SUPERPHOSPHATE AND ROCK PHOSPHATE AS SOURCES OF PHOSPHORUS AND CALCIUM FOR ALFALFA

by

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INTRODUCTION

Phosphorus has been called the master key of Agriculture. Its first use as a fertilizer was in the form of crushed bone. However, the present source of considerable phosphorus for direct fertilizer use is rock phosphate. In 1951, 1,039,624 tons of rock phosphate, which made up 16 per cent of the total phosphorus applied as fertilizer, were employed for direct application in the United States (20).

Rock phosphate is one of the least readily available forms of phosphorus for plant utilization. It is, however, an inexpensive concentrated material which may be of value under certain conditions (6).

Field and greenhouse tests have shown that phosphatic fertilizers having large proportions of water-soluble phosphorus have given greater yield responses than have those which contained a large portion of their available phosphorus in simply the citrate soluble form. Superphosphate contains mainly water-soluble forms of phosphorus. Rock phosphate contains mainly unavailable forms of phosphorus and that small amount which is regarded as available is merely citrate soluble.

Numerous experiments have shown that finely ground raw phosphate rock will increase yields of crops when such is applied to phosphorus deficient soils. It is important to compare the relative efficiency of raw rock phosphate with that of more soluble sources of phosphorus such as superphosphate. The best form for the farmer to use, of course, is the one that will produce the greatest increases in crop yields for each dollar invested.

As a general rule, the soils of the eastern one-third of Kansas are acid in nature and low in available phosphorus. It was the purpose of this experiment first to compare rock phosphate and superphosphate as sources of phosphorus for alfalfa under both acid and essentially neutral soil conditions and secondly to compare rock phosphate and calcium hydroxide with respect to effectiveness in neutralizing soil acidity and/or supplying calcium both to the exchange complex of the soil and to the plant.

REVIEW OF LITERATURE

The distribution of ortho phosphate ions seems to vary with the pH of the solutions. When the soil is distinctly alkaline (pH above 7.5), the $PO_4^{\equiv}$ ion apparently is dominant. This form is used least by plants. But as the pH is lowered and the soil becomes slightly to moderately acid (pH from 5.5 - 7.0) the $HPO_4^{=}$ and $H_2PO_4^{-}$ ions prevail. At greater acidities (pH below 5.5) $H_2PO_4^{-}$ ions tend to dominate. These two forms, especially the latter, seems to be absorbed most readily by higher plants and probably by microorganisms also. Thus by the regulation of soil pH, phosphorus availability is subject to some control, providing a sufficient total amount of this constituent is present (11).

The activity of the soil phosphorus is affected in another way by pH, in this case indirectly. Studies by Metzger (14) with acid soils have shown that added soluble phosphorus is precipitated, at least in part, by free oxides of iron and/or aluminum. In slightly acid soils, calcium also may account for some fixation of this element.

Robertson, et al. (19) reported that liming of acid soils to pH values of 6 to 6.5 increased the availability of applied phosphorus when residual phosphorus was rather low and when the sesquioxides were low in amount. Liming these soils above pH 6 to 6.5 caused the percentage of phosphorus in the plant derived from the fertilizer to level off or decline, probably due to the formation of relatively unavailable tribasic forms of calcium phosphates. Liming soils which were high in residual phosphorus reduced the availability of fertilizer phosphorus regardless of the sesquioxide content. Uptake of phosphorus from currently applied superphosphate was highest from the soils high in sesquioxide content irrespective of rate of liming.

McLean and Cook (12) investigated the yield and phosphorus contents of alfalfa that was grown in pot cultures of six different soils which were previously limed to different pH levels and used both with and without fertilizer. The amounts of phosphorus extracted by four chemical methods from the soil samples both prior to seeding and after harvest of the crop were used to evaluate the effect of soil reactions on the availability of native and applied phosphorus. The greatest uptake of phosphorus by alfalfa occured at a pH of about 7.5, the highest employed in the experiment. In most instances, the phosphorus contents of the plants were highest at a pH of about 7.5 at which level the yields were either similar to or higher than those obtained at any lower pH. The results of these phosphorus extractions showed that liming to or slightly above the neutral point increased the amount of available soil phosphorus in most instances.

Whitson and Stoddart (25) observed less response to applied phosphate in limed soil than with acid soils. They suggested that phosphorus in the acid soils was largely present as the highly insoluble iron and aluminum phosphate instead of the more available calcium phosphate which was present in well limed soils. Ellis, et al., (4) suggested that the pH of the soil should be 6.0 or less for satisfactory utilization of rock phosphate.

Joos and Black (9) reported that the availability of phosphorus in phosphate rock was relatively high at both pH 4.6 and pH 5.6 but low at pH 6.6. They also reported that 5 months incubation increased the availability of the phosphate rock at pH 4.6 or 5.6 but reduced it at pH 6.6.

Truog (23) reported that liming of distinctly acid soils to pH of near 7.0 transformed rather rapidly considerable unavailable phosphorus to readily available forms. Other workers have reported that liming increases phosphate availability in soils. (7, 16). Lewis, et al., (10) found that rock phosphate was ineffective in furnishing phosphorus to plants under calcareous soil conditions.

Jones (8) quoted research done by Roberts, et al., in which Roberts reported that rock phosphate (30% total P_2O_5) became available slowly, particularly on limed land. However, over a long period, yields of crops showed rock phosphate on limed soils to be as effective as was one-half its weight in superphosphate (16% available P_2O_5).

Fine and Bartholomew (5) reported that Fraps concluded after numerous pot experiments that the availability of finely ground rock phosphate averaged about 40 per cent of that of superphosphate.

The availability varied from 0 to 95 per cent with different soils. Availability was not consistently high with acid soils although such a general trend was observed.

Crops have varied greatly in abilities to utilize phosphorus from rock phosphate under different soil conditions. Truog (24) classified plants on the basis of their ability to use phosphorus from rock phosphate and proposed that the ability of a plant to use phosphorus from rock phosphate was related to a plant's calcium uptake. He indicated that the solution of rock phosphate in a soil could be represented by the equation:

$$Ca_3(PO_4)_2 + 2H_2CO_3 \longrightarrow Ca_2H_2(PO_4)_2 + Ca(HCO_3)_2.$$

Since both of the products of the reaction are only slightly soluble; they would have to be removed from solutions in order for the reaction to proceed indefinitely. Consequently plants with a high Ca requirement would remove each of the products more completely than plants with a low calcium content. The former should, therefore, utilize rock phosphate to a better advantage than the latter. Also, acid soils should consume the excess $Ca(HCO_3)_2$ and thus, make it possible for plants of low calcium content to feed more advantageously on rock phosphate.

Rogers, et al., (20) stated that in general cereals are poor feeders upon phosphorus contained in rock phosphate, whereas buckwheat and some legumes such as sweet clover, alfalfa, and red clover are strong feeders.

Drake and Steckel (3) reported that plants with roots that have high cation exchange capacities (ragweed and smartweed) were quite effective in obtaining phosphorus from soil and rock phosphate.

These were two to three times as effective as the lower exchange root systems (lambs quarter and wheat) in solubilizing soil phosphorus and rock phosphate for the following sudan grass crop. Plant roots with high cation exchange capacity bonded calcium with greater energy than low cation exchange roots. Drake and Steckel reported two important mechanisms to be involved in phosphorus release, (a) bonding of calcium by the root colloid to dissolve the rock phosphate crystal, and (b) complexing of Al and Fe by organic anions to release soil aluminum and iron phosphates.

Cook (2) designed an experiment to test the theory proposed by Truog. He used oats, corn, millet, and buckwheat in quartz sand cultures in which rock phosphate served as a source of phosphorus. The cultures contained either H-saturated bentonite or Ca-saturated organic exchange material. Cook found that oats, corn, and millet used rock phosphate only in the presence of H-saturated exchange material, while buckwheat utilized it in the presence of either H or Ca-saturated exchange material. This supported Truog's theory since corn, oats, and millet each have low calcium requirements.

