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THE EFFECT OF DIFFERENT COLLOIDAL SOIL MATERIALS ON THE EFFICIENCY OF SUPERPHOSPHATE

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INTRODUCTION

Comparatively little is known of how different soils affect the efficiency of superphosphate. Numerous practical experiments such as those determining the comparative values of different phosphatic fertilizers have thrown little light on the subject. In most such experiments, no value for the efficiency of superphosphate is obtained that can be fairly compared with that obtained in another soil. More intensive experiments involving determinations of the phosphoric acid recovered in the crop show that some soils must affect the efficiency of superphosphate profoundly, since the proportion of applied phosphoric acid recovered in the crop is frequently only 10 to 20 percent (*26, 39*),[1] as compared with 90 percent and 60 percent recoveries of nitrogen and potassium (*50, 51*). But experiments of this kind have not furnished comparable figures for a wide variety of soils, since utilization of the applied phosphoric acid varies with the kind of crop and is affected by varying climatic conditions as well as by the character of the soil.

Laboratory studies of the fixation of phosphoric acid by soils have been made in great numbers since Warington (*52*) investigated the subject in 1868. These experiments by themselves are inadequate

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[1] Italic numbers in parentheses refer to Literature Cited, p. 36.

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to show how the efficiency of superphosphate for crops is affected by soils, since laboratory methods of determining the availability of the fixed phosphoric acid at best only approximate the plant's capacity for assimilating phosphoric acid. But some of these studies throw light on results obtained in vegetative experiments with plants, and these are discussed later.

The study of soil colloids has suggested to several investigators (*18, 23*) that the efficiencies of different phosphatic fertilizers may be largely affected by the colloidal soil material. Experiments have already been conducted with artificial iron, alumina, and silica gels, which are presumably similar in some respects to the colloidal material of the soil. Years ago Prianischnikow (*40*) showed that the addition of hydrous ferric oxide to sand cultures depressed the efficiency of bone meal for barley, and Pfeiffer and Blanck (*38*) showed that a mixture of alumina and silica gels depressed the efficiency of potassium acid phosphate for yellow lupines. More recent experiments by Lemmermann and Wiessmann (*31*), Gile and Smith (*23*), and Jessen and Lesch (*29*) showed that colloidal silica may increase the efficiencies of various phosphates including superphosphate.

This investigation was undertaken with the idea of determining how the efficiency of superphosphate as a fertilizer is affected by a number of natural, widely different, colloidal soil materials.

PLAN AND METHODS

The comparative effects of different soil colloids on phosphate utilization by the plant was investigated by means of vegetative experiments in sand cultures involving some 1,400 pots. In order to limit the study, only one kind of crop, millet, was grown, and practically all the work was conducted with one phosphatic fertilizer, superphosphate.

Before it was possible to determine the conditions that would give a fair comparison of different colloids, it was found necessary to study the following subjects: Modifications of the base fertilizer used with superphosphate; method of applying the superphosphate; effect of the soil on superphosphate as influenced by quantity of soil, by quantity of phosphate, and by reaction of the medium; the effects of colloidal and noncolloidal fractions of the soil. Information was also obtained regarding the effect of an artificial colloid, activated charcoal, on the efficiencies of superphosphate and ground rock phosphate, and regarding different methods of calculating fertilizer efficiencies.

The data of the different experiments, some of which bear on more than one of the above-mentioned subjects, are shown at the end of this report; the summarized results are given under the various headings.

The general plan adopted for experiments designed to show the effect of a soil colloid on superphosphate efficiency called for one series of pots containing pure quartz sand and another series filled with a mixture of sand and soil, the soil being applied at a rate to furnish about 1 percent of colloidal material.

All pots received the same base fertilizer which was designed to supply all essential nutrients in excess, except phosphorus. The pure quartz-sand series was installed as a basis for comparison. It received increasing quantities of superphosphate, and the efficiency

of the superphosphate in this nonreactive medium, lacking colloidal material, was taken as 100 percent. From the results of this standard series a curve was plotted showing the increased growth to be attained, under the experimental conditions, with any quantity of P_2O_5 below the maximum. In the soil-sand series some pots received no phosphate, and others received a quantity of phosphate less than the optimum. The yield of the no-phosphate pots, which received some phosphoric acid from the added soil, was subtracted from that of the phosphate pots to give the yield attributable to the superphosphate application.

The efficiency of the superphosphate in the soil-sand mixture is calculated against the assumed 100 percent efficiency in pure quartz sand, on the basis of the comparative quantities of superphosphate required to produce the same increased yield in the two mediums. The quantity of phosphoric acid that gives the same increase in pure sand as that actually obtained in the soil-sand mixtures is found by consulting curves plotted for yields of the pure-sand series. The ratio of these two quantities of phosphoric acid times 100 gives the efficiency of superphosphate in the sand-soil mixture, as a percentage. The advantages of this method of calculating efficiencies have been pointed out in a previous publication (20). Theoretically, the dry weight of the crop is adequate data for calculating efficiencies by this method, and determination of the quantity of P_2O_5 recovered in the crop is unnecessary. However, some 70 of the crops were analyzed, and a comparison was obtained of efficiencies based on the two kinds of data. This is discussed under a subsequent heading. Unless otherwise specified, efficiencies reported in the following tables were based on the oven-dry weights of the crops.

This method of measuring the influence of soil colloids on phosphate efficiency assumes that the soil or soil colloids affect growth only by affecting the phosphate. Obviously, this is true only within limits. It is quite conceivable that the addition of soil or soil colloidal material might in some cases reduce the availability of nutrients added in supposed excess to a point where they, rather than the phosphorus, would be in minimum. The soil could also provide elements affecting growth that were not present in the simple quartz medium. The hydrogen-ion concentration of the medium is in most cases altered somewhat by the addition of soil; likewise, the water relations, probably the microorganisms, and the protection of roots against injury from salt concentrations are affected by the addition of colloidal soil material.

As a matter of fact, a few cases were encountered in this work where some of these possible effects of soil additions were operative to such an extent as to render impossible or inaccurate the proposed method of measuring phosphate efficiency. The addition of Fallon soil, for instance, in one experiment (table 16) [2] rendered iron so unavailable in the soil-sand medium that millet showed a marked chlorosis and growth was reduced more by lack of iron than by lack of phosphorus. In another experiment (table 30) the peat of pH 3.5 rendered the peat-sand mixture so acid that growth with the given amount of superphosphate was doubtless less than it otherwise would have been, and the influence of the peat on phosphate efficiency was obscured.

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[2] Tables 11 to 31 appear in the Appendix.

However, so long as the quantity of phosphate supplied was kept in minimum these secondary effects of the colloidal material were, except as noted, of negligible importance as compared with the effect on the phosphate. It is evident from results obtained in experiments reported in tables 17, 21, and 22 that the quantity of phosphorus available to the plant was the factor controlling growth in this work. In these experiments the addition of Nipe soil and of Sassafras and Clarksville subsoils reduced yields markedly below those of corresponding pots in the pure quartz-sand series when the quantity of superphosphate applied was small, but when sufficient superphosphate was supplied the yields in some cases became even greater than those in the sand series.

In only four of the experiments described here was the extracted colloidal fraction used in the sand cultures; in the other experiments the whole soil was added to the sand in an amount sufficient to supply the desired quantity of colloidal material. It would seem, therefore, that this work was largely a study of the effect of the whole soil on phosphate efficiency rather than a study of the colloidal material, unless it were assumed that the noncolloidal part of the soil was without influence on phosphate utilization. This last assumption appears valid, except for soils containing noncolloidal carbonate of lime, since it is evident from previous work (3) that distinctively mineral, noncolloidal soil particles have slight reactivity as compared with the colloidal soil material. However, direct evidence as to the comparative effects of colloidal and noncolloidal soil fractions was obtained in four experiments described later. This work cannot be discussed in detail at this point, but the results indicate that the procedure of adding the whole soil to the sand on the basis of colloidal content may give fully as fair a comparison of the effects of different soil colloids as the use of extracted colloidal fractions. Either method is open to some objection.

Details of the procedure followed in conducting the tests are given below.

Glazed earthenware crocks of 1-gallon capacity were used as containers. Each pot was filled with 5,000 g of quartz sand, or 5,000 g of sand and soil.

A uniform mixture of the soil or superphosphate with the sand was obtained by moistening the sand with about 1 percent of water to prevent segregation of materials. The superphosphate applications were mixed with small quantities of sand or soil prior to being mixed with the bulk of the material.

The base fertilizers used in different experiments are shown in table 1. They were added to the pots in solution before planting. In some experiments conducted during periods favorable to rapid growth, a further application of nitrogen and potassium (base fertilizer no. 9) was added to all pots when the nitrogen was nearing exhaustion in the pots carrying the greatest growth. Experiments in which this supplementary fertilizer (no. 9) was applied are noted in table 1.

TABLE 1.—*Composition of base fertilizers used in the different experiments*

Base fertilizer no.	$Ca(NO_3)_2.4\ H_2O$	$(NH_4)_2\ SO_4$	KCl	$MgSO_4.7\ H_2O$	$Fe_2(C_4H_4O_6)_3.H_2O$	$MnSO_4.2\ H_2O$
	Grams per pot	Grams per pot	Grams per pot	Grams per pot	Grams per pot	Grams per pot
1	1.070	0.491	0.446	0.914	0.074	0.033
2	.535	.31	.338	.457	.0185	.0017
3	.535	.31	.338	.457	---	---
4	.535	.31	.338	.457	.037	.0017
5	.202	.31	.125	.33	.0185	.0017
6	.535	.31	.338	.457	.0185	.0017
7	.552	---	---	.457	.0185	.0017
8	.652	---	---	.457	.0185	.0017
9	---	.155	---	---	.0185	.001?

Base fertilizer no.	KNO_3	NaCl	$CuCl_2$	H_3BO_3	Total salts less water crystallization	Concentration total salts	Table in which use of fertilizer is reported
	Grams per pot	Grams per pot	Grams per pot	Grams per pot	Grams per pot	Parts per 1,000 of H_2O	
1					2.23	2.79	11.
2					1.26	1.58	All except 11.
3					1.24	1.55	12.
4					1.28	1.60	12.
5	0.295				1.05	1.31	12.
6		0.131			1.39	1.74	14.
7	.462	.131			1.22	1.53	14, 29.
8	.462	.131	0.0008	0.0074	1.23	1.54	14.
9	.232				.387	.48	12, 16, 17, 19-23, 29, 31.

German, or foxtail, millet (*Setaria italica*) seed were planted, and as the seedlings became established they were thinned to 10 plants per pot.

The pots were kept in a glasshouse, the temperature of which varied from about 75° in winter to 110° F. on hot days in early summer. The position of the pots relative to one another was changed daily, except Sunday, in a regular manner. The water content of the sand, determined by weighing the pots, was kept at approximately 17 percent by the addition of distilled water.

In winter months the plants were grown until heads began to appear. At other times of the year they were grown until a shortage of nitrogen developed in the high-phosphate pots of the check series, as indicated by yellowing of the lowest leaves. The duration of the experiments varied from 20 to 50 days, depending on temperature and light relations.

Only the plant aboveground was harvested. The oven-dry weights reported were obtained by first thoroughly air-drying the crop and then drying for 2 hours at 105° C.

Replication of the treatments varied somewhat in different experiments to conform with the accuracy desired and the number of treatments in the experiment. In experiments involving a few pots, less replication was needed to attain a given accuracy than in experiments involving a greater number. Apparently this was owing to the fact that conditions in the glasshouse were more uniform in a small space than in a large one. Usually all treatments were replicated four times. However, as the work progressed and uniform lots of sand lacking in phosphorus were obtained, it became evident that it was not necessary to replicate the no-phosphate treatments, since growth

here was so slight, about 0.1 g of dry matter per pot, that an exact determination of this quantity was unessential.

SOILS AND MATERIALS

The quartz sand used in this work was a commercial grade of "glass sand." It contained no soil or clay, but one lot, used in experiments reported in tables 11 and 16, contained enough soluble alkali to impart a hydrogen-ion concentration of 7.5 to the material with fertilizer salts added, and another lot was evidently contaminated with some phosphate, as shown by the results of experiments reported in tables 13, 17, and 23. That used in the other experiments was apparently free from impurities affecting plant growth, and did not change the hydrogen-ion concentration of distilled water appreciably.

Seventeen surface soils, 14 subsoils, 2 peats, and 3 activated charcoals were tested for their effects on the efficiency of superphosphates. With two exceptions, the soils were taken from the collection of soils from different parts of the United States utilized in the colloid studies described in previous publications. The location of the soils and the chemical composition of the whole soil and of the colloid present are given in a previous bulletin (44). The adsorption and other properties are also described in previous publications (22, 4).

The Brazil soil was a surface sample taken from a coffee plantation in Sao Paulo, Brazil. It is not an authentic sample of a well-defined soil type, but it was used in this work as the colloidal material had a very low silica sesquioxide ratio. It contained about 56 percent of colloidal material as ascertained by the water-adsorption method (43). The analysis of the colloid is given in table 2.

TABLE 2.—*Chemical composition of colloids extracted from the Nipe and Brazil soils* [1]

Name of colloid	SiO_2	Al_2O_3	Fe_2O_3	Cr_2O_3	MnO	CaO	MgO
	Percent	Percent	Percent	Percent	Percent	Percent	Percent
Nipe	12.48	17.93	52.92	0.67	0.69	0.33	0.12
Brazil	24.23	34.10	21.86		.18	.45	.07

Name of colloid	K_2O	Na_2O	TiO_2	P_2O_5	SO_3	Mols $\dfrac{SiO_2}{Al_2O_3+Fe_2O_3}$
	Percent	Percent	Percent	Percent	Percent	
Nipe	0.34	Trace	0.64	0.06	0.02	0.41
Brazil	.28	...do	1.82	.23	.13	.85

[1] Analyses by G. Edgington.

The lot of Nipe soil was of the same type as that described in a previous bulletin (1) but was a new field sample. The analysis of the colloid is given in table 2. The colloid content of the soil was 66 percent as ascertained by the water-adsorption method.

The quantities of colloidal material present in the different soils were calculated in most cases from data regarding adsorption of water and dye, given in a previous publication (22). In a few cases this was supplemented by later data as to the quantity of colloid actually isolated, or the quantity of water vapor adsorbed by the soil over 3.3 percent by weight sulphuric acid. Before being used in the pot

experiments, the soils were passed through a ½-millimeter sieve to promote intimate mixture with the sand and phosphate.

The same sample of superphosphate was used in all the following experiments. It contained 18 percent available P_2O_5 and was ground to pass a 150-mesh screen before being mixed with the soil or sand.

The rock phosphate used in a few experiments was a Tennessee brown-rock phosphate, ground to such fineness that 78.3 percent passed a 300-mesh screen and 99.7 percent passed 100 mesh. The total P_2O_5 content was 33.73 percent.

The physical characteristics of the two peats used in the experiment reported in table 30 have been described by Feustel and Byers (*13*). The one of pH 5.8 was a saw-grass peat from Clewiston, Fla., 10 to 16 inches in depth; and the peat of pH 3.5 was the 24- to 30-inch layer of a sedimentary peat from Beaufort, N.C.

Charcoals applied in experiments reported in tables 30 and 31 were prepared from activated charcoal supplied by the Chemical Warfare Service. As received, the activated charcoal contained considerable ash, including phosphorus and iron, but a lot of this was purified to give "charcoal of pH 4.1" in the following manner: About 1 pound of charcoal was boiled with 5 successive 1,500-c c portions of 10 percent hydrochloric acid. It was then washed with 1,800 c c of H_2O 23 times, the water being removed each time by suction through a clay filter. The charcoal was then treated twice with 1,500-c c portions of normal NaCl to facilitate removal of acid and then washed with 1,800-c c additions of water 32 times. The last washings had a pH of approximately 4.1 and gave no test for chloride.

Charcoal described as "charcoal pH 4.3" was prepared in the same manner except for variations in quantities of sample, water, etc. The lot designated as "charcoal of pH 9.6" was also prepared similarly, except that preceding the treatment with normal NaCl the sample was treated with 1,000 c c of 10 percent sodium hydroxide. The treatment with sodium hydroxide released large quantities of chloride which must have been closely held by the charcoal, since preceding the treatment with alkali the sample had been washed 30 times with water and the last washings gave only a weak test for chloride.

EXPERIMENTAL RESULTS

The results of the various experiments are shown in tables 11 to 31. Figures given for the efficiency of superphosphate are based on the weight of the crop in all cases where the content of P_2O_5 is not mentioned. In order to condense the data, the yields of individual pots are omitted, and only average yields are shown, together with the probable error of the average. The probable error, calculated by the formula $P.\ E. = 0.6745\sqrt{\dfrac{\Sigma d^2}{n\ (n-1)}}$, is given more as a short method of showing all the data obtained than as a strict measure of accuracy. In these experiments the variation of duplicates seemed to be determined largely by the position of the pots in the greenhouse during early growth. Such being the case, the average figure for variable duplicates in fairly distributed locations might be practically as accurate as the average figure for closely agreeing duplicates exposed to uniform conditions, although the probable errors would be very different in the two cases. Probably the Student method of

calculating probable error would give a fairer estimate of accuracy in these experiments than the usual method.

THE BASE FERTILIZER

It was desirable that the base fertilizer used in this work should give both a good growth in pure quartz sand and a high availability of the superphosphate. There are grounds for believing that these two qualities, in their highest development, may be incompatible in the same fertilizer, since the base fertilizer giving the greatest growth in sand with excess phosphate would probably give a small increase per unit of phosphate, in other words, a low availability of the phosphate. But a fertilizer was finally adopted which seemed to satisfy both requirements fairly well.

In the first experiment (table 11) trial was made of a base fertilizer that was similar, except for addition of $MnSO_4$, to a fertilizer used in a previous study with fairly satisfactory results (23).

The composition of this fertilizer is shown in table 1, under the heading no. 1. Growth with this fertilizer was hardly satisfactory, as the seedlings seemed to be somewhat slower in getting established in the pure sand cultures than in the series containing soil. This was thought to be owing to too high a concentration of salts. Also, it was apparent from the results of the experiment shown in table 11 that the quantity of manganese used in the base fertilizer markedly cut down the efficiency of the smaller superphosphate application.

An experiment (table 12) was then conducted with salt mixtures (nos. 2, 3, 4, and 5 of table 1), which were much lower in manganese and contained only about one half the salts per pot as the preliminary fertilizer. The quantities of iron, manganese, calcium, and magnesium were varied in these fertilizers, to learn whether the quantities applied affected the efficiency of superphosphate in pure quartz sand. The results of this experiment (table 12) showed that there was little to choose between the fertilizers in their effects on superphosphate, except that no. 4, with the high iron, was inferior. Fertilizer no. 2 was therefore used in further experiments.

With these smaller quantities of fertilizer, growth seemed perfectly satisfactory, but it was observed in subsequent experiments that plants in the soil-sand mixtures usually gained a slightly better start than those in pure sand, although the ultimate growth was much less. The ratio of salts to water in these experiments was only about one fourth that used by Ayres (6) in his study of sand cultures.

It was thought that this better start might be connected with the acidity of the medium. An experiment (table 13) was therefore conducted to ascertain whether the quartz-sand medium and base fertilizer could be improved by the addition of calcium carbonate. Precipitated calcium carbonate was used, and this was mixed uniformly with the sand. The early growth of the plants was about the same in all the pots, but in later growth the following significant differences developed. The carbonate additions markedly depressed the growth made with the smaller applications of superphosphate; growth with 0.12 g of P_2O_5 was greatest in the series receiving 0.4 g of $CaCO_3$; and a chlorosis became most pronounced in the series receiving 1.6 g of $CaCO_3$. Apparently the addition of 0.4 g of $CaCO_3$ lowered the availability of the superphosphate, while it rendered the medium somewhat more favorable for growth with an excess of superphosphate.

The 1.6 g of $CaCO_3$ not only lowered the availability of the super-phosphate, but it diminished the availability of iron to such an extent that a good growth could not be attained with a heavy application of superphosphate. It thus seemed that even small additions of lime to the base fertilizer would be of doubtful value.

A trial was then made to find whether the base fertilizer could be improved through additions of sodium, copper, and boron, or through a change in the hydrogen-ion concentration brought about either by the use of sodium bicarbonate or by supplying the nitrogen all as nitrate rather than one half as nitrate and one half as ammonium sulphate. The salt mixtures used were nos. 2, 6, 7, and 8 of table 1, and the results of the experiment are shown in table 14. Obviously, the addition of sodium, copper, and boron did not improve growth in the sand cultures well supplied with superphosphate; probably suffi-cient of these elements, if needed, was present as impurities picked up from containers used for sand and water and from the superphosphate and other salts applied. Even the small application of sodium bicar-bonate was plainly injurious, and the substitution of all nitrate for one half nitrate and one half ammonia was unfavorable also.

The addition of Sharkey soil, which increases superphosphate effi-ciency, did not increase growth in the acid medium afforded by one half NO_3 and one half NH_4; but it increased growth in the all-nitrate medium. Possibly the phosphate supply was somewhat below opti-mum in this slightly alkaline medium, and the Sharkey soil added some available phosphate.

No further modifications of base fertilizer no. 2 were attempted, and this was used as the standard in subsequent experiments. It was found later that the slightly better start of plants in the soil-sand mixtures than in the pure sand cultures was probably due to the colloidal material protecting the young seedlings from temporary un-favorable concentrations of salts near the surface when the seedlings were getting a start. This was largely overcome by special care in watering during that period.

When, in the early part of this study, it was found that the addition of certain soils to quartz sand rendered small quantities of super-phosphate almost entirely unavailable, it was suspected that such a pronounced effect might be abnormal. Since the concentration of salts in the pot cultures was greater than would be encountered under ordinary field conditions, it was thought that the base fertilizer might have in some way activated the reaction of the soil with the phosphate. Mattson (32), for instance, has shown a marked solubility of the iron and aluminum of colloidal soil material after treatment with concen-trated solutions of ammonium chloride. In water cultures, however, where no soil is present, the concentration of salts has little effect on the absorption of phosphates by plants, according to Breazeale and McGeorge (9).

Accordingly, an experiment was conducted in which half the normal quantity of the standard base fertilizer (no. 2, table 1) was compared with the usual application. Owing to the small quantity of nutrient salts applied to part of the pots, the plants were grown to only about one half the usual size. The results of the experiment (table 15) show that the soil addition depressed growth to just as great an extent with half the base fertilizer as with the full application. It is also

evident from the growth made with the two fertilizers in pure quartz sand that the concentration of the standard fertilizer was favorable for growth.

METHODS OF APPLYING SUPERPHOSPHATE

In a preliminary experiment (table 11) application of the superphosphate in a layer 1 inch deep, about one fourth inch below the seed, was compared with applications mixed uniformly with the whole mass of sand, or sand and soil. In the soil-sand mixture the soil, as well as the phosphate, was confined to a 1-inch layer. A marked difference was observed between the two methods of application, and further tests were conducted in experiments described in tables 12, 16, and 17. The results obtained are summarized in table 3. In all cases, except one, there is a distinct difference in favor of the layer application, but the difference is especially marked in the soil-sand mixture.

TABLE 3.—*Summary of results obtained on comparing applications of superphosphate and soil in layers with applications uniformly mixed with all the quartz sand* [1]

Conditions of comparison			Efficiency of application in a layer [1]	Efficiency of corresponding application uniformly mixed [2]
Kind of soil added to quartz sand and the quantity, expressed as grams, of colloid present	Kind of base fertilizer used	P_2O_5 applied per pot		
		Gram	*Percent*	*Percent*
None	No. 1, high Mn	0.04	332	100
	do	.12	168	100
	No. 2, standard	.06	120	100
	No. 3, Fe and Mn omitted	.06	150	100
	No. 4, double Fe	.06	97	87
	No. 5, Ca and Mg reduced	.06	120	97
	No. 2, standard	.06	95	100
Nipe, 50 g	No. 2, standard	.12	42	10
Brazil, 50 g	No. 1, high Mn	.12	123	13
Cecil subsoil, 50 g	No. 2, standard	.00	60	14

[1] Data obtained from tables 11, 12, 16, and 17.
[2] The superphosphate is assumed to be 100 percent efficient where it was uniformly mixed with all the sand and the standard base fertilizer no. 2 was used.

The results show the necessity of using great care in applying the phosphates in the following tests on the effects of different soils on phosphate efficiency. It was thought best in all this work to adopt the method of mixing the phosphate and soil uniformly with the whole quantity of sand. This method was expected to give more uniform results in the pure sand cultures, and it would hardly be advisable to confine the soil to a layer in the soil-sand cultures, since the physical condition of this layer would be quite different when different soils were used.

The favorable effect of the layer application is probably due in part to the plants obtaining a quicker start through the increased quantity of phosphate within reach of the first roots. There was about five times as much phosphate per unit volume in the layer as in a similar zone of the sand receiving the uniform application. The fact that when the comparison was conducted in pure quartz sand the difference in favor of the layer application was considerably greater during early growth than it was when the plants were cut suggests this advantage of stimulus to early growth. If this is the true explanation, it indicates that the phosphates do not move to the roots so much as the roots move to the phosphates.

EFFECT OF INCREASING QUANTITIES OF SOIL ON THE EFFICIENCY OF SUPER-PHOSPHATE

Data given in tables 17 to 22, inclusive, snow now the efficiency of a fixed quantity of superphosphate varies as increasing quantities of soil are mixed with the quartz sand. The results are shown graphically in figure 1.

The curves for different soils all show the same general form; the efficiency falls rapidly with the first additions of soil and is not much affected by further increments. The two curves for Nipe soil, no. 1, plotted for the series receiving 0.05 g of P_2O_5 per pot, and no. 3 for the series receiving 0.135 g of P_2O_5 show that the falling off in efficiency with increasing quantities of soil is less sharp, the more superphosphate is applied.
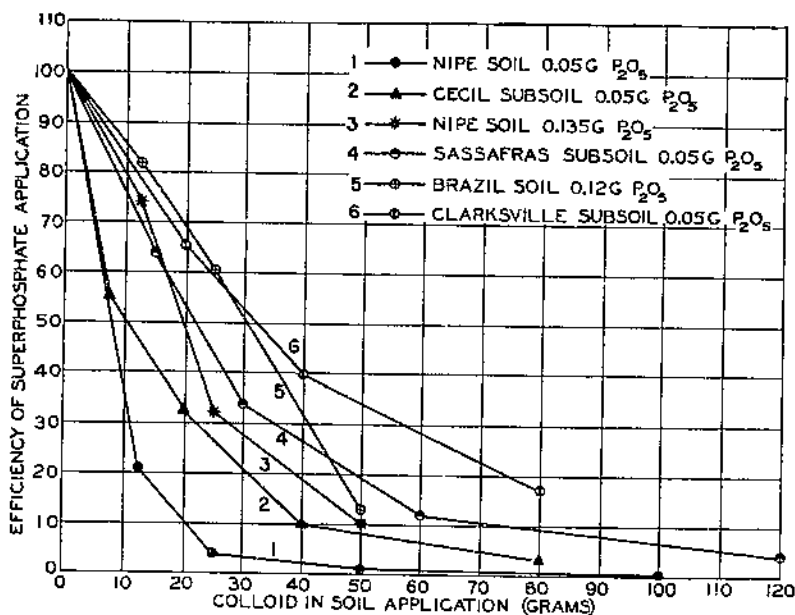
FIGURE 1.—Efficiency of a superphosphate application as affected by the quantity of soil mixed with quartz sand.

It is apparent from a comparison of these curves that comparative figures for the effects of different soils on phosphate efficiency may vary considerably, according to whether the comparison is based on the effect of 25 or 50 g of soil colloid.

EFFICIENCIES OF INCREASING SUPERPHOSPHATE APPLICATIONS WITH A FIXED QUANTITY OF SOIL

Before the effects of different soil colloids on superphosphate could be compared, it was necessary to determine how the effect varied with the quantity of superphosphate applied. Measurements of the effect of a fixed quantity of soil on the efficiencies of different quantities of superphosphate are found in tables 15, 17, 18, 21, and 22. The results of the different experiments are shown in figure 2, and a representative experiment is illustrated in figure 3.

Evidently in all cases the efficiency of the superphosphate, as expressed, is practically a straight-line function of the quantity of phosphate applied. Within the limits of experimental error, all curves would, on projection, pass through the origin. Actually,
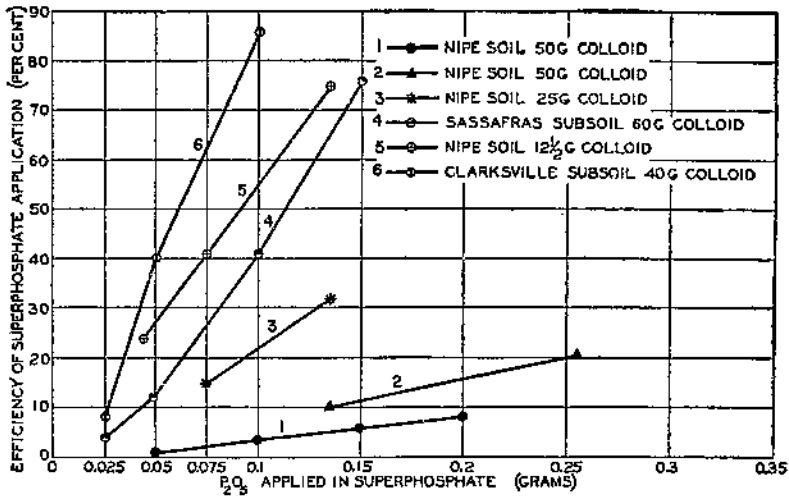
FIGURE 2.—Efficiency of superphosphate in mixtures of soil and sand as affected by the quantity of phosphate applied.

however, when the first and last points on the curve are used for projection, 4 of the 6 curves cut the abscissa within points corresponding to 0.018 and 0.021 g P_2O_5. Some such point might be the true origin of the curves, as there may be some quantity of phosphates held so tightly by the soil as to be completely unavailable to the plant.
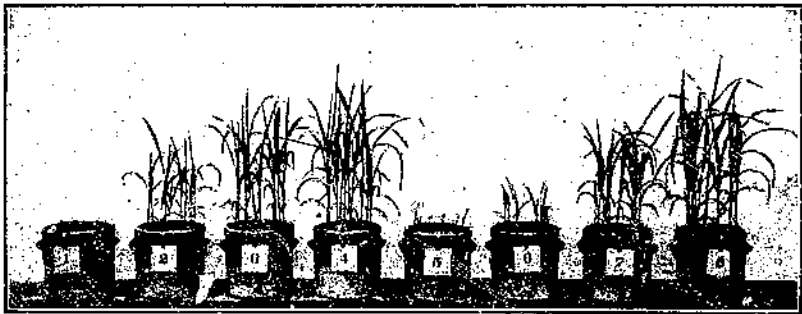
FIGURE 3.—Effect of increasing supersphosphate in sand and in a sand-Sassafras-subsoil mixture as shown by the growth of millet (table 21).   1, Sand only, no P_2O_5; 2, sand only, 0.025 g P_2O_5; 3, sand only, 0.05 g P_2O_5; 4, sand only, 0.1 g P_2O_5; 5, sand and soil, 0.025 g P_2O_5; 6, sand and soil, 0.05 g P_2O_5; 7, sand and soil, 0.1 g P_2O_5; 8, sand and soil, 0.15 g P_2O_5.

