoric acid in a Lufkin fine sandy loam at College Station (27) was markedly increased by applications of superphosphate and there was a considerable downward movement of phosphoric acid into lower levels of the soil. On the other hand, active phosphoric acid in a Lake Charles clay loam at Beaumont (28) did not increase significantly, except with very heavy applications of superphosphate, and no evidence was found to indicate a downward movement into lower levels. The phosphates were fixed in the Lake Charles clay loam in compounds which were insoluble in 0.2 N nitric acid. When soils are high in iron which is soluble in dilute acids, they have a considerably higher fixing power than soils which are low in that respect (34).

The presence of various compounds other than phosphates may have a considerable effect upon the efficiency with which plants may utilize phosphoric acid already in the soil or introduced in applications of superphosphate. Calcium carbonate in the fertilizer or in the soil may decrease the availability of superphosphate (17). Basic compounds of calcium applied to the soil to reduce soil acidity may reduce the availability of phosphate if applied at the same time as the fertilizer or if mixed with the fertilizer (17). Nitrate of soda increased the effect of calcium carbonate in reducing availability. The relative effect of liming materials on the availability of phosphoric acid already present in the soil varied widely with different kinds of soils. Working with 6 selected soils of low basicity from the East Texas Timber Country, it was found (15) that limestone increased the size of the crop and the amount of phosphoric acid removed; the effect of the lime was small at first but increased with succeeding crops. The quantity of phosphoric acid removed by crops had practically no effect upon the quantity of active phosphoric acid remaining in the soil at the end of the experiments (15); evidently the phosphoric acid taken up by the plants was drawn directly or indirectly from the more insoluble phosphates in the soils.

Methods and Samples

The methods used in the present work were briefly as follows:

Total phosphoric acid, P_2O_5: The soil was ignited with magnesium nitrate, the mixture was dissolved in hydrochloric acid, filtered, and phosphoric acid was then determined by the volumetric method of the Association of Official Agricultural Chemists (1).

Active phosphoric acid, P_2O_5: Two hundred grams of soil were digested 30 minutes at 40°C. in 2,000 cc. of 0.2 N nitric acid and filtered (10). After evaporating and drying to remove silica, phosphoric acid in an aliquot was precipitated with molybdate solution, the precipitate dissolved in caustic potash and titrated with nitric acid as in the volumetric method.

Basicity: An aliquot of 10 cc. of the filtrate from the digestion above was heated to boiling and, after cooling, titrated with 0.1 N sodium hydroxide, using phenolphthalein indicator. The percentage of nitric acid neutralized by the soil, divided by 10, gives the basicity, expressed as the percentage of calcium carbonate.

Soils: Nearly all of the samples used had been sent in by members of the Division of Soil Survey, U. S. Bureau of Soils, as being representative of the principal types of soil in the various areas of Texas. Surface soils in most cases were collected to a depth of 7 inches; most of the subsoils were from the depth of 7 to 19 inches. The soils were dried, passed through a quarter-inch mesh sieve to remove plant material and rocks, mixed, and stored in galvanized iron cans with closely fitting covers. The average chemical analyses of Texas soils, together with other information, are given elsewhere (25).

Pot experiments: Five kilograms of soil were weighed into galvanized iron pots, the fertilizer mixed with the soil, and water equivalent to 50% of the water-holding capacity of the soil was added. Two or three pots containing soil to be tested for phosphoric acid received 1 gram of ammonium nitrate and 1 gram of potassium sulfate (NK), while other pots received the same additions plus 1 gram of dicalcium phosphate (NPK). Weighted quantities of seed were then planted. After the seedlings were well established, they were thinned to 3 plants of corn or about 12 plants of grain sorghum per pot. The pots were kept in a greenhouse. The crops, after harvesting, were dried at about 40°C., weighed, and analyzed for phosphoric acid by the volumetric method. In most cases, corn was grown from about March 15 to May 15. After the corn was harvested, milo or kafir was usually planted in the same pots. The quantity of phosphoric acid removed by the crop was calculated from the weight and the analysis, and is expressed in parts per million of dry soil.

Relation of the Active Phosphoric Acid of the Soil to the Amounts of Phosphoric Acid Removed by Crops and to the Weights of the Crops

The average relations of the active phosphoric acid of the soils to the phosphoric acid removed from the soil per crop, to the weights of the crops, and to the average basicity and total phosphoric acid in all of the soils are shown in Table 1. The phosphoric acid removed by the crops and the weights of the crops from the soils which did not receive phosphoric

Table 1. Average relation of active phosphoric acid of the soil to the phosphoric acid removed by crops and to the weights of the crops.

Group as to active phosphoric acid p.p.m.	Active phosphoric acid p.p.m.	Phosphoric acid removed per crop p.p.m.	Weight per crop NK gm.	Weight per crop NPK gm.	Total phosphoric acid in soil %	Basicity of soil %	Number of soils
0 to 10	8	2.6	6.9	27.7	.037	1.73	75
11 to 20	15	4.9	11.6	28.8	.042	1.79	68
21 to 30	25	8.3	16.6	30.2	.052	3.85	40
31 to 50	40	8.0	16.9	28.3	.056	3.98	57
51 to 100	74	8.8	17.3	25.3	.071	4.71	46
101 to 200	138	11.0	19.4	29.5	.077	5.31	52
201 to 400	279	13.1	23.3	34.7	.088	3.05	21
Over 400	536	18.2	25.6	28.8	.133	4.46	16

acid increased with the active phosphoric acid content of the soils. This is in accord with work previously published (10, 18), such as the data in Table 2 which are taken from Bulletin 267, published in 1920. The total phosphoric acid and basicity in the soils averaged in Table 1 show a ten-

Table 2. Relations of active phosphoric acid of soils to phosphoric acid removed by crops and to weight of crops (From Bulletin 267, 1920).

Active phosphoric acid p.p.m.	Number of soils	Phosphoric acid removed per crop p.p.m. of soil	Weight per crop NK gm.	Weight per crop NPK gm.
7.3	18	2.7	7.0	28.3
14.8	44	4.5	10.3	21.2
25.1	9	5.6	14.0	30.1
34.8	8	12.8	25.9	39.6
48.3	10	8.2	19.5	28.8

dency to increase with the active phosphoric acid. The average weights of the crops produced on the soils with complete fertilizer were reasonably uniform, ranging from 25.3 to 34.7 grams.

Correlation and regression coefficients are discussed in a later section.

Relation of Other Factors to the Quantities of Phosphoric Acid Removed by Crops

In order to secure information on the relations of factors other than active phosphoric acid to the quantities of phosphoric acid removed by the crops, the data were arranged in several different ways and averaged as shown in Table 3. The groups used for active phosphoric acid, total phosphoric acid, total nitrogen, active potash and basicity are the same as those used in classifying the constituents of the soils of Texas (25) into grades 1, 2, 3, 4, 5, with the exception of one group of active potash. The number of soils which contain less than 50 parts per million of active potash was too small to justify a separate group.

Table 3 shows that the quantities of phosphoric acid taken up by the crops is related to the quantities of active phosphoric acid in the soil, but is influenced to a considerable extent by other factors. With the same quantities of active phosphoric acid, crops grown in surface soils took up considerably more phosphoric acid than those grown in subsoils. There are some exceptions, but this is the rule in most of the comparisons in Table 3. This is in line with the conclusion previously stated (18), that,

Table 3. Effect of other constituents of the soil upon the phosphoric acid removed from soils at similar levels of active phosphoric acid.

	Active phosphoric acid, p.p.m.					Active phosphoric acid, p.p.m.				
	0 to 30	31 to 100	101 to 200	201 to 400	Over 400	0 to 30	31 to 100	101 to 200	201 to 400	Over 400
	Phosphoric acid removed from surface soils, p.p.m.					Phosphoric acid removed from subsoils, p.p.m.				
Total phosphoric acid, %	4.9	5.2	...	...	...	2.0	4.4	...	...	...
0 - .025	6.0	10.7	14.0	...	...	2.9	5.8	1.9	...	...
.026 - .050	4.9	9.7	14.2	11.6	15.2	3.9	4.2	5.1	6.3	9.6
.101 - .150	11.6	12.5	19.6	19.9	27.0	5.2	2.9	4.7	...	19.4
Over .150	14.0	24.2	...	...	20.3	8.1	...	5.5	...	...
Total nitrogen, %										
0 - .030	4.9	9.6	...	...	...	1.8	14.9	...	6.0	...
.031 - .060	5.5	9.1	21.4	...	...	2.0	4.2	1.7	...	20.9
.061 - .090	4.7	10.2	12.8	...	25.0	3.5	3.6	5.2	6.5	5.1
.091 - .120	8.3	10.9	11.3	20.5	20.7	4.6	5.5	5.3	4.5	...
Over .120	9.8	15.4	17.7	13.7	26.5	7.6	28.0	13.7	5.4	...
Active potash, p.p.m.										
0 - 100	4.9	6.9	8.5	...	...	2.1	2.8	4.3	...	...
101 - 200	6.6	10.4	12.4	...	...	3.9	4.9	5.5	7.2	...
201 - 300	6.4	11.6	18.3	19.0	...	2.8	6.1	5.7	3.4	...
301 - 400	11.8	11.6	18.5	...	...	6.0	3.9	4.1	...	7.4
Over 400	14.0	16.3	15.8	15.6	23.6	...	9.4	3.0	7.6	26.6
Basicity, %										
0 - .30	6.1	11.1	19.6	...	...	2.2	11.6	...	...	...
.31 - .60	4.4	12.9	20.9	...	...	2.7	4.4	...	6.9	...
.61 - 2.00	5.4	11.1	15.5	19.3	39.3	3.0	6.3	4.9	9.7	44.3
2.01 - 5.00	12.4	4.8	13.1	6.3	16.2	1.4	5.4	6.1	4.5	8.9
Over 5.00	10.1	12.5	12.2	7.8	13.3	4.2	3.0	3.7	3.4	7.4
Phosphoric acid absorbed, %										
0 - 25	5.5	11.2	20.3	19.0	...	1.8	...	...	...	...
26 - 50	5.0	11.1	17.2	8.4	12.7	1.4	3.3	2.4	5.4	...
51 - 75	6.2	10.9	8.9	14.8	27.9	1.8	4.3	3.8	...	...
Over 75	7.2	11.6	7.8	11.4	18.0	2.5	1.3	2.1	3.5	...

with the same quantities of active phosphoric acid, the weight of the first crop and the average phosphoric acid removed from surface soils was 50% larger than from subsoils.

With similar quantities of active phosphoric acid in the soils, larger quantities of phosphoric acid were usually removed by the crops grown on soils which contained larger quantities of total phosphoric acid, total nitrogen, and active potash. In the groups of soils which contained from 0 to 30 p.p.m. of active phosphoric acid, the phosphoric acid removed by the crops averaged 4.9 p.p.m. from soils which contained less than .025% total phosphoric acid, and 14.0 p.p.m. from soils which contained more than .150% total phosphoric acid. The phosphoric acid removed by crops averaged 4.9 p. p. m. from soils containing less than .03% total nitrogen, but was 9.8 p.p.m. from soils containing more than .120% total nitrogen. The phosphoric acid removed by crops averaged 4.9 p.p.m. from soils containing less than 100 p.p.m. active potash, but was 14.0 p.p.m. from soils containing more than 400 p.p.m. active potash. Similar increases are evident for the soils which contained from 31 to 100 p.p.m. active phsophoric acid. With soils which contained more than 100 p.p.m. active phosphoric acid, the effects of different amounts of the constituents referred to above, while still evident, are not so regular. However, the number of soils in these groups was quite small. The relations between the active phosphoric acid in the soil and the phosphoric acid removed by the crops were especially close when the soils were low in total nitrogen, total phosphoric acid, and active potash.

From soils which contained less than 30 p.p.m. active phosphoric acid, the plants removed larger quantities of phosphoric acid when the basicity was over 2% than when it was below 2%. This relation was reversed with soils containing over 100 parts per million, since the plants removed less phosphoric acid when the basicity was above 2% than when it was below this amount. The capacity of the soils to fix added phosphoric acid had no regular effect upon the quantity of phosphoric acid removed by the plants.

The relation of the composition of the soils to the quantity of phosphoric acid removed by crops, expressed as percentages of the number of soils in the different groups, is shown in Table 4. When the active phosphoric acid was less than 30 p.p.m., 68% of the soils produced crops which contained less than 4.9 p.p.m. of phosphoric acid; when the soils contained from 31 to 100 p.p.m. of active phosphoric acid, 36% of the soils furnished less than 4.9 p.p.m. of phosphoric acid to the crops. Table 4 also shows that the quantities of phosphoric acid taken up by the crops are related not only to the amount of active phosphoric acid in the soils, but also to the amounts of total phosphoric acid, nitrogen, and active potash. There seems to be little relation between the quantity of phosphoric acid removed by the crops and the quantities of acid-soluble potash, acid-soluble lime, and phosphoric acid absorbed by the soils.

From the data available, it may be concluded that, with soils of similar active phosphoric acid content, higher quantities of phosphoric acid were removed from soils in which total phosphoric acid, total nitrogen, and active potash are relatively high than from those in which these constituents are relatively low.

Table 4. Percentage of soils in different groups based upon the quantity of phosphoric acid removed per crop and grades of various constituents.

Constituent and grade	Number of soils	Percentage of soils in groups based on quantity of phosphoric acid removed: 0 to 4.9 p.p.m.	5.0 to 9.9 p.p.m.	10.0 to 19.9 p.p.m.	over 19.9 p.p.m.	Removal at 50% of soils p.p.m.
All soils	363	48	25	18	9	
Active phosphoric acid, p.p.m.						
Grade 5 0 to 30	174	68	24	7	1	2.9
" 4 31 to 100	97	36	28	34	2	5.2
" 3 101 to 200	54	35	17	22	26	8.5
" 2 201 to 400	22	14	41	27	18	9.2
" 1 Over 400	16	0	25	44	31	13.9
Total phosphoric acid, %						
Grade 5 0 - .025	83	83	17	0	0	2.5
" 4 .026 - .050	126	44	29	25	2	5.9
" 3 .051 - .100	85	40	28	19	13	6.3
" 2 .101 - .150	59	27	27	29	17	8.8
" 1 Over .150	10	0	20	60	20	16.9
Nitrogen, %						
Grade 5 0 - .030	25	72	16	12	0	2.6
" 4 .031 - .060	86	68	23	8	1	3.7
" 3 .061 - .120	177	49	26	21	4	5.1
" 2 .120 - .780	59	12	32	27	29	10.7
" 1 Over .180	10	10	20	20	50	19.9
Acid-soluble potash, %						
Grade 5 0 - .10	23	62	30	8	0	3.8
" 4 .11 - .20	36	36	33	25	6	6.2
" 3 .21 - .40	87	71	18	7	4	2.7
" 2 .41 - .80	83	45	27	19	9	6.1
" 1 Over .80	42	30	23	28	19	8.6
Active potash, p.p.m.						
Grade 5 0 - 50	20	80	20	0	0	2.5
" 4 51 - 100	63	73	22	5	0	3.0
" 3 101 - 200	110	53	28	18	1	4.4
" 2 201 - 400	95	39	30	21	10	6.3
" 1 Over 400	65	15	20	37	28	13.2
Basicity, %						
Grade 5 0 - .30	65	54	31	14	1	4.1
" 4 .31 - .60	44	61	14	18	7	4.1
" 3 .61 - 2.00	113	41	27	20	12	6.3
" 2 2.01 - 5.00	41	51	22	22	5	4.5
" 1 Over 5.00	100	47	27	19	7	5.1
Acid-soluble lime, %						
Grade 5 0 - .10	21	63	16	16	5	3.9
" 4 .11 - .20	25	40	44	16	5	5.0
" 3 .21 - .40	38	50	29	16	5	5.2
" 2 .41 - 2.00	98	50	22	18	10	4.9
" 1 Over 2.00	81	50	25	17	8	5.0
Phosphoric acid absorbed, %						
0 - 25	17	41	29	23	7	5.2
26 - 50	46	48	35	13	4	5.0
51 - 75	57	54	19	21	6	4.7
Over 75	50	68	18	10	4	2.6

Low, Medium, and High Availability of Phosphoric Acid in Soils Containing Similar Quantities of Active Phosphoric Acid

In order to study further the causes for differences in phosphoric acid removed by crops from soils similar in active phosphoric acid content, the soils were divided into groups according to the active phosphoric acid in the soils, and then further divided into subgroups containing soils from which the crops removed quantities of phosphoric acid which could be considered as low, intermediate or high for each main group. The results are shown in Table 5.

The soils similar in active phosphoric acid content from which the plants removed relatively low quantities of phosphoric acid contained

Table 5. Average composition of soils from which plants removed low, intermediate, or high quantities of phosphoric acid.

Number of soils	Range of active phosphoric acid p.p.m.	Phosphoric acid removed by crops p.p.m.	Active phosphoric acid p.p.m.	Total phosphoric acid %	Weight of crop NK gm	Weight of crop NPK gm	Phos. acid removed by crop p.p.m.	Phos. acid absorbed %	Nitrogen %	Active potash p.p.m.	Total potash %	Acid soluble lime %	Basicity %	pH
						Low group								
31	0- 10	0-1.5	8	.027	3.0	25.6	1.1	73.2	.053	118	.29	.49	1.69	6.23
18	11- 20	0-2.5	15	.034	4.7	22.0	1.8	57.3	.057	135	.28	1.63	1.66	6.76
7	21- 30	0-3.5	25	.043	5.0	15.5	2.2	65.6	.060	101	.32	6.34	10.46	7.78
16	31- 50	0-4.0	39	.062	7.7	17.6	3.2	51.7	.072	160	.59	6.26	9.58	7.83
15	51-100	0-4.5	70	.060	6.3	21.1	2.7	72.1	.078	207	.58	5.64	9.15	8.07
23	101-200	0-6.0	134	.068	9.2	25.6	3.6	70.9	.092	282	.69	4.94	8.53	8.00
7	201-400	0-7.5	285	.088	13.1	36.5	4.4	63.0	.099	365	.70	3.36	5.97	7.81
5	Over 400	0-9.0	482	.103	14.5	21.7	7.2	82.4	.076	454	.79	2.47	5.83	7.55
						Intermediate group								
34	0- 10	1.6- 4.0	8	.041	7.2	25.2	2.8	67.1	.058	121	.24	5.16	7.20	6.94
37	11- 20	2.6- 7.5	15	.041	11.7	30.1	5.0	53.3	.071	154	.27	2.25	3.20	6.77
24	21- 30	3.6- 9.5	25	.040	14.7	30.5	6.5	36.6	.081	160	.24	2.73	5.65	6.91
26	31- 50	4.1-11.5	40	.055	17.2	31.9	7.4	45.8	.080	227	.33	2.73	6.55	7.20
15	51-100	4.6-13.5	73	.058	19.7	29.0	7.8	37.9	.084	311	.54	1.79	3.57	7.42
11	101-200	6.1-16.5	139	.085	18.9	29.9	10.1	65.0	.093	497	.78	3.69	7.56	7.91
9	201-400	7.6-20.0	294	.088	25.7	36.8	12.5	63.4	.125	568	.72	1.74	3.03	7.58
7	Over 400	9.1-27.0	560	.153	26.1	28.8	15.7	62.2	.122	640	.94	3.43	5.12	7.59
						High group								
8	0- 10	4.1 and up	8	.062	18.3	38.6	8.0	50.0	.080	168	.33	4.33	5.91	6.88
9	11- 20	7.6 " "	17	.068	22.8	35.9	11.3	65.0	.109	148	.37	7.63	12.79	7.17
8	21- 30	9.6 " "	25	.097	29.6	36.1	17.7	71.3	.115	250	.54	8.70	20.04	7.50
13	31- 50	11.6 " "	41	.057	27.7	34.9	15.9	49.5	.094	218	.32	3.57	4.80	7.41
14	51-100	13.6 " "	77	.088	26.9	28.4	17.0	58.2	.108	401	.54	2.99	5.34	7.10
16	101-200	16.6 " "	142	.078	34.7	36.5	23.1	33.7	.104	434	.54	3.30	5.36	7.28
5	201-400	20.1 " "	276	.095	33.8	36.9	26.0	42.2	.129	561	.66	.68	1.16	7.23
3	Over 400	27.1 " "	553	.140	41.1	40.7	38.7	61.6	.182	1009	.97	.87	1.66	7.00
						General averages								
122	Low		80	.052	6.2	22.9	2.7	48.1	.070	195	.49	3.42	5.85	7.25
163	Intermediate		76	.055	14.7	29.8	6.6	50.0	.078	238	.38	3.10	5.32	7.07
76	High		96	.079	28.6	34.8	17.8	54.2	.107	341	.49	4.29	7.32	7.20

smaller amounts of total phosphoric acid, nitrogen and active potash than the soils from which intermediate or high quantities of phosphoric acid were removed. The differences were greater with soils which were low in active phosphoric acid than with those which were high. The relations between total posphoric acid, nitrogen and active potash and the availability of the phosphoric acid in soils containing similar amounts of active phosphoric acid are thus similar to those brought out in a different way in the preceding section.

Acid-soluble lime, total potash, and the quantity of phosphoric acid absorbed by the soil had little apparent relation to the relative quantities of phosphoric acid removed by the crops. Soils from which high quantities of phosphoric acid were removed contained relatively high amounts of these constituents, with the exception of total potash. The greatest differences between the groups were in the weights of the crops; this was to be expected, since the higher quantities of phosphoric acid removed, for which these groups were subdivided, would naturally be associated with larger crops.

The average phosphoric acid removed by two successive crops from soils which contained similar quantities of active phosphoric acid but differed in other characteristics is shown in Table 6. As in work previously

Table 6. Effect of level of active phosphoric acid upon the phosphoric acid removed by two crops from different soil groups (p.p.m. of soil).

	0 to 30 Active	31 to 100 Active	101 to 200 Active	201 to 400 Active	Over 400 Active
All soils	8.7	16.6	23.3	26.0	38.3
Surface soils	13.4	20.3	30.4	34.2	41.2
Subsoils	6.6	10.8	10.3	11.5	30.6
Basicity below 2%	9.5	14.1	19.8	14.8	29.1
Basicity above 2%	8.4	18.8	32.6	39.4	75.6
Humid section	10.3	19.1	21.2	26.8	31.9
Subhumid section	10.0	13.5	20.2	26.2	41.7
Humid, low basicity, surface	11.8	22.4	38.3	...	...
Humid, low basicity, subsoil	6.2	12.7	...	...	...
Humid, high basicity, surface	22.3	22.4	31.8	28.3	43.7
Humid, high basicity, subsoil	6.0	15.1	10.9	16.9	13.7
Subhumid, low basicity, surface	9.0	21.4	35.9	49.3	74.4
Subhumid, low basicity, subsoil	5.3	9.9	12.9	16.2	77.9
Subhumid, high basicity, surface	22.1	14.0	17.2	15.6	28.9
Subhumid, high basicity, subsoil	12.3	7.1	9.0	6.7	17.2

discussed, a relation between active phosphoric acid in the soil and phosphoric acid removed by the crops is evident. The degree and effect of the relation differed with different groups of soils. The differences are larger with surface soils than with subsoils. When the soils contained less than 30 p.p.m. of active phosphoric acid, the phosphoric acid removed by the crops averaged 13.4 p.p.m. from surface soils and only 6.6 p.p.m. from subsoils. Phosphoric acid removed by the crops from soils which contained less than 30 p.p.m. of active phosphoric acid averaged 9.5 p.p.m. in soils in which the basicity was below 2%, and 8.4 p.p.m., or nearly the same, in the soils in which the basicity was above 2%. In surface soils and subsoils from the subhumid section of the state, phosphoric acid removed by crops had no relation to active phosphoric acid in soils of high basicity (an irregular range from 6.2 to 17.2 p.p.m.) but showed a very high relation to active phosphoric acid in soils of low basicity (a regular increase from 9.0 to 74.4 p.p.m.).

The data in Table 6 clearly show that the phosphoric acid removed by crops from soils of similar active phosphoric acid content depends to a certain extent upon whether the sample is a surface soil or a subsoil, whether the basicity is less than 2% or more than 2%, and whether the soil came from the humid or subhumid region of the state.

A further study of the factors which affect the amounts of phosphoric acid removed by crops from soils arranged in groups of similar active phosphoric acid content but of different general characteristics is given in Table 7. In this table, the number of soils which, though similar in active

Table 7. Distribution of soils within different groups from which plants removed low, intermediate, and high amounts of phosphoric acid.

Groups compared	As percentage of total number of soils: Low (36)	Intermediate (45)	High (19)	Total (100)	As percentages within each group: Low	Intermediate	High
Humid	15	24	12	51	29	47	24
Subhumid	21	21	7	49	43	43	14
Surface	11	26	17	54	20	48	32
Subsoil	25	19	2	46	54	41	5
Basicity below 2%	18	34	14	66	27	52	21
Basicity above 2%	18	11	5	34	53	32	15
Light texture	18	27	7	52	35	52	13
Heavy texture	18	18	12	48	38	38	24
Humid, low basicity	10	19	8	37	27	51	22
Humid, high basicity	5	5	4	14	37	36	27
Subhumid, low basicity	8	15	6	29	27	52	21
Subhumid, high basicity	13	6	1	20	65	30	5
Light texture, surface	4	16	7	27	15	59	26
Light texture, subsoil	14	10	1	25	56	40	4
Heavy texture, surface	7	10	10	27	26	37	37
Heavy texture, subsoil	11	9	1	21	52	43	5
Low basicity, surface	4	18	13	35	11	51	38
Low basicity, subsoil	14	16	1	31	45	52	3
High basicity, surface	7	8	4	19	37	42	21
High basicity, subsoil	11	3	1	15	73	20	7
Humid, surface	4	13	11	28	14	46	40
Humid, subsoil	11	11	1	23	48	48	4
Subhumid, surface	7	13	6	26	27	50	23
Subhumid, subsoil	14	8	1	23	61	35	4

phosphoric acid content, gave up low, medium, or high quantities of phosphoric acid to crops are compared in groups of factors. The percentage distribution of the soils with respect to both the total number of soils and to the number of soils within each subgroup are given. The term availability will here be applied to the active phosphoric acid for convenience, though it is not correct, since the active phosphoric acid does not seem to be removed by the crops.

When only one factor at a time is considered, the data given in Table 7 show that the relative availability of active phosphoric acid was higher in surface soils than in subsoils, in soils from the humid section of the state than in those from the subhumid section, in soils of basicity lower than 2% than in soils of basicity higher than 2%, and in soils of heavy texture than in those of light texture. When more than one factor at a time is considered, the same general relations hold, but information concerning the interaction of factors is obtained. In surface soils, availability was higher in heavy textured soils than in light textured soils, but there was little difference in subsoils. In soils of basicity over 2%, availability was higher in soils from the humid section than in those from the subhumid section, but there was little difference due to source of soils in which basicity was low. Availability was highest in surface soils of low basicity and heavy texture from the humid section and lowest in subsoils of basicity over 2% and light texture from the subhumid section.

In another arrangement of the data, various groups of soils were averaged as shown in Table 8. Averages given in this table show that, in all the groups, surface soils contain more active phosphoric acid and slightly more total phosphoric acid, yielded larger crops, and provided more phosphoric acid to the crops than did the subsoils. Soils with a basicity below 2%, as compared with those having a basicity above 2%, contained smaller quantities of active phosphoric acid and total phosphoric acid; however, the weights of the crops and the phosphoric acid removed by the crops from the two groups of soils were practically the same. Soils of the humid section, as compared with those from the subhumid section, contained smaller quantities of active phosphoric acid and smaller quantities of total phosphoric acid, but produced practically as large crops which contained as much phosphoric acid. The surface soils of the humid section with low basicity contained smaller amounts of active phosphoric acid and of total phosphoric acid and yielded smaller crops and amounts of phosphoric acid to the crops than corresponding soils of high basicity. The soils of low basicity from the subhumid section contained larger quantities of active phosphoric acid and total phosphoric acid and yielded larger crops and more phosphoric acid in the crops than corresponding soils of the humid section. The subhumid surface soils of high basicity, as compared with similar soils from the humid section, contained larger amounts of active phosphoric acid and total phosphoric acid but yielded slightly smaller crops and less phosphoric acid in the crops.

Table 8. Average phosphoric acid in soils, phosphoric acid removed by crops, and weight of crops from different groups of soils.

Soil group	Number of soils	Phosphoric acid in soils		Phosphoric acid removed by		Weight of crops	
		Active p.p.m.	Total %	One crop mgm.	Two crops mgm.	One crop gm.	Two crops gm.
All soils	320	88	.060	8.3	16.2	15.1	29.9
Surface soils	188	103	.064	11.2	21.7	19.5	39.2
Subsoils	132	66	.056	4.5	8.9	9.0	21.1
Basicity low (less than 2%)	188	54	.040	7.7	15.5	14.9	31.2
Basicity high (above 2%)	132	136	.089	8.9	17.2	18.2	31.7
Humid section	162	40	.055	8.0	15.5	14.5	29.8
Subhumid section	158	118	.065	8.6	17.0	15.6	32.9
Humid, low basicity, surface	54	29	.035	8.5	16.7	16.7	34.6
Humid, high basicity, surface	38	130	.098	14.7	28.5	22.0	43.1
Subhumid, low basicity, surface	62	101	.051	12.2	24.5	21.5	43.7
Subhumid, high basicity, surface	34	195	.099	10.2	19.1	18.0	35.4
Humid, low basicity, subsoil	41	15	.035	3.6	8.1	7.0	16.3
Humid, high basicity, subsoil	29	95	.070	5.4	10.5	10.5	25.7
Subhumid, low basicity, subsoil	31	65	.038	5.1	9.9	9.7	23.6
Subhumid, high basicity, subsoil	31	117	.086	4.2	8.7	8.6	20.4

Statistical Studies of the Factors

Statistical studies of the data from each individual soil offer certain advantages in addition to the presentation of the data by averages. Each individual set of observations is given its proportionate weight in the various calculations. The significance of differences and relations between the data may be mathematically estimated. Where relations are of high significance, quantitative statements of the relations may be calculated. The methods used are described by Snedecor (33) and by Fisher (3). The individual sets of data, from which the averages given in Table 8 were calculated, were used in connection with the statistical studies to be discussed below.

Correlation Coefficients

The correlation coefficients for active phosphoric acid and for total phosphoric acid in different groups of soils, as related to the phosphoric acid removed by one crop and by two crops and to the weights of the crops, are given in Table 9. The relations between active phosphoric acid and total phosphoric acid in the soil are also given.

The coefficients are significant when they exceed the smallest significant coefficient as given in the first column of figures.

When all of the soils were combined into one group (line 1 of Table 9), the coefficients of correlation for all of the comparisons were highly significant. The correlation coefficients for phosphoric acid removed by the crops were usually higher for two crops than for one crop, or for the weights of either one or two crops. The coefficients for active phosphoric acid averaged slightly higher than for total phosphoric acid.

When the soils were divided into two groups, for single comparisons, the coefficients were still highly significant in nearly all cases. The coefficients were very similar for surface soils and for subsoils. As already shown, less phosphoric acid was removed from subsoils than from surface soils of similar active phosphoric acid content, but this did not affect the degree of correlation. Coefficients for active phosphoric acid were much larger in soils of low basicity than in those of high basicity. Coefficients for total phosphoric acid were considerably smaller in soils of low basicity than in soils of high basicity. Coefficients for soils from the humid region of the state were usually considerably smaller than those for soils from the subhumid section.

When the soils were divided into eight groups, the coefficients for active phosphoric acid were highly significant for soils of low basicity, while those for surface soils of high basicity from the humid region are barely significant. Coefficients for total phosphoric acid were highly significant in surface soils of high basicity and in soils of low basicity from the subhumid region. Active phosphoric acid and total phosphoric acid were significantly correlated in only three groups of soils, all of which were from the subhumid region.

Correlation coefficients for the relation between the phosphoric acid removed and the weights of crops were calculated for all the groups listed in Table 9. With the data from one crop (corn), the lowest figure was .87 for humid, high basicity, surface soils and subhumid, low basicity subsoils, and the highest (.99) for humid, high basicity, subsoils, and subhumid,

Table 9. Coefficients of simple correlation between phosphoric acid in the soil and phosphoric acid in the crops and weight of crops.

Soil group	Smallest significant coefficient	Active phosphoric acid in soils				Total phosphoric acid in soils	Total phosphoric acid in soils			
		Phosphoric acid removed		Weight of crops			Phosphoric acid removed		Weight of crops	
		One crop	Two crops	One crop	Two crops		One crop	Two crops	One crop	Two crops
All soils	.11	.35**	.37**	.29**	.21**	.65**	.44**	.52**	.26**	.25**
Surface soils	.15	.44**	.47**	.36**	.34**	.62**	.57**	.56**	.38**	.27**
Subsoils	.17	.40**	.49**	.31**	.43**	.39**	.29**	.40**	.25**	.25**
Basicity low (below 2%)	.14	.77**	.81**	.58**	.56**	.46**	.36**	.40**	.29**	.29**
Basicity high (above 2%)	.17	.24*	.26**	.25*	.28**	.14	.60**	.56**	.43**	.45**
Humid section	.15	.41**	.40**	.36**	.34**	.41**	.51**	.42**	.33**	.33**
Subhumid section	.16	.50**	.54**	.40**	.43**	.67**	.51**	.54**	.40**	.40**
Humid, low basicity, surface	.27	.75**	.77**	.72**	.55**	.05	.01	.07	.13	.16
Humid, high basicity, surface	.31	.33*	.25	.32*	.24	.12	.88**	.40**	.49**	.38**
Subhumid, low basicity, surface	.25	.85**	.89**	.67**	.57**	.99**	.82**	.84**	.63**	.56**
Subhumid, high basicity, surface	.33	.23	.33*	.25	.24	.53**	.59**	.75**	.46**	.40**
Humid, low basicity, subsoil	.30	.48**	.86**	.49**	.48**	.07	.24	.29	.13	.28
Humid, high basicity, subsoil	.36	.11	.24	.19	.33	.32	.16	.24	.17	.27
Subhumid, low basicity, subsoil	.35	.87**	.94**	.70**	.75**	.93**	.92**	.85**	.72**	.80**
Subhumid, high basicity, subsoil	.35	.09	.09	.11	.22	.06	.39*	.39*	.26	.39*

* Significant correlation
**Highly significant correlation

high basicity subsoils. For two crops, they were lowest (.80), with humid, low basicity, surface soils and highest (.99) with high basicity soils. The correlation was high in all cases, but was not 1.00 in any group of soils.

The proportions of the variations in the data which may be attributed to concurrent variations in active phosphoric acid or total phosphoric acid were estimated by squaring the coefficients of correlation (Table 10). For active phosphoric acid, the groups in which these proportions were appreciable were soils of low basicity. Active phosphoric acid is thus a reasonable basis for prediction with soils which are low in basicity; it is not a good basis for soils with a basicity of over 2%. For total phosphoric acid, the relations were appreciable in surface soils of high basicity and in soils of low basicity from the subhumid region; total phosphoric acid is thus a reasonable basis for prediction in these soils but not in other soils. The relations are closer with two crops than with one crop, with phosphoric acid removed by the crops than with the weights of the crops, and with soils from the humid region of the state than with those from the subhumid region.

Regression Equations

Regression equations show the mathematical relation between two quantities, so that, if one is known, the other can be calculated. If the relation between the active phosphoric acid and the phosphoric acid removed by crops can be expressed as a straight line, the phosphoric acid removed can be calculated by multiplying the quantity of active phosphoric acid by a factor and adding a constant.

Equations for simple regression, which conform to the equation of a straight line, $y = mx + b$, were calculated for the data secured in this work. For this purpose, y represented the calculated quantity of phosphoric acid removed by the crops in parts per million of the soil; x, the quantity of active (or of total) phosphoric acid in the soil in parts per million; m, the coefficient of the active (or total) phosphoric acid which

Table 10. Percentage of variation in phosphoric acid removed by crops or in weights of crops attributed to concurrent variations in phosphoric acid in soils.

Soil group	Active phosphoric acid in soils				Total phosphoric acid in soils			
	Removed		Weights		Removed		Weights	
	One crop	Two crops	One crop	Two crops	One crop	Two crops	One crop	Two crops
ll soils	12	14	8	4	19	27	7	6
ırface soils	19	22	13	12	32*	31*	14	7
ıbsoils	16	24	10	18	8	16	6	6
ow basicity (below 2%)	59*	66*	34*	31*	13	16	8	8
igh basicity (above 2%)	6	7	6	8	36*	31*	19	20
umid section	17	16	13	12	26	18	11	11
ıbhumid section	25	29	16	18	26	29	16	16
umid, low basicity, surface	57*	59*	51*	30*	0	0	2	2
umid, high basicity, surface	14	10	14	10	76*	16	24	14
ıbhumid, low basicity, surface	84*	80*	44*	32*	67*	71*	40*	31*
ıbhumid, high basicity, surface	5	11	6	13	35*	56*	21	16
umid, low basicity, subsoil	23	74*	24	29	6	8	3	9
umid, high basicity, subsoil	1	6	4	11	3	6	3	8
ıbhumid, low basicity, subsoil	76*	88*	49*	56*	67*	71*	51*	64*
ıbhumid, high basicity, subsoil	1	1	1	5	15	15	17	14

*High relation

gives the change in quantity removed associated with unit change in active (or total) phosphoric acid in the soil; and b, a constant which states the difference between the quantity expected and the quantity which would be expected on the basis of changes in active (or total) phosphoric acid alone. The numerical values of these characters for a particular group of soils may differ considerably from those for some other group. In the tables to follow, the quantity b will be designated as the constant, while the quantity m will be designated as the regression coefficient of active phosphoric acid or other basis for calculation. The regression coefficients for total phosphoric acid were based upon parts per million rather than per cent, in order to conform to the units used for the quantity of phosphoric acid removed.

The regression constants and coefficients of various groups of soils are given in Table 11. The active phosphoric acid, in parts per million, multiplied by the appropriate coefficient, plus the constant, gives the calculated number of parts per million of phosphoric acid that would be expected to be removed by the crops. Thus, for 10 p.p.m. of active phosphoric acid in a surface soil of low basicity from the humid section, the amount of phosphoric acid to be expected in one crop would be $10 \times .206 + 2.6 = 4.66$ p.p.m. The table shows that there are relations between the active phosphoric acid and the phosphoric acid removed by the crops with soils or subsoils of less than 2% basicity in the humid region. A relation between the total phosphoric acid and the phosphoric acid removed occurs in soils of more than 2% basicity from both the humid and the subhumid regions. In soils of low basicity in the subhumid region, there is a definite relation between the quantities of total phosphoric acid

Table 11. Characteristics of equations for regression of phosphoric acid removed by crops on active and total phosphoric acid in the soils.

Soil group	Average phosphoric acid removed p.p.m.	Active phosphoric acid Constant	Active phosphoric acid Coefficient	Total phosphoric acid Constant	Total phosphoric acid Coefficient
		Surface soils, one crop			
Humid, low basicity**	8.5	2.6	.206*	8.5	.0002
Humid, high basicity	14.7	10.8	.029	–12.3	.0276*
Subhumid, low basicity	12.2	6.1	.060*	0.1	.0238*
Subhumid, high basicity	10.3	8.6	.008	1.3	.0090*
		Surface soils, two crops			
Humid, low basicity	16.1	7.2	.310*	14.6	.0004
Humid, high basicity	28.5	23.3	.040	6.6	.0246*
Subhumid, low basicity	24.5	12.0	.133*	0.3	.0488*
Subhumid, high basicity	19.1	15.8	.017	2.2	.0171*
		Subsoils, one crop			
Humid, low basicity	3.6	1.5	.132*	2.9	.0019
Humid, high basicity	5.4	4.9	.005	3.3	.0031
Subhumid, low basicity	5.1	1.2	.060*	–4.7	.0260*
Subhumid, high basicity	4.2	3.5	.003	–0.8	.0059*
		Subsoils, two crops			
Humid, low basicity	7.0	0.7	.414*	5.6	.0041
Humid, high basicity	10.5	10.0	.016	6.2	.0061
Subhumid, low basicity	9.9	2.8	.109*	–7.2	.0454*
Subhumid, high basicity	8.7	8.0	.006	1.9	.0125*

* A significant proportion of the phosphoric acid removed is accounted for by this regression coefficient.

**Low basicity, less than 2%; high basicity above 2%.

Table 12. Average relations of certain factors at different levels of active phosphoric acid in surface soils of low basicity.

nge of active phosphoric acid, p.p.m.	0 to 15	16 to 30	31 to 100	Above 100
mber of soils in group	23	30	30	19
erages				
Active phosphoric acid, p.p.m.	10.4	21.8	51.0	214.8
Phosphoric acid removed, p.p.m.	7.9	22.6	36.6	41.9
Weight of two crops, grams	19.6	29.7	47.8	66.1
rrelation coefficients				
Active phosphoric acid and phosphoric acid removed	.48*	.46**	.45**	.00
Active phosphoric acid and weight of crops	.31	.44*	.39*	.21
Phosphoric acid removed and weight of crops	.91**	.88**	.77**	.47*
gression characteristics				
Active phosphoric acid and phosphoric acid removed				
Constant	1.47	3.61	10.31	42.81
Coefficient of active phosphoric acid	.618	.417	.241	.00
Active phosphoric acid and weight of crops				
Constant	9.98	6.60	26.55	65.12
Coefficient of active phosphoric acid	.927	1.057	.416	.00
Phosphoric acid removed and weight of crops				
Constant	0.16	2.89	4.67	23.38
Coefficient of weights of crops	.394	.330	.376	.279

* Significant correlation
**Highly significant correlation

and the phosphoric acid withdrawn by the crops used. The numerical value of the regression constants and coefficients differed widely between different groups of soils.

Correlation and Regression Within Groups Based on Active Phosphoric Acid

Since the relation between the active phosphoric acid in the soil and the phosphoric acid removed by crops is greatest for surface soils of low basicity, the relations were further studied within groups of these soils. The four groups studied were as follows: 0 to 15, 16 to 30, 31 to 100 and over 100 p.p.m. of active phosphoric acid. The results are given in Table 12. The coefficients of correlation between active phosphoric acid and phosphoric acid removed were nearly the same within the first three groups, but was zero in the group of soils which contained over 100 p.p.m. of active phosphoric acid. The regression coefficients for active phosphoric acid and phosphoric acid removed were .618, .417, .241, and 0 respectively. The regression constants increased, being 1.47, 3.61, 10.31, and 42.8. This indicates that factors other than the content of active phosphoric acid became increasingly important with increases in the amounts of active phosphoric acid in the soils. The active phosphoric acid was more closely correlated to the phosphoric acid removed than to the weights of the crops, except in the last group.

With less than 100 p.p.m. of active phosphoric acid, there is thus a high relation between the active phosphoric acid in the soils of low basicity and the phosphoric acid removed by the crops and the weight of the crops, but above the 100 p.p.m. levels, the relation becomes much lower; it is perhaps of minor importance in most soils containing more than 100 p.p.m. of active phosphoric acid.

Effect of Cropping on Active Phosphoric Acid of Some Soils

When soils were analyzed for active potash before and after cropping in pot experiments, it was found that the loss in active potash accounted for about 40% of the potash taken up by the crops (21). Previous work indicates that cropping does not decrease the active phosphoric acid of the soil (18). The active phosphoric acid was determined before and after cropping in some pot experiments. The average results for four crops are given in Table 13. Although appreciable quantities of phosphoric acid

Table 13. Average effect of cropping on active phosphoric acid of soils (p.p.m.)

Number of soils	Group based on active phosphoric acid	Average active phosphoric acid in soils Before cropping	After cropping	Phosphoric acid removed by crop
8	7 to 10	8.2	17.3	10.5
13	11 to 20	16.3	23.1	19.3
8	21 to 30	24.3	21.5	21.8
18	31 to 50	40.0	42.2	35.0
3	51 to 70	61.6	66.0	53.0
50	7 to 70	27.5	31.4	23.1

were removed by the plants, little or no change in amounts of active phosphoric acid remaining in the soils was observed. In some cases, active phosphoric acid was slightly greater after cropping than before cropping. This may be caused by the roots of the plants in the soil making some of the phosphoric acid soluble in the acid, and is evident chiefly with the groups of soils containing less than 20 p.p.m. of active phosphoric acid. Either the phosphoric acid removed by the plants came from soil phosphates other than the fraction which is soluble in 0.2 N nitric acid, or the action of the plants and the chemical changes in the soil caused a replenishment of the soluble fraction by phosphoric acid derived from more insoluble compounds in the soil.

Availability of Total Phosphoric Acid of Some Soils

The availability of a plant nutrient in fertilizers has long been measured by pot experiments in which definite amounts of the nutrient under study are added to soils containing abundant quantities of the other nutrients. The effect of the nutrient under study was then measured by ascertaining the gain in weight of the crop or the increase in the quantity of nutrient removed by the crop. Examples of this type of work on fertilizers containing phosphoric acid have been reported by Ross and Jacobs (31) and by Haskins (29). This method has seldom been applied to soils for studying the availability of their constituents. However, the writers (26) have used it in a study of the availability of the potash in the soil.

In a similar study on phosphoric acid, an amount of the soil under study calculated to contain 100 milligrams of total phosphoric acid was added to 5,000 grams of a Lufkin fine sandy soil which was known to respond to phosphate fertilizers, together with carriers of nitrogen and potash. The usual greenhouse procedure, previously described, was followed from this point. Superphosphate and rock phosphate were included for the purpose of comparing these phosphates with soil phosphates. The quantity of phosphoric acid taken up by the crops from the Lufkin fine sandy loam soil which did not receive phosphate was deducted from the quantities taken up by the crops on the soils which received the soil tested.

Table 14. Phosphoric acid recovered by corn from additions which contained 100 milligrams of total phosphoric acid.

Source of phosphoric acid	Weight of crop gm.	Per cent in crop	Phosphoric acid Removed mgm.	Phosphoric acid Percentage recovered
Basal soil	19.4	.17	33.6	0
Superphosphate	32.3	.21	67.8	34.2
Rock phosphate	23.3	.21	47.8	14.2
Crockett very fine sandy loam	19.2	.17	32.6	-1.0
Kirvin fine sandy loam	18.3	.19	34.8	1.2
Bell clay	19.9	.18	35.2	1.6
Wilson clay loam	18.6	.19	35.3	1.7
Webb fine sandy loam	18.3	.19	35.3	1.7
Wilson clay	18.6	.19	35.3	1.7
Abilene clay loam	20.7	.17	35.8	2.2
Miller clay	15.6	.24	36.9	3.3
Lufkin fine sandy loam	20.5	.18	36.9	3.3
Hunt black clay	23.1	.17	40.0	6.4
Trinity clay	16.3	.26	42.4	8.8
Ochlockonee fine sandy loam	27.0	.16	44.0	10.4
Houston clay	16.9	.26	44.5	10.9
Uvalde clay loam	14.4	.31	44.6	11.0
Houston black clay	18.6	.25	45.8	12.2
Catalpa clay	16.9	.28	46.5	12.9
Denton clay	30.7	.18	54.3	20.7

The availability of the total phosphoric acid in the soils to corn grown in 1937 is shown in Table 14. The increase due to the phosphoric acid in the added soil ranged from 0 to 20.7 milligrams (equivalent to 20.7% of the total phosphoric acid added). The increase in phosphoric acid removed by the crop due to the addition of the soil being studied was low (less than 3.5 milligrams) in 9 of the 17 soils used. The change in phosphoric acid in the crops from these 9 soils ranged from a loss of 1.2 milligrams to a gain of 3.3 milligrams, with an average of 1.76 milligrams. The recovery from the remaining 8 soils was high, and averaged 11.66 milligrams. Of the 9 soils in which phosphoric acid had a low availability, 8 were low in basicity; of the 8 soils in which the phosphoric acid had a high availability, 7 were high in basicity.

The analyses of the soils in which the phosphoric acid had a low availability were averaged in one group, and those in which the availability was high were averaged in another group; these averages are given in Table 15. The Miller clay, a calcareous bottomland soil, was omitted from the low group. The soils from which the recovery of phosphoric acid was low averaged considerably lower in total nitrogen, total phosphoric acid,

Table 15. Composition of soils with low availability of phosphoric acid compared with those with high availability.

	Low availability	High availability
Total nitrogen, per cent	.087	.140
Total phosphoric acid, per cent	.042	.103
Active phosphoric acid, p.p.m.	23	121
Total potash, per cent	.73	1.14
Active potash, p.p.m.	245	317
Acid-soluble lime, per cent	.46	8.91
Basicity, per cent	.80	14.70
Number of soils	8	8
pH	7.14	7.80
Average availability, per cent	1.8	11.7

active phosphoric acid, total potash, and active potash than the group in which the recovery was high. The greatest differences, however, were in acid-soluble lime and in basicity, in which the low recovery group was much lower than the high recovery group. The fact that the corn removed larger quantities of phosphoric acid from soils which were high in total phosphoric acid indicated that the phosphoric acid is more available per unit in these soils. Only 5.5% of the total phosphoric acid in the low group was soluble in 0.2 N nitric acid (active), while 11.8% of that in the high group was soluble.

In all soils except one, the availability of the phosphoric acid was less than that in rock phosphate. The phosphoric acid removed by the crops was greater than the amount of active phosphoric acid in the soil in 4 of the 17 soils; all 4 of these soils were highly calcareous. The phosphoric acid removed, expressed as percentages of the active phosphoric acid in the added soil, averaged 38% in soils of low basicity. Much of the phosphoric acid which was taken up by the corn plants from the soils of high basicity was from compounds in the soil which were insoluble in 0.2 N nitric acid.

Another experiment was conducted in 1938 with 9 soils, of which 8 were high in basicity. The results are given in Table 16. The quantity of phosphoric acid removed by the first crop, corn, from four of the soils was less than that removed from the basal soil without any addition. The fact that the corn plants contained relatively high percentages of phosphoric acid but were low in weight indicated that some factor other than phosphoric acid affected the growth. After the corn was harvested, milo was planted without any further addition of phosphoric acid. The milo removed much more phosphoric acid than the corn. Because of irregularities in the growth of the corn and probably consequent irregularities in the milo, the discussion of results will be limited to the combined data for both crops. The quantity of phosphoric acid recovered from 8 of the 9 soils exceeded the quantity recovered from rock phosphate, and in 5 of them, the recovery was over twice as large. The single exception was a Lufkin fine sandy loam, the only soil of low basicity used in the series. The recovery of phosphoric acid from the soils was considerably less than that from superphosphate. Recovery from the soil of low basicity considerably exceeded the quantity of active phosphoric acid in the original soil.

The results of this work show that soils differ markedly in the availability of their total phosphoric acid; some of this variability may be attributed to basicity of the soils. Availability, per unit of phosphoric acid, is higher in soils which are high in total and active phosphoric acid, lime, basicity, and probably nitrogen. The quantity available in some calcareous soils may be considerably greater than is indicated by the quantity of active phosphoric acid. Phosphoric acid in some calcareous soils may be considerably more available than that in rock phosphate, but is always less than that in superphosphate.

Availability of Fixed Phosphoric Acid

The availability of the phosphate fixed by a number of soils was also studied briefly. In this work, soils having a fixing power of over 80% for phosphoric acid were selected. The amount of soil which would fix 100 milligrams of phosphoric acid was treated with a weak phosphate solu-

Table 16. Phosphoric acid removed by corn and milo in 1938 from additions which contained 100 milligrams of total phosphoric acid.

Source of phosphoric acid	Corn Dry weight gm.	Corn Phosphoric acid %	Corn Phosphoric acid Total removed mgm.	Corn Phosphoric acid Increase mgm.	Milo Dry weight gm.	Milo Phosphoric acid %	Milo Phosphoric acid Total removed mgm.	Milo Phosphoric acid Increase mgm.	Both crops Dry weight gm.	Both crops Phosphoric acid Total removed mgm.	Both crops Phosphoric acid Percentage recovered
Basal soil	17.4	.25	44.0	Check	15.4	.14	21.6	Check	32.8	65.6	Check
Superphosphate	21.5	.37	79.5	35.5	24.0	.15	35.3	13.7	45.4	114.8	49.2
Rock phosphate	18.0	.27	48.1	4.1	19.4	.17	32.4	10.8	37.4	80.5	14.9
Lufkin fine sandy loam	18.7	.25	46.2	2.2	15.8	.18	28.9	7.3	34.5	75.1	9.5
Hunt black clay	18.7	.29	54.2	10.2	16.3	.17	27.7	6.1	35.0	81.9	16.3
Harlingen clay	7.7	.46	35.4	-8.6	22.5	.23	51.8	30.2	30.2	87.2	21.6
Uvalde clay loam	9.4	.37	34.8	-9.2	25.3	.21	53.9	32.3	34.7	88.7	23.1
Denton clay	19.4	.31	60.7	16.7	21.8	.16	35.5	13.9	41.2	96.2	30.6
Miller clay	10.1	.40	40.0	-3.6	29.9	.19	55.9	34.3	40.0	96.3	30.7
San Benito clay	10.8	.41	44.0	0	31.1	.17	52.9	31.3	41.9	96.9	31.3
Houston clay	10.2	.34	34.4	-9.6	25.2	.25	63.7	42.1	35.4	98.1	32.5
Trinity clay	11.4	.40	45.3	1.3	29.5	.20	58.1	36.5	40.9	103.4	37.8

tion. After 24 hours, with periodic shaking, the soil was allowed to settle, centrifuged, and the solution poured off. Water was added to equal the original volume, and the soil suspension again centrifuged and separated. The washing was repeated, the residual solution and washings were combined and made up to volume, and the phosphoric acid determined. The decrease of phosphoric acid in solution was taken to be the quantity fixed by the soil.

The soil from this treatment (containing 100 milligrams of fixed phosphoric acid) was mixed with 5000 gms. of the basal soil. Equal quantities of the original soil were likewise mixed with other lots of the basal soil, and there were also check pots to which no soil was added. Ammonium nitrate and potassium sulphate were added to all pots and the work was completed as already described for pot experiments, with corn as the experimental crop. The average results from 3 pots of soil for each treatment are given in Table 17. From 19% to 29% of the fixed phosphoric

Table 17. Recovery of fixed phosphoric acid by corn.

Soil type	Basicity %	pH	Fixing power of soil %	Phosphoric acid removed by crops: Basal soil plus untreated soil mgm.	Phosphoric acid removed by crops: Basal soil plus soil with fixed phosphoric acid mgm.	Recovery of fixed phosphoric acid %
Nacogdoches fine sandy loam	0.5	6.5	97	42.8	62.1	19.3
Houston black clay	5.6	8.0	88	57.8	86.9	29.1
Wilson clay loam	1.1	7.2	76	49.3	71.3	22.0
Susquehanna fine sandy loam	0.8	4.8	99	46.9	68.8	21.9

acid was taken up by the crops. A check test with superphosphate was not made, but comparisons with Tables 15 and 16 show that the fixed phosphoric acid had a high availability.

The fixing power of the Houston black clay and of the Wilson clay loam is probably primarily due to limestone, so that the phosphorus is probably fixed as tricalcium phosphate. In the other two soils, the phosphorus was probably fixed in iron compounds. In all cases, the availability of the fixed phosphoric acid was comparatively high.

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Summary

The quantities of phosphoric acid removed by one and by two crops of corn and milo or kafir and the weights of the crops produced in pot experiments in a greenhouse were determined with about 375 soils from various parts of Texas.

The average amount of phosphoric acid removed per crop ranged from 2.6 parts per million from soils which contained less than 10 p.p.m. of

active phosphoric acid to 18.2 p.p.m. from soils which contained more than 400 p.p.m. of active phosphoric acid. The phosphoric acid (P_2O_5) dissolved by 0.2 N nitric acid is termed the active phosphoric acid. On an average, the quantities of the phosphoric acid removed by the crops increased as the active phosphoric acid in the soils increased. The phosphoric acid removed by crops from surface soils was greater than that removed from subsoils containing equal quantities of active phosphoric acid, but the correlation coefficients were nearly the same.

From soils which contained similar amounts of active phosphoric acid, the average quantities of phosphoric acid removed per crop increased with increases in total phosphoric acid, total nitrogen, and active potash in the soils. With surface soils which contained from 31 to 100 p.p.m. of active phosphoric acid, the average phosphoric acid removed by the plants ranged from 5.2 p.p.m. when the total phosphoric acid was less than 0.25% to 24.2 p.p.m. when the total phosphoric acid was over .150%. The average phosphoric acid removed was 9.6 p.p.m. when the total nitrogen was less than 0.03% and 15.4 p.p.m. when the nitrogen was over 0.120%.

When the soils, grouped according to their content of active phosphoric acid, were then averaged in subgroups according to whether the quantities of phosphoric acid removed from them by the crops were relatively low, intermediate, or high, the averages for total phosphoric acid, total nitrogen, and active potash in the soils were also relatively low, intermediate, or high.

When the soils were divided into groups based upon certain characteristics, the percentages of the soils within each group from which the quantity of phosphoric acid removed by the crops was relatively low were 54% for subsoils as compared with 20% for surface soils, 43% for soils from the subhumid section of the state as compared with 29% for soils from the humid section, 53% for soils of high basicity as compared with 27% for soils of low basicity, and 38% for soils of heavy texture as compared with 35% for soils of light texture.

Coefficients of correlation between the quantities of active phosphoric acid in the soils and the quantities of phosphoric acid removed by the crops were higher when surface soils (.47) or subsoils (.49) were considered separately than when all soils were placed together (.37). The coefficients were much higher (.81) for soils with basicities below 2% than for those above 2% (.26). The coefficients were high and significant for surface soils when the basicity was less than 2% from either humid or subhumid sections, but low and not significant when the basicity was over 2%. Two crops gave higher correlation coefficients than did one crop. Weights of crops gave lower correlation coefficients than the phosphoric acid removed by the crops.

The correlation between the total phosphoric acid of the soil and the phosphoric acid removed by the crops was high for soils with basicity above 2% (.60). The correlation was not significant for humid soils of low basicity, either surface or subsoils, or for humid subsoils of high basicity. The correlation for total phosphoric acid is significant for both humid and subhumid surface soils with basicity exceeding 2%.

Equations for simple regression, which give quantitative statements of the relation between phosphoric acid removed and phosphoric acid in the soil, are given for different groups of soils. The significance of the regression coefficients was similar to that of the correlation coefficients.

When the surface soils of basicity less than 2% were arranged in groups according to their content of active phosphoric acid, coefficients for correlation and characteristics for regression curves decreased in significanec as the active phosphoric acid in the soils increased; significant characteristics were secured only with soils which contained less than 100 p.p.m. of active phosphoric acid. Coefficients of correlation for phosphoric acid in two crops decreased from .48, .46, and .45 in soils which contained 0-15, 16-30, and 31-100 p.p.m. active phosphoric acid, respectively, to 0 in soils which contained over 100 p.p.m. Constants in the regression curves for the lowest and highest groups of soils were 1.47 p.p.m. and 42.81 p.p.m., while the coefficients of active phosphoric acid were .618 and .00.

Phosphoric acid removed by the crops came either directly or indirectly from compounds in which the phosphoric acid was insoluble in 0.2 N nitric acid. Active phosphoric acid in 50 soils averaged 27.5 p.p.m. before cropping and 31.4 p.p.m. after cropping, although the crops removed phosphoric acid from the soil equivalent to 23.1 p.p.m.

From additions of soil which contained 100 milligrams of total phosphoric acid, crops removed from 0 to 20.7% of the added phosphoric acid, as compared with 34.2% from superphosphate and 14.2% from rock phosphate. The availability of the soil phosphoric acid so measured was much higher in calcareous soils than in noncalcareous soils.

From 20% to 30% of the phosphoric acid fixed from solution by 4 soils was removed by one crop of corn.

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