Fried and MacKenzie (6) using neutron irradiated phosphate investigated the effect of soil pH, rate of application, and crop species on the plant utilization of phosphorus and calcium from rock phosphate and superphosphate. With rock phosphate, the higher the pH, the lower the relative proportion of fertilizer to soil phosphorus absorbed by plant. At the end of four cuttings 4.8, 4.1, and 2.2 per cent of the rock phosphate were utilized by alfalfa at pH values of 4.9, 5.5, and 5.8, respectively. The corresponding utilization figures obtained with superphosphate were 14.2, 18.6, and 16.5 per cent, respectively.

The total uptake of phosphorus by rye grass from rock phosphate was as much as 16.4 times that of calcium from the same materials. With alfalfa as the test crop, the ratio of phosphorus to calcium from the rock phosphate varied from 3.08, 5.32, and 6.98 at pH values of 4.9, 5.5, and 5.8, respectively, with the first crop and from 2.92, 4.83, and 5.58 at the pH values of 4.9, 5.5, and 5.8, respectively, with the fourth crop. Fried and MacKenzie concluded that after dissolution of rock phosphate occurs, the resultant ions act independently in their relations with the plant. They further concluded that at pH 5.8, plant removal of phosphorus from superphosphate equaled or exceeded removal from rock phosphate, even when the latter material was applied at four times the P_2O_5 rate.

Murdock and Seay (15) concluded the following from their greenhouse work with superphosphate-rock phosphate mixtures:

1. Clover was a better feeder on rock phosphate than wheat,

2. The amount of available rock phosphate phosphorus was increased with increased rates of application,

3. About three and one-half to four times as much rock phosphate phosphorus as superphosphate phosphorus was needed to give equal yield and plant phosphorus contents when the phosphorus sources were applied separately.

METHODS OF STUDY

Soil Material Used

Four surface soil materials were used in this greenhouse study. These were collected from field sites in the fall of 1956 and brought to Manhattan, Kansas. Three of the soil materials were from southeastern Kansas locations while one was from a north-central location. Natural soil fertility as well as nature of the soil parent material varied among these locations. Pertinent information about these soil samples is provided in Table 1.

Soil Amendments Used

Fertilizers used in this greenhouse included triple superphosphate (0-42-0) and finely ground rock phosphate. This sample of Florida rock phosphate was ground so that 85 percent of it passed a 200 mesh sieve. It had a total phosphorus content equivalent to 33.7 percent P_2O_5 and an available phosphorus content equivalent to about two percent P_2O_5. Calcium hydroxide was used as the liming material.

Laboratory Procedure

Laboratory analyses of each of the four soils were made with respect to pH measurements, lime requirement determination, exchangeable hydrogen, total cation exchange capacity, available phosphorus content, and contents of exchangeable calcium and potassium before the start of the greenhouse experiment. After the termination of the greenhouse portion of the experiment,

Table 1. General characterization of original soils used in greenhouse experiment.

Soil Type and Sampling Location	pH	Lime 1/ Requirement (Lbs./A)	Avail. 2/ P (Lbs./A)	Exch. K (Lbs./A)	Org. 3/ Matter (%)	Exch. 4/ H^+ m.e/100g	Exch. Ca^{++} m.e/100g	Cation Exch. 5/ Capacity m.e/100g
Parsons silt loam, Thayer Exp. Field, Neosho	5.9	3,000	25	135	1.9	6.4	9.9	18.6
Bates fine sandy loam, South of Dennis, Labette County	5.1	6,000	17	126	2.8	11.2	3.4	12.7
Cherokee silt loam, Columbus Exp. Field, Cherokee County	5.5	4,000	14	140	2.2	7.1	5.4	13.0
Idana silty clay loam, Donald and Stanley Thurlow's farm, Wakefield, Clay County	5.2	5,000	34	540	2.2	9.6	12.6	24.6

1/ Determined by the method of Woodruff (26)
2/ Determined by a modified method of Bray and Kurtz (1)
3/ Determined by a modified method of Walkley-Black (17)
4/ Determined by a procedure of Mehlich (13)
5/ Determined according to Rendig's method (18)

exchangeable calcium, available phosphorus, lime requirement, and pH determinations were made.

Plant material was dried and weighed in order to determine the yield. It later was analyzed for contents of phosphorus and calcium.

Soil Analyses

The pH determinations were made with a standard glass electrode, using a soil to water ratio of 1 to 1. Lime requirement values were determined by two methods. One method combined the use of the glass electrode and the use of a solution buffered at pH 7.0 as suggested by Woodruff (26). The buffered solution contained dissolved calcium acetate, p-nitrophenol and magnesium oxide. This particular buffer solution does not react unfavorably with the soil and furthermore its rate of reaction is rapid.

The other measurement of lime requirement was accomplished by using 50 g. samples of the soils. These were placed in 250 ml. Erlemeyer flasks. Varying amounts, as shown in Table 2, of $Ca(OH)_2$ were added to each flask, and 50 ml. of distilled water were added to each flask. The flasks then were placed on a rotary shaker and allowed to turn for twenty-four hours. The pH of the soil-water suspension then was determined by the glass electode method. The equivalent amount of $CaCO_3$ that raised the pH of this suspension to 7.0 or nearest to pH 7.0 was taken as lime requirement (Table 2).

The procedure of Mehlich (13) was used for the determination of exchangeable hydrogen in each soil. Ten g. of soil were placed in a 125 ml. Erlenmeyer flask and 25 ml. of the buffer solution

Table 2. Effect of addition of various amounts of $Ca(OH)_2$ upon pH values of four soil series.

Equivalent Amount of $CaCO_3$ Applied (Tons/A)	Amount of $Ca(OH)_2$ Added to 50 g. Soil (gm/flask)	Mean 1/ pH Values of Soil Solutions			
		Parsons	Bates	Cherokee	Idana
0.5	.0185	6.5	5.5	6.1	5.6
1.0	.037	7.0*	5.7	6.6	6.2
1.5	.0555	7.3	6.1	6.9*	6.5
2.0	.074	7.6	6.4	7.2	6.8
2.5	.0925	7.8	6.6	7.5	7.1*
3.0	.111	8.2	6.9	7.8	7.3
3.5	.1295	8.4	7.0*	7.8	7.4
4.0	.148	8.6	7.2	8.2	7.8
4.5	.1665	8.7	7.4	8.6	7.9
5.0	.185	8.8	7.6	8.8	8.0

Note: 1/Average of duplicate trials.
* Values used for lime requirement.

(0.5 N barium chloride and 0.2 N ethanolamine) were added. The material in the flask was mixed occasionally by swirling and allowed to stand for one-half hour. The soil solution was filtered slowly. An additional 25 ml. of buffer solution were used during the filtration. By adding small increments, the soil then was leached with 100 ml. of the replacement solution (250 g. of barium chloride in four l. of distilled water plus 10 ml. of the buffer solution). An internal indicator, methyl purple, was used and the leachate was titrated with 0.1 N HCl. The titration was checked against a blank containing 50 ml. of the buffer solution and 100 ml. of the replacement solution. All calculations were made with this blank determination as a reference. The difference between the titration of the soil and the blank is the amount of exchangeable hydrogen expressed as m.e. 100 g. of soil.

Total cation exchange capacity was determined according to Rendig's (18) method with some modifications. Two g. samples of air dried soil were placed into 100 ml. centrifuge tubes. The soil was washed once with a 50 ml. portion of 1 N calcium chloride, twice with 1 N calcium acetate, and once again with 1 N calcium chloride. The soil was suspended each time by means of a rubber ball stirer attached to an electric motor. The suspension was centrifuged until the supernatant liquid became clear. The washings then were discarded. Thus the soil sample was saturated with calcium ions. The soil sample then was washed once with distilled water, four times with 95 per cent ethyl alcohol, and twice with absolute methyl alcohol. The washings were discarded. The soil was washed four times with 1 N ammonium acetate (adjusted to pH 7.0) to replace the calcium ions. These washings with ammonium acetate were collected in a 250 ml. volumetric flask made to volume with 1 N ammonium acetate. Calcium was then determined by means of the Beckman model D U spectrophotometer with flame attachment. The total exchange capacity was then determined by the amount of calcium recorded.

The exchangeable calcium was determined by the following method: Two g. samples of air dried soil were placed into 100 ml. centrifuge tubes. The soil was washed four times with 50 ml. portions of 1 N ammonium acetate (adjusted to pH 7.0). The soil was resuspended each time by means of a rubber ball stirer attached to an electric motor and centrifuged until the supernatant liquid was clear. The washings were collected, and calcium was determined by means of the Beckman model D U spectrophotometer with flame attachment. Exchangeable calcium was then determined.

The colorimetric method of Bray and Kurtz (1) was used to determine available phosphorus. Available phosphorus was extracted from the soil with a solution that was 0.025 N with respect to HCl and 0.03 N with respect to NH_4F. A soil to solution ratio of 1 to 50 was used in the extraction of available phosphorus.

The organic matter content was determined by modification of the method of Walkley-Black (Peech, et al., 17). One and one-half g. of soil were transferred to a 500 ml. Erlenmyer flask, and 10 ml. of 1 N potassium dicromate was added to the soil. Then 20 ml. of concentrated sulfuric acid were added rapidly. After the flask cooled, 200 ml. of water, 10 ml. of concentrated phosphorus acid, and 0.5 ml. of barium diphenylaminesulfonate indicator were added.

The soil solution was then titrated with ferrous sulfate to determine the amount of potassium dichromate that was reduced by the soil. The percentage organic matter was then determined by multiplying the number of ml. of potassium dicromate reduced by the soil times a constant 0.69 and dividing by weight of soil sample.

For the determination of exchangeable potassium in the soil, 50 ml. of 1 N ammonium acetate extracting solution were added to a 10 g. sample of air dried soil. The mixture was then shaken mechanically for 10 minutes. The suspension was filtered. A measured amount of solution containing an internal standard, lithum nitrate, was added to an aliquot of the filtrate. This was analyzed for content of potassium by use of the Perkin-Elmer model 52 A flame emission spectrophotometer.

Plant Analyses

Before analyses for calcium and phosphorus were made, the alfalfa from each cutting was dried in a forced air draft oven at 105° C.

Wet digestion with nitric and perchloric acids was used. Two g. samples of finely ground plant material were transferred to 250 ml. beakers. To this 25 ml. of nitric acid, 20 ml. water, and 20 ml. of perchloric acid were added. The beaker and its contents were then placed on the hot plate to be digested to white crystals. The residue was then dissolved in 20 ml. of hot 2 N hydrochloric acid. The liquid was then filtered through phosphorus free filter paper into 250 ml. volumetric flasks. The beakers and the funnels were rinsed several times with distilled water, and the filtrate was made to a volume of 250 ml. with distilled water. An aliquot of this solution was taken and diluted as necessary to determine calcium on the beckman flame photometer. Another aliquot was taken, neutralized by 0.1 N solium hydroxide, made to a known volume, and used in determining phosphorus content by use of the Coleman Junior photoelectric colorimeter.

Greenhouse Technique

Soil materials for the greenhouse experiment were passed through a ¼ inch hail screen, thoroughly mixed, and air dried. One gallon glazed earthware pots were used to contain the greenhouse cultures. The pot cultures contained 4,000 g. of air dried soil from each of Parsons silt loam, Bates fine sandy loam, and Idana silty clay loam soils and 3,500 g. of soil from the Cherokee silt loam soil. The pots were spaced approximately one inch apart on the greenhouse bench.

The treatments, which included three rates of rock phosphate and two rates of superphosphate, were applied to both acid and limed soil. A control culture was included for each. This corresponded to the equivalent of 12 treatments. Each was replicated four times for each soil (Table 3) making a total of 48 pot cultures for each of the four soils.

The rate of application of the fertilizer for the treatments was determined by applying approximately the same equivalents of calcium in the form of rock phosphate as were required by the lime requirement for each soil. This determined the heaviest rate of application of rock phosphate for each soil. The other two rates

Table 3. Treatments used in greenhouse experiment with soils shown.

Treatment	Parsons silt loam		Bates fine sandy loam		Cherokee silt loam		Idana silty clay loam	
	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)
1	0	0	0	0	0	0	0	0
2	0	40 (SP)*	0	140 (SP)*	0	70 (SP)*	0	100 (SP)*
3	0	160 (SP)*	0	560 (SP)*	0	280 (SP)*	0	400 (SP)*
4	0	40 (RP)**	0	140 (RP)**	0	70 (RP)**	0	100 (RP)**
5	0	160 (RP)**	0	560 (RP)**	0	280 (RP)**	0	400 (RP)**
6	0	640 (RP)**	0	2,240 (RP)**	0	1,120 (RP)**	0	1,600 (RP)**
7	2,000	0	7,000	0	3,500	0	5,000	0
8	2,000	40 (SP)*	7,000	140 (SP)*	3,500	70 (SP)**	5,000	100 (SP)*
9	2,000	160 (SP)*	7,000	560 (SP)*	3,500	280 (SP)**	5,000	400 (SP)*
10	2,000	40 (RP)**	7,000	140 (RP)**	3,500	70 (RP)**	5,000	100 (RP)**
11	2,000	160 (RP)**	7,000	560 (RP)**	3,500	280 (RP)**	5,000	400 (RP)**
12	2,000	640 (RP)**	7,000	2,240 (RP)**	3,500	1,120 (RP)**	5,000	1,600 (RP)**

Note: SP = Concentrated superphosphate RP = Rock phosphate
* Avail. P_2O_5 ** Total P_2O_5

of rock phosphate were 1/4th and 1/16th of the full rate.

The two rates of superphosphate for each soil were determined so as to supply the same amount of P_2O_5 (in the form of available P_2O_5) as was applied in the two lower rates of rock phosphate (expressed as total P_2O_5) (Table 3).

The required amounts of $Ca(OH)_2$ and fertilizer were determined for each soil treatment, weighed, and mixed thoroughly throughout the soil mass.

Alfalfa was planted in March, 1957. The method of planting involved the removal of approximately ½ inch of soil from the pot, placement of the seed on the exposed surface, followed by replacement of the removed layer of soil.

The stands of plants were thinned to 25 per pot during the third week after initial emergence. Distilled water was supplied daily or as needed to maintain good soil moisture conditions. The plants were harvested at a stage of from one-half to full bloom.

The four crops were harvested during the first week in June, the first week in July, the first week in August, and the first week in September of 1957, respectively.

After the fourth crop was harvested, soil samples were taken. This was accomplished by removing from each pot five one inch cores taken to a depth of the pot cultures. These samples were ground and analyzed in the laboratory.

Statistical Methods Used

Statistical analyses were accomplished for the data obtained from the greenhouse study. Analyses of variance and determinations of least significant differences (where applicable) were made according to the method of Snedecor (21). Analysis of variance was determined by considering each soil as a separate completely rondomized experiment.

An analysis of variance was computed for each soil for each individual cutting of alfalfa. Total yields from four cuttings of each treatment were obtained by addition. Another analysis of variance, as mentioned above, was calculated for each set of total yield data. Analyses of variance were calculated for phosphorus and calcium accumulations by plants.

Analyses of variance were also determined for contents of phosphorus and calcium in the plant material produced by each cutting.

EXPERIMENTAL RESULTS

Alfalfa Yields

Various alfalfa yield data are listed in Tables 4 to 7, inclusive. Significant variations in yields occurred with each of the four soils. The application of lime and of the heavy rate of rock phosphate alone increased total yields on each soil. Increased total yields also were produced by both rates of superphosphate alone and the intermediate rate of rock phosphate alone on the Bates, Cherokee, and Parsons soils. Greater total yields were obtained from Idana, Cherokee and Bates soils by both rates of superphosphate combined with lime and the heavy rate of rock phosphate combined with lime than were produced by use of lime alone. The greatest total yield of alfalfa for each soil was

Table 4. Yield of alfalfa grown on Parsons silt loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Yield of Alfalfa (grams / pot)				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	6.9	3.3	5.0	3.2	18.4
2	0	40 (SP)*	8.4	6.7	5.9	3.4	24.4
3	0	160 (SP)*	10.4	6.8	6.3	3.5	27.0
4	0	40 (RP)**	6.4	5.4	6.3	3.0	21.1
5	0	160 (RP)**	8.6	5.8	7.0	3.6	25.0
6	0	640 (RP)**	9.0	6.0	6.7	3.8	25.5
7	2,000	0	9.1	6.2	6.6	3.8	25.7
8	2,000	40 (SP)*	9.8	5.8	6.4	3.7	25.7
9	2,000	160 (SP)*	11.7	9.0	8.1	4.0	32.8
10	2,000	40 (RP)**	7.3	6.0	7.6	3.4	24.3
11	2,000	160 (RP)**	9.4	6.4	7.2	3.7	26.7
12	2,000	640 (RP)**	9.2	6.4	7.3	4.1	27.0
	L.S.D. P = .05		.73	1.88	1.35	.62	4.4
	L.S.D. P = .01		.98	2.52	1.82	.83	5.9

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail P_2O_5
** Total P_2O_5

Table 5. Yield of alfalfa grown on Bates fine sandy loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Yield of Alfalfa (grams / pot)				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	1.8	0.9	2.5	1.5	6.7
2	0	140 (SP)*	4.1	3.2	4.0	2.6	13.9
3	0	560 (SP)*	5.8	5.1	5.2	3.4	19.5
4	0	140 (RP)**	2.4	1.7	3.2	2.0	9.3
5	0	560 (RP)**	4.2	3.9	4.9	3.0	16.0
6	0	2,240 (RP)**	3.0	2.8	3.9	2.5	12.2
7	7,000	0	7.5	6.5	6.4	3.4	23.8
8	7,000	140 (SP)*	9.7	9.1	7.6	4.7	31.1
9	7,000	560 (SP)*	10.2	9.3	7.2	4.8	31.5
10	7,000	140 (RP)**	7.5	6.2	6.3	4.5	24.5
11	7,000	560 (RP)**	6.7	6.6	6.2	3.7	23.2
12	7,000	2,240 (RP)**	8.6	9.2	7.4	5.1	30.3
	L.S.D. P = .05		1.95	.60	1.26	.80	5.1
	L.S.D. P = .01		2.62	.82	1.70	1.08	6.9

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail P_2O_5
** Total P_2O_5

Table 6. Yield of alfalfa grown on Cherokee silt loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean Yield of Alfalfa (grams / pot) [1/] First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	2.8	2.4	3.6	2.5	11.8
2	0	70 (SP)*	5.3	3.6	4.8	3.3	17.0
3	0	280 (SP)*	9.2	6.8	7.0	4.4	27.4
4	0	70 (RP)**	4.4	3.4	4.6	3.7	16.1
5	0	280 (RP)**	5.5	4.6	5.3	3.8	19.2
6	0	1,120 (RP)**	6.1	5.2	6.2	4.8	22.3
7	3,500	0	8.0	6.1	6.9	4.0	25.0
8	3,500	70 (SP)**	10.2	7.9	7.7	4.7	30.5
9	3,500	280 (SP)**	12.9	10.0	9.0	5.9	37.8
10	3,500	70 (RP)**	9.0	6.1	6.9	4.1	26.1
11	3,500	280 (RP)**	8.4	6.1	6.3	4.2	25.0
12	3,500	1,120 (RP)**	9.7	8.0	8.4	5.4	31.5
	L.S.D. P = .05		1.49	1.75	1.65	.705	4.9
	L.S.D. P = .01		2.00	2.35	2.21	.948	6.6

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail P_2O_5
** Total P_2O_5

Table 7. Yield of alfalfa grown on Idana silty clay loam in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean Yield of Alfalfa (grams / pot) [1/]				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	7.6	6.2	6.6	4.6	25.0
2	0	100 (SP)*	8.4	9.5	7.6	5.2	30.7
3	0	400 (SP)*	10.0	8.1	6.5	5.0	29.6
4	0	100 (RP)**	9.2	8.1	7.8	5.0	30.1
5	0	400 (RP)**	7.6	8.1	6.9	5.0	27.6
6	0	1,600 (RP)**	9.1	9.2	8.2	5.6	32.1
7	5,000	0	10.8	9.3	8.3	5.0	33.4
8	5,000	100 (SP)*	13.7	11.4	8.7	6.5	40.3
9	5,000	400 (SP)*	16.4	12.6	9.0	6.7	44.7
10	5,000	100 (RP)**	10.6	10.2	8.8	6.0	35.6
11	5,000	400 (RP)**	11.4	9.3	8.5	5.8	35.0
12	5,000	1,600 (RP)**	12.8	10.7	9.1	6.4	39.0
	L.S.D. P = .05		3.48	2.36	1.76	1.40	5.8
	L.S.D. P = .01		4.68	3.16	2.37	1.88	9.1

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

produced by the combination of the heaviest rate of superphosphate with lime.

Least significant yield values varied from one cutting to another. With the Parsons soil (Table 4) at the time of the first cutting all treatments except low rates of rock phosphate with and without lime increased yields; at the time of the second cutting all treatments were effective; at the time of the third cutting application of lime alone, all treatments which included lime, and the two heaviest rates of rock phosphate alone were effective; and at the time of the fourth cutting application of the heaviest rate of rock phosphate with and without lime, lime alone, and the heaviest rate of superphosphate with lime increased yields. Also at the time of the first, second, and third cuttings, the application of heaviest rate of superphosphate with lime effected a greater increase than did lime alone. Combination of the low rate of superphosphate with lime also effected a greater increase in yield than did lime alone at the time of the first cutting.

The only treatments that failed to increase yields in the case of the Bates soil (Table 5) at the time of the first cutting were the lowest and highest rates of rock phosphate alone. With the second cutting each treatment increased the yield of alfalfa. At the times of the third and fourth cuttings the low rate of rock phosphate alone was the only treatment that did not increase the yield. Yields also were increased over those from lime alone by application of both rates of superphosphate with lime at the times of the first, second, and fourth cuttings; by application of heaviest rate of rock phosphate with lime at the times of the second and fourth cuttings; and by application of the lowest rate of rock phosphate with lime at the time of the fourth cuttings.

The yields of alfalfa were increased on Idana soil (Table 7) by application of low rate of superphosphate alone, lime alone, and heaviest rate of rock phosphate alone at the time of the second cutting and by all applications of superphosphate with lime and almost all applications of rock phosphate with lime at the time of each cutting of alfalfa.

Analyses of Plant Material

Phosphorus Uptake. Phosphorus accumulations by alfalfa are listed in Tables 8 to 11, inclusive. The heavy application of superphosphate with lime produced the greatest increase in total phosphorus uptake from each soil. However, a large increase in total phosphorus uptake was produced by application of heaviest rate of rock phosphate alone on Idana, Cherokee, and Parsons soils, of the low rate of superphosphate with and without lime on Idana, Bates, and Cherokee soils. The Bates soil also showed an increase in total phosphorus uptake from the two heaviest rates of rock phosphate alone and from the heaviest rate of rock phosphate with lime.

Increased phosphorus uptake occurred in the case of Parsons soil at the time of the first and third cuttings as a result of each rate of application of superphosphate with and without lime, at the time of the second cutting from each fertilizer treatment, and at the time of the fourth cutting from application of the heaviest rate of rock phosphate with and without lime and from heaviest rate of superphosphate with lime (Table 8).

Table 8. Phosphorus uptake by alfalfa grown on Parsons silt loam soil.

Treat-ment	Equivalent: Amount of $CaCO_3$ (Lbs./A)	Amount of: P_2O_5 (Lbs./A)	Mean uptake of Phosphorus (mg. / pot) 1/				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	6.4	5.1	7.2	3.7	22.4
2	0	40 (SP)*	10.9	11.5	10.3	4.3	37.0
3	0	160 (SP)*	16.9	15.3	14.1	5.7	52.0
4	0	40 (RP)**	6.6	9.5	9.6	4.1	29.8
5	0	160 (RP)**	10.0	10.8	12.2	5.4	38.4
6	0	640 (RP)**	12.3	12.8	14.9	7.3	47.3
7	2,000	0	9.1	9.3	9.9	4.8	33.1
8	2,000	40 (SP)*	11.2	10.1	10.7	4.8	36.8
9	2,000	160 (SP)*	18.5	17.8	17.8	6.8	60.9
10	2,000	40 (RP)**	7.8	10.6	9.8	4.4	32.6
11	2,000	160 (RP)**	9.9	9.9	12.5	4.7	37.0
12	2,000	640 (RP)**	10.5	11.9	13.4	7.6	43.4
	L.S.D. P = .05		3.19	3.33	2.86	2.15	7.6
	L.S.D. P = .01		4.29	4.47	3.85	2.88	10.3

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

In the case of Bates soil (Table 9) an increased phosphorus uptake occurred at the time of each cutting as a result of each application of superphosphate, as a result of applications of one-fourth the full rate of rock phosphate alone, and as a result of application of the full rate of rock phosphate with and without lime. Lime alone also increased phosphorus uptake at the times of both the first and second cuttings.

With Cherokee soil (Table 10), increased phosphorus uptake occurred at the time of each cutting as a result of application of heaviest rate of superphosphate with and without lime and as a result of application of the two heaviest rates of superphosphate alone. Phosphorus uptake also was increased at the times of the first, second and third cuttings as a result of application of all rates of rock phosphate with lime and as a result of application of the superphosphate with lime. Lime without phosphate increased phosphorus uptake at the time of the first and second cuttings, and low rates of application of rock phosphate increased phosphorus uptake at the time of the fourth cutting.

Phosphorus uptake from Idana soil was increased at the time of each cutting by application of heaviest rate of rock phosphate with and without lime and by application of either rate of superphosphate with lime (Table 11). The heaviest rate of application of superphosphate alone and one-fourth of the full rate of application of rock phosphate with lime increased phosphorus uptake at the times of the first, second and third cuttings. Application of just lime and the low rate of application of rock phosphate also increased phosphorus uptake at the times of the first cutting. The low rate

Table 9. Phosphorus uptake by alfalfa grown on Bates fine sandy loam soil.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean uptake of Phosphorus (mg. / pot) 1/ First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	2.9	2.1	4.4	2.3	11.7
2	0	140 (SP)*	10.6	6.9	10.8	5.0	33.3
3	0	560 (SP)*	16.8	15.5	10.4	10.2	52.9
4	0	140 (RP)**	5.6	4.1	6.1	3.6	19.4
5	0	560 (RP)**	9.4	9.2	15.4	7.2	41.2
6	0	2,240 (RP)**	9.8	8.8	13.0	10.9	42.5
7	7,000	0	8.2	7.7	6.4	3.5	25.8
8	7,000	140 (SP)*	15.0	11.2	15.2	7.3	48.7
9	7,000	560 (SP)*	22.2	24.5	22.8	13.0	82.5
10	7,000	140 (RP)**	7.7	7.9	7.9	3.9	27.4
11	7,000	560 (RP)**	7.4	8.9	9.9	4.5	30.7
12	7,000	2,240 (RP)**	11.0	14.0	12.5	9.1	46.6
	L.S.D. P = .05		5.44	4.66	2.81	2.41	7.86
	L.S.D. P = .01		7.31	2.26	3.78	3.24	10.56

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 10. Phosphorus uptake by alfalfa grown on Cherokee silt loam soil.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean uptake of Phosphorus (mg. / pot) 1/				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	3.8	3.7	4.4	3.4	15.3
2	0	70 (SP)*	7.3	6.2	7.3	4.2	25.0
3	0	280 (SP)*	18.4	15.2	17.5	10.5	61.6
4	0	70 (RP)**	6.0	5.7	6.2	5.4	23.3
5	0	280 (RP)**	8.2	8.6	9.7	7.2	33.7
6	0	1,120 (RP)**	13.3	12.2	16.0	14.4	55.9
7	3,500	0	8.5	7.3	7.6	4.3	27.7
8	3,500	70 (SP)**	13.4	12.4	11.7	5.0	42.5
9	3,500	280 (SP)**	27.0	22.1	23.0	14.6	86.7
10	3,500	70 (RP)**	10.2	8.0	8.8	4.2	31.2
11	3,500	280 (RP)**	9.6	9.0	9.9	5.2	33.7
12	3,500	1,120 (RP)**	11.3	11.0	14.1	4.5	40.9
	L.S.D. P = .05		2.92	3.45	3.62	2.02	9.8
	L.S.D. P = .01		3.92	4.63	4.87	2.71	13.1

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 11. Phosphorus uptake by alfalfa grown on Idana silty clay loam soil.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ uptake of Phosphorus (mg. / pot)				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	8.0	10.3	10.3	6.1	34.7
2	0	100 (SP)*	10.6	17.6	13.8	8.4	50.4
3	0	400 (SP)*	17.4	17.6	14.3	10.2	59.5
4	0	100 (RP)**	11.8	14.1	14.3	8.9	49.1
5	0	400 (RP)**	10.2	14.6	12.4	8.8	46.0
6	0	1,600 (RP)**	13.2	18.9	19.3	12.3	63.7
7	5,000	0	12.8	12.2	12.8	6.1	43.9
8	5,000	100 (SP)*	20.4	21.6	16.4	9.5	67.9
9	5,000	400 (SP)*	31.2	34.4	22.8	14.7	103.1
10	5,000	100 (RP)**	12.7	12.5	13.9	8.0	47.1
11	5,000	400 (RP)**	13.6	14.2	12.5	7.4	47.7
12	5,000	1,600 (RP)**	15.8	14.6	16.9	9.9	57.2
	L.S.D. P = .05		4.46	2.23	4.38	1.97	11.1
	L.S.D. P = .01		5.99	2.99	5.88	2.64	15.0

Note: SP= Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

of application of superphosphate alone and two lower rates of application of rock phosphate alone increased phosphorus uptake at the times of the second and fourth cuttings.

Phosphorus Content of Alfalfa. Phosphorus contents of alfalfa are shown in Tables 12 to 15, inclusive. With Parsons soil (Table 12) the phosphorus content of the plant material showed an increase at the time of the first and second cuttings as a result of application of either superphosphate alone, superphosphate plus lime, or the full rate of rock phosphate alone. At the times of each of the first two cuttings, superphosphate alone produced the greatest increase in percentage phosphorus in the alfalfa. However, at the times of the third and fourth cuttings, an increase in phosphorus content of plant material was produced by application of full rate of rock phosphate with and without lime and heaviest rate of superphosphate with lime. With the third cutting, superphosphate with lime caused the greatest increase in percentage of phosphorus in plant material, but the full rate of rock phosphate with lime caused the greatest increase in percentage phosphorus at the time of the fourth cutting.

In the case of the Bates soil (Table 13) the phosphorus content of the plant material was increased at the time of the first cutting by each application of either rock phosphate or superphosphate without lime; at the time of the third cutting by application of each low rate of superphosphate alone, the two heaviest rates of rock phosphate alone, and the heaviest rate of superphosphate with lime; and at the time of the fourth cutting by the heaviest rate of rock phosphate alone and heaviest rate of

Table 12. Effect of soil amendments and fertilizer upon phosphorus content of alfalfa grown on Parsons silt loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Phosporus Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	.092	.157	.146	.114
2	0	40 (SP)*	.130	.172	.175	.128
3	0	160 (SP)*	.163	.225	.156	.163
4	0	40 (RP)**	.101	.182	.154	.137
5	0	160 (RP)**	.119	.187	.177	.152
6	0	640 (RP)**	.137	.210	.219	.179
7	2,000	0	.100	.153	.151	.128
8	2,000	40 (SP)*	.114	.184	.168	.130
9	2,000	160 (SP)*	.158	.198	.221	.172
10	2,000	40 (RP)**	.104	.179	.135	.130
11	2,000	160 (RP)**	.106	.158	.175	.126
12	2,000	640 (RP)**	.119	.186	.186	.184
	L.S.D. P = .05		.017	.038	.036	.052
	L.S.D. P = .01		.023	.051	.047	.070

Note: SP = Concentrated superphosphate
RP = Rock Phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 13. Effect of soil amendments and fertilizer upon phosphorus content of alfalfa grown on Bates fine sandy loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Phosphorus Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	.161	.254	.179	.155
2	0	140 (SP)*	.287	.283	.279	.202
3	0	560 (SP)*	.276	.316	.208	.307
4	0	140 (RP)**	.234	.239	.199	.181
5	0	560 (RP)**	.230	.304	.312	.203
6	0	2,240 (RP)**	.313	.315	.341	.436
7	7,000	0	.110	.119	.103	.101
8	7,000	140 (SP)*	.154	.199	.202	.156
9	7,000	560 (SP)*	.216	.263	.314	.270
10	7,000	140 (RP)**	.104	.154	.133	.108
11	7,000	560 (RP)**	.107	.134	.160	.114
12	7,000	2,240 (RP)**	.128	.153	.172	.178
	L.S.D. P = .05		.058	.107	.064	.064
	L.S.D. P = .01		.077	.143	.086	.082

Note: S.P. = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail P_2O_5
** Total P_2O_5

Table 14. Effect of soil emendments and fertilizer upon phosphorus content of alfalfa grown on Cherokee silt loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Phosphorus Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	.156	.162	.123	.134
2	0	70 (SP)*	.139	.179	.150	.128
3	0	280 (SP)*	.199	.230	.251	.142
4	0	70 (RP)**	.139	.172	.135	.147
5	0	280 (RP)**	.150	.192	.178	.188
6	0	1,120 (RP)**	.220	.232	.200	.320
7	3,500	0	.107	.120	.111	.108
8	3,500	70 (SP)**	.132	.158	.151	.106
9	3,500	280 (SP)**	.208	.221	.257	.247
10	3,500	70 (RP)**	.114	.132	.127	.101
11	3,500	280 (RP)**	.115	.150	.145	.124
12	3,500	1,120 (RP)**	.117	.138	.168	.181
	L.S.D. P = .05		.029	.043	.059	.035
	L.S.D. P = .01		.039	.058	.080	.047

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 15. Effect of soil amendments and fertilizer upon phosphorus content of alfalfa grown on Idana silty clay loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Phosphorus Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	.109	.185	.158	.133
2	0	100 (SP)*	.128	.186	.179	.162
3	0	400 (SP)*	.174	.218	.221	.203
4	0	100 (RP)**	.137	.170	.180	.179
5	0	400 (RP)**	.134	.182	.180	.176
6	0	1,600 (RP)**	.146	.205	.235	.218
7	5,000	0	.122	.132	.152	.120
8	5,000	100 (SP)*	.148	.190	.188	.148
9	5,000	400 (SP)*	.190	.272	.252	.220
10	5,000	100 (RP)**	.120	.124	.182	.133
11	5,000	400 (RP)**	.119	.182	.145	.129
12	5,000	1,600 (RP)**	.124	.136	.188	.155
	L.S.D. P = .05		.032	.038	.054	.029
	L.S.D. P = .01		.043	.051	.072	.039

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

superphosphate with and without lime. At the time of the second cutting still more of the treatments produced significant increases in phosphorus content of plant material, but with this cutting there was a decrease in phosphorus content of plant material as a result of application of just lime. The third cutting also reflected a decrease in phosphorus content of the plant material as a result of application of just lime. In almost every cutting, the treatments which produced the lowest and highest contents of phosphorus in the plant material were lime alone and heaviest rate of rock phosphate alone, respectively.

With Cherokee soil (Table 14) the phosphorus content of the plant material was increased at the time of each cutting by application of the heaviest rate of rock phosphate alone and the heaviest rate of superphosphate with and without lime. Also with the fourth cutting, there was an increase due to the applications of either of the two lowest rates of rock phosphate alone and the heaviest rate of rock phosphate with lime. There was a decrease in phosphorus content of the plant material at the time of the first cutting as a result of the application of lime alone and lime plus each rate of rock phosphate. The plant material produced by that treatment involving the heaviest rate of rock phosphate alone almost always contained the greatest content of phosphorus.

The phosphorus content of the plant material produced on Idana soil was increased at the time of the first cutting by application of each rate of rock phosphate alone and by each rate of application of superphosphate with and without lime (Table 15). With the second cutting only the heaviest rate of superphosphate with lime effected an increase. With the third cutting application of the heaviest rate of rock phosphate alone and application of the heaviest rate of superphosphate with lime caused an increase. With each cutting the heaviest rate of superphosphate caused the greatest increase in phosphorus content of plant material.

Calcium Uptake. Calcium accumulations by alfalfa are listed in Tables 16 to 19, inclusive. The total calcium uptake for four cuttings of alfalfa from each soil was increased by liming. However, applications of rock phosphate and superphosphate effected still greater increases in calcium accumulated from each of Cherokee, Bates, and Idana soils. Plant material produced on Cherokee soil reflected an increase in calcium accumulation as a result of application of the full rate of rock phosphate alone. The greatest total amount of calcium accumulated by alfalfa was from the treatment involving the heaviest rate of rock phosphate with lime on each of Bates and Idana soils and from that treatment involving the heaviest rate of superphosphate with lime on each of the Cherokee and Parsons soils.

The least significant differences for calcium accumulations by alfalfa varied somewhat with each cutting produced upon the four soils.

With Parsons soil (Table 16) an increase in calcium uptake occurred with the first cutting as a result of application of the heaviest rate of superphosphate alone, as a result of combining both rates of superphosphate with lime, by combining two heavier rates of rock phosphate with lime. Any of the treatments which

Table 16. Calcium uptake by alfalfa grown on Parsons silt loam soil.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean uptake of Calcium (mg. / pot) [1/]				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	120.7	53.5	64.2	76.2	314.6
2	0	40 (SP)*	169.0	91.2	80.9	85.0	426.1
3	0	160 (SP)*	188.6	84.2	85.8	83.1	434.3
4	0	40 (RP)**	135.3	86.4	81.7	79.8	383.2
5	0	160 (RP)**	168.7	75.6	92.2	104.4	440.9
6	0	640 (RP)**	172.8	75.8	84.5	85.3	418.0
7	2,000	0	177.5	101.7	98.9	92.9	471.0
8	2,000	40 (SP)*	196.9	94.4	100.0	94.9	486.2
9	2,000	160 (SP)*	213.2	116.2	116.9	101.6	547.9
10	2,000	40 (RP)**	135.4	90.1	117.9	77.1	420.5
11	2,000	160 (RP)**	201.8	97.9	116.3	91.6	507.6
12	2,000	640 (RP)**	193.6	91.9	105.1	116.3	506.9
	L.S.D. P = .05		61.4	34.8	26.6	24.2	105.8
	L.S.D. P = .01		82.5	46.6	35.8	32.5	142.2

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 17. Calcium uptake by alfalfa grown on Bates fine sandy loam soil.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean[1/] uptake of Calcium (mg. / pot)				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	35.4	18.2	33.0	35.9	122.5
2	0	140 (SP)*	70.5	52.3	47.2	56.2	226.2
3	0	560 (SP)*	90.3	65.8	55.4	62.9	274.4
4	0	140 (RP)**	37.2	32.6	47.0	39.0	155.8
5	0	560 (RP)**	66.3	51.6	62.8	68.3	249.0
6	0	2,240 (RP)**	38.3	38.9	41.2	57.0	175.4
7	7,000	0	176.6	112.1	142.2	102.6	533.5
8	7,000	140 (SP)*	262.5	150.5	157.0	146.8	716.8
9	7,000	560 (SP)*	281.0	130.0	135.6	142.2	688.8
10	7,000	140 (RP)**	210.2	99.4	144.8	121.6	576.0
11	7,000	560 (RP)**	217.6	126.8	149.2	144.6	638.2
12	7,000	2,240 (RP)**	299.5	187.9	178.3	178.2	843.9
	L.S.D. P= .05		43.7	32.9	23.6	28.2	133.4
	L.S.D. P = .01		58.8	44.2	31.7	37.9	179.2

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 18. Calcium uptake by alfalfa grown on Cherokee silt loam soil.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean uptake of Calcium (mg. / pot) [1] First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	45.9	29.3	37.6	50.4	163.2
2	0	70 (SP)*	84.7	41.5	50.5	75.5	252.2
3	0	280 (SP)*	173.0	83.0	71.1	97.6	424.7
4	0	70 (RP)**	59.6	40.1	52.0	93.8	245.5
5	0	280 (RP)**	92.7	54.7	62.8	92.4	302.6
6	0	1,120 (RP)**	111.6	66.3	159.5	106.8	444.2
7	3,500	0	194.1	87.9	113.3	117.2	512.5
8	3,500	70 (SP)**	244.1	106.6	119.2	133.8	603.7
9	3,500	280 (SP)**	281.6	114.7	117.8	168.2	682.3
10	3,500	70 (RP)**	181.6	94.0	102.0	124.1	501.7
11	3,500	280 (RP)**	177.7	93.1	105.4	137.2	513.4
12	3,500	1,120 (RP)**	217.4	123.9	126.3	160.7	628.3
	L.S.D. P = .05		39.5	23.6	28.1	23.6	74.8
	L.S.D. P = .01		53.1	31.7	37.7	31.7	99.2

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 19. Calcium uptake by alfalfa grown on Idana silty clay loam soil.

Treat-ment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean[1/] uptake of Calcium (mg. / pot)				
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting	Total
1	0	0	116.7	65.1	66.6	80.2	328.6
2	0	100 (SP)*	137.6	92.9	78.2	89.2	398.0
3	0	400 (SP)*	158.8	77.0	60.1	99.8	395.7
4	0	100 (RP)**	168.3	73.6	74.3	87.5	403.7
5	0	400 (RP)**	141.6	79.0	72.1	90.6	383.3
6	0	1,600 (RP)**	127.6	97.5	86.4	96.2	407.7
7	5,000	0	167.6	85.6	112.5	99.0	464.7
8	5,000	100 (SP)*	214.4	99.5	99.2	124.6	537.7
9	5,000	400 (SP)*	244.5	103.3	108.0	117.6	573.3
10	5,000	100 (RP)**	182.7	129.8	114.0	117.0	543.5
11	5,000	400 (RP)**	197.9	115.0	122.0	110.8	545.7
12	5,000	1,600 (RP)**	216.9	124.2	119.1	129.0	589.2
	L.S.D. P = .05		52.9	31.6	22.5	22.4	95.5
	L.S.D. P = .01		71.1	42.4	30.2	30.1	128.3

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

included lime caused increased calcium accumulations at the times of the second and third cuttings. With the first cutting, application of the intermediate rate of rock phosphate alone, the heaviest rate of each of superphosphate and rock phosphate with lime caused increases in calcium accumulations by alfalfa.

Increase uptake of calcium occurred with Bates soil with each cutting as a result of liming alone (Table 17). However, at the time of the first cutting, both rates of superphosphate with lime and the heavy rate of rock phosphate with lime increased calcium uptake more than did lime alone. With the second, third, and fourth cuttings, only the applications of the heaviest rates of rock phosphate with lime increased calcium uptake more than did lime alone. Calcium uptake also was increased by application of the low rate of superphosphate alone at the time of the second cutting, by application of heaviest rate of superphosphate alone at the times of the first and second cuttings, and by application of one-fourth of the full rate of rock phosphate alone at the times of the second, third, and fourth cuttings.

In the case of Cherokee soil (Table 18), increased uptake of calcium occurred at the times of the first and second cuttings as a result of each treatment except the low rates of superphosphate and rock phosphate alone and at the time of the third cutting by each treatment with the exceptions of two lowest rates of rock phosphate alone and low rate of superphosphate alone. However, with the fourth crop each treatment effected greater uptake of calcium than did the control. Combination of the heaviest rate of superphosphate with lime effected greater accumulations of calcium by alfalfa at the times of the first, second and fourth cuttings than did mere treatment with lime alone. The same effect was noted for combination of the full rate of rock phosphate with lime at the times of the second and fourth cuttings.

Calcium uptake was increased at the time of the first cutting by application of lime alone and was further increased by application of heaviest rate of superphosphate with lime in the case of Idana soil (Table 10). However, with the second cutting, liming failed to produce a significant increase in calcium uptake whereas combination of phosphate with lime did. With this cutting the heaviest rate of rock phosphate alone also produced an increase in calcium uptake. The two rates of rock phosphate with lime caused greater accumulation of calcium than did lime alone. Lime alone produced an increase in calcium uptake at the time of the third cutting. Although lime alone did not produce an increase in calcium uptake at the time of the fourth cutting, each phosphate treatment produced an increase. Also both the lowest rate of application of superphosphate with lime and heaviest rate of rock phosphate alone produced increases in calcium accumulated when compared with lime alone.

Calcium Content of Alfalfa. Calcium contents of alfalfa are reported in Tables 20 to 23, inclusive. Calcium content of alfalfa produced by the Parson soil (Table 20) at the time of the first and third cuttings did not reflect significant variations with treatments. At the time of the second cutting, alfalfa produced on control cultures contained the greatest percentage of calcium. An increase in the calcium content of alfalfa at the time of the fourth

Table 20. Effect of soil amendments and fertilizer upon calcium content of alfalfa grown on Parsons silt loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Calcium Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	1.77	1.87	1.27	2.36
2	0	40 (SP)*	2.02	1.35	1.38	2.51
3	0	160 (SP)*	1.90	1.23	1.36	2.40
4	0	40 (RP)**	2.07	1.60	1.32	2.68
5	0	160 (RP)**	1.97	1.26	1.32	2.88
6	0	640 (RP)**	1.99	1.26	1.26	2.12
7	2,000	0	1.94	1.60	1.51	2.45
8	2,000	40 (SP)*	2.03	1.63	1.58	2.55
9	2,000	160 (SP)*	1.83	1.30	1.44	2.55
10	2,000	40 (RP)**	1.77	1.49	1.57	2.33
11	2,000	160 (RP)**	2.15	1.57	1.63	2.47
12	2,000	640 (RP)**	1.96	1.42	1.45	2.81
	L.S.D. P = .05		N S	.12	N S	.25
	L.S.D. P = .01		N S	.16	N S	.34

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference
N.S. = None significant

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 21. Effect of soil amendments and fertilizer upon calcium content of alfalfa grown on Bates fine sandy loam soil in greenhouse experiment comparing the twelve treatments shown.

Treat-ment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Calcium Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	2.02	2.02	1.22	2.36
2	0	140 (SP)*	1.50	1.57	1.18	2.05
3	0	560 (SP)*	1.56	1.26	1.06	1.87
4	0	140 (RP)**	1.52	1.67	1.44	1.99
5	0	560 (RP)**	1.51	1.31	1.28	2.30
6	0	2,240 (RP)**	1.28	1.42	1.08	2.28
7	7,000	0	1.73	1.74	2.24	2.98
8	7,000	140 (SP)*	2.73	1.64	2.07	3.15
9	7,000	560 (SP)*	2.75	1.40	1.88	2.98
10	7,000	140 (RP)**	2.82	1.62	2.30	3.46
11	7,000	560 (RP)**	3.24	1.91	2.42	3.62
12	7,000	2,240 (RP)**	3.47	2.06	2.31	3.47
	L.S.D. P = .05		.35	.51	.25	.57
	L.S.D. P = .01		.47	N.S.	.34	.77

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference
N.S. = None significant

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 22. Effect of soil amendments and fertilizer upon calcium content of alfalfa grown on Cherokee silt loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Calcium Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	1.45	1.15	1.01	1.99
2	0	70 (SP)*	1.60	1.16	1.06	2.28
3	0	280 (SP)*	1.88	1.22	1.02	2.21
4	0	70 (RP)**	1.36	1.20	1.12	2.18
5	0	280 (RP)**	1.62	1.16	1.16	2.43
6	0	1,120 (RP)**	1.82	1.30	2.56	2.34
7	3,500	0	2.44	1.44	1.65	2.93
8	3,500	70 (SP)**	2.20	1.36	1.55	2.86
9	3,500	280 (SP)**	2.17	1.15	1.31	2.84
10	3,500	70 (RP)**	2.06	1.54	1.48	3.04
11	3,500	280 (RP)**	2.14	1.52	1.54	3.22
12	3,500	1,120 (RP)**	2.25	1.56	1.50	2.96
	L.S.D. P = .05		.52	.26	.26	.35
	L.S.D. P = .01		.70	.31	.31	.47

Note: SP = Concentrated superphosphate
RP = Rock phosphate
L.S.D. = Least significant difference

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

Table 23. Effect of soil amendments and fertilizer upon calcium content of alfalfa grown on Idana silty clay loam soil in greenhouse experiment comparing the twelve treatments shown.

Treatment	Equivalent Amount of $CaCO_3$ (Lbs./A)	Amount of P_2O_5 (Lbs./A)	Mean 1/ Calcium Content of Plant Material (%)			
			First Cutting	Second Cutting	Third Cutting	Fourth Cutting
1	0	0	1.58	1.02	1.00	1.74
2	0	100 (SP)*	1.72	1.00	1.04	1.74
3	0	400 (SP)*	1.60	.96	.95	1.86
4	0	100 (RP)**	1.82	.91	.96	1.75
5	0	400 (RP)**	1.86	.98	1.06	1.82
6	0	1,600 (RP)**	1.61	1.05	1.06	1.70
7	5,000	0	1.58	.94	1.37	1.96
8	5,000	100 (SP)*	1.57	.87	1.14	1.43
9	5,000	400 (SP)*	1.50	.82	1.22	1.76
10	5,000	100 (RP)**	1.74	1.26	1.28	1.98
11	5,000	400 (RP)**	1.74	1.20	1.42	1.91
12	5,000	1,600 (RP)**	1.70	1.16	1.31	2.02
	L.S.D. P = .05		N.S.	.20	.17	N.S.
	L.S.D. P = .01		N.S.	.27	.23	N.S.

Note: SP = Concentrated superphosphate
RP = Rock Phosphate
L.S.D. = Least significant difference
N.S. = None significant

1/ Mean of four replications
* Avail. P_2O_5
** Total P_2O_5

cutting was produced as a result of application of the two lowest rates of rock phosphate alone and as a result of combination of the heaviest rate of rock phosphate with lime.

With Bates soil (Table 21) the calcium content of alfalfa was increased at the time of the first cutting by application of each rate of superphosphate and rock phosphate with lime and at the time of the third and fourth cuttings by application of lime alone. Calcium content was increased at the time of the first cutting as a result of each treatment which combined lime and phosphate. Combination of one rate of rock phosphate with lime effected an increase at the time of the fourth cutting. With the second cutting of alfalfa, no soil treatment effected an increase in plant calcium content.

Liming increased the calcium content of the alfalfa at the time each cutting of alfalfa was made on Cherokee soil (Table 22). The heaviest rate of rock phosphate alone effected an increase in calcium content of alfalfa at the times of the third and fourth cuttings. The lowest rate of application of rock phosphate alone caused an increase in calcium content at the time of the fourth cutting.

No significant variations in the calcium contents of alfalfa were produced at the times of the first and fourth cuttings produced on Idana soil (Table 23). However, with the second cutting, the application of lowest rate of rock phosphate plus lime produced an increase in the calcium content of the plant material.

Analyses of Soil After Four Cuttings of Alfalfa

Available Phosphorus. The amounts of available phosphorus, as found in the soil cultures after the harvesting of four cuttings of alfalfa, are shown in Table 24. Each soil reflected an increase in available phosphorus where either the full rate of superphosphate or rock phosphate was applied alone and where the full rate of superphosphate was applied with lime.

The application of the lowest rate of rock phosphate seemed to be as effective as the same amount of P_2O_5 applied as available phosphorus (superphosphate) in the cases of the Cherokee and Parsons soils. However, with the Cherokee soil the heaviest rate of superphosphate was more effective than even that rate of rock phosphate which supplied four times as much total P_2O_5. In the case of the Parsons soil, the heaviest rate of rock phosphate alone increased the available phosphorus content more than did superphosphate alone where the latter was applied at such rate as to furnish only one-fourth as much P_2O_5. Addition of lime reduced the availability of phosphorus in the cases of Parsons and Cherokee soils. This was true for each source of applied phosphorus, but the effect was most noticeable where rock phosphate had been applied.

In the cases of the Bates and Idana soils, the intermediate rate of rock phosphate alone increased the available phosphorus more than did the low rate of superphosphate alone. However, the heaviest rate of superphosphate alone increased available phosphorus considerably more than the heaviest rate of rock phosphate alone.

Table 24. Effect of soil treatments on available phosphorus content after production of four cuttings of alfalfa comparing the twelve treatments in Table 3.

Treat-ment	Mean available phosphorus (Lbs./A) [1/]			
	Parsons Silt Loam	Bates Fine Sandy Loam	Cherokee Silt Loam	Idana Silty Clay Loam
1	31	28	23	37
2	31	41	23	50
3	42	132	46	115
4	35	32	22	40
5	35	50	30	60
6	44	93	38	97
7	34	22	22	32
8	31	34	24	46
9	40	108	43	105
10	22	18	23	36
11	30	21	31	34
12	30	30	30	48

Note: 1/ Mean of four replications

In both of the above mentioned cases, the amounts of added P_2O_5 were four times as great with rock phosphate as with superphosphate. Addition of lime reduced the availability of phosphorus in both Bates and Idana soil cultures. With these soil cultures, the reduction of available phosphorus by application of lime was from three to four times as great with rock phosphate as with superphosphate treatments.

Exchangeable Calcium. The amounts of exchangeable calcium, as found in the soil cultures after the harvesting of four cuttings of alfalfa, are shown in Table 25. Only the Bates soil cultures reflected changes in contents of exchangeable calcium as a result of the mere addition of rock phosphate. Such changes were small in magnitude. Addition of lime increased exchangeable calcium in each soil culture. The increases, as based upon original levels of exchangeable calcium, were as follows:

Parsons	- 3%
Bates	- 191%
Cherokee	- 45%
Idana	- 19.8%

Changes in pH Values of Soils. The pH values of the soil cultures, as found after the harvesting of four cuttings of alfalfa, are shown in Table 26. In the case of the Bates soil culture, the application of the heaviest rate of rock phosphate alone caused a small increase in soil pH. Liming of each of the soils raised the pH to 6.7 or higher.

Lime Requirement Values of Soils. Lime requirement values for each of the soil cultures as found after the harvesting of four cuttings of alfalfa are shown in Table 27. Lime requirement was

Table 25. Effect of soil treatments on exchangeable calcium after four cuttings of alfalfa comparing the twelve treatments in Table 3.

Treatment	Mean1/ exchangeable calcium (m.e. / 100 g.)			
	Parsons silt loam	Bates fine sandy loam	Cherokee silt loam	Idana silty clay loam
1	9.9	3.4	5.4	12.6
2	9.3	3.4	5.1	11.2
3	8.7	3.4	4.9	10.5
4	8.6	3.5	5.2	11.3
5	9.2	3.6	5.3	11.8
6	9.3	4.0	3.8	11.6
7	10.2	9.8	7.8	15.1
8	10.4	9.6	8.1	15.6
9	10.1	9.6	8.0	15.1
10	10.6	9.7	8.3	15.6
11	10.4	9.9	8.5	15.3
12	10.3	9.7	8.4	14.9

Note: 1/ Mean of four replications

Table 26. Effect of soil treatments on pH after four cuttings of alfalfa comparing the twelve treatments shown in Table 3.

Treat- ment	Mean pH values of soil cultures [1]			
	Parsons silt loam	Bates fine sandy loam	Cherokee silt loam	Idana silty clay loam
1	6.2	5.3	5.7	5.4
2	6.0	5.3	5.7	5.4
3	6.1	5.2	5.4	5.3
4	6.1	5.30	5.8	5.4
5	6.2	5.30	5.7	5.5
6	6.2	5.4	5.7	5.5
7	6.7	6.8	6.7	6.7
8	6.7	6.7	6.6	6.8
9	6.6	6.7	6.6	6.7
10	6.7	6.8	6.6	6.8
11	6.8	6.8	6.8	6.9
12	6.7	6.6	6.6	6.8

Note: 1/ Mean of four replications

Table 27. Effect of soil treatments on lime requirement value after four cuttings of alfalfa comparing the twelve treatments shown in Table 3.

Treatment	Mean[1/] lime requirement of soils after cropping. (Lbs./A)			
	Parsons silt loam	Bates fine sandy loam	Cherokee silt loam	Idana silty clay loam
1	2,250	6,000	2,875	4,750
2	3,000	5,625	3,000	4,750
3	3,125	6,625	3,000	4,750
4	3,000	5,375	2,625	5,000
5	3,000	5,875	2,375	4,375
6	2,750	5,125	2,375	4,000
7	1,250	1,250	1,375	1,875
8	1,125	1,750	1,375	1,875
9	1,750	2,000	1,750	2,000
10	1,500	1,875	1,250	1,375
11	1,750	2,000	1,375	1,125
12	1,875	2,000	1,500	1,250

Note: 1/ Mean of four replications

increased on each of Parsons, Bates, and Cherokee soