THE AVAILABILITY OF PHOSPHORUS IN CALCAREOUS AND NON-CALCAREOUS SOILS

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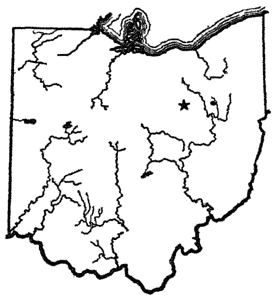

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THE AVAILABILITY OF PHOSPHORUS IN CALCAREOUS AND NON-CALCAREOUS SOILS

J. W. AMES AND C. J. SCHOLLENBERGER

One phase of a comprehensive investigation of the phosphorus content of Ohio soils has consisted of a study of the relative availability of the phosphorus supply of calcareous soils as contrasted with that of soils of a non-calcareous nature. Under practical farm conditions, phosphorus is usually the element limiting production of staple crops on most of the soils of Ohio, but in the eastern half of the State lack of lime is a factor of equal or possibly even greater importance. The constant growth in the practice of liming, as its beneficial results become better known to farmers has resulted in some acid soils being made quite as basic as those naturally calcareous. The effect of this change in reaction—larger supply of calcium and possibly increased amount of available nitrogen—upon the assimilation of native or added phosphorus is a subject of interest.

Calcareous soils are proverbially fertile soils. They are generally well supplied with phosphorus in consequence of the organic origin of the limestone, and practically all the phosphorus is concentrated in the residual soil. Further, the statement has been made, apparently first by Hilgard (13) and often repeated by others, that in the presence of calcium carbonate the soil may contain a lower percentage of phosphorus and still supply sufficient for the needs of the crop. So generally have acid soils been found to need phosphorus that it has been stated that blue litmus paper is a good indicator for both phosphorus and lime deficiencies (31). The opinion has often been expressed by American investigators in this field that phosphorus native to acid soils is largely combined with iron and aluminum, while that added as soluble phosphate in fertilizers and not at once consumed by the crop may share the same fate and become unavailable to succeeding crops. On the other hand, the phosphorus of soils well supplied with lime has been supposed to occur as tricalcium phosphate, and added phosphate not at once consumed by plants should tend to pass into that form and remain available. It is difficult to find any justification in theory for some of these older views; there is direct experimental evidence against others, as, for instance, the repeated observation that phosphates of iron and aluminum are more available than tricalcium phosphate (20), and the finding of Gile and Carrero's (9) that lime does not lower the rate at which soluble phosphate decreases in efficiency after being mixed with soil. On the other hand, a considerable part of the soil's total stock of phosphorus is now known to exist in organic combinations, and the effect of lime upon the organic phosphorus is a matter of interest. It has been suggested (19) that lime makes more available the phosphorus so combined. According to Koch and Oelsner (14) there is an organism, *Nucleobacter*, in soil, the specific function of which is to break down nucleoproteins with liberation of phosphate. They claim that lime is essential for the activity of this organism.

REVIEW OF PREVIOUS WORK

The effect of lime upon the availability of phosphorus added in fertilizers has been investigated quite frequently. It has generally been found that liming tends to decrease the usefulness of tricalcium phosphate, and to enhance the value of natural aluminum phosphates. Altho the water and citrate soluble forms of calcium phosphate may be less effective in extremely calcareous soils, on soils needing lime its beneficial influence in other respects may be expected to predominate. Plummer (23) has reviewed at some length the literature on the effect of lime on phosphates in the soil.

Efforts have been made to study by means of solvents possible changes in soil phosphorus attributable to liming. Hartwell and Kellogg (12) found that the solubility in water of the soil phosphorus especially was increased after adding hydrated lime at the rate of 10 tons per acre, the mixtures being leached at once. Guthrie and Cohen (10) found that similar mixtures, kept moist for a month, invariably decreased in content of phosphorus soluble in water. Bradley (2) states that water soluble phosphorus remained unchanged for six weeks following the addition of lime to soil and the mixtures kept constantly moist. Christie and Martin (3) maintained mixtures of soil and calcium carbonate at the rate of one ton per acre, or the equivalent in calcium oxide, at optimum moisture content for one week. Only two out of seven soils showed a significant increase in water soluble phosphorus. Spurway (27) percolated mixtures of soil and calcium carbonate or hydrated lime, each at the rate of one ton per acre, after 2 and 15 days standing in saturated condition. Large increases in the phosphorus content of the percolates were noted. Robinson and Bullis (25) prepared mixtures of soil with calcium carbonate or hydrate sufficient to satisfy the lime requirement, and maintained the mixtures at optimum moisture content and at room temperature. After intervals of 24 hours, 3 months, and 6 months, water extracts of samples from the jars were prepared. No significant change in amount of water soluble phosphorus was observed.

Extraction with dilute acids also was tried by Hartwell and Kellogg (12); the limed soil was found to contain less soluble phosphorus; but it was shown that if extra acid had been used, sufficient to compensate for that neutralized by the lime in the soil, there would have been found but very slight difference in solubility of the phosphorus attributable to liming. Fraps (7) treated soils with calcium carbonate, and kept the mixtures moist for nearly 6 months. Extraction with dilute nitric acid, of strength adjusted to be fifth-normal at the end of the digestion, showed that in two out of three cases the solubility of the phosphorus had been reduced, as compared with checks kept dry and run at the same time. Gaither (8) determined fifth-normal nitric acid soluble phosphorus in soil to which various amounts of burned lime up to 25 tons per acre had been applied. A quite regular increase in solubility of phosphorus, proportional to the rate of liming, was reported. Ellet and Hill (5) were unable to find any change in solubility of phosphorus in the case of soil limed in the field, altho fifth-normal nitric acid reflected differences due to phosphorus fertilization. Fraps (6) could detect no significant difference in fifth-normal nitric acid soluble phosphorus in the case of five soils limed, potted, and cropped previous to analysis. Starkey and Gordon (28) have studied adsorption of phosphates from solutions of regulated hydrogen-ion concentration by the hydrogels of silica and ferric oxide, which are believed to occur as coatings on soil grains. They find that the general effect of decrease in hydrogen-ion concentration is to reduce adsorption of phosphate, for as acidity is reduced, phosphate held by these colloids becomes more available.

Effect upon crop growth is the final criterion upon which any conclusions as to the influence of lime upon availability of phosphorus must be based. Studies of solubility in reagents can only be useful by suggesting an explanation for the observed effect upon the plant. It is known that there is a general relation between available nutrients and the amount and composition of a crop grown under normal conditions. This is beautifully shown by solution and sand culture experiments, of which those of Pfeiffer, Simmermacher, and Rippel (22) are of special interest in this connection. These investigators conducted a study of the utilization of nutrients as affected by modification of the light and water supply, and the presence of absorbents, calcium carbonate and aluminum hydroxide in the case of the phosphoric acid series. The crop was oats, grown in zinc pots containing 16 kg. sand; to one series of pots 100 g. calcium carbonate and 10 g. aluminum hydroxide were added, while another series had light and water supply restricted. The pots were fertilized the same, except that the amount of phosphorus supplied as dicalcium phosphate was variable. The calcium carbonate and aluminum hydroxide addition had an adverse influence upon the assimilation of phosphoric acid, shown by the smaller crops grown on all the pots except those with the very largest additions of phosphate. The crop from these limed pots also contained reduced percentages of phosphoric acid, except in the cases of those receiving the smallest amounts of phosphate, which supported only an insignificant growth. On the other hand, pots of the series grown under adverse conditions of light and moisture supply bore greatly reduced crop with generally higher phosphorus content than those of crops grown under optimum conditions.

M. von Wrangell (32) grew various crops in pots of sand with additions of tricalcium phosphate and increasing amounts of calcium carbonate. From the yields obtained and $CaO: P_2O_5$ ratio in the crops, it is concluded that individual plants show a stoichiometric relation between assimilation of lime and phosphoric acid. The yield of oats, for instance, was halved by the addition of one molecule of calcium carbonate, and no influence of the phosphate was noticeable where 5 molecules were added. In contrast, with a distinctly lime loving plant (buckwheat), 675 molecules of the carbonate scarcely sufficed to overcome the effect of the phosphate. Rippel (24) concludes from the results of field experiments on soils of various lime contents that if von Wrangell is correct in her deductions, then calcium phosphate is not a normal constituent of the soil.

Notwithstanding these relations between supply of nutrient elements and the amount and composition of dry matter in the crop produced, few of the numerous efforts to study the soil by analyses of plants grown thereon have attained much success. Hartwell and Kellogg (12) have reported analyses of turnips grown on limed and unlimed soil, from which it is concluded that lime had increased the utilization of the phosphatic fertilizers applied. Hartwell (11), in a continuation of work along the same line, made nine comparisons of growth and composition of turnips on limed and unlimed soil. In three instances liming increased the growth of the turnips and the crop contained a higher percentage of phosphorus. In the other six cases, liming caused no increase in crop and the percentage of phosphorus in the turnips was practically unchanged. Fraps (7) grew a number of crops in pots and determined the phosphorus content in a study of the effect of liming upon soil phosphorus. While plant growth in the pots was not entirely satisfactory, the average withdrawal of phosphorus from the soil of the pots receiving lime was greater than that from unlimed pots. This was the result of both greater growth and higher average content of the crops on limed pots. A distinct tendency toward a reciprocal relation between the amount of dry matter produced and its phosphorus content was noticeable. With three out of five soils, a double dose of lime caused the average removal of phosphorus to be larger than that resulting from the smaller application. Lyon and Bizzell (18, 19) found that liming increased removal of phosphorus in crops from one soil, but not from another, in lysimeters.

INDICATIONS FROM CROPS GROWN ON FERTILITY PLOTS

In Bulletin 221 (1), of the Ohio Station, analyses of wheat grown on sections E and B of the 5-year rotation at Wooster are discussed, and the relation of the composition of the crop to the fertilizer treatment of the soil pointed out. The east and west ends of each section had been limed at different dates, so that the effect of recent liming should be evident. Differences in phosphorus content and yield attributable to liming were interpreted to mean that *liming had promoted the assimilation of phosphorus, both native and added, by the wheat plant.* A relation between fertilizer treatment on the one hand and yield and phosphorus content of the crop on the other was well defined. It appeared to be so consistent that the composition of wheat grown on a soil promised to serve better than any chemical method as an index to the available supply of phosphorus in that soil.

Further confirmation of these observations was considered desirable, and accordingly samples were taken from the wheat grown on the plots of Section C, 5-year rotation at Wooster, during the season of 1910. From the data presented in Table 1 it may be seen that the phosphorus content of the grain varies quite consistently with fertilizer treatment, yield also being considered. On this soil, highly deficient in phosphorus, the addition of that element in available form is reflected in increased yield of wheat. If nitrogen is not supplied in addition (Plots 2 and 8) the amount of phosphorus offered apparently cannot be used to the best advantage, but is to a great extent assimilated and increases the phos-

TABLE 1.—YIELDS AND COMPOSITION OF WHEAT GRAIN, SECTION C, 5-YEAR ROTATION, 1910

Plot	Fertilizer treatment for wheat only—entire rotation				East unlimed		West limed	
	Acid phosphate	Muriate of potash	Nitrate of soda	Dried blood	Yield	Phosphorus	Yield	Phosphorus
	Pounds	*Pounds*	*Pounds*	*Pounds*	*Bushels*	*Percent*	*Bushels*	*Percent*
1	....	....	....	....	6.9	0.28	11.6	0.32
2	160 (320)	....	....	....	16.0	.37	20.3	.38
3	....	100 (260)	....	....	6.3	.32	10.3	.34
4	....	....	....	....	4.8	.32	9.0	.30
5	....	....	120 (440)	50	9.7	.29	10.8	.32
6	160 (320)	....	120 (440)	50	23.3	.33	25.3	.33
7	....	....	....	....	6.7	.32	8.2	.31
8	160 (320)	100 (260)	....	....	16.7	.39	19.8	.40
9	....	100 (260)	120 (440)	50	6.8	.31	13.0	.33
10	....	....	....	....	9.4	.32	7.9	.35
11	160 (320)	100 (260)	120 (440)	50	26.5	.33	27.0	.34
12	160 (320)	100 (260)	200 (680)	50	27.1	.31	28.3	.33
13	....	....	....	....	4.5	.32	7.6	.33
14	160 (240)	100 (180)	120 (280)	50	21.4	.33	20.7	.34
15	160	100	120	50	20.2	.31	24.1	.33
16	....	....	....	....	3.6	.32	7.4	.32
17	160 (480)	100 (260)	60 (220)	25	24.6	.39	26.8	.39
18	Barnyard manure, 8 tons (16)........				28.3	.39	33.4	.43
19	....				6.1	.31	10.0	.31
20	Barnyard manure, 4 tons (8)........				21.5	.37	25.6	.34
21	Same elements as 17, nitrogen in oilmeal........				24.6	.40	26.2	.39
22	....				6.4	.31	8.0	.33
23	Same elements as 17, nitrogen in dried blood........				25.3	.42	25.2	.41
24	Same elements as 17, nitrogen in $(NH_4)_2SO_4$........				27.1	.38	28.4	.40
25	....				5.7	.31	10.3	.33
26	Same elements as 11, phosphorus in bonemeal........				23.6	.35	27.4	.34
27	Same elements as 11, phos. in dissolved boneblack........				26.5	.33	31.3	.34
28	....				7.9	.32	15.4	.33
29	Same elements as 11, phosphorus in basic slag........				28.3	.34	29.0	.37
30	Same elements as 17, nitrogen in tankage........				28.7	.40	29.3	.40
	Average unfertilized checks........				6.2	.31	9.5	.32
	Average fertilized with phosphorus........				21.6	.36	24.1	.37

phorus content of the grain. With an adequate supply of nitrogen in addition to phosphorus, as on Plot 6, the yield is again raised, but the phosphorus content of the grain falls to what may be considered a normal figure. Observe that on Plot 9, to which no phosphorus but abundant nitrogen and potash are furnished, the lack of phosphorus is indicated by the small yield; the phosphorus content of the grain is scarcely significantly lower than that of the crop grown on check plots. There is evidently a minimum figure for phosphorus in grain, and a deficiency in phosphorus supply will be reflected in yield rather than in composition. But whenever the phosphorus supply is relatively greater than that of nitrogen, the fact is indicated by an increase in the phosphorus content of the grain. Plots 11, 26, 27, and 29 receive a complete fertilizer with a high ratio of nitrogen to phosphorus; the yields are high and the average phosphorus content of the grain is but little above that of unfertilized check plots. Plot 12 receives more nitrogen, and responds with a slight increase in yield, and a slightly lowered percentage of phosphorus. Plots 17, 21, 23, 24, and 30 receive the same amounts of phosphorus for wheat, but more in the rotation, applied to other crops. Also, the nitrogen supplied is much less than that of the plots just discussed. The effect is to cause a small decrease in crop, but a large increase in the phosphorus content of the grain.

The east end of Section C has never been limed; the west end had received burned lime at the rate of one ton per acre seven years before these samples were grown. Notwithstanding the small size and remoteness of the application, it appears to have had a distinct effect upon the phosphorus content of the wheat grain. Yields are invariably greater upon the limed side and the average phosphorus content of grain grown on the limed ends of the plots is slightly higher. This is true of the wheat from plots fertilized with phosphorus as well as the crop from those without fertilizer. This indicates that lime has promoted the assimilation of phosphorus by wheat on the Wooster soil. Calculation by Student's method (17) of the odds that the difference in average phosphorus content of grain grown on limed plots as compared with that grown on unlimed plots is significant, gave the following results: Odds are 16 to 1 that the difference of .01 percent in phosphorus content of grain grown on limed check plots over that from unlimed checks is not due to chance alone. This is not significant. A similar treatment of data from all plots fertilized with phosphorus indicated odds of 2000 to 1 that the grain from limed fertilized plots averaged as much as .01 percent higher in phosphorus than grain grown on similar plots without lime. In other words, one is not justified in the conclusion that lime has had any effect upon phosphorus native to the unfertilized soil, but it is certain that lime has enabled the plant to take up more phosphorus from the fertilized soil.

At the time of harvest, the appearance of the wheat indicated that the crop on the limed ends of the plots was slightly greener. As nitrogenous fertilizers have an influence in the same direction, one might conclude that the chief mode of action of lime is thru the nitrogen supply. As has been stated, the data obtained from analysis of the crop have indicated that phosphorus rather than nitrogen was the element increased in availability as the result of liming. It may be, however, that the influence of lime has been almost entirely upon the plant, as maintained by True (30), rather than upon soil constituents. The increased percentage of phosphorus and decreased nitrogen content of wheat grain grown upon the limed soil is possibly the result of more favorable conditions of growth and development. The lime has made soil conditions more favorable, with the result that at the time of harvest the grain grown on the limed soil has really been better matured, altho the crop on the unlimed side has appeared riper, simply because it turned yellow first. Slight differences in composition of grain grown in long continued plot experiments cannot be attributed solely to a specific effect of lime upon any particular soil constituent; for, in fact, the cumulative effect of years of treatment may be concerned and a whole train of factors involved, including physical and biological as well as chemical characteristics of the limed and unlimed soil.

PLAN OF EXPERIMENT

The apparently regular relation between composition and yields of wheat grown on plots on the one hand and fertilizer elements supplied on the other, gave reason for hope that by growing wheat under carefully controlled conditions some trustworthy evidence as to the relation between liming and utilization of phosphorus, both that applied as fertilizer and that native to the soil, might be secured. While samples of wheat grown on limed and unlimed areas of some of the soil types chosen could have been obtained, it was considered that climatic differences were too great a factor to permit any comparison between soil types. As LeClerc and Yoder (16) have shown, climate has a greater influence than soil or fertilization upon the characteristics of wheat grain. It was decided, therefore, to procure large quantities of the several soils, and grow all the crops under climatic and other conditions as uniform and with as close adherence to field practice as possible.

Earthenware cylinders sunk in the earth, similar to those used at the Tennessee and New Jersey stations appeared to be ideal containers for the soils. The sewer pipe cylinders were 20 inches inside diameter and 14 inches long, including the bell. They were set in the ground in rows of 10 cylinders each, about 3 feet from center to center. The sewer pipes were placed bell end down, with the top edge about one inch above the soil level. There was no special provision for drainage from each cylinder; the place selected was well drained and two lines of tile were put in to cross all the rows, between cylinders 3 and 4 and 7 and 8, about 3 feet beneath the surface. A cage of common hexagon mesh wire fencing protected the growing crops from birds and animals.

The descriptions of the soils are as follows:

Rows 1 and 2.—Clermont silt loam, from roadway between plots on Clermont County experiment farm. Surface soil, 0—6 inches; subsurface, 6—12 inches. The soil is a light gray silt loam. It is naturally very poorly drained and is considered very acid, as clover cannot be grown. Liming, drainage, and the use of phosphated manure has proved the best treatment in field tests.

Rows 3 and 4.—Clyde clay, from roadway on Paulding County experiment farm. Surface soil, 0—6 inches; subsurface, 6—12 inches, but without sharp line of demarcation. A dark gray to black heavy silty clay, of lacustrine origin; not responsive to fertilization or liming. This soil is naturally high in fertility and crop yields are limited by lack of drainage and peculiar mechanical properties of the soil.

Rows 5 and 6.—Upshur clay, from orchard on Washington County infirmary farm. Surface soil, 0—6 inches; subsurface, 6—12 inches. A heavy red clay, derived from red shale. Acid phosphate is used with some profit in a corn, soybeans, wheat, clover rotation, but there seems to be a greater need for lime.

Rows 7 and 8.—Dunkirk sandy loam, from cultivated field near Avery, Erie County. Surface soil, 0—8 inches, is a fine sand, colored gray by organic matter; subsurface, 8—12 inches, a yellow sand. The surface soil is acid, but streaks of carbonate are found at a depth of 4 or 5 feet. This is a productive soil, and in the field has favorable moisture conditions.

Rows 10 and 11.—Volusia silt loam, from cultivated field 2½ miles north of Austinburgh, Ashtabula County. Surface soil, 0—6 inches, a grayish brown silt loam, was used to fill the cylinders. This is a heavy impervious soil, not well drained. Responsive to liming and phosphoric acid fertilization.

Rows 16 and 17.—Wooster silt loam, from field in grass on the Experiment Station farm. Surface, 0—6 inches; subsurface, 6—12 inches. A yellow brown friable silt loam, on similar, but heavier, subsurface. The soil is productive when properly treated. Its greatest need is phosphorus and lime.

The Clyde clay in rows 3 and 4 is the only soil among those described which is alkaline to litmus paper and can be considered calcareous, but the carbonate content is very low. There are no important areas of strongly calcareous soils in Ohio. The Miami series of soils are of calcareous origin and contain much rotten limestone in their lower depths, but the surface soils are usually quite free from carbonate and often so thoroly leached that they are neutral or even slightly acid to tests.

Samples for analysis were taken from the mixed soil of each type during the filling of the cylinders. The analytical data for these soils are presented in Table 2.

TABLE 2.—COMPOSITION OF SOILS

Soil	Depth	Nitrogen	Phosphorus		Potassium		Calcium		Magnesium		Calcium carbonate		Litmus test
			Total	Soluble*	Total	Soluble*	Total	Soluble*	Total	Soluble*	Present	Required	
	In.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Lb.*†	*Lb.*†	
Clermont silt loam	0–6	0.09	0.04	0.0002	1.34	0.008	0.23	0.09	0.22	0.01	.....	4,800	acid
	6–12	.04	.03	.0002	1.51	.008	.22	.09	.33	.02	......	......	acid
Clyde clay	0–6	.37	.10	.0214	2.34	.025	.94	.52	.72	.05	450	4,300	alkaline
	6–12	.21	.08	.0168	2.55	.021	.85	.46	.77	.03	570	.....	alkaline
Upshur clay	0–6	.11	.03	.0009	2.12	.015	.28	.22	.93	.03	.....	7,200	acid
	6–12	.05	.02	.0008	2.24	.014	.19	.15	.98	.02	......	.....	acid
Dunkirk sandy loam	0–8	.07	.04	.0103	1.63	.008	.76	.05	.32	.01	50	3,000	acid
	8–12	.03	.05	.0080	1.68	.007	.78	.05	.36	.01	150	......	neutral
Volusia silt loam	0–6	.21	.05	.0009	1.42	.009	.20	.06	.39	.01	.....	12,400	acid
Wooster silt loam	0–6	.10	.04	.0006	1.45	.013	.24	.08	.28	.02	......	4,700	acid
	6–12	.07	.03	.0002	1.56	.009	.20	.06	.39	.02	......	......	acid

*Soluble in fifth-normal nitric acid.
†Pounds per acre of 2,000,000 pounds of soil.

The soils were secured during the spring of 1913. The cylinders were filled to the proper depth with subsurface soil, which was tamped very firmly to insure compactness such as exists in the field. The cylinders were then filled with the surface soil in the same way, not tamping this so firmly, however. The soil was filled in level full, but subsequent settling brought the soil inside and outside the cylinders to about the same level.

The first cylinder in each row was left without treatment; the second received lime in the form of precipitated calcium carbonate, the amount applied being that indicated by the lime requirement* determination, and shown in Table 2. This pair of pots was designed to show the effect of lime upon the assimilation of phosphorus native to the soil. The third cylinder received phosphorus only, 4.536 g. 16 percent acid phosphate being applied, equal to 200

*Equivalent to the soil's ability to decompose calcium carbonate under certain arbitrary conditions. Ten parts soil, one part $CaCO_3$, 50 parts water 2½ hours boiling in vacuo (50°C).

pounds per acre. The fourth cylinder received both lime and phosphorus at the same rates as the second and third, with the object of determining the influence of lime upon added available phosphorus. The fifth and sixth cylinders had phosphorus as those before, with 2.27 g. nitrate of soda, equivalent to 100 pounds per acre. The sixth cylinder had lime also, at the former rate. These treatments were designed to give information as to the part played by increased availability of nitrogen as the result of liming. The seventh cylinder was fertilized with acid phosphate and muriate of potash, 1.13 g. per pot, or 50 pounds per acre. Number 8 had the same with lime. Numbers 9 and 10 received complete fertilizer—phosphorus, nitrogen, and potassium, all at the above rates—and 10 was limed in addition. The seventh and following cylinders were so fertilized with the idea of learning the requirements of the several soils. It is a matter of regret that they were not used to duplicate the first four cylinders. However, all received phosphorus at the uniform rate, and half of them had lime, hence they offer a means of studying the effect of lime upon the assimilation of added phosphorus. The soils were in place in the cylinders of one row of each pair in June, 1913, allowing sufficient time to grow a crop of soybeans before sowing wheat. It was considered desirable to do this, as it would tend to bring the soils into more nearly normal condition than would standing idle after placing in pots. The soybeans grew fairly well on all cylinders, and were harvested when mature. Examination of the roots disclosed nodules in every cylinder, altho no effort had been made to inoculate the soils.

As soon as the soybeans were removed, the soil in the cylinders was cultivated and fertilized in preparation for wheat. The fertilization was the same as for the beans, save that to those cylinders receiving nitrogen, nitrate of soda at the rate of 50 pounds and dried blood at the rate of 100 pounds per acre were applied. Ohio 8106 (Fultz) wheat was sown Sept. 25, 1913, in three rows five inches apart, single seeds one-half inch apart in the rows. The same amount of seed was used for each pot, at a rate slightly over 2 bushels per acre. The wheat grew well on all pots and survived the winter in fair condition, no protection whatever having been given the plants. In April the cylinders were seeded to red clover. The wheat came to maturity in an apparently normal manner and was harvested during the first week of July, 1914. Sparrows did slight damage, in spite of all precautions, and 6 or 8 heads on practically every cylinder were destroyed by loose smut.

After the wheat had been removed from the cylinders, the clover grew well. It suffered considerable damage during the winter, however, and the yields were quite erratic. Wheat was again sown on the old cylinders, fertilized as before but not limed a second time. A duplicate series of cylinders, which had been filled with soil secured from the same places as that first used, was limed, fertilized, and sown to wheat as the first crop. The seed was treated for smut prevention and the cage repaired so that loss of crop from birds was thereafter prevented. The season was less favorable, however, and yields were less than those secured the first year.