However, except for this small unexplored region lying near the limits of experimental accuracy, it is evident from the curves that there is no definite saturation point of the soil which must be exceeded before any phosphoric acid at all is available. It seems, on the other hand, that the absolute quantity of phosphate rendered unavailable by the

soil increases with increasing application up to a certain point (table 4), although the percentage rendered unavailable decreases.

TABLE 4.—*Summary of results showing how the efficiency of superphosphate in a soil-and-sand mixture varies with the quantity of superphosphate applied*

Table no. from which data were obtained	Kind of soil mixed with quartz sand, and quantity in terms of colloid content	P_2O_5 applied per pot	Efficiency of the P_2O_5	Quantity P_2O_5 rendered ineffective by the addition of soil to quartz sand
		Grams	*Percent*	*Grams*
18	Nipe soil, 50 g	0.05	1	0.0495
		.10	3.5	.0965
		.15	6	.1410
		.20	8	.1840
17	do	.135	10	.1215
		.255	21	.2015
17	Nipe soil, 25 g	.075	15	.0638
		.135	32	.0918
17	Nipe soil, 12½ g	.045	24	.0342
		.075	41	.0443
		.135	75	.0338
21	Sassafras subsoil, 60 g	.025	4	.0240
		.050	12	.0440
		.100	43	.0590
		.150	77	.0345
22	Clarksville subsoil, 40 g	.025	8	.0230
		.050	40	.0300
		.100	86	.0140

The slopes of curves for the Clarksville and Sassafras subsoils and for Nipe soil applied at the rate of 12½ g of colloid suggest that these particular applications might render some quantity of superphosphate more efficient than superphosphate in pure quartz sand, in spite of the fact that these soil additions markedly depressed the efficiency of small quantities of superphosphate. This, however, is projecting the results into the region of maximum growth where this method of study, or the particular technic employed, breaks down. As pointed out under Plan and Methods, the method of testing efficiencies adopted is valid only so long as the comparison between the pure quartz sand and the soil-sand cultures is made with a quantity of superphosphate that is in minimum. When a quantity of superphosphate near the optimum is used, secondary effects of the soil which are beneficial to growth begin to affect the yield, and with still more phosphate the yield should become higher in the soil-sand mixture than in pure sand, as actually occurred in some cases (tables 17, 21, 25).

In table 4 the quantities of P_2O_5 rendered unavailable, or ineffective, as compared with superphosphate in pure sand, are given. This shows better than the graphs how markedly the "fixed", or ineffective, P_2O_5 increases as increasing quantities of superphosphate are applied. Another point not brought out in the graphs is that the Clarksville and Sassafras subsoils and Nipe soil, at the rate of 12½ g of colloid, seemingly render ineffective less P_2O_5 from the heaviest superphosphate application than from smaller applications. In these three cases the quantity of superphosphate applied was sufficient to bring the growth into the region of maximum growth where the method of studying efficiencies is inapplicable, since there, the soil-sand cultures are at an advantage over the pure sand cultures.

The marked increase in efficiency of large over small applications of superphosphate in the presence of soil evidently holds for most of the soils. Data are given in tables 16 and 23 for the efficiency of 0.12 g P_2O_5 in the presence of different soil applications providing 50 g of colloid. The figures obtained for efficiency in these experiments may be compared with those obtained in other experiments where the superphosphate application was 0.05 g P_2O_5 per pot. Mentioning the efficiency of the 0.12 g P_2O_5 application first and that of the 0.05 g P_2O_5 second, the results are as follows: Cecil soil, 70 against 28; Norfolk soil, 24 against 6; Sassafras soil, 111 against 75; Hagerstown subsoil, 40 against 4; and Orangeburg subsoil, 33 against 1.

Inasmuch as curves for the efficiency of increasing applications of superphosphate all approximate straight lines passing through the origin, it is evident that the effects of different soils on efficiency can be fairly compared on the basis of any one fixed quantity of superphosphate. The quantity used for the comparison described later was 0.05 g of P_2O_5 per pot, this being a dose below the optimum for pure quartz sand and one that gives measurable increases in growth with markedly depressing soils.

The facts brought out in this particular section of the study may have a further bearing on the comparative effects of different soils on superphosphate. The fact that the percentage of the superphosphate application rendered unavailable decreases with increasing size of the application suggests that the effects of different soils on a given phosphate application may depend largely on how nearly saturated the soils are with P_2O_5. The soils that are more nearly saturated with P_2O_5 would evidently render unavailable a smaller proportion of any superphosphate application than the less saturated soils; in other words, they would depress efficiency less.

EFFECTS OF COLLOIDAL AND NONCOLLOIDAL SOIL FRACTIONS ON SUPERPHOSPHATE

Although it seems evident from previous work on the properties of colloidal and noncolloidal soil fractions (3) that the reaction of noncalcareous soils with superphosphate must be confined almost exclusively to the colloidal material, an attempt was made to show this directly. The plan was to separate the soil into colloidal and noncolloidal fractions and compare the effects of these fractions on superphosphate efficiency with the effect of the unfractionated soil material.

Certain difficulties in this simple procedure were apparent at the outset. A complete separation of colloidal material is practically impossible; hence the noncolloidal fraction is bound to contain more or less colloid. However, the quantity of colloid remaining in the noncolloidal fraction can be estimated fairly well by the water-adsorption method (43), and allowance can be made for this in interpreting the results. A more serious difficulty anticipated was that the effect of the colloid on superphosphate might be altered by the process of extraction, since early work showed that the adsorptive capacities of some colloids for dye, water, and ammonia were materially altered by the extraction process (22). Alteration was especially feared in this work, inasmuch as the soils suitable for this experiment, those markedly depressing the efficiency of superphosphate, contain colloid that is difficult to extract, and ammonia must be used to obtain fairly clean separation. A third difficulty

anticipated was that the fractions might accumulate sufficient heavy metals in the process of separation to render them injurious to plants. The agitator used for dispersing the soil and the supercentrifuge used for separating the colloid expose copper, brass, tin, and iron to the soil and water under somewhat abrasive conditions.

The Cecil, Sassafras, and Clarksville subsoils, which markedly depressed superphosphate efficiency, were fractionated for this experiment by a procedure previously described (27). Approximately 90 percent of the colloid present in each soil was extracted by repeated use of the dispersion apparatus and addition of distilled water brought to a pH of 8 or 9 with ammonia. Tests of the noncolloidal fractions for adsorption of water vapor indicated that they contained 6 to 8 percent of unextracted colloidal material. The extracted colloidal material was dried on the steam bath and ground to pass a ½-millimeter sieve before being mixed with the sand.

The three soils were not fractionated at the same time. Fractions of the Cecil subsoil were first prepared and these were at once used
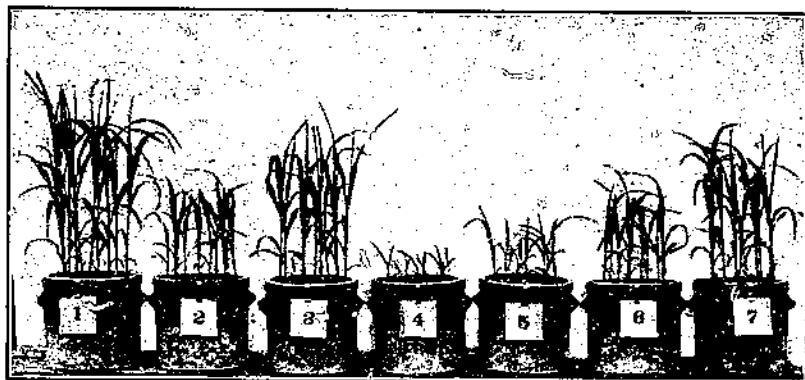
FIGURE 4.—Effects of colloidal and noncolloidal fractions on superphosphate as shown by the growth of millet (table 20). 1, Sand only, 0.05 g P_2O_5; 2, sand plus 20 g of colloidal fraction, 0.05 g P_2O_5; 3. sand plus 40 g of noncolloidal fraction, 0.05 g P_2O_5; 4, sand plus soil at rate of 80 g of colloid, 0.05 g P_2O_5; 5, sand plus soil at rate of 40 g of colloid, 0.05 g P_2O_5; 6, sand plus soil at rate of 20 g of colloid, 0.05 g P_2O_5; 7, sand plus soil at rate of 10 g of colloid, 0.05 g P_2O_5.

in the pot experiment shown in table 19. A year later fractions of the Sassafras subsoil and Clarksville subsoil were prepared and used shortly thereafter in experiments shown in tables 21 and 22. Fortunately, at this time it was decided, for no particular reason, to repeat also the experiment with the Cecil subsoil fractions, utilizing what remained of the material prepared in the previous year. The results of this experiment are shown in table 20 and illustrated in figure 4. There were thus three experiments with freshly prepared fractions and one with fractions 1 year old.

Tables 19, 21, and 22, giving data for the fractions applied shortly after preparation, show that the extracted colloids depress the efficiency of superphosphate much more than an application of the whole soil containing the same amount of colloid; the noncolloidal fractions depress superphosphate slightly or markedly less than a similar quantity of extracted colloid; and the combined fractions depress the superphosphate much more than equivalent quantities of the untreated soils. The experiment with the Cecil subsoil

fractions repeated a year after the fractions had been prepared gave somewhat different results (table 20). The extracted colloid gave the same efficiency of superphosphate as the soil application furnishing a like quantity of unextracted colloid. The noncolloidal residue applied at double the rate of the extracted colloid depressed growth much less than the colloidal fraction.

Only this qualitative idea of the effects of the fractions is afforded by the figures given in tables 19 to 22, since, as already shown in figure 1, the depression in phosphate efficiency is not in direct proportion to the quantity of soil applied, but falls off at a diminishing rate as the soil is increased. A quantitative measure of the effect of a fraction, however, is given by the quantity of soil required to produce the same result (that is, the same lowering in efficiency) as the fraction. The results obtained in the four experiments are shown in this quantitative manner in table 5. The quantities of soil required to produce the same results as the fractions were obtained from the curves given in figure 1.

TABLE 5.—*Summary of results showing the effects of colloidal and noncolloidal soil fractions on the efficiency of superphosphate in quartz sand*[1]

Soil type	Extracted colloid, applied per pot	Colloid in quantity of untreated soil, producing same effect	Noncolloidal residue, applied per pot	Colloid in quantity of untreated soil, producing same effect	Extracted colloid and noncolloidal residue, combined in proportions present in soil, applied per pot	Whole untreated soil, producing same effect
	Grams	*Grams*	*Grams*	*Grams*	*Grams*	*Grams*
Cecil subsoil	40	90	47	72	44	112
Cecil subsoil, fractions 1 year old	20	20	40	15		
Sassafras subsoil	40	80	40 / 120	21 / 26	60	153
Clarksville subsoil	40	110	40 / 120	35 / 64	80	377

[1] Calculations based on data given in tables 19 to 22.

If, for convenience in discussing the results of table 5, it is assumed that only the colloid in the untreated soil affects the phosphate, then it appears that the year-old extracted colloid of Cecil subsoil is equal in effectiveness to the unextracted colloid, but the three other freshly prepared, extracted colloids are 2 to nearly 3 times as effective as the soil colloid. It seems obvious, then, that the reactivity of the colloidal material in the soil is increased by the process of extraction, and that this increased reactivity is lost as the fraction ages.

The figures in the fourth and fifth columns showing the effects of noncolloidal fractions might be fairly well explained on similar grounds, that the extraction process had increased the reactivity of the unextracted colloid in these fractions and this activity was largely, but not completely, lost in the case of Cecil subsoil by aging for 1 year. Figures for the recombined soil fractions in the last two columns of the table give direct proof that the process of separating the fractions has markedly increased the effect of the material on plant growth, whatever the explanation. The increased effect of freshly prepared

colloid may be due to increased hydration of ferric oxide with consequent greater facility for combination with phosphoric acid, or it may be that the freshly prepared colloid after being dried on the water bath is more permeable to the solution and consequently reacts more readily with the phosphoric acid. The loss of activity on aging might be due to dehydration, or the permeability may be lessened on aging.

From comparison of fresh and aged Cecil colloids it seems that increased reactivity of the colloid is the chief reason for recombined soil fractions having a much greater effect than untreated soil; but observation of the plants during growth indicates that another factor may play a part in this enhanced effectiveness of the recombined soil fractions.

In all four experiments it was noted that plants growing in pots receiving the noncolloidal fraction differed somewhat in appearance from plants receiving untreated soil or extracted colloid. In the pots with the noncolloidal fractions the stand of plants was very irregular; the larger plants were as dark green as any plants in the experiment but were affected with a slight striation in the leaves that was usually most pronounced in the next to last leaf; root development was also inferior to that of plants making similar growth in the presence of untreated soil, the roots being short and stubby, similar to those developed in an unfavorable medium. On the other hand, plants growing in pots receiving the extracted colloid had the same appearance as those making equivalent growth in the presence of the untreated soil. There is thus some indication in the appearance of the plants that the noncolloidal residues and the recombined fractions may owe part of their effect to another factor. This factor may be a contamination of the fraction with heavy metals picked up in the process of fractionation. The fact that the effect of the noncolloidal fraction measured in terms of the whole soil was not trebled when the quantity applied was trebled is in accord with this supposition.

Several months after the characteristics mentioned above of plants grown with the extracted noncolloidal fractions were noted, it was found that Forbes (14), several years ago, described as symptoms of copper injury in corn plants some of the same characteristics: viz, a yellow striation of the leaves and a restricted development of roots, crinkled in form.

The results of these experiments support the idea that the colloidal material is the only part of the soil affecting the efficiency of superphosphate, since the colloidal fractions show a much greater effect than the noncolloidal fractions. But the demonstration is far from clear-cut, because both fractions exert more than their required effects. These discrepancies seem to be satisfactorily explained by changes, including contamination, brought about in the process of separation; hence it is assumed in the discussion that follows that the soil colloids are the material affecting the superphosphate.

Further evidence that reaction of the soil with superphosphate is chiefly concerned with the colloidal material lies in the high percentages of phosphoric acid found in soil colloids by several investigators (10, 19, 44), since it is probable that the high percentages are chiefly due to adsorption. This is supported by Ford's (15) data showing that the use of superphosphate on the experiment plots of

the Kentucky Agricultural Experiment Station has enriched with phosphoric acid chiefly the clay fraction. Brown and Byers' (*10*) data showing that the highest content of phosphoric acid usually occurs in the 1 to 5 micron fraction, suggest that adsorption of phosphoric acid may lead to some aggregation of the soil colloids.

EFFECTS OF DIFFERENT SOIL COLLOIDS ON SUPERPHOSPHATE EFFICIENCY

The conditions adopted for determining the effects of different soil colloids on superphosphate were as follows: The different soils were added to the quartz sand in amounts which would furnish 50 g of colloidal material in each case; the superphosphate application furnished 0.05 g of P_2O_5 per pot; and base fertilizer no. 2 of table 1, with part ammonia and part nitrate nitrogen, was used. Somewhat different values would probably have been obtained with different quantities of soil and phosphate, with a test plant that was a "stronger feeder" on phosphate than millet, with a base fertilizer physiologically alkaline rather than acid, or with superphosphate applied some time prior to planting. The particular values obtained for the efficiency of superphosphate are therefore of general significance only in a comparative sense.

Data for the effects of the different soils under these experimental conditions are found in 10 experiments reported in tables 18, 20, 21, 24, 25, 26, 27, 28, 29, and 31. These experiments were conducted at different times under varying conditions of light, temperature, and humidity. The results of these experiments are brought together in table 6.

TABLE 6.—*Correspondence between silica-sesquioxide ratio of the soil colloid and effect of the soil on the efficiency of superphosphate in quartz sand* [1]

Soil type (surface soils)	pH concentration of medium after growth	$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$ ratio of colloid	Average efficiency of superphosphate in soil-sand mixture [2]	Duplicate determinations of efficiency	Soil type (subsoils)	pH concentration of medium after growth	$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$ ratio of colloid	Average efficiency of superphosphate in soil-sand mixture [2]	Duplicate determinations of efficiency
			Percent					*Percent*	
Sharkey	4.8	3.23	148		Wabash	4.6	3.33	175	
Wabash	4.7	3.16	198		Marshall	5.6	2.87	52	
Stockton	6.7	2.87	146		Stockton	8.1	2.85	130	
Marshall	5.0	2.82	142		Miami	7, 8, 7.9	2.66	28	38, 18
Carrington	4.8	2.75	54	50, 58	Carrington	5.0	2.64	78	
Miami	4.8, 5.2	2.50	62	73, 48	Clarksville	4.8 to 5.4	2.10	13	10, 19, 10, 14
Clarksville	4.6 to 5.3	2.18	71	73, 77, 64, 68	Sassafras	6.3	1.89	18	16, 19
Hagerstown	6.7, 6.9	1.91	11	11, 10	Huntington	6.2	1.89	4	
Huntington	4.6	1.86	72		Hagerstown	6.6, 6.8	1.89	8	10, 6
Sassafras	4.7, 4.4	1.85	75	51, 98	Norfolk	4.6	1.84	1	
Orangeburg	4.4	1.83	66		Manor	5.3	1.81	20	
Chester	5.6	1.77	38		Chester	4.7	1.79	2	
Manor	4.7, 4.9	1.74	50	60, 40	Orangeburg	4.8	1.71	1	
Norfolk	5.2	1.67	6		Cecil	4.5 to 5.7	1.20	17	23, 24, 10, 11, 9
Cecil	4.9 to 5.2	1.34	28	14, 32, 37					
Brazil [3]		.85	<13						
Nipe	6.5	.41	1						
Coefficient of correlation between silica-sesquioxide ratio and efficiency		+0.84					+0.83		

[1] Soils applied at rate of 50 g of colloid per pot, superphosphate at rate of 0.05 g of P_2O_5.
[2] As compared with 100, for efficiency in sand alone.
[3] Superphosphate applied at rate of 0.12 g of P_2O_5 instead of 0.05 g. Judging by the results with other soils, notably the Nipe, the efficiency with 0.05 g of P_2O_5 would have been 1 or 2. The value 2 is used in calculating the correlation coefficient.

The accuracy of the average figures given for the efficiency of super-, phosphate in columns 4 and 9, or the range within which these figures are significant, can be judged somewhat from variations in the duplicate determinations shown in columns 5 and 10. Differences between duplicates are probably chiefly due to the usual experimental errors attending pot experiments and probably in part to variable growth conditions in different experiments and to slight differences in the various lots of quartz sand.

The variation in the effects of different soils on superphosphate is very remarkable. In the presence of Nipe soil, superphosphate is only one hundredth part as efficient as in pure quartz sand, whereas in the presence of Wabash soil it is almost twice as efficient as in sand. A similar wide variation obtains in the effects of subsoils. The figures for efficiencies above 100 percent are not anomalous, for it was found by analyzing the crops that in the quartz sand cultures the recovery of P_2O_5 in the part of the plant aboveground was only 30 to 40 percent of that applied.

The figures given for hydrogen-ion concentration show that this wide variation in the effects of different soils is not primarily concerned with the reaction, although, as will be shown later, the hydrogen-ion concentration affects the results somewhat.

Another fact standing out clearly is the difference in the effects of soil and subsoil materials. In every case except the Carrington, the subsoil imparts a lower efficiency to superphosphate than the corresponding topsoil. In the case of the Wabash and Stockton soils and subsoils the differences are hardly significant, but in all other cases they are obviously real, and in the case of the Marshall, Clarksville, Huntington, Sassafras, Orangeburg, and Chester soils the depressing effect of the subsoil is enormous, as compared with that of the soil.

When the surface soil and subsoil materials are taken as forming a single series there is practically no correspondence between silica-sesquioxide ratios of the colloids and effects of the materials on superphosphate. If, however, soil and subsoil materials are considered in separate groups, a fairly good correspondence obtains between silica-sesquioxide ratios and efficiency figures in the case of both soil and subsoil colloids, the correlation coefficients being, respectively, +0.84 and +0.83. These coefficients indicate somewhat less than the actual correspondence, since the efficiency is apparently not a straight-line function of the ratio. It seems, then, that the silica-sesquioxide ratio is one of the factors concerned with, or associated with, the action of the material on superphosphate. But it is obviously not the chief factor; because soil and subsoil materials give very different results, although they have practically the same ratios in nearly all cases.

The fact that differences between the effects of soil and subsoil materials are so marked and so general points to some difference generally obtaining between soil and subsoil colloids as one of the chief factors determining the effects of the colloids. Complete ultimate analyses of the colloids previously made by Robinson and Holmes (44) show that in the case of these soils the colloids from the topsoil and subsoil strata are very much alike in composition. The only consistent differences are in the minor constituents—manganese, organic matter, nitrogen, and the anions, P_2O_5, Cl_2, SO_4. These constituents are nearly always higher in the surface soil colloids. An increase in manganese would be expected to depress rather than

enhance phosphate efficiency, but organic matter in some instances has been found to increase the efficiency of insoluble phosphates; and an increased percentage of P_2O_5 might also be considered favorable as indicating a reduced affinity of the colloid for phosphate, owing to the colloid being more nearly saturated with phosphorus.

Table 7 gives the percentages of P_2O_5 and organic matter in the colloids, previously published (44), for comparison with the effects of the soils on phosphate efficiency.

TABLE 7.—*Relation between comparative effects of topsoil and subsoil on super-phosphate efficiency and other data for topsoil and subsoil*

Soil type	Efficiency of super-phosphate	P_2O_5 in colloidal material	Yield in soil-sand mixture minus yield in pure sand without superphosphate	Organic matter in colloidal material
	Percent	*Percent*	*Grams*	*Percent*
Wabash soil	198	0.25	+0.34	5.6
Wabash subsoil	175	.24	+.11	5.6
Stockton soil	146	.06	+.49	1.2
Stockton subsoil	130	.20	+1.24	2.8
Marshall soil	142	.40	+1.53	8.6
Marshall subsoil	52	.21	0	4.0
Sassafras soil	75	.47	+.11	6.3
Sassafras subsoil	18	.08	+.03	1.6
Huntington soil	72	.64	+.53	9.8
Huntington subsoil	4	.35	−.13	6.1
Clarksville soil	71	.65	+.05	5.7
Clarksville subsoil	13	.38	−.05	2.3
Orangeburg soil	66	.42	+.23	4.3
Orangeburg subsoil	1	.17	−.01	1.6
Miami soil	61	.11	+.02	3.7
Miami subsoil	28	.21	−.01	.9
Carrington soil	54	.28	+.01	11.6
Carrington subsoil	78	.14	−.11	4.5
Manor soil	50	.28	−.65	3.7
Manor subsoil	20	.46	−.23	2.6
Chester soil	38	.20	+.17	4.1
Chester subsoil	2	.15	−.09	5.0
Cecil soil	28	.25	+.03	2.3
Cecil subsoil	15	.11	0	1.4
Hagerstown soil	11	.30	−.05	7.0
Hagerstown subsoil	8	.20	−.07	2.7
Norfolk soil	6	.23	−.13	4.7
Norfolk subsoil	1	.20	−.26	2.7

There is practically no correspondence between the efficiency figures of different soils or subsoils and the percentages of organic matter or phosphorus present, but in all cases except two a higher percentage of organic matter in the topsoil colloid than in the subsoil colloid correlates with higher superphosphate efficiency. The figures for percentages of P_2O_5 are not so significant. In 5 cases out of 14 a higher percentage of P_2O_5 in the topsoil or subsoil colloid is not in qualitative agreement with the comparative efficiency figures of topsoil and subsoil.

It was thought that a better indication of the comparative phosphorus saturations of topsoil and subsoil colloids might be afforded by the proportion between PO_4 and the sum of the anion equivalents, PO_4, Cl, and SO_4. But, strangely enough, this proportion seemed to be practically a constant for the soil and subsoil colloids analyzed by Robinson and Holmes (44). Data given for 24 samples show that the PO_4 anion averaged 63.6 percent of the total anion equivalents,

and the standard deviation of single samples from the average was only ±9.5. This, incidentally, seems to be analagous to the fairly constant proportion of calcium in the exchangeable bases, to which attention has been called by Anderson and Mattson (4).

Another figure indicative of phosphorus saturation of the colloid may be obtained from certain data of the pot experiments. The increases in growth produced by the simple addition of soil to quartz sand without a superphosphate application ought to be significant, since this treatment constitutes a sort of Neubauer test for the availability of soil phosphorus, and phosphorus saturation ought to be related in some measure to availability. At least, one would hardly expect a soil to be high in available phosphorus if the colloidal material were markedly unsaturated with phosphoric acid and vice versa. Increases in growth produced by the addition of different soils to quartz sand without a superphosphate application are shown in column 4 of table 7.

These figures, representative of the availability of the soil phosphorus, agree with the efficiency data so far as the comparative effects of soil and subsoil are concerned, for all soils except the Stockton and Carrington. Possibly special conditions were operative in the case of these two soils, since they were exceptions also to the agreement of efficiency data with percentages of P_2O_5 and organic matter. The availability figures also show a low correlation with the efficiency figures of different soils and subsoils. In this respect the availability data are more significant than either the percentage of total P_2O_5 or the percentage of organic matter.

It should be pointed out, however, that the figures tabulated as indicative of available phosphorus are only approximate and not strictly comparable for all soils, owing to the fact that the pure-sand cultures evidently contained small but variable amounts of phosphate impurities in the different experiments. This is shown by the yields of the pure-sand-no-phosphate pots, varying in different experiments from 0.06 g to 0.36 g of dry matter. Most of the availability data were taken from experiments where the yields of these check pots were from 0.06 to 0.15 g, and are therefore nearly comparable. But figures for the Huntington, Carrington, Manor, and Norfolk soils were available only in experiments where there were obviously more phosphate impurities, the check pots yielding 0.31 and 0.36 g, respectively. Under these conditions no significance should be attached to varying negative values. So far as availability of soil phosphorus is concerned, all negative values mean simply zero availability. The comparative magnitudes of the negative values are due to varying amounts of phosphorus impurities in different experiments and to the effects of the soils in rendering these impurities unavailable. The different negative values, therefore, constitute simply a further test of the soil's influence on phosphate efficiency conducted with small amounts of phosphate impurities. The different positive values, on the other hand, are to be regarded as indicating different quantities of available phosphorus in the soils.

The data presented thus far indicate that the wide differences of soil material on superphosphate efficiency are dependent in some degree on the silica-sesquioxide ratio of the colloidal material. There is also some evidence that variations in the effects of those colloids that depress superphosphate efficiency may be largely dependent on the

extent to which these colloids are saturated with phosphorus. This is suggested by the increased efficiency of increasing superphosphate applications, pointed out in a previous section, by the comparative percentages of total phosphorus in soils and subsoils, and by data indicating the availability of the phosphorus present in the soil. Evidence as to other factors governing the effects of different soils on superphosphate was obtained in further experiments.

Laboratory studies of other investigators substantiate some of the facts and conclusions discussed in this section.

That surface soils contain more available phosphoric acid than subsoils is supported by data reported by Engels (*12*), Kling and Engels (*30*), and Hasenbäumer and Balks (*24*). According to these investigators, surface soils contain more phosphoric acid soluble in citric acid and more phosphoric acid available by the Neubauer method than subsoils. Also, according to Honcamp and Steinfatt (*28*), the quantity of phosphoric acid soluble in 10 percent hydrochloric acid is greater in surface soils than subsoils, and the part of the acid-soluble phosphoric acid which is available by the Neubauer method is greater in surface soils. Also, recent data of McGeorge (*34*) indicate that phosphoric acid removable by electrodialysis is likewise higher in surface soils than in subsoils.

That a high availability of the soil phosphorus is associated with high saturation of the soil with phosphoric acid, or at least, with low ability of the soil to adsorb more phosphoric acid, is indicated by another recent investigation. Rauterberg (*42*) shows that in the case of 19 soils, a fairly close inverse relation obtains between the phosphoric acid available by Neubauer's method and the phosphate adsorbed from a phosphate solution. In the case of three soils high in available phosphorus, there was a release of phosphate ions to the phosphate solution instead of adsorption.

Scarseth (*45*), in a recent study of Alabama soils, found that soils containing colloids of low silica-sesquioxide ratios had a marked tendency to fix more phosphate than soils containing colloids of high ratios. The criterion of fixation was solubility of the P_2O_5 in a water extract.

THE HYDROGEN-ION CONCENTRATION AS A FACTOR INFLUENCING THE EFFECT OF SOIL ON SUPERPHOSPHATE EFFICIENCY

Columns 2 and 7 of table 6 show that the different soil-sand mixtures had very different hydrogen-ion concentrations in many cases. Although it is obvious from the table that the effects of different soils were not primarily dependent on the hydrogen-ion concentration, it was presumed that this had some influence on the results, since an effect of liming on superphosphate efficiency was observed in a previous study (*21*).

In nearly all experiments approximate determinations were made of the hydrogen-ion concentration of the soil and sand mixtures after the plants had been harvested. The colorimetric method was used, and the proportion of soil to water was about 1 to 2. The determinations were accurate to only about two tenths of a pH.

As data accumulated, it became evident that the following conditions affected the hydrogen-ion concentration: The growth of the plants, the composition of the base fertilizer, and the nature of the soil addition. When the standard base fertilizer supplying one half

nitrate and one half ammonia nitrogen was used in pure quartz sand the pH of the medium was about 6.5 before planting and about 4.5 after the growth of the plants. (See tables 13, 18, 19, etc.) When an all-nitrate base fertilizer was used the plants rendered the sand more alkaline, about pH 7.3 (tables 14 and 18). The soil tended to modify the hydrogen-ion concentration developed in pure sand to that of the soil, the effect of the soil varying with its buffer capacity and the growth made by the plants.

Two experiments (tables 28 and 29)were conducted to determine whether the effect of the soil on superphosphate efficiency varies appreciably at different hydrogen-ion concentrations. In these experiments the hydrogen-ion concentrations of the soil-sand mixtures were varied by the application of sodium bicarbonate and by the use of two different base fertilizers, the standard (no. 2 of table 1) producing an acid reaction and the all-nitrate fertilizer (no. 7 of table 1) producing an alkaline reaction. The results of the two experiments are brought together in table 8.

TABLE 8.—*Summary of results which show the effect of the hydrogen-ion concentration on the efficiency of superphosphate in a mixture of soil and quartz sand* [1]

Kind of soil mixed with quartz sand	pH of medium after growth	Efficiency of superphosphate shown in—	
		Experiment 16	Experiment 18
		Percent	*Percent*
Cecil soil	5.0	32	
	5.2		37
	6.2		33
	6.3	33	
	6.6		16
	7.1		22
Cecil subsoil	4.5	24	
	5.7		11
	7.2		4
	7.8		2
	8.2	13	
	4.6		68
Clarksville soil	5.3	77	
	6.3	27	
	6.6		44
	7.7		38
Clarksville subsoil	4.8	19	
	5.4		14
	6.8		2
	6.8		7
	6.9	8	
	4.4		98
Sassafras soil	4.7	51	
	5.6		35
	6.3	22	
	6.0		32

[1] In all cases 0.05 g of P_2O_5 was applied per pot and soil added at rate of 50 g of colloid per pot. Base fertilizer varied to produce different reactions.

It should be borne in mind that the hydrogen-ion determinations in table 8, as in all others, show the hydrogen-ion conentration of the medium that was finally developed by the growth of the plants. At the beginning of the experiments the acid mediums were less acid than at the end; the pots receiving only the all-nitrate fertilizer were less alkaline at the beginning than at the end of the experiment, and pots receiving sodium bicarbonate were more alkaline at the beginning than at the end of the experiment.

It is obvious from the results as a whole that the hydrogen-ion concentration has a marked influence on the extent that soil depresses the availability of superphosphate. The limits of maximum and minimum availability of the superphosphate cannot be defined closely because sufficient results were not obtained and the hydrogen-ion concentration varied more or less during the period of growth; but it seems certain that the maximum availability of superphosphate in the presence of these soils is in the acid range, somewhere about pH 4.5 to 5.0. The minimum availability seems to be somewhere around neutrality, pH 6.5 to 7.5, and there is a suggestion of a small increase in availability in the distinctly alkaline range.

These results are in accord with results obtained by Teakle (47) and by Gaarder (16) in studies of the solubility of phosphate ions in the presence of various cations. Gaarder found that the solubility of PO_4 ions in the presence of a mixture of Ca, Mg, Fe, Al, and Mn ions in excess was at a maximum at a pH near 4.5 and at a minimum around 5 to 6.5, and that the solubility increased again slightly between 6.5 and 8.0. He further found that some of the relations between cations and PO_4 solubility were greatly changed by the addition of silica.

Other soils may show a more constant effect on superphosphate at different hydrogen-ion concentrations than the Cecil, Clarksville, and Sassafras soils. If the analogy between these results and those of Gaarder holds further, the high silica colloids would be less affected by differences in acidity or alkalinity than the soils tested. But the results obtained are sufficient to show that the hydrogen-ion concentration is one of the factors determining the action of soil on superphosphate. If all the soils and subsoils could have been tested at the same hydrogen-ion concentration, it is possible that the efficiency figures would have shown a somewhat better correspondence with the silica-sesquioxide ratios. It seems probable that the two most marked exceptions to the parallelism between efficiency values and silica-sesquioxide ratios, the efficiency values for Hagerstown soil and Miami subsoil, may be due to the reactions of pH 6.7 and 7.8, respectively, obtaining in the soil-sand mixtures (table 6).

EFFECTS OF CHARCOAL AND PEAT ON THE EFFICIENCY OF SUPERPHOSPHATE AND ROCK PHOSPHATE

The marked differences observed in most cases between the effects of soil and subsoil on superphosphate suggested experiments with some purely organic materials. Tests were made with peat and activated charcoal. Peat was selected as an organic material, presumably analagous to the more persistent part of the soil organic matter, and activated charcoal was used because of its high adsorptive power and its "insolubility." The characteristics of these samples are described under Soils and Materials.

The peats and samples of activated charcoal purified from acid would all tend to render the medium more acid. A sample of activated charcoal purified from alkali was therefore included, to give some indication as to whether the results obtained were due solely to changes in the hydrogen-ion concentrations.

Two experiments were conducted with these materials (tables 30 and 31). One of these is illustrated in figure 5. The yields of the no-phosphate pots show that the charcoals without superphosphates

had practically no effect on growth; hence they contributed only traces of available phosphorus. The peats, however, contributed a measurable quantity of available phosphorus, something approximately equivalent to the superphosphate application of 0.025 g of P_2O_5 in the pure quartz sand series.

The significant results of the two experiments are more readily seen in table 9. It will be noted that all samples except the peat of pH 3.5 increased the efficiency of superphosphates in pure sand quite markedly. In the soil-sand mixtures equally marked increases were produced by one of the charcoal samples. These increases produced were of the same order as those produced by soil colloids with highest silica-sesquioxide ratios. Since only 10 g of the organic materials were applied in these experiments, as compared with 50 g of the soil colloids, it seems that these organic materials have much more effect on superphosphate than the best of the inorganic soil colloids.

These results with superphosphate cannot, on the whole, be ascribed to changes in the hydrogen-ion concentration of the medium brought about by the organic materials, for in three cases where the efficiency
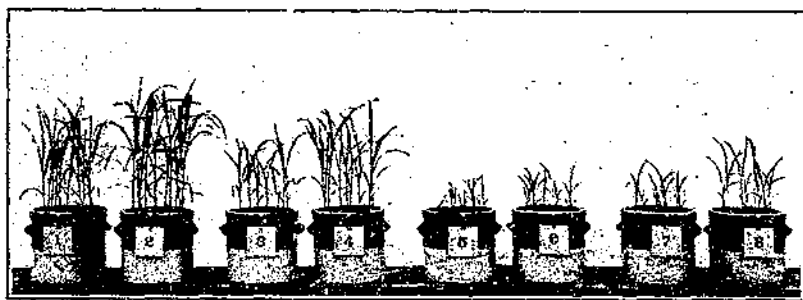
FIGURE 5.—Effect of charcoal in pure sand and in sand-soil mixtures as shown by the growth of millet (table 31). 1, Sand only, 0.05 g P_2O_5; 2, sand plus charcoal, 0.05 g P_2O_5; 3, sand plus Clarksville topsoil, 0.05 g P_2O_5; 4, sand plus Clarksville topsoil and charcoal, 0.05 g P_2O_5; 5, sand plus Clarksville subsoil, 0.05 g P_2O_5; 6, sand plus Clarksville subsoil and charcoal, 0.05 g P_2O_5; 7, sand plus Cecil subsoil, 0.05 g P_2O_5; 8, sand plus Cecil subsoil and charcoal, 0.05 g P_2O_5.

was markedly increased the charcoals produced no measurable alteration in the hydrogen-ion concentration. It is probable, however, that the reaction influenced the results somewhat, although the reactions of the mediums with and without the charcoals and peats are all in, or close to, the general region where maximum availability of the phosphate would be expected. Probably the reduced efficiency of superphosphate in sand with peat of pH 3.5 is only apparent, the growth being reduced by too marked acidity.

The results obtained with rock phosphate are similar to those obtained with superphosphate, except that charcoal of pH 9.6 purified from alkali reduced the efficiency of rock phosphate below the efficiency in pure sand. The final pH of 6.3 in this case was in the range within which superphosphate would likewise be expected to show a reduced efficiency. Thus there is evidence that the reaction of the medium is highly important in determining the efficiency of rock phosphate. It is obvious, however, that the beneficial effects of the charcoals and peats on the availability of rock phosphates are not due solely to modifications in the hydrogen-ion concentration, since there were increased efficiencies of rock phosphate attending changes in the pH from 4.8 to 5.0, 5.4, and 4.2.

If the two results which were presumably determined chiefly by the hydrogen-ion concentration are disregarded, it seems that the organic materials increased the efficiency of superphosphate somewhat more than the efficiency of rock phosphate. This is very different from the effects obtained with silica gel some years ago. In that experiment, the addition of silica gel to pure quartz sand more than doubled the efficiency of rock phosphate and raised the efficiency of superphosphate by only 19 percent. The efficiency of rock phosphate in pure sand in that experiment was practically identical with the efficiency obtained in this work (table 30), so the experiments are obviously comparable.

TABLE 9.—*Summary of results showing the effects of activated charcoal and peat on the efficiencies of superphosphate and rock phosphate in quartz sand, and in mixtures of quartz sand and soil* [1]

Kind of charcoal or peat	Medium to which charcoal or peat was added	pH after growth with superphosphate		Efficiency of superphosphate as compared with 100 for the efficiency in each medium without charcoal or peat	pH after growth with rock phosphate		Efficiency of rock phosphate as compared with 100 for the efficiency in sand alone
		In medium with charcoal or peat	In corresponding medium without charcoal or peat		In sand with charcoal or peat	In sand alone	
				Percent			*Percent*
Charcoal of pH 4.1____	Sand alone_____	4.2	4.2	130	____	____	____
Charcoal of pH 4.3____	____do_____	4.5	4.5	155	5.0	4.8	117
Charcoal of pH 9.6____	____do_____	5.3	4.5	132	6.3	4.8	42
Peat of pH 5.8_____	____do_____	5.6	4.5	206	5.4	4.8	150
Charcoal of pH 4.1____	Sand and Clarksville topsoil.	4.7	4.2	125	____	____	____
Charcoal of pH 4.1____	Sand and Clarksville subsoil.	4.8	5.3	220	____	____	____
Charcoal of pH 4.1____	Sand and Cecil subsoil.	4.5	4.6	188	____	____	____
Peat of pH 3.5_____	Sand alone_____	4.2	4.5	68	4.2	4.8	150

[1] Figures are based on data given in tables 12 and 17.

Silica gel, the charcoals, and the peats are alike in having the capacity for an exchange adsorption of cations, but the charcoals, and possibly the peats, have the capacity for adsorbing anions also. It was shown in a previous publication (23) that addition of silica gel to a suspension of rock phosphate in water increases the amount of phosphate in solution, and Gaarder (16) has shown that silica gel increases the amount of PO_4 ions in solution in the presence of the precipitating ions Al, Ca, etc. Possibly part of the effect of the silica gel, charcoals, and peats on the efficiency of phosphates lies in the adsorptive capacity of these materials for cations, ions forming insoluble phosphates such as Fe, Al, Ca, being adsorbed, and hydrogen or sodium ions forming soluble phosphates being released. It will be recalled that, prior to being washed, the charcoals were treated with NaCl. So they obviously exchanged Na or H ions.

Although there is evidence that such adsorptive effects are concerned in the action of these materials on superphosphate and rock phosphate, it is believed that an examination of a water extract of the sand or soil-sand mixtures would indicate that the cation and soluble PO_4 relations had not been changed sufficiently by the organic

materials and silica gel to account for the effects on efficiency. It was shown, for instance, in table 12, that an appreciable reduction of the Ca and Mg in the base fertilizer and a reduction of the Fe below the amount used in the standard fertilizer produces no changes in the efficiency of superphosphate in pure sand; and when all the salts of the base fertilizer are reduced by one half, the early growth is not affected (table 15).

Probably an essential feature of the action of these materials in promoting phosphate efficiency is a micellar effect of the silica and organic particles. In the zone of contact between the roots and the adsorptive particles the reactions mentioned are doubtless intensified, owing to their being localized. Wiegner (54), for example, has shown a marked increase of hydrogen ions in the immediate neighborhood of soil particles, presumably in the so-called "doubled layer" of micron dimensions. A grosser localization of reaction in the vicinity of plant roots has recently been noted by Thom and Humfeld (48) and it was observed in this work that even in the pure sand cultures the hydrogen-ion concentration was often notably greater in the part of the pot where the roots were most abundant. Granting a localization of the reactions, the results obtained in the examination of free solutions would probably give only a qualitative indication of what may take place to a much greater degree in restricted zones of root "feeding", or, more particularly, in the micellar areas of the colloid particles.

The results obtained with these insoluble organic materials indicate, so far as they go, that the organic content of a soil colloid may be an important factor in determining the effect of the colloid on superphosphate. It would seem that the presence of organic matter in the soil colloid would tend to render the colloid promotive rather than depressive of phosphate efficiency, but the characteristics of the organic constituent of a soil colloid can hardly be distinctive from that of the material as a whole. If, for instance, the soil colloid as a whole is unsaturated with bases, the organic matter present is probably likewise unsaturated. Doubtless the effect of organic materials free from inorganic colloids would likewise vary considerably, according to the degree that they were saturated with different ions such as Ca, H, PO_4.

AVAILABILITY OF ROCK PHOSPHATE

It was not planned to study the effect of soil colloids on the efficiency of rock phosphate, but in the early part of this work rock phosphate was applied to some of the pots in order to determine whether the availability of this material was affected as much as superphosphate. The sand used in this experiment contained some alkali, so the pH of the sand and soil-sand mixtures were about 7.5. In this experiment (table 16) the rock phosphate showed no availability whatsoever, either in the pure quartz sand or in the soil-sand mixtures. This is very different from the 24 percent efficiency developed in the pure quartz sand of the experiment just discussed (table 30) where the pH was 4.5.

These results, and the practical unavailability of rock phosphate in limed soils frequently observed (21, 41), indicate that the availability of rock phosphate is governed primarily by the hydrogen-ion

concentration. However, the results given in table 30 and the previous results with silica gel show that within the range of acid reaction other factors may promote or depress the efficiency of this material.

EFFICIENCIES CALCULATED FROM THE WEIGHT OF THE CROP AND FROM THE P_2O_5 RECOVERED IN THE CROP

In this work the efficiency of superphosphates was usually calculated from the weight of the crop, as described in detail under Plan and Methods; whereas, the recognized method is to base the calculation on the quantity of P_2O_5 in the crop. A theoretical justification for using simply the crop weight as a criterion of efficiency was given in a previous publication (20), but it seemed advisable to compare the two methods. Accordingly, a good many of the crops were analyzed for P_2O_5 by methods of the Association of Official Agricultural Chemists (5), the dry matter being ignited with magnesium nitrate and the phosphoric acid determined volumetrically.

The essential analytical results are shown in tables 24, 25, 30, and 31. The crops receiving no phosphate fertilizer were of course analyzed in estimating the P_2O_5 recovered, but these figures, of no particular significance, are not shown in the tables.

Usually when different phosphatic fertilizers are compared with a standard fertilizer the efficiencies are calculated simply from the ratio of the quantities of P_2O_5 recovered, modified by the ratio of quantities of P_2O_5 applied if these quantities are different for the standard and unknown fertilizer. When several different quantities of the standard phosphate have been applied it is theoretically more accurate to base the efficiency calculation on the comparative quantities of the two fertilizers required to give the same recovery of P_2O_5 (20). This method, described under Plan and Methods, was used in calculating the figures given in tables 24, 25, 30, and 31 for efficiencies based on P_2O_5 recovered. These two methods can also be followed when the data used are simply crop increases instead of P_2O_5 recovered.

Table 10 shows efficiencies calculated by the two methods, using both the weights of crop increases and of P_2O_5 recovered as criteria.

TABLE 10.—*Comparison of different methods of calculating efficiencies of phosphate*

[Data from tables 17, 24, 25, 30, 31]

Conditions of experiment			Efficiency calculated from ratio of—		Efficiency calculated from comparative quantities of P_2O_5 required to give equal—	
P_2O_5 applied per pot (gram)	Kind of phosphate	Materials added to quartz sand	Weights of crop increases	Quantities of P_2O_5 recovered	Increases in weights of crops	Quantities of P_2O_5 recovered
			Percent	*Percent*	*Percent*	*Percent*
0.05	Super	Carrington soil	54	49	51	50
.05	___do___	Carrington subsoil	78	75	76	78
.05	___do___	Clarksville soil	66	68	64	73
.05	___do___	Clarksville subsoil	14	9	13	10
.05	___do___	Manor soil	61	58	58	60
.05	___do___	Manor subsoil	22	18	21	20
.05	___do___	Miami soil	06	70	63	73
.05	___do___	Miami subsoil	41	35	38	38
.05	___do___	Chester soil	36	44	30	38
.05	___do___	Sharkey soil	138	204	159	148
.05	___do___	Stockton soil	141	204	186	146

Table 10.—*Comparison of different methods of calculating efficiencies of phosphate*—Continued

			Efficiency calculated from ratio of—		Efficiency calculated from comparative quantities of P_2O_5 required to give equal—	
P_2O_5 applied per pot (gram)	Kind of phosphate	Materials added to quartz sand	Weights of crop increases	Quantities of P_2O_5 recovered	Increases in weights of crops	Quantities of P_2O_5 recovered
			Percent	*Percent*	*Percent*	*Percent*
0.05	Super_____	Stockton subsoil_____	102	172	105	130
.20	Rock_____	Nothing_____	10	24	16	24
.05	Super_____	Charcoal of pH 4.3_____	149	152	200	106
.20	Rock_____	___do_____	18	28	19	28
.05	Super_____	Charcoal of pH 9.6_____	125	141	153	132
.20	Rock_____	___do_____	7	11	7	10
.05	Super_____	Peat of pH 5.8_____	152	231	215	206
.20	Rock_____	___do_____	26	39	27	36
.05	Super_____	Peat of pH 3.5_____	50	72	52	68
.20	Rock_____	___do_____	13	39	14	30
.05	Super_____	Charcoal of pH 4.1_____	163	140	_____	130
.05	___do_____	Clarksville soil_____	50	45	64	64
.05	___do_____	Clarksville soil and charcoal_____	101	71	100	80
.05	___do_____	Clarksville subsoil_____	8	4	12	10
.05	___do_____	Clarksville subsoil and charcoal_____	16	11	27	22
.05	___do_____	Cecil subsoil_____	11	7	18	16
.05	___do_____	Cecil subsoil and charcoal_____	25	15	42	30

If columns 6 and 7 are compared, it will be seen that it makes little difference whether the efficiencies are based on weights of crop increases or on quantities of P_2O_5 recovered when the method of calculation used in this study is followed. The only consistent differences between the two bases of calculation are in the efficiencies of rock phosphate, the efficiency calculated from the P_2O_5 recovered being uniformly higher than the efficiency calculated simply from the increases in yield. This is doubtless owing to the fact that with the physiologically acid fertilizer used in these experiments, the assimilation of P_2O_5 from rock phosphate is at an accelerated rate. As the plants grow and use up the nitrogen, the medium becomes increasingly acid and the rock phosphate becomes increasingly available.

Columns 4 and 5 show efficiencies calculated by the commonly used, old method, in which efficiencies are obtained simply from the ratio of the quantities of P_2O_5 recovered. Here, also, efficiencies based on the two kinds of data, weight of crop and weight of P_2O_5 recovered, agree fairly well for the most part. But when the efficiencies are much over 100, the use of data on crop increases evidently gives lower results than data of P_2O_5 recovered. The poor correspondence of high efficiencies is due to the fact that in these cases the method compares a large yield with a smaller one, and the percentage of P_2O_5 is usually higher in the large yields than in the smaller ones. The true efficiency value in these cases should be near the figures based on P_2O_5 recovered.

DISCUSSION OF RESULTS

The preceding experiments indicate that several factors are involved in the effects of soil colloids on superphosphate; namely, the silica-sesquioxide ratio, the saturation of the colloid with P_2O_5, the effect of the colloid on the hydrogen-ion concentration of the medium, and the content of organic matter. The relative importance of these factors doubtless varies from colloid to colloid, but there are grounds for believing that as a rule the order of importance is as follows: Saturation with P_2O_5, silica-sesquioxide ratio, effect on hydrogen-ion concentration, and organic matter.

Degree of saturation with P_2O_5 is considered a more important factor than the silica-sesquioxide ratio in view of the follo,.ing facts: There is practically no correspondence between silica-sesquioxide ratios and effects of the colloids on superphosphate until the colloids are separated into soil and subsoil materials, and the degree of saturation with P_2O_5 seems to be the feature chiefly responsible for the difference in the effects of soil and subsoil colloids.

The effect of the soil colloid on the hydrogen-ion concentration of the medium is obviously not so important a factor as the silica-sesquioxide ratio, for colloids that increase the efficiency of superphosphate markedly render the medium acid in some cases and neutral to alkaline in others. The same is true of colloids that markedly depress superphosphate efficiency. On the other hand, the highest efficiencies of superphosphate are associated with high silica-sesquioxide ratios in all instances, and the lowest efficiencies are associated with ratios below 2. Although less important on the whole than the silica-sesquioxide ratio, the hydrogen-ion concentration was shown to be of marked influence within certain ranges of the ratio. Sufficient soils were not tested to determine whether the influence was as marked for colloids with the highest ratios as for colloids with silica-sesquioxide ratios below 2.20.

Organic matter, if a factor in the effect of soil colloids on superphosphate, seems to be less important than the other factors. No relation is apparent between the organic content of colloids and efficiency values when soil and subsoil colloids are considered separately; nor can the more marked exceptions to the correspondence between silica-sesquioxide ratio and efficiency values be explained on the basis of organic content as well as by the influence of the hydrogen-ion concentration. Although these comparisons suggest that organic constitutents of the colloid have little effect on superphosphate, the direct experiments with organic materials gave very positive indications. The direct experiments, however, were not sufficiently extended to show in what measure the effects of organic materials are associated with different kinds and quantities of adsorbed ions other than H and OH. If the effect is largely dependent on the adsorbed ions, it would be difficult to divorce the effects of organic matter from those associated with the silica-sesquioxide ratio.

A study of the mechanism by which soil colloids promote or depress the efficiency of superphosphate was not undertaken in this investigation, but the data obtained have a bearing on this question even if they do not warrant definite conclusions.

Several facts indicate that the depressive effect of soil colloids on superphosphate cannot be ascribed primarily to precipitation in free

solution by cations released from the colloids by base exchange with the fertilizer salts. The colloids that depress superphosphate most are those that have the smallest base-exchange capacity, this capacity following fairly closely the silica-sesquioxide ratio. The chief exchangeable cation of the colloids is calcium, and a considerable quantity of this is already present in salts of the base fertilizer and in the superphosphate itself. There is, of course, the possibility that those unsaturated colloids of low base-exchange capacity released exchangeable iron, aluminum, and manganese ions which precipitated the phosphate, but this seems improbable in view of the fact that the efficiency of superphosphate was found to be higher in the acid range where the exchange of iron and aluminum should be greater. On the other hand, the depressive effect of soil on superphosphate was influenced by the hydrogen-ion concentration in about the way one would predict from Gaarder's work showing how the hydrogen-ion concentration affects the solubility of PO_4 ions in the presence of various cations.

Although precipitation by ions in free solution may play a part in the depressive effect of some colloids, probably most of the effect is due to combination of the PO_4 ions with the iron and aluminium surfaces exposed by soil colloids. According to Weiser and Porter (53), and Bancroft and Ackerman (7), alumina gels combine either directly or by exchange, according to the condition of the gel. This mechanism would account for the various factors that seem to be involved in the depressive effects of soil colloids. Combination of phosphate ions would obviously be less in proportion as such surfaces are already saturated with phosphate and the quantity of PO_4 ions combined with increasing applications of phosphate would not be expected to show a sharp maximum. The iron and aluminum surfaces capable of combining with the phosphate would be expected to show some correspondence to the silica-sesquioxide ratio. The hydrogen-ion concentration would affect the quantity of PO_4 combined and the stability of the combination in the manner observed in the experiments on influence of the hydrogen-ion concentration. And finally, organic materials would be expected to promote rather than depress phosphate efficiency since they would be expected to offer a surface having some properties similar to those of silica.

Although the capacity of the colloid for fixing phosphate may be indicated by the silica-sesquioxide ratio, it is not necessarily sharply defined by the ratio, since the capacity could vary with both the reactivity and the extent of the iron and aluminum surfaces. This is suggested by the experiments with the extracted colloids of the Cecil subsoil in the fresh and year-old conditions. Also, a marked difference in the reactivity of fresh and aged artificial gels has been frequently observed.

According to the preceding hypothesis, soil colloids imparting a higher efficiency to superphosphate than pure quartz sand would present little if any unsaturated iron or aluminum surface to superphosphate. Also, the silica surface would necessarily have some activity in order to render it more effective than the inert quartz sand. This silica surface of the soil colloids would probably act on phosphates in the same way as the artificial silica gel and organic materials previously discussed. Having an affinity for cations, it

could render phosphates more soluble in the film of contact between root and colloid particles by combining with precipitating ions.

Two general facts brought out in this investigation, the marked effects of soil colloids on superphosphate and the correspondence between these effects and the silica-sesquixide ratios, throw light on some previous laboratory investigations of soil phosphorus.

Recently, the effect of adding clays to sand cultures was studied by Blanck and Von Oldershausen (8). Notable differences in yield were produced by the clay applications, which they could ascribe only in part to the acid nature of the clay. Since there were no data to show that the phosphate supply was adequate, it seems probable that the results might have been due to the effects of the clays on the efficiency of the phosphate applied.

In connection with the relationship found between phosphate availability and the silica-sesquioxide ratio of soil colloids, it is interesting to note that a similar suggestion was made by Gans (17) some 20 years ago. According to Gans the availability of phosphates is dependent on a fixed relation between the silica-alumina and bases in the zeolitic part of the soil. An investigation by Tacke and Arnd (46) shows that the particular relationship suggested by Gans does not hold, but the results of this work show that Gans' basic idea of a relationship between colloid composition and phosphate availability was correct.

The favorable effects of high silica colloids observed in this work and the significance attributed to the so-called "soluble" silica found in soil extracts are doubtless related. According to McGeorge (33), Hawaiian soils which are well supplied with available phosphoric acid yield more silica to a 4 percent hydrochloric acid extraction than soils needing phosphate fertilizers. Hoffman (25) found a less close relation of fertilizer requirements to water soluble silica, but Němec's (35, 36) work shows a close correspondence between water-soluble silica and the phosphate requirements indicated by the Neubauer test, also a correspondence between the phosphoric acid and the silica soluble in water extracts of soils. These correlations might be explained on the grounds that varying quantities of soluble silica indicate soil colloids of varying silica-sesquioxide ratios. As previously shown (table 7), the colloids high in silica have less capacity for fixing phosphoric acid, are presumably more nearly saturated, and therefore supply more available phosphoric acid.

Certain laboratory methods of estimating the phosphate requirements of soils seem to recognize empirically the widely varying capacities of soil colloids for rendering phosphates unavailable. According to the citric acid method, a soil needs phosphate fertilization not only when citric-acid-soluble phosphoric acid falls below a certain value, but also when the citric-acid-soluble P_2O_5 is less than 25 percent of the total P_2O_5 soluble in strong acid. The supposition has not been tested, but one would expect that a lower percentage of the total phosphoric acid would be soluble in weak acid, the lower the silica-sesquioxide ratio of the colloidal soil material; for the lower the ratio the greater the capacity for fixing phosphate. Němec's (37) observation that phosphatic fertilizers do not exert their full effect on soils yielding more than 50 mg of citrate soluble iron per 100 g of soil probably could be similarly explained on the grounds that such soils

contain low silica-sesquioxide ratio colloids which have a high capacity for fixing phosphoric acid and are likely to be unsaturated.

Truog's (49) method of estimating available phosphoric acid calls for digestion of the soil with H_2SO_4 adjusted to a pH of 3.0. The concentration of P_2O_5 in solution at this acidity, according to Gaarder's (16) data would be governed by the comparative amounts of P_2O_5 and iron dissolved, modified to some extent by the presence of silica, alumina, and iron gels. The quantity of P_2O_5 dissolved, as shown by Engels' (12) data combined with that of Rauterberg (42) would be greater the more nearly the soil is saturated with P_2O_5. The quantity of iron dissolved one would expect to be greater the lower the silica-sesquioxide ratio of the colloid, and Robinson and Holmes' data (44) for a few colloids indicate this is the case. It would follow, then, that when Truog's method is applied to soils containing colloids of similar silica-sesquioxide ratios, it should show comparative degrees of saturation with P_2O_5 or comparative availability of the P_2O_5. And when the method is applied to soils containing colloids of different silica-sesquioxide ratios, the results would reflect the kind of colloid present fully as much as the degree of saturation.

The main facts brought out in this investigation have a bearing on the practical use of phosphatic fertilizers.

The low efficiency shown by superphosphate in the presence of soil colloids with low silica-sesquioxide ratios, and the high efficiency shown in the presence of colloids with high ratios is in general accord with practical experience in the use of superphosphate. The greater part of the superphosphate produced in the United States is consumed in the southeastern and eastern parts of the country, and in these regions colloids with low silica-sesquioxide ratios predominate, so far as can be judged from the available data of Robinson and Holmes (44) and of Byers and Anderson (2, 11). Many factors affect this large consumption of superphosphate, but it seems probable that no inconsiderable fraction of the phosphate used in these regions goes toward saturating the soil with phosphoric acid. In the Middle West, where the soil colloids are as a rule higher in silica, less superphosphate is used per acre. Here, also, factors such as rainfall, economic conditions, and prevailing crops doubtless contribute toward smaller applications. But a higher efficiency of the superphosphate is evidently likewise a factor, for crop increases produced in this region with small amounts of phosphates are often notably large, as compared with those produced in the East and Southeast.

The capacity shown by the Brazil and Nipe soils for rendering normal applications of superphosphate practically ineffective is suggestive. Evidently comparatively enormous applications of superphosphates would be needed to attain a moderate availability of added phosphate in such soils. A normal application of superphosphate would probably produce such small crop increases on these soils that one lacking information regarding the high fixing power of the soils would naturally conclude that the soils did not need phosphatic fertilizers. A survey made of agricultural soils containing colloids of low silica-sesquioxide ratios might show considerable areas of soil in the United States so unsaturated with phosphoric acid and of such high capacity for fixing added phosphate that fair productivity could only be obtained through heavy phosphatic fertilization.

The experiments made with comparatively few subsoils in this investigation indicate that a condition of low phosphoric acid saturation, and consequent low phosphate availability, is rather general for subsoils where the silica-sesquioxide ratio of the colloid is not above 2. This suggests the need for exceptionally heavy applications of phosphatic fertilizers where such subsoils are exposed, as in eroded areas. Estimates of the extent of soil erosion indicate that subsoil fertilization may become an important economic problem. Although nitrogen has usually been considered the chief fertilizer requirement of subsoils, a few investigators have pointed out the need for phosphates. Possibly the long time usually required for building up the productivity of subsoils is owing to an inadequate use of phosphates. If, at the start, sufficient phosphoric acid were applied to feed the soil as well as the crop, it might be that the time required to restore the productivity of subsoils to that of surface soils could be considerably shortened.

The silica-sesquioxide ratio of the soil colloids may prove to be a good indicator of areas where special methods of fertilizer distribution are important. If the soil colloids are of the kind that depress the efficiency of superphosphate, it would seem desirable to apply the phosphate in such a manner as to minimize this effect. The few tests conducted in this study suggest that this may be accomplished by applying the phosphate in a restricted zone near the seed. On the other hand, if the soil tends to enhance the efficiency of superphosphate, possibly equally as good results may be obtained with a more uniform distribution (table 3).

SUMMARY

This investigation deals with the effects of different colloidal soil materials on the efficiency of superphosphate. The effects are determined by comparing the growth made by millet (*Setaria italica*) in pure quartz sand with the growth made in sand to which sufficient soil is added to supply 1 percent of colloidal material. Data of some 1,400 pots are reported.

The addition of some soils to quartz sand reduces the efficiency of superphosphate. The reduction in efficiency is greater, the larger the soil application, and less, the larger the application of superphosphate.

Efficiency of the superphosphate also varies with the method of application, applications confined to a 1-inch layer below the seed producing larger yields than applications uniformly mixed with the whole mass of sand and soil.

When soils with depressing effects are present, the efficiency of superphosphate seems to be highest at a pH of 4.5 to 5.0 and lowest in the neighborhood of neutrality.

Comparison of the effects of isolated colloidal and noncolloidal soil fractions indicates that the effects of soil on the efficiency of superphosphate are largely localized in the colloidal fraction. The comparison, however, is somewhat imperfec', presumably owing to contamination of the noncolloidal fraction with copper or other heavy metals.

Determinations are given of the effects of 17 surface soils and 14 subsoils on the efficiency of superphosphate. The effects of the

different soils vary remarkably. If an efficiency of 100 percent is assumed for the efficiency of superphosphate in pure quartz sand, additions of some soils reduce the efficiency to 1 percent, whereas others raise the efficiency to 148 and 198 percent. Thirteen of the fourteen subsoils tested impart a lower efficiency than the corresponding surface soils.

The effects of surface soils on superphosphate correlate fairly well with the silica-sesquioxide ratios of the colloids present, soils containing colloids with high silica-sesquioxide ratios enhancing the efficiency of superphosphates and those containing colloids with low ratios depressing efficiency. The same is true of subsoil materials also.

Determinations of the effect of two purely organic colloids, activated charcoal and peat, are also reported. These increase the efficiency of superphosphate and rock phosphate in pure quartz sand and the efficiency of superphosphate in sand and soil mixtures.

The effect of a soil colloid on superphosphate seems to depend on several factors, namely, the degree to which the colloidal material is saturated with phosphoric acid, the silica-sesquioxide ratio of the colloid, the effect of the colloid on the hydrogen-ion concentration of the medium, and the content of organic matter. The relative importance of the different factors is believed to be in the order given, the first mentioned being most important. The manner in which the various factors affect superphosphate is discussed.

The availability of rock phosphate, on the other hand, seems to be governed primarily by the hydrogen-ion concentration of the medium, but within the acid range other factors may influence the availability of this material.

The efficiencies of superphosphate calculated from the weights of crop increases are about the same as those calculated from the quantities of phosphoric acid recovered in the crops.

The observed effects of soil colloids on superphosphate are discussed in their relation to known laboratory methods of determining available phosphoric acid and in their bearing on actual fertilizer practice.

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APPENDIX

Tables 11–31 are those from which the composite tables (1–10) in the text have been derived. Although considerable reference is made in the text to tables 11–31 the significance of the data which they contain is enhanced by their consolidation in those tables which appear in logical sequence in the text. In order to avoid an excess of tabulation throughout the text, while giving the necessary data of the individual tables, and demonstrating the steps by which the more significant composite tables have been derived, tables 11–31 have been placed in this Appendix.

TABLE 11.—*Applications of superphosphate and soil in layers compared with applications mixed uniformly with all the sand; effect of omitting Mn from the base fertilizer; influence of quantity of soil on the efficiency of superphosphate; effect of mixing a soil (Sharkey) enhancing phosphate efficiency with a soil (Brazil) depressing efficiency* [1]

Kind of base fertilizer	P_2O_5 applied per pot	Manner in which super-phosphate applied	Soil mixed with quartz sand [2]	Average oven-dry yield per pot of plants above-ground	Probable error of the average	Efficiency of super-phos-phate
	Gram			*Grams*	*Gram*	*Percent*
	0		None	0.14	0	
No. 1	.04	Uniformly	do	.60	.05	100
	.08	do	do	.82	.10	100
	.12	do	do	1.34	.05	100
	.16	do	do	2.17	.15	100
No. 1, Mn omitted	.04	do	do	.94	.02	220
	.12	do	do	1.92	.03	135
	.04	In layer	do	1.51	.04	332
	.12	do	do	2.40	.05	168
	.12	Uniformly	Brazil soil, supplying 50 g of colloid.	.31	.02	13
No. 1	.12	do	Brazil soil, supplying 25 g of colloid.	.78	.02	61
	.12	do	Brazil soil, supplying 12½ g of colloid.	1.06	.06	82
	.12	do	Brazil and Sharkey, supplying 25 g of colloid each.	.90	.03	72
	.12	In layer	Brazil soil supplying 50 g of colloid, applied in a layer.	1.71	.08	123

[1] All treatments replicated 4 times.   [2] Quantity expressed in terms of colloid content.

TABLE 12.—*Different base fertilizers for quartz sand compared*

(Applications of superphosphate in layers compared with those mixed uniformly with all the sand) [1]

Kind of base fertilizer	P_2O_5 applied per pot	Manner in which the superphosphate mixed with the quartz sand	Average oven-dry yield per pot of plants above-ground	Probable error of average	Efficiency of super-phos-phate [2]
	Gram		*Grams*	*Gram*	*Percent*
	0		0.29	0	
No. 2, standard	.06	Uniformly	2.98	.11	100
	.12	do	4.40	.11	100
	.18	do	4.72	.11	100
	.06	In layer	3.26	.06	120
No. 3, Fe and Mn omitted	.06	Uniformly	2.94	.03	100
	.06	In layer	3.69	.02	150
No. 4, double Fe	.06	Uniformly	2.57	.09	87
	.06	In layer	2.92	.19	97
No. 5, Ca and Mg reduced	.06	Uniformly	2.89	.07	97
	.06	In layer	3.25	.10	120

[1] All treatments replicated 4 times.
[2] Superphosphate uniformly mixed and used with standard fertilizer taken as 100 percent.

TABLE 13.—*Effect of precipitated calcium carbonate on growth in quartz sand with standard base fertilizer* [1]

Treatment with calcium carbonate	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield per pot of plants above-ground	Probable error of the average
	Gram		*Grams*	*Gram*
None	0	4.5	0.78	0.08
	.03	4.7	1.49	.05
	.06	4.7	1.83	.03
	.12	4.7	1.66	.07
CaCO₃, 0.4 g per pot [2]	0	6.7	.45	.01
	.03	6.9	1.13	.14
	.06	6.9	1.72	.38
	.12	6.9	1.89	.05
CaCO₃, 0.8 g per pot [2]	0	7.4	.47	.03
	.03	7.4	1.03	0
	.06	7.4	1.48	.04
	.12	7.4	1.70	.02
CaCO₃, 1.6 g per pot [2]	0	8.0	.34	.02
	.03	7.8	.83	.02
	.06	8.0	1.22	.07
	.12	8.0	1.46	.03

[1] All treatments replicated 3 times.
[2] Plants in series receiving CaCO₃ slightly chlorotic at times; chlorosis most pronounced with 1.6 g of CaCO₃.

TABLE 14.—*A comparison of different base fertilizers* [1]

Base fertilizer no.	Special features of base fertilizer		Soil added at rate of 25 g of colloid per pot	pH of medium after growth	Average oven-dry yield per pot of plants above-ground	Probable error of the average
	Source of nitrogen	Special salts added				
					Grams	*Gram*
2	½ NH₄, ½ NO₃	None	None	4.9	2.56	0.04
6	do	NaCl	do		2.30	.06
		do	Sharkey	4.9	2.56	.06
		NaCl+0.66 g of NaHCO₃	None	7.5	1.68	.04
7	All NO₃	NaCl+1.31 g of NaHCO₃	do		.91	.04
		None	do		2.00	.04
		CuCl, H₃BO₃	do	7.3	2.18	.06
8	do	do	Sharkey	6.9	2.49	.04
		CuCl, H₃BO₃+0.66 g of NaHCO₃	None	8.8	1.21	.05
		CuCl, H₃BO₃+0.31 g of NaHCO₃	do		.30	.01

[1] Each pot received 1.2 g of P_2O_5 from superphosphate; all treatments replicated 3 times.

TABLE 15.—*Concentration of the base fertilizer as a factor influencing the extent that soil additions lower the efficiency of superphosphates* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	pH of medium after growth—		Average oven-dry yield, per pot, of plants aboveground			
		With standard base fertilizer	With one half standard base fertilizer	With standard base fertilizer	Probable error of average	With one half standard base fertilizer	Probable error of average
	Gram			*Gram*	*Gram*	*Gram*	*Gram*
None	0	8.0	6.6	0.11	0	0.12	0
	.05	4.7	5.3	.39	.04	.41	.02
	.10	5.7	5.9	.52	.02	.48	.04
Nipe	0	6.9	6.4	.09	0	.98	0
	.10	6.3	6.3	.12	.01	.12	0
	.20	6.5	6.5	.18	0	.18	.01

[1] All treatments replicated 4 times. Nipe soil added at rate of 50 g of colloid per pot.

TABLE 16.—*Effects of different soils on the efficiencies of superphosphate and rock phosphate in quartz sand. Applications of phosphate and colloid, in 1-inch layers, compared with applications uniformly mixed with all the sand* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	Kind of phosphate applied	Manner in which phosphate or phosphate and soil was mixed with sand	Average oven-dry yield per pot, of plants aboveground	Probable error of average	Efficiency of superphosphate
	Gram			*Grams*	*Gram*	*Percent*
	0	None		0.14	0	
	.06	Super	Uniformly	2.99	.11	100
	.09	...do	....do	4.25	.12	100
None	.12	...do	....do	5.16	.06	100
	.18	...do	....do	6.24	.06	100
	.06	...do	In layer	2.77	.20	95
	.36	Rock	Uniformly	.15	0	0
	.36	...do	In layer	.16	.01	0
	0	None		.12	0	
Cecil soil	.12	Super	Uniformly	3.99	.18	70
	.36	Rock	...do	.13	.01	0
	0	None		.10	0	
Cecil subsoil	.12	Super	Uniformly	.90	.03	14
	.06	...do	In layer	1.78	.16	60
	.36	Rock	Uniformly	.10	0	0
	.36	...do	In layer	.12	0	0
	0	None		.12	0	
Sassafras soil	.12	Super	Uniformly	5.37	.16	111
	.36	Rock	...do	.12	0	0
	0	None		.13	0	
Sassafras subsoil	.12	Super	Uniformly	2.75	.12	46
	.36	Rock	...do	.17	.01	0
	0	None		.21	.01	
Fallon soil	.06	Super	Uniformly	2.87	.15	[2]95+
	.12	...do	...do	4.45	.25	[2]78+
	.36	Rock	...do	.23	.01	0

[1] All treatments replicated 4 times. All soil applications at rate of 50 g of colloid per pot. pH about 7.5, except where Fallon soil added, pH about 8.0.
[2] Plants chlorotic and limited in growth owing to a deficient assimilation of iron.

TABLE 17.—*Efficiency of superphosphate in a mixture of Nipe soil and quartz sand, as affected by the quantities of soil and superphosphate* [1]

[The sand contained some P_2O_5 as impurity]

Rate at which Nipe soil applied, calculated as grams of colloid per pot (grams)	P_2O_5 applied per pot	Average oven-dry yield per pot of plants aboveground	Probable error of the average	Total P_2O_5 per pot on assumption sand contained 0.015 g of available P_2O_5 [2]	Efficiency of total P_2O_5 on assumption sand contained 0.015 g of available P_2O_5
	Gram	*Grams*	*Gram*	*Gram*	*Percent*
	0	2.01	0.18	0.015	100
	.03	4.46	.09	.045	100
None	.06	5.18	.11	.075	100
	.12	5.51	.10	.135	100
	.18	5.67	.11	.195	
50	0	.09	0	.015	0
50	.12	1.82	.16	.135	10
50 [3]	.12	4.74	.05	.135	42
50	.24	4.66	.27	.255	21
	.06	1.57	.08	.075	15
25	.12	4.32	.04	.135	32
	.24	5.97	.09	.255	
	.03	1.56	.14	.045	24
12½	.06	3.32	.12	.075	41
	.12	5.82	.03	.135	75

[1] All treatments replicated 4 times.
[2] This quantity arrived at by plotting curve of increased growth against increased applications of superphosphate and then projecting curve beyond the origin to the point for a 0.1-g crop. Other experiments indicate that 0.1 g is the approximate weight of crop when no P_2O_5 is present.
[3] Colloid and phosphate applied in a 1-inch layer, one fourth inch below seed.

TABLE 18.—*Efficiency of superphosphate in a mixture of Nipe soil and quartz sand, as affected by the quantity of soil and of superphosphate* [1]

Kind of soil mixed with quartz sand, and quantity in terms of colloid content	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield, per pot, of plants aboveground	Probable error of the average	Efficiency of superphosphate
	Gram		*Grams*	*Gram*	*Percent*
None	0	5.9	0.28	0.02	---
	.025	4.9	2.08	.02	100
	.050	5.0	3.12	.06	100
	.100	5.0	4.06	.06	100
Nipe soil, 100 g of colloid	0	6.2	.05	0	---
	.050	6.5	.06	0	---
	0	6.5	.06	0	---
Nipe soil, 50 g of colloid	.050	---	.10	.01	1
	.100	---	.29	.02	3.3
	.150	---	.68	.06	6
	.200	5.4	1.19	.04	8
Nipe soil, 25 g of colloid	0	6.5	.07	0	---
	.050	6.0	.20	.02	4
Nipe soil, 12½ g of colloid	0	6.7	.08	0	---
	.050	4.7	.81	.04	21

[1] All treatments replicated 4 times.

TABLE 19.—*Colloidal and noncolloidal fractions of Cecil subsoil compared as to their effects on the efficiency of superphosphate in quartz sand* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield per pot of plants aboveground	Probable error of the average	Efficiency of superphosphate
	Gram		*Grams*	*Gram*	*Percent*
None	0	6.5	0.09	0.01	---
	.025	4.1	1.33	.07	100
	.050	4.1	2.09	.17	100
	.100	4.3	2.47	.13	100
Untreated soil, at rate of 20 g of colloid	0	6.0	.06	0	---
	.150	4.1	3.03	.13	100
Untreated soil, at rate of 40 g of colloid	0	6.5	.07	0	---
	.150	4.1	1.83	.21	28
Untreated soil, at rate of 60 g of colloid	0	6.5	.06	0	---
	.150	4.2	1.31	.10	17
Extracted colloid, 40 g	0	6.7	.07	.01	---
	.150	6.2	.89	.13	11
Noncolloidal residue, 47 g	0	6.7	.09	0	---
	.150	6.2	1.15	.08	14
20 g of extracted colloid, 24 g of residue colloid	0	6.7	.07	0	---
	.150	4.5	1.53	.22	22

[1] All treatments replicated 4 times.

TABLE 20.—*Colloidal and noncolloidal fractions of Cecil subsoil compared, 1 year after separation, as to their effects on the efficiency of superphosphate in quartz sand* [1]

Kind and quantity of soil mixed with quartz sand	P_2O_5 applied per pot	Average oven-dry yield, per pot, of plants aboveground	Probable error of the average	Efficiency of superphosphate
	Gram	Grams	Gram	Percent
None	0	0.07	0	------
	.05	3.84	.07	100
	.10	4.94	.13	100
Untreated soil at rate 10 g of colloid	0	.07	0	------
	.05	2.11	.02	55
Untreated soil at rate 20 g of colloid	0	.06	0	------
	.05	1.25	.04	32
Untreated soil at rate 40 g of colloid	0	.07	0	------
	.05	.49	.05	11
Untreated soil at rate 80 g of colloid	0	.07	0	------
	.05	.20	0	3
Extracted colloid, 20 g	0	.08	0	------
	.05	1.36	.06	34
Noncolloidal residue, 40 g	0	.08	0	------
	.05	2.31	.14	62

[1] No-phosphate treatments not replicated; other treatments replicated 3 times.

TABLE 21.—*Colloidal and noncolloidal fractions of Sassafras subsoil compared as to their effects on the efficiency of superphosphate in quartz sand* [1]

Kind and quantity of soil mixed with quartz sand	P_2O_5 applied per pot	Average oven-dry yield, per pot, of plants aboveground	Probable error of the average	Efficiency of superphosphate
	Gram	Grams	Gram	Percent
None	0	0.06	0	------
	.025	1.68	.06	100
	.050	3.65	.12	100
	.100	4.73	.06	100
Untreated soil at rate 15 g of colloid	0	.07	------	------
	.050	2.24	.08	64
Untreated soil at rate 30 g of colloid	0	.10	------	------
	.050	1.22	.09	34
Untreated soil at rate 60 g of colloid	0	.09	------	------
	.050	.47	.02	12
Untreated soil at rate 120 g of colloid	0	.10	------	------
	.050	.21	0	4
Extracted colloid, 40 g	0	.06	0	------
	.050	.36	.03	8
Noncolloidal residue, 40 g	0	.08	------	------
	.050	1.82	.09	52
	0	.08	------	------
	.050	1.42	.09	42
20 g extracted colloid and 40 g of noncolloidal residue	0	.08	------	------
	.050	.71	.04	20
Untreated soil at rate 60 g of colloid	.025	.14	0	4
	.100	2.90	.06	41
	.150	5.07	.11	77

[1] No-phosphate treatments not replicated; other treatments replicated 4 times.

TABLE 22.—*Colloidal and noncolloidal fractions of Clarksville subsoil compared as to their effects on the efficiency of superphosphate in quartz sand* [1]

Kind and quantity of soil mixed with quartz sand	P_2O_5 applied per pot	Average oven-dry yield, per pot, of plants above-ground	Probable error of the average	Efficiency of super-phosphate
	Gram	Grams	Gram	Percent
None	0	0.07	0	
	.025	1.29	.07	100
	.050	2.15	.19	100
	.100	4.34	.22	100
Untreated soil at rate 20 g of colloid	0	.06		
	.050	1.57	.05	66
Untreated soil at rate 40 g of colloid	0	.07		
	.050	1.03	03	40
Untreated soil at rate 80 g of colloid	0	.07		
	.050	.51	.03	20
Extracted colloid, 40 g	0	.08		
	.050	.19	.01	4
Noncolloidal residue, 40 g	0	.07		
	.050	1.19	.10	46
Untreated soil at rate of 120 g	0	.07		
	.050	.70	.05	28
20 g of extracted colloid and 60 g of noncolloidal residue	0	.08		
	.050	.38	.03	14
Untreated soil at rate of 40 g of colloid	.025	.17		8
	.100	3.77	.07	86

[1] No-phosphate treatments not replicated; other treatments replicated 4 times.

TABLE 23.—*Effects of different soils on the efficiency of superphosphate in quartz sand* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield per pot, of plants above-ground	Probable error of the average	Efficiency of super-phosphate
	Gram		Grams	Gram	Percent
None	0	4.8	0.36	0.04	
	.06		2.76	.04	100
	.12	4.7	2.89	.04	
	.18		2.96	.07	
Huntington soil	0	4.6	.89	.05	
	.06	4.6	2.02	.12	72
Huntington subsoil	0	4.7	.23	.01	
	.12	4.6	2.13	.96	40
Norfolk soil	0	4.8	.23	.01	
	.12	4.8	1.39	.14	24
Norfolk subsoil	0	4.8	.10	0	
	.12	4.7	.87	.06	16
Orangeburg subsoil	0	4.8	.12	.01	
	.12	4.6	1.68	.04	33

[1] All treatments replicated 4 times. Soils applied at rate of 50 g of colloid per pot.

TABLE 24.—*Effects of different soils on the efficiency of superphosphate in quartz sand* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield per pot, of plants above-ground	Probable error of the average	Efficiency of superphosphate calculated from weight of crop	Quantity of P_2O_5 applied recovered in crop	Efficiency of superphosphate calculated from P_2O_5 in crop
	Gram		Grams	Gram	Percent	Gram	Percent
None	0	6.0	0.31	0.07	------	0	------
	.025	5.9	1.92	.14	100	.00774	100
	.050	5.4	3.32	.31	100	.01637	100
	.100	5.4	4.60	.17	100	.03406	100
Carrington soil	0	4.8	.35	.03	------	------	------
	.050	4.8	1.98	.15	51	.00779	50
Carrington subsoil	0	5.4	.20	.01	------	------	------
	.050	5.0	2.54	.12	76	.01235	78
Clarksville soil	0	4.8	.27	.02	------	------	------
	.050	4.8	2.27	.18	64	.01111	73
Clarksville subsoil	0	5.5	.10	0	------	------	------
	.050	5.0	.52	.03	13	.00151	10
Manor soil	0	4.7	.26	.01	------	------	------
	.050	4.7	2.09	.12	58	.00959	60
Manor subsoil	0	5.4	.08	0	------	------	------
	.050	5.3	.75	.05	21	.00293	20
Miami soil	0	5.3	.25	.02	------	------	------
	.050	5.2	2.23	.17	63	.01152	73
Miami subsoil	0	7.9	.11	0	------	------	------
	.050	7.9	1.33	.03	38	.00570	38

[1] All treatments replicated 4 times; soils applied at rate of 50 g of colloid per pot.

TABLE 25.—*Effects of different soils on the efficiency of superphosphate in quartz sand* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield per pot, of plants above-ground	Probable error of the average	Efficiency of superphosphate calculated from weight of crop	Quantity of P_2O_5 applied recovered in crop	Efficiency of superphosphate calculated from P_2O_5 in crop
	Gram		Grams	Gram	Percent	Gram	Percent
None	0	5.7	0.15	0.01	------	------	------
	.025	------	1.73	.12	100	0.00639	100
	.050	------	2.79	.14	100	.01091	100
	.100	4.8	4.06	.11	100	.03520	100
Chester soil	0	------	.32	.02	------	------	------
	.050	5.6	1.26	.06	30	.00480	38
Chester subsoil	0	------	.06	0	------	------	------
	.050	4.7	.13	0	2	------	------
Hagerstown soil	0	------	.10	0	------	------	------
	.050	6.7	.43	.01	11	------	------
Hagerstown subsoil	0	------	.08	0	------	------	------
	.050	6.6	.38	.02	10	------	------
Sharkey soil	0	5.0	.74	.06	------	------	------
	.050	4.8	4.38	.12	159	.02229	148
Stockton soil	0	6.9	.64	.02	------	------	------
	.050	6.7	4.37	.10	186	.02222	146
Stockton subsoil	0	8.1	1.39	.05	------	------	------
	.050	8.1	4.08	.05	105	.01878	130

[1] All treatments replicated 4 times; soils applied at rate of 50 g of colloid per pot.

TABLE 26.—*Effects of different soils on the efficiency of superphosphate in quartz sand* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield per pot, of plants above-ground	Probable error of average	Efficiency of super-phosphate
	Gram		*Grams*	*Gram*	*Percent*
None	0	5.6	0.10	0	
	.025	5.2	.39	.03	100
	.100	4.5	1.99	.12	100
Wabash soil	0	4.7	.41	.01	
	.050	4.7	1.39	.08	198
Wabash subsoil	0	4.9	.21	.01	
	.050	4.6	1.08	.02	175
Cecil soil	0	5.5	.08	0	
	.050	4.9	.16	.01	14

[1] All treatments replicated 4 times; soil added at rate of 50 g of colloid per pot.

TABLE 27.—*Effects of different soils on the efficiency of superphosphate in quartz sand* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	pH of medium after growth	Average oven-dry yield per pot, of plants above-ground	Probable error of average	Efficiency of super-phosphate
	Gram		*Grams*	*Gram*	*Percent*
None	0	5.7	0.09	0	
	.025		1.50	.11	100
	.050	4.6	3.12	.08	100
	.100		4.02	.10	100
Carrington soil	0		.12		
	.050	4.8	1.78	.10	58
Hagerstown soil	0		.09		
	.050	6.9	.36	.01	10
Hagerstown subsoil	0		.08		
	.050	6.8	.22	.01	6
Huntington subsoil	0		.08		
	.050	6.2	.19	.02	4
Manor soil	0	4.8	.08		
	.050	4.9	1.16	.08	40
Marshall soil	0		1.67		
	.050	5.0	5.08	.12	142
Marshall subsoil	0	6.2	.09		
	.050	5.6	1.57	.03	52
Miami soil	0		.11		
	.050	4.8	1.47	.09	48
Miami subsoil	0		.08		
	.050	7.8	.58	.01	18
Norfolk soil	0		.10		
	.050	5.2	.29	.02	6
Norfolk subsoil	0		.07		
	.050	4.6	.09	0	1
Orangeburg soil	0	4.5	.32		
	.050	4.4	2.27	.20	66
Orangeburg subsoil	0		.08		
	.050	4.8	.11	.10	1
Sassafras subsoil	0		.28		
	.050	6.3	.75	.06	16

[1] No-phosphate treatments not replicated; other treatments replicated 5 times. Soils applied at rate of 50 g of colloid per pot.

TABLE 28.—*Influence of hydrogen-ion concentration on the extent that soil additions lower the efficiency of superphosphate* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	NaHCO$_3$ added per pot	pH of medium after growth	Oven-dry yield, per pot, of plants aboveground			Efficiency of superphosphate
				Series A	Series B	Average	
	Gram	*Gram*		*Grams*	*Grams*	*Grams*	*Percent*
None	0	0	6.2	0.12	0.12	0.12	----
	.05	0	4.2	2.90	2.37	2.64	100
	.10	0	4.2	3.66	3.16	3.41	100
	0	.4	8.0	.08	.07	.08	----
	.05	.4	5.0	2.03	1.77	1.90	72
Cecil soil	0	0	6.1	.09	.09	.09	----
	.05	0	5.0	.96	.84	.90	32
	0	.6	6.3	.11	.09	.10	----
	.05	.6	6.3	.92	.95	.94	33
Cecil subsoil	0	0	5.6	.06	.08	.08	----
	.05	0	4.5	.84	.53	.69	24
	0	.6	8.0	.07	.07	.07	----
	.05	.6	8.2	.32	.45	.39	13
Clarksville soil	0	0	5.5	.16	.18	.17	----
	.05	0	5.3	1.77	2.45	2.11	77
	0	.6	6.3	.10	.10	.10	----
	.05	.6	6.3	.61	.97	.79	27
Clarksville subsoil	0	0	5.3	.07	.07	.07	----
	.05	0	4.8	.54	.55	.55	19
	0	.6	6.9	.06	.05	.06	----
	.05	.6	6.9	.23	.28	.26	8
Sassafras soil	0	0	5.3	.15	.18	.17	----
	.05	0	4.7	1.44	1.45	1.45	51
	0	.6	6.5	.11	.12	.12	----
	.05	.6	6.3	.58	.79	.69	22

[1] Each treatment replicated 2 times; soils added at rate of 50 g of colloid per pot.

TABLE 29.—*Influence of hydrogen-ion concentration on the extent that soil additions lower the efficiency of superphosphate* [1]

Kind of soil mixed with quartz sand	P_2O_5 applied per pot	Base fertilizer	NaHCO$_3$ added per pot	pH of medium after growth	Average oven-dry yield, per pot, of plants aboveground	Probable error of the average	Efficiency of superphosphate
	Gram		*Gram*		*Grams*	*Gram*	*Percent*
None	0	No. 2, standard	0	6.6	0.06	----	----
	.05	----do----	0	3.9	2.74	0.12	100
	.10	----do----	0		3.45	.04	100
	0	No. 2, standard	0		.09	----	----
	.05	----do----	0	5.2	1.06	.07	37
	0	----do----	.6		.10	----	----
	.05	----do----	.6	6.2	.88	.05	33
Cecil soil	0	No. 7, all nitrate	0	6.6	.06	----	----
	.05	----do----	0	6.0	.49	.08	16
	0	----do----	.4		.08	----	----
	.05	----do----	.4	7.1	.07	.01	22
	0	No. 2, standard	0		.06	----	----
	.05	----do----	0	5.7	.36	.04	11
Cecil subsoil	0	----do----	.4		.07	----	----
	.05	----do----	.4	7.2	.19	.02	4
	0	----do----	.6		.06	----	----
	.05	----do----	.6	7.8	.14	.01	2
	0	No. 2, standard	0		.09	----	----
	.05	----do----	0	4.6	1.91	.04	68
Clarksville soil	0	----do----	.6		.06	----	----
	.05	----do----	.6	6.6	1.20	.07	44
	0	No. 7, all nitrate	.4		.07	----	----
	.05	----do----	.4	7.7	1.05	.03	38
	0	No. 2, standard	0		.05	----	----
	.05	----do----	0	5.4	.41	.03	14
Clarksville subsoil	0	----do----	.6		.06	----	----
	.05	----do----	.6	6.8	.15	0	2
	0	No. 7, all nitrate	.4		.06	----	----
	.05	----do----	.4	6.8	.23	.01	7
	0	No. 2, standard	0		.17	----	----
	.05	----do----	0	4.4	2.77	.02	98
Sassafras soil	0	----do----	.6		.10	----	----
	.05	----do----	.6	5.6	1.03	.04	35
	0	No. 7, all nitrate	.4		.12	----	----
	.05	----do----	.4	6.9	1.51	.11	52

[1] No-phosphate treatments not replicated; other treatments replicated 3 times. Soils added at rate of 50 g of colloid per pot.

TABLE 30.—*Effects of activated charcoal and peat on the efficiencies of superphosphate and raw rock phosphate in quartz sand* [1]

Kind of colloid or peat mixed with quartz sand	P_2O_3 applied per pot and source superphosphate or raw rock phosphate	pH of medium after growth	Average oven-dry yield, per pot of plants above-ground	Probable error of the average	Efficiency of phosphate calculated from weight of crop	Quantity of P_2O_3 applied recovered in the crop	Efficiency of phosphate calculated from P_2O_3 in crop
	Gram		*Grams*	*Gram*	*Percent*	*Gram*	*Percent*
None	0	5.8	0.15	0.01			
	0.025 super [2]	4.8	.87	.01	100	0.00597	100
	0.050 rock [3]	4.5	1.65	.17	100	.01090	100
	0.100 rock [3]	4.5	2.37	.09	100	.02448	100
	0.200 rock [3]	4.8	1.09	.03	16	.01036	24
Charcoal of pH 4.3	0	6.3	.19	.01			
	0.050 super [2]	4.5	2.42	0	200	.01983	168
	0.200 rock [3]	5.0	1.28	.04	19	.01219	28
Charcoal of pH 9.6	0	6.4	.24	.01			
	0.050 super [2]	5.3	2.11	.07	153	.01533	132
	0.200 rock [3]	6.7	.66	.02	7	.00486	10
Peat of pH 5.8	0	5.6	.80	.03			
	0.050 super [2]	5.6	3.06	.04	215	.02521	206
	0.200 rock [3]	5.4	2.34	.03	27	.01672	36
Peat of pH 3.5	0	4.2	.71	.10			
	0.050 super [2]	4.2	1.46	.12	52	.00788	68
	0.200 rock [3]	4.2	1.48	.06	14	.01670	36

[1] Treatments with peat of pH 5.8 duplicated; treatments with peat of pH 3.5 and with charcoal triplicated; controls in quartz sand alone replicated 4 times. Charcoals and peats added at rate of 10 g per pot.
[2] Superphosphate.
[3] Rock phosphate.

TABLE 31.—*Effects of activated charcoal of pH 4.1 on the efficiency of superphosphate in quartz sand and quartz-sand-soil mixtures* [1]

Kind of soil mixed with quartz sand	P_2O_3 applied per pot	pH of medium after growth	Charcoal of pH 4.1 added per pot	Average oven-dry yield per pot of plants above-ground	Probable error of average	Efficiency of superphosphate, calculated from dry weight	Quantity of P_2O_3 applied recovered in the crop	Efficiency of superphosphate, calculated from P_2O_3 in crop
	Gram		*Grams*	*Grams*	*Gram*	*Percent*	*Gram*	*Percent*
	0	6.6	0	0.06	0			
None	.025		0	.93	.08	100	0.00465	100
	.050	4.2	0	2.86	.04	100	.01783	100
	.100		0	3.88	.06	100	.04094	100
	0		10	.10	0			
Clarksville soil	.050	4.2	10	4.65	.12	200+	.02484	130
	0		0	.08	0			
	.050	4.6	0	1.48	.06	64	.00818	64
	0		10	.12	0			
Clarksville subsoil	.050	4.7	10	2.95	.03	100	.01267	80
	0		0	.07	0			
	.050	5.3	0	.28	.01	12	.00078	10
	0		10	.08	0			
Cecil subsoil	.050	4.8	10	.54	.03	27	.00188	22
	0		0	.07	0			
	.050	4.6	0	.38	.03	16	.00131	16
	0		10	.08	0			
	.050	4.5	10	.79	.07	42	.00264	30

[1] No-phosphate treatments replicated 3 times; other treatments 4 times; soils added at rate of 50 g of colloid per pot.

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