DISCUSSION OF RESULTS

In Tables 3 to 8, inclusive, data obtained from the first crop of wheat are presented in columns headed 1914, that from the second crop of these cylinders in columns 1916 A, and from the first crop on the second series of cylinders in columns 1916 B. This arrangement facilities comparison of the three sets of results. The weights of crop, phosphorus contents, and removal of phosphorus from the soil are tabulated for each crop, and data from the three crops are averaged for each treatment. Data from the first six cylinders only are fully presented, that from cylinders 7, 8, 9, and 10 being used only in the averages of all fertilized cylinders, which thus include four unlimed and four limed cylinders for each crop. In addition, there are included averages of all unlimed and all limed fertilized cylinders for three crops. In these general averages of fertilized cylinders, 12 pairs of data are compared, a number sufficiently large to justify the use of Student's method for judging the significance of an average. This is the only statistical method adapted to the purpose, as it takes into consideration the pairing of the data and emphasizes differences between the individuals of each pair. In this particular instance it is the effect of lime in which we are most interested, with no regard for other fertilizer treatment or seasonal differences.

Clermont silt loam (Table 3).—Cylinders filled with this soil averaged lowest in productivity. Neither lime alone nor phosphorus alone produced an appreciable increase in average yield; when used together they produced a good crop. Nitrogen and phosphorus together were quite effective in increasing yields, and lime was effective with this combination. General averages of all fertilized cylinders indicate a gain from liming; the calculated odds that an increase as great would not have resulted from chance alone are 50 to 1 with reference to grain, and 114 to 1 when the entire crop is considered.

TABLE 3.—CLERMONT SILT LOAM

Treatment		Weight of crop				Phosphorus in crop				Phosphorus removed from soil			
		1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
None	Wheat	27.6	38.9	24.4	30.3	0.48	0.44	0.41	0.44	0.133	0.172	0.099	0.134
	Straw	59.4	87.5	56.2	67.7	.12	.09	.06	.09	.071	.082	.032	.062
	Total	87.0	126.4	80.6	98.0	.23	.20	.16	.20	.204	.254	.131	.196
Limed	Wheat	38.3	22.7	30.0	30.3	.43	.44	.35	.41	.165	.100	.106	.124
	Straw	73.7	59.8	59.0	64.2	.06	.09	.04	.06	.044	.057	.024	.041
	Total	112.0	82.5	89.0	94.5	.19	.19	.15	.17	.209	.157	.130	.165
Acid phosphate	Wheat	32.4	37.7	27.3	32.5	.43	.40	.38	.41	.139	.152	.105	.132
	Straw	52.6	78.3	46.5	59.1	.06	.07	.05	.06	.033	.054	.023	.037
	Total	85.0	116.0	73.8	91.6	.20	.18	.17	.18	.173	.206	.128	.169
Acid phosphate Limed	Wheat	62.6	44.3	51.7	52.9	.40	.42	.40	.41	.253	.187	.209	.216
	Straw	105.4	89.2	83.3	92.6	.05	.07	.08	.06	.050	.063	.065	.059
	Total	168.0	133.5	135.0	145.5	.18	.19	.20	.19	.303	.250	.274	.275
Acid phosphate Nitrogen	Wheat	66.2	24.2	59.0	49.8	.36	.48	.40	.40	.241	.116	.234	.197
	Straw	128.8	72.8	94.6	98.7	.05	.13	.07	.08	.064	.097	.065	.075
	Total	195.0	97.0	153.6	148.5	.16	.22	.20	.18	.305	.213	.299	.272
Acid phosphate Nitrogen Limed	Wheat	65.9	49.6	54.6	56.7	.40	.42	.39	.40	.261	.207	.212	.227
	Straw	123.1	97.9	91.2	104.1	.06	.08	.06	.06	.068	.077	.053	.066
	Total	189.0	147.5	145.8	160.8	.17	.19	.18	.18	.329	.284	.265	.293
Average Fertilized	Wheat	45.2	32.0	46.4	41.2	.39	.44	.39	.40	.177	.140	.179	.165
	Straw	83.8	74.8	78.7	79.1	.05	.10	.07	.07	.045	.072	.054	.057
	Total	129.0	106.8	125.1	120.3	.17	.20	.19	.18	.222	.212	.233	.222
Average Fertilized Limed	Wheat	52.7	44.6	55.2	50.8	.40	.41	.40	.40	.213	.185	.218	.205
	Straw	102.3	93.1	94.3	96.6	.06	.08	.07	.07	.057	.071	.063	.064
	Total	155.0	137.7	149.5	147.4	.17	.19	.19	.18	.270	.256	.281	.269

Percentages of phosphorus in both grain and straw grown on unfertilized cylinders were generally reduced by lime. As the yields average about the same, the average removal of phosphorus by the limed crops was less; but a calculation of odds shows that this difference is not significant. Grain grown on cylinders fertilized with acid phosphate only averaged lower in phosphorus content than that grown on untreated soil. This result was quite at variance with what had been expected. Neither has nitrogen used with acid phosphate reduced the phosphorus content of the grain to a significant extent. About the only conclusion that can be drawn with respect to the effect of lime upon the availability of phosphorus in this soil is that a higher average removal of phosphorus from the fertilized soil resulted from the use of lime. The odds that a difference in averages as large would not have been chance alone are 114 to 1. This difference in removal is dependent solely upon the size of the crop. So far as can be judged from the composition of either the wheat or the straw, there was sufficient available phosphorus in both the untreated soil and that receiving lime alone for the production of crops considerably larger than were harvested.

Clyde clay (Table 4.)—As might have been expected from the contrast in chemical composition, the Clyde clay was much more productive than the Clermont silt loam. In spite of the fact that this soil is not acid to litmus paper, lime has apparently caused a slight increase in yield in many instances. With both average unfertilized cylinders and average of all fertilized cylinders the odds that this difference may not have been due to chance are so small that the significance is very doubtful. Similar results were obtained from calculations with other data, and there is no convincing evidence that lime had any effect upon crops grown on this soil, nor upon the availability of the phosphorus to wheat, in spite of the wide variations in average figures in the table.

TABLE 4.—CLYDE CLAY

Treatment		Weight of crop				Phosphorus in crop				Phosphorus removed from soil			
		1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
None	Wheat	69.3	54.2	65.1	62.9	0.42	0.42	0.40	0.41	0.288	0.227	0.259	0.258
	Straw	129.7	113.0	116.9	119.9	.07	.07	.05	.07	.094	.081	.061	.079
	Total	199.0	167.2	182.0	182.8	.19	.18	.18	.18	.382	.308	.320	.337
Limed	Wheat	114.4	58.5	72.2	81.7	.35	.43	.39	.38	.404	.253	.284	.314
	Straw	194.6	112.0	116.3	141.0	.06	.07	.05	.06	.123	.077	.062	.087
	Total	309.0	170.5	118.5	222.7	.17	.19	.18	.18	.527	.330	.346	.401
Acid phosphate	Wheat	117.4	49.7	48.5	71.9	.41	.44	.43	.42	.482	.221	.209	.304
	Straw	166.6	101.5	81.3	116.4	.04	.12	.09	.07	.061	.116	.075	.084
	Total	284.9	151.2	129.8	188.3	.19	.22	.22	.21	.543	.337	.284	.388
Acid phosphate Limed	Wheat	114.2	58.7	44.7	72.5	.48	.44	.40	.45	.546	.257	.178	.327
	Straw	173.8	99.8	76.3	116.6	.08	.12	.08	.09	.138	.116	.063	.106
	Total	288.0	158.5	121.0	189.1	.24	.24	.20	.23	.684	.373	.241	.433
Acid phosphate Nitrogen	Wheat	109.9	49.4	55.5	71.6	.33	.47	.42	.39	.366	.230	.235	.277
	Straw	170.1	104.6	106.7	127.1	.05	.16	.09	.09	.082	.165	.095	.114
	Total	280.0	154.0	162.2	198.7	.16	.26	.20	.20	.448	.395	.330	.391
Acid phosphate Nitrogen Limed	Wheat	116.7	57.5	48.5	74.2	.45	.44	.41	.44	.526	.251	.201	.326
	Straw	173.3	98.7	97.5	123.2	.07	.13	.09	.09	.126	.126	.086	.113
	Total	290.0	156.2	146.0	197.4	.22	.24	.20	.22	.652	.377	.287	.439
Average Fertilized	Wheat	126.1	59.3	60.7	82.0	.39	.44	.42	.41	.487	.261	.254	.334
	Straw	205.4	105.5	111.9	140.0	.05	.12	.08	.08	.113	.128	.093	.111
	Total	331.5	164.8	172.6	223.0	.18	.24	.20	.20	.600	.389	.347	.445
Average Fertilized Limed	Wheat	131.7	64.1	61.9	85.9	.44	.44	.41	.43	.573	.280	.255	.369
	Straw	211.5	116.1	114.2	147.3	.06	.12	.08	.09	.138	.143	.092	.124
	Total	343.2	180.2	176.1	233.2	.21	.24	.20	.21	.711	.423	.347	.493

Upshur clay (Table 5).—This red clay was quite productive, altho less so than the Clyde clay. The effect of lime was very slight, nor have fertilizers produced any increase in yield which can be considered significant. The most that can be said is that there was no evidence of any action of lime upon phosphorus in the soil.

TABLE 5.—UPSHUR CLAY

Treatment		Weight of crop				Phosphorus in crop				Phosphorus removed from soil			
		1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
None	Wheat	60.3	78.0	66.7	68.3	0.48	0.40	0.36	0.41	0.288	0.310	0.237	0.278
	Straw	126.7	130.0	111.3	122.7	.11	.06	.05	.07	.141	.075	.057	.091
	Total	187.0	208.0	178.0	191.0	.23	.19	.17	.19	.429	.385	.294	.369
Limed	Wheat	95.6	57.5	48.3	67.1	.42	.40	.40	.41	.400	.232	.193	.275
	Straw	162.4	98.0	80.2	113.5	.07	.06	.07	.07	.119	.061	.056	.079
	Total	258.0	155.5	128.5	180.6	.20	.19	.19	.20	.519	.293	.249	.354
Acid phosphate	Wheat	110.8	47.4	64.0	74.1	.40	.48	.40	.41	.439	.226	.253	.306
	Straw	190.2	110.8	96.2	132.4	.07	.14	.08	.09	.126	.158	.075	.120
	Total	301.0	158.2	160.2	206.5	.19	.24	.21	.21	.565	.384	.328	.426
Acid phosphate Limed	Wheat	83.6	56.1	68.0	69.2	.42	.44	.40	.42	.350	.249	.269	.289
	Straw	112.0	95.4	104.0	103.8	.09	.11	.08	.09	.096	.105	.081	.094
	Total	195.6	151.5	172.0	173.0	.23	.23	.20	.22	.445	.354	.350	.383
Acid phosphate Nitrogen	Wheat	64.1	41.2	57.3	54.2	.40	.44	.40	.41	.256	.182	.231	.223
	Straw	101.9	82.8	90.3	91.7	.07	.12	.09	.09	.069	.103	.086	.086
	Total	166.0	124.0	147.6	145.9	.20	.23	.21	.21	.324	.285	.317	.309
Acid phosphate Nitrogen Limed	Wheat	93.0	56.6	70.0	73.2	.40	.43	.39	.41	.371	.243	.275	.296
	Straw	146.0	111.4	120.0	125.8	.06	.12	.08	.08	.092	.131	.091	.105
	Total	239.0	168.0	190.0	199.0	.19	.22	.19	.20	.463	.374	.366	.401
Average Fertilized	Wheat	97.8	53.2	59.8	70.3	.41	.44	.41	.41	.397	.234	.244	.292
	Straw	160.7	106.7	102.7	123.3	.07	.12	.09	.09	.105	.131	.092	.109
	Total	258.5	159.9	162.5	193.6	.19	.23	.21	.21	.502	.365	.336	.401
Average Fertilized Limed	Wheat	100.9*	59.5	63.3	72.2	.41	.44	.40	.41	.412	.261	.252	.305
	Straw	160.3	106.1	116.6	124.7	.07	.11	.08	.08	.115	.119	.094	.107
	Total	261.2	165.6	179.9	196.9	.20	.23	.19	.21	.527	.380	.346	.412

*Average of three.

Dunkirk sandy loam (Table 6).—This sandy soil produced very high yields of wheat. As the soil had a low lime requirement, the considerable average increase in yield attributable to a small application of lime without fertilizer is rather surprising. Calculation of the odds that a difference as great may not have been due to chance gave but 6 to 1 for both total crop and grain alone, so that the increase cannot be considered significant. The effect of lime upon the crop on fertilized cylinders was generally unfavorable. Odds are 90 to 1 that the decrease in average yield of grain on all fertilized and limed cylinders as compared with those unlimed would not have been so great from chance alone. With respect to total crop the odds are 60 to 1. This would indicate that lime has really reduced the yield on fertilized cylinders. This can scarcely be attributed to any harmful effect upon phosphorus assimilation, however, as both grain and straw grown on these limed cylinders average higher in phosphorus and the odds are only 7 to 1 that the decrease of .04 gram in phosphorus removal attributable to liming fertilized cylinders may not have been chance.

TABLE 6.—DUNKIRK SANDY LOAM

Treatment		Weight of crop				Phosphorus in crop				Phosphorus removed from soil			
		1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
None	Wheat	82.9	35.6	89.1	69.2	0.40	0.38	0.40	0.39	0.330	0.135	0.354	.273
	Straw	154.1	79.8	135.[illegible]	123.3	.07	.07	.07	.07	.105	.058	.096	.086
	Total	237.0	115.4	225.0	192.5	.18	.17	.20	.19	.435	.193	.450	.359
Limed	Wheat	110.3	82.1	84.0	92.1	.35	.41	.41	.38	.382	.335	.344	.354
	Straw	197.7	150.4	123.6	157.2	.06	.08	.07	.07	.122	.120	.084	.109
	Total	308.0	232.5	207.6	249.3	.16	.20	.21	.19	.504	.455	.428	.463
Acid phosphate	Wheat	96.6	56.3	96.6	83.2	.37	.42	.37	.38	.359	.237	.362	.319
	Straw	163.4	99.9	158.4	140.6	.07	.09	.06	.07	.107	.087	.090	.095
	Total	260.0	156.2	255.0	223.8	.18	.21	.18	.19	.406	.324	.452	.424
Acid phosphate Limed	Wheat	103.9	66.2	75.4	81.8	.40	.44	.42	.42	.415	.294	.316	.342
	Straw	184.1	118.8	145.8	149.6	.07	.13	.09	.09	.124	.159	.130	.137
	Total	288.0	185.0	221.2	231.4	.19	.24	.20	.21	.539	.453	.446	.479
Acid phosphate Nitrogen	Wheat	135.2	87.3	121.6	114.7	.40	.40	.40	.40	.538	.353	.493	.461
	Straw	224.8	164.2	200.4	196.5	.05	.08	.08	.07	.120	.138	.155	.138
	Total	360.0	251.5	322.0	311.2	.18	.20	.20	.19	.658	.492	.648	.599
Acid phosphate Nitrogen Limed	Wheat	158.8	64.3	80.6	101.2	.40	.42	.42	.41	.638	.268	.341	.416
	Straw	263.2	103.7	153.9	173.6	.06	.11	.08	.07	.150	.112	.124	.129
	Total	422.0	168.0	234.5	274.8	.19	.23	.20	.20	.788	.380	.465	.545
Average Fertilized	Wheat	127.9	82.3	106.5	105.6	.38	.41	.39	.39	.488	.339	.412	.413
	Straw	219.1	138.4	178.4	178.6	.06	.09	.06	.07	.129	.129	.108	.122
	Total	347.0	220.7	284.9	284.2	.18	.21	.18	.19	.617	.469	.520	.535
Average Fertilized Limed	Wheat	114.3	69.3	75.8	86.5	.42	.42	.42	.42	.482	.291	.318	.364
	Straw	196.2	112.3	145.7	151.4	.07	.11	.09	.09	.133	.129	.132	.131
	Total	310.5	181.6	221.5	237.9	.20	.23	.20	.21	.615	.420	.450	.495

Volusia silt loam (Table 7).—The Volusia silt loam is the most acid soil included in the test, and gave a remarkable increase in crop when lime alone was applied. Acid phosphate alone caused about the same increase, but when lime was added its effect was to cause a further large increase in yield. The wheat grown on the untreated cylinders bore a very low proportion to the total crop, but averaged highest in phosphorus. With lime alone, percent phosphorus in grain is higher than when both lime and acid phosphate were applied. Nitrogen was effective in increasing the yield, and reduced the phosphorus content of the grain slightly. There seems to be a reciprocal relation between yield of grain and its phosphorus content, at least with the first six cylinders. In these cases, lime increased yields and reduced percent of phosphorus in grain. Averages of all fertilized cylinders do not show this effect of lime; in this case lime has apparently increased the percent of phosphorus in the whole plant without affecting that of either grain or straw. This is due to the improvement in ratio of grain to total crop which was one of the effects of lime on this soil. Averaged data from all fertilized cylinders indicate odds of 50 to 1 that an increase in grain as large as that indicated did not result from

TABLE 7.—VOLUSIA SILT LOAM

Treatment		Weight of crop				Phosphorus in crop				Phosphorus removed from soil			
		1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
None	Wheat	24.7	9.0	23 4	19.0	0.49	0.42	0.42	0.45	0.120	0.037	0 098	0.085
	Straw	50.3	23.5	248.1	107.3	.12	.10	.06	.07	.062	.023	.146	.077
	Total	75.0	32.5	271.5	126.3	.24	.19	.09	.13	.182	.060	.244	.162
Limed	Wheat	82.3	57.7	52.0	64.0	.40	.41	.40	.40	.331	.234	.207	.257
	Straw	127.7	101.9	89.8	106.5	.06	.08	.07	.07	.080	.084	.059	.074
	Total	210.0	159.6	141.8	170.5	.20	.20	.19	.19	.411	.318	.266	.331
Acid phosphate	Wheat	81.6	42.1	64.0	62.6	.44	.40	.36	.40	.358	.167	.231	.252
	Straw	135.4	84.9	139.0	119.8	.08	.08	.05	.07	.105	.066	.073	.081
	Total	217.0	127.0	203.0	182.4	.21	.19	.15	.18	.463	.233	.303	.333
Acid phosphate Limed	Wheat	92.4	47.2	92.4	77.3	.39	.42	.38	.39	.360	.197	.354	.304
	Straw	145.6	132.3	140.1	139.3	.07	.09	.06	.07	.099	.121	.081	.100
	Total	238.0	179.5	232.5	216.6	.19	.18	.19	.17	.459	.318	.435	.404
Acid phosphate Nitrogen	Wheat	80.9	50.2	83.2	71.4	.38	.42	.39	.38	.269	.213	.321	.268
	Straw	141.1	85.8	171.2	132.7	.05	.08	.05	.05	.071	.064	.081	.072
	Total	222.0	136.0	254.4	204.1	.15	.20	.16	.17	.340	.278	.402	.340
Acid phosphate Nitrogen Limed	Wheat	97.6	75.3	100.6	91.2	.34	.43	.37	.37	.328	.323	.370	.340
	Straw	177.4	128.2	178.4	161.3	.05	.09	.05	.06	.087	.112	.098	.099
	Total	275.0	203.5	279.0	252.5	.15	.21	.17	.17	.415	.434	.468	.439
Average Fertilized	Wheat	71.8	48.8	68.8	63.1	.38	.40	.37	.38	.274	.197	.253	.241
	Straw	133.4	89.5	166.2	129.7	.06	.08	.05	.06	.081	.063	.083	.076
	Total	205.2	138.3	235.0	192.8	.17	.19	.14	.16	.355	.260	.336	.317
Average Fertilized Limed	Wheat	94.9	63.4	72.9	77.1	.36	.43	.37	.38	.346	.273	.270	.296
	Straw	164.1	122.6	163.3	150.0	.06	.09	.05	.06	.091	.108	.086	.095
	Total	259.0	186.0	236.2	227.1	.17	.21	.15	.17	.437	.381	.356	.391

chance alone, and 88 to 1 with respect to total crop. Odds that the increase in removal of phosphorus from limed and fertilized cylinders would not have been so great from chance alone were 160 to 1.

Lime certainly increased the crop and caused more phosphorus to be utilized, but it cannot be concluded that lime affected the availability of the phosphorus. Composition of grain seems to indicate that there was a fairly uniform supply of available phosphorus in all cases.

Wooster silt loam (Table 8).—The inclusion of this soil in the cylinder test was to ascertain to what extent results from wheat grown on cylinders would resemble those from field-plot samples. It should be noted, however, that the soil placed in the cylinders had not been subjected to the exhaustive cropping and fertilizer treatment which the plots have had. This may be an explanation for the results obtained from fertilizer applied to the cylinders. The untreated soil bore fair crops, but lime caused quite an increase. Acid phosphate alone produced an increase, but with lime the crops did not average significantly larger than those which followed lime alone. Nitrogen when added with phosphorus, on both limed and unlimed cylinders, resulted in a much greater increase than could be

TABLE 8.—WOOSTER SILT LOAM

Treatment		Weight of crop				Phosphorus in crop				Phosphorus removed from soil			
		1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.	1914	1916 A	1916 B	Av.
		Gm.	*Gm.*	*Gm.*	*Gm.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Gm.*	*Gm.*	*Gm.*	*Gm.*
None	Wheat	30.7	32.5	34.0	32.4	0.47	0.38	0.36	0.40	0.146	0.124	0.122	0.131
	Straw	54.3	68.0	69.2	63.8	.09	.05	.05	.06	.048	.036	.037	.040
	Total	85.0	100.5	103.2	96.2	.23	.16	.15	.18	.194	.160	.159	.171
Limed	Wheat	46.0	50.3	57.6	51.3	.39	.38	.38	.38	.180	.191	.219	.196
	Straw	67.0	89.9	100.2	85.7	.06	.06	.04	.05	.042	.051	.044	.046
	Total	113.0	140.2	157.8	137.0	.20	.17	.17	.18	.222	.242	.263	.242
Acid phosphate	Wheat	38.4	47.3	40.8	42.2	.41	.40	.45	.42	.159	.188	.185	.177
	Straw	70.6	80.3	81.7	77.5	.08	.06	.10	.08	.059	.051	.082	.064
	Total	109.0	127.6	122.5	119.7	.20	.19	.22	.20	.218	.239	.267	.241
Acid phosphate Limed	Wheat	37.2	47.4	70.4	51.7	.43	.43	.40	.42	.161	.206	.280	.216
	Straw	72.8	81.6	111.6	88.6	.08	.09	.05	.07	.058	.070	.061	.063
	Total	110.0	129.0	182.0	140.3	.20	.21	.19	.20	.219	.276	.341	.279
Acid phosphate Nitrogen	Wheat	56.6	50.8	72.7	60.0	.37	.41	.36	.38	.211	.207	.264	.227
	Straw	91.4	87.7	116.9	98.7	.05	.07	.05	.06	.046	.061	.058	.055
	Total	148.0	138.5	189.6	158.7	.17	.19	.17	.18	.257	.268	.322	.282
Acid phosphate Nitrogen Limed	Wheat	75.4	74.5	83.7	77.9	.34	.40	.36	.36	.253	.296	.303	.284
	Straw	134.6	117.5	119.3	123.8	.06	.06	.05	.06	.079	.071	.059	.070
	Total	210.0	192.0	203.0	201.7	.16	.19	.18	.18	.332	.367	.362	.354
Average Fertilized	Wheat	51.2	48.6	61.7	53.9	.38	.40	.39	.39	.194	.193	.239	.209
	Straw	83.8	83.4	108.2	91.8	.06	.07	.06	.06	.050	.055	.067	.057
	Total	135.0	132.0	169.9	145.6	.18	.19	.18	.18	.244	.248	.306	.266
Average Fertilized Limed	Wheat	63.7	47.5	65 9	59.0	.37	.41	.40	.39	.239	.197	.261	.232
	Straw	114.8	93.7	105.8	104.8	.06	.08	.06	.07	.075	.071	.066	.071
	Total	178.5	141.2	171.7	163.8	.18	.19	.19	.18	.314	.268	.327	.303

attributed to phosphorus alone. On the unfertilized cylinders, the average phosphorus content of the grain was reduced by lime, and the same is noticed on those cylinders which had both phosphorus and nitrogen, but there is no difference on those which had phosphorus alone. The latter bore grain with highest average phosphorus content. In some respects these results resemble those obtained from the examination of plot-grown samples; in other ways, there is little resemblance. The results from the unfertilized cylinders do not offer much proof that availability of native phosphorus was increased by lime applied to the Wooster soil in cylinders.

While the average results from the check-plot samples (Table 1) apparently indicated this effect, the odds were not high enough for the difference to be considered certain. Averaged data from all fertilized cylinders indicate a slight increase in yield of grain from lime, but the odds that as great a difference might not be due to chance are but 6 to 1. This is not significant, neither are the odds with respect to total crop, 13 to 1. Removal of phosphorus from fertilized cylinders appears to have been significantly increased by liming, as the odds are 35 to 1 that so great a difference would not have resulted from chance alone. Lime has enabled the plant to utilize more phosphorus from the fertilized soil. The average percentage of phosphorus in grain grown on cylinders is very high compared with that of the plot-grown samples, and differences attributable to fertilizers are less. The soil used in the cylinders seems quite well supplied with available phosphorus.

There were considerable differences in the three crops. The first year's yields were in nearly all instances the largest, but with lowest percentages of phosphorus in grain. The crop 1916 B was grown on new soil, just as the first had been, altho it did not follow soybeans. A less favorable season was probably the reason for the much smaller crop, rather than any influence of the soybeans. The second crop in the first cylinders, 1916 A, was even smaller, possibly because the soil in these cylinders had become more compact, having been in place for two years. Yields on some of the cylinders were very heavy compared with those of an equal area of soil in the field. The poorest soil without treatment was the Volusia silt loam. Limed and fertilized, this became quite productive. The most productive was the Dunkirk sandy loam, to which treatment was of no help. Of the four soils which gave larger average yields on the limed unfertilized cylinders, only one, the Volusia silt loam, furnished data indicating that lime had certainly increased the average fertilized yield. On the other hand, the Clermont silt loam, altho not showing any increase in average yield from lime alone, was helped by lime when used with fertilizer. The Clyde clay and Dunkirk sandy loam gave large average increases in yield as the result of liming alone, but the irregular nature of the data which enter into these averages causes the calculated odds that the differences are not due to chance to be too low for certainty. The Upshur clay was scarcely at all affected by lime, but the Volusia silt loam was consistently benefitted. Altho lime appears to have increased the yield of the unfertilized Wooster silt loam, the same cannot be said of the fertilized cylinders.

The ratio of grain to total crop was quite low in the case of many of the crops produced on cylinders without treatment. This feature was generally accomplished by high phosphorus percentages in the grain, and in these cases conclusions cannot be drawn as to whether lime had any effect upon phosphorus native to the soil. In all these instances, however, average removal of phosphorus was greatest from limed cylinders.

INDICATIONS FROM ANALYSES OF SEEDLINGS

The rather unsatisfactory results secured from these attempts to grow crops to maturity in cylinders and the inconclusive data obtained from analyses of the crops so grown indicated that the problem of the effect of lime upon availability of phosphorus would have to be attacked from another angle. Young seedlings contain a high percentage of phosphorus in dry matter and absorb this element with avidity if it is available. Older plants will have absorbed more, but the greater production of dry matter reduces the percentage differences. In the case of plants grown out of doors and exposed to the elements there is also the factor of removal of mineral matter by rain or dew, to which attention has been directed by Le Clerc and Breazeale (15). Young plants may be expected to suffer less loss from this cause than those nearer maturity.

TABLE 9.—PHOSPHORUS CONTENT OF OAT PLANTS SAMPLED AT DIFFERENT STAGES OF GROWTH, STRONGSVILLE, 5-YEAR ROTATION, SECTION B, PLANTED APRIL 6, 1918

Plot	Treatment	June 4		July 2		July 29		Yields per acre	
		Floats	Lime	Floats	Lime	Floats	Lime	Floats	Lime
		Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Bu.*	*Bu.*
1	....	0.38	0.21	0.21	0.14	0.17	0.14	72.5	42.5
2	Acid phosphate...........	.38	.34	.18	.14	.16	.14	83 8	70.0
4	....	.38	.26	.17	.15	.16	.16	74.1	21.9
5	$NaNO_3$..................	.38	.24	.16	.13	.16	.13	79.1	25.9
6	Acid phosphate, $NaNO_3$...	.38	.33	.16	.13	.16	.15	94.4	63.1
7	....	.38	.27	.17	.13	.16	.16	82.2	37.5
8	Acid phosphate, KCl.....	.35	.30	.17	.14	.17	.14	91.9	82.5
9	KCl, $NaNO_3$...........	.39	.26	.16	.13	.15	.13	100.3	58.8
10	....	.37	.28	.15	.14	.16	.14	91.3	62.5
11	Complete fertilizer........	.37	.30	.15	.14	.15	.14	96.3	86.6
12	Complete fertilizer, extra N	.35	.31	.15	.14	.14	.13	96.3	86.9
13	....	.37	.28	.17	.13	.15	.15	74.1	53.4
16	....	.35	.25	.19	.14	.16	.14	79.7	43.8
17	Complete fertilizer.........	.37	.33	.18	.17	.16	.14	100.6	90.6
18	Yard manure, 16 T........	.37	.32	.15	.16	.16	.14	91.3	77.8
19	....	.36	.32	.18	.16	.15	.14	84.4	64.7
	Average checks.......	.37	.27	.18	.14	.16	.15	....	....
	Odds*.................	1,600 to 1		700 to 1		39 to 1		....	....

*Student's method. Odds that as great a difference between the averages would not have been due to chance alone.

In Table 9 are presented analyses of oat plants taken at different dates from some of the plots of Section B, 5-year rotation at Strongsville. This section has been cross-dressed with floats (finely ground raw rock phosphate) on one end, and with ground limestone on the other. These were applied at the rate of one and two tons per acre, respectively, per rotation. Three applications had been made prior to the time the oats grown on the plots were sampled. The treatment of these plots is described in Bulletin 305, with special reference to the effects of phosphorus carriers (29), and in other publications of the Ohio Station. The data in Table 9 require little comment; the striking effect of the phosphate upon the phosphorus content of the young plants and the tendency toward disappearance of differences attributable to fertilization as the plants approach maturity are obvious.

TABLE 10.—YIELD, PHOSPHORUS CONTENT, AND HEIGHT OF MILLET, 1922

Row	Cylinder	Crop		Phosphorus	Row	Cylinder	Crop		Phosphorus
		Weight grams	Height inches	percent			Weight grams	Height inches	percent
Clermont silt loam					Clyde clay				
1 2	1 1	9.8 12.9	5 6	0.19 .16 } 0.18	3 4	1 1	6.7 5.7	6 5	0.25 .34 } .29
1 2	2 2	8.3 11.6	5 6	.25 .18 } .21	3 4	2 2	12.8 10.9	6 5	.25 .31 } .28
1 2	3 3	15.6 8.8	5 6	.23 .29 } .25	3 4	3 3	13.0 24.5	8 6	.32 .27 } .29
1 2	4 4	8.9 6.0	5 4	.28 .42 } .34	3 4	4 4	19.3 6.0	7 4	.27 .45 } .31
Upshur clay					Dunkirk sandy loam				
5 6	1 1	12.9 15.8	6 8	.20 .20 } .20	7 8	1 1	12.4 10.8	3 4	.20 .19 } .20
5 6	2 2	11.1 11.3	4 5	.22 .22 } .22	7 8	2 2	10.8 19.0	4 5	.21 .34 } .30
5 6	3 3	18.5 14.8	7 6	.28 .24 } .26	7 8	3 3	7.9 15.4	3 5	.26 .26 } .26
5 6	4 4	2.2 19.4	3 6	.48 .29 } .30	7 8	4 4	8.5 19.3	3 6	.22 .22 } .22
Volusia silt loam					Wooster silt loam				
10 11	1 1	11.9 13.2	5 5	.16 .17 } .17	17 16	1 1	11.4 6.0	6 5	.17 .17 } .17
10 11	2 2	9.7 23.4	5 7	.22 .23 } .23	17 16	2 2	9.5 14.7	6 5	.17 .22 } .20
10 11	3 3	19.6 17.9	5 4	.30 .16 } .23	17 16	3 3	25.1 22.9	6 5	.35 .25 } .30
10 11	4 4	12.2 23.1	6 7	.25 .21 } .23	17 16	4 4	19.5 19.0	6 5	.20 .28 } .24

After growing to maturity a variety of crops in the cylinders, it was decided to grow a cereal crop to be cut at an early stage of growth. As most of the unlimed cylinders and some of those once limed had become quite unproductive, a complication of cylinder experiments encountered by Mooers (21) and by him attributed to loss of lime, a small application of lime was made to all the soils except the Clyde clay. The application of 25 grams to each cylinder is equivalent to 1100 pounds per acre. Cylinder 3 and 4 received monocalcium phosphate equivalent to 500 pounds 16 percent acid phosphate per acre. Millet was considered a crop well adapted to the purpose, and was sown June 14 and cut July 25, making six weeks growth.

The Clyde and Upshur clays were in poor physical condition due to unfavorable moisture supply, and this delayed germination in some cases and caused poor stands in others. The results obtained are presented in Table 10. They include weights of air dry crops, percentages of phosphorus therein, and estimated average heights of plants when cut. The percentages of phosphorus in the crops are also averaged by combining the crops of duplicate cylinders and considering them as one. With every soil save the Clyde clay, the unfertilized soil previously limed produced crops having a higher average percentage of phosphorus than that of crops grown on soils previously untreated. The composition of the millet grown on the Clyde clay was least affected by either lime or phosphate, and this was the only instance in which the addition of available phosphate to a soil previously unlimed was not evident in the phosphorus content of the crop.

The exhaustion of the available phosphorus by the extended cropping to which the cylinders had been subjected is indicated by the contrast in phosphorus content of millet grown on the very fertile Clyde clay with that of the crop grown on the untreated cylinders filled with other soils. With half the soils, the crop from limed and fertilized cylinders contained a higher percentage of phosphorus than that from the cylinders receiving fertilizer only—with one soil there was no change, and with two there were decreases in this respect. In this experiment the effect of lime in promoting the assimilation of phosphorus native to the soil has been more apparent than the effect upon phosphorus added in fertilizer.

INDICATIONS FROM AN ARTIFICIAL ROOT

The idea underlying all the work discussed has been to use the plant as an indicator of the effect of lime upon the availability of phosphorus. It has been reasoned that if either a good supply or a deficiency of available phosphorus is evident in the phosphorus content of field-grown crops, and if similar differences in phosphorus content of the crop should be observed in the product of limed and unlimed soils in cylinders, the effect of lime upon phosphorus availability may be inferred. But there is the possibility that lime may not have acted upon the phosphorus of the soil at all—the effect may have been primarily upon the plant. As True (30) has expressed it, the calcium ion must be present in excess of a certain minimum, or other nutrient materials in the soil solution will not be "physiologically available"—altho present, the plant is unable to absorb them. The problem is thus thrown back upon chemical methods for solution.

Efforts have been made to secure some evidence on the composition of the soil solution by means of an artificial root, a porous porcelain filter tube or pad of filter paper, buried in the soil. Even if the true soil solution could be secured by these methods, it is doubtful whether information so gained would throw light upon the present problem. The soil solution is known to be very dilute with respect to phosphate, and the plant does not simply imbibe this dilute solution. The phosphate enters more rapidly than the water, possibly by a simple process of diffusion, which can be continuous because the phosphate which enters the roots is transported elsewhere or elaborated into other forms. Thus, the rate at which the phosphate concentration of the soil solution is renewed when a portion of the phosphate is withdrawn may be of more importance than the actual magnitude of this concentration, since the latter is always small. It seems possible to imitate plant roots in this respect.

A collodion sac filled with some substance which will precipitate phosphates in a very insoluble form and have no tendency itself to diffuse outward, should be worth trying. Hydrated ferric oxide was suggested as a suitable phosphorus absorbent. It was prepared by dialysis, this being continued until chlorine was reduced to a very low figure, and the iron was in gelatinous form. A trial showed that a collodion sac containing this hydrated ferric oxide could collect phosphorus from a phosphorus solution as dilute as one-half part per million, which is of the same order of magnitude as some soil solutions. Sacs were prepared, using the same 100-ml. flask for all, and keeping other details as uniform as possible. The same quantity (20 ml.) of the ferric oxide gel. was placed in each, and the sac then buried in the soil, made to a thin mud with water and contained in a beaker.

The beakers with their contents were kept in a saturated atmosphere, and stirred at intervals. At the end of three months the sacs were removed, cleaned, and their phosphorus content determined, with the following results, from which a blank of 0.2 mg. was subtracted in each case:

	Phosphorus content	
	Unlimed soil	Limed soil
Clermont silt loam	0.1 mg.	0.3 mg.
Clyde clay	1.2 mg.	1.0 mg.
Upshur clay	0.1 mg.	0.2 mg.
Dunkirk sandy loam	2.1 mg.	2.3 mg.
Volusia silt loam	0.4 mg.	0.2 mg.
Wooster silt loam	2.5 mg.	0.9 mg.

These figures stand in an order something like that of the productive power of the soils—the Dunkirk sandy loam was the most productive, and the Clyde clay next. The Wooster soil, however, is entirely out of line and its indications in this experiment are at variance with other results. With five out of six soils, differences were very slight, and these were not consistent. This experiment furnished no significant indication that lime has any effect upon soil phosphorus.

CHANGES IN SOIL DUE TO TREATMENT

A chemical examination to determine possible changes in composition of the soils which could be attributed to liming and cropping in cylinders was undertaken. For this purpose, samples were taken from untreated and limed cylinders of several of the soil types first placed, and compared with samples of the same soils taken at the time the cylinders were filled, eight years before. The samples were extracted by digesting 200 g. dry soil with one liter 1 percent hydrochloric acid for one-half hour, filtered on 15 cm. Buchner funnel, washed with two liters dilute acid, and finally with one liter cold water saturated with carbon dioxide. The acid extract and washings were made to four liters and aliquots taken for determinations of calcium, magnesium, and phosphorus. The cakes of acid-extracted soil were extracted with 2.5 percent ammonia, and determinations of total and inorganic phosphorus made on aliquots of the extracts, as described in a former publication (26). Approximately hundred-gram portions of the dried samples were shaken with two parts of water, and after a half hour were filtered on a Buchner for determinations of the pH value by comparison with buffers and indicators according to Clark (4). As a support for the soil on the funnel, an ashless filter paper soaked in successive changes of water was employed. Tests showed that after this treatment the paper had no effect upon the reaction of distilled water filtered thru it.

The results of the analytical work are presented in Table 11. In every instance, samples from the untreated cylinders are lower than the original soil in acid soluble calcium and magnesium. In

TABLE 11.—COMPOSITION OF SOILS AS PLACED AND AFTER 8 YEARS IN CYLINDERS

Soil	Dissolved from soil by washing with 1 percent HCl			Phosphorus dissolved from acid extracted soil by NH_4OH			pH value of 1:2 water extract	Soil treatment
	Ca.	Mg.	P	Total	Inorganic	Organic		
	Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*		
Clermont silt loam	0.082	0.011	0.0014	0.0155	0.0021	0.0134	5.4	Original soil
	.055	.008	.0020	.0156	.0018	.0138	5.1	1. Untreated, cropped
	.107	.010	.0016	.0152	.0023	.0129	5.8	2. Limed, cropped
Clyde clay	.615	.073	.0407	.0340	.0025	.0315	6.4	Original soil
	.529	.054	.0380	.0383	.0026	.0357	5.8	1. Untreated, cropped
	.578	.055	.0368	.0378	.0028	.0350	6.2	2. Limed, cropped
Upshur clay	.246	.042	.0034	.0078	.0010	.0068	5.3	Original soil
	.183	.033	.0041	.0086	.0014	.0072	5.1	1. Untreated, cropped
	.263	.030	.0038	.0077	.0010	.0067	5.8	2. Limed, cropped
Dunkirk sandy loam	.044	.006	.0243	.0136	.0053	.0083	5.3	Original soil
	.022	.004	.0221	.0160	.0060	.0100	4.9	1. Untreated, cropped
	.038	.005	.0223	.0149	.0057	.0092	5.3	1. Limed, cropped

two cases, liming did not maintain the original content of acid soluble calcium. Two soils originally well supplied with acid soluble phosphorus lost in that constituent, but two containing little phosphorus in this form gained slightly. Organic phosphorus increased very slightly in most of the cases, but the increase was less when lime was applied. Soils placed in cylinders and not limed invariably became more acid, and in one case the limed soil was more acid than the original soil. There is a well marked relation between calcium soluble in dilute acid and pH value.

SUMMARY

The idea that the phosphorus of acid soils is in an unavailable condition, and that thru liming it may be made more available, has long been held, altho no entirely satisfactory explanation or proof that this is generally the case has been offered. From data obtained from analyses of wheat grain grown on fertility plots with and without lime, it is deduced that liming the Wooster soil has had a slightly favorable influence upon phosphorus assimilation. Differences in composition of grain grown on plots differently fertilized are pointed out and discussed. Should similar differences appear in the crop grown on soils in cylinders with varied lime and fertilizer treatments, it was hoped that a clue to the effect of lime upon phosphorus availability in these soils would be obtained.

During the first years of the test, wheat grew well on the cylinders, but the yields and composition of the crops indicated that phosphorus was not the limiting factor, hence the effect of lime upon availability of this element was not very plainly shown.

The Clermont silt loam was the only soil furnishing any indication that lime depressed the availability of phosphorus native to the soil. The Clyde clay and Dunkirk sandy loam furnished inconclusive indications that lime had caused increased removal of phosphorus from the unfertilized soil. The Upshur clay indicated no effect due to lime. The Volusia silt loam and Wooster silt loam bore increased crops as the effect of lime alone, and phosphorus removal from the unfertilized soil was increased by lime.

Lime caused no change in average phosphorus content of grain grown on fertilized Clermont silt loam, and caused small but significant increases in crop and phosphorus removal. Averaged yield was slightly increased by lime applied to fertilized cylinders of Clyde clay, and phosphorus percentage in grain and removal of phosphorus from soil were increased. The data, however, are too variable to indicate significant differences.

As with the unfertilized soil, lime had but very slight effect upon the wheat grown on the fertilized Upshur clay.

Yields of wheat upon fertilized Dunkirk sandy loam were adversely affected by lime, and the average removal of phosphorus from limed cylinders was less. Average percent of phosphorus in grain was greater in the crop of limed cylinders. No unfavorable effect of lime upon phosphorus assimilation in this soil was proved.

Yield and phosphorus removal from fertilized cylinders of Volusia silt loam were significantly increased by lime, but phosphorus content of the grain was unchanged.

The average crop on fertilized cylinders of Wooster silt loam was not significantly increased by lime, and the percentage of phosphorus in grain was not affected. Removal of phosphorus from the soil was increased by an amount which seems barely significant.

From analyses of oat plants it appears that the difference in phosphorus content of crop attributable to fertilization becomes less as the age of the plants increases. Millet grown on the cylinders and cut at an early stage indicated increased percentages of phosphorus in the crop grown on the limed unfertilized cylinders of every soil except Clyde clay. Indications with respect to fertilized cylinders were more varied.

An experiment with an artificial root indicated but slight differences in phosphorus availability due to lime, except with the Wooster silt loam, in which case a decrease was indicated.

After eight years in cylinders, the most pronounced changes in composition of the soils were in calcium soluble in dilute acid and in reaction. The soils had become much more acid, and appreciable changes in the solubility of phosphorus, indicating depletion as the result of cropping, were noted in two cases. In every case, organic phosphorus in the unlimed cylinder was higher than it had been in the original soil.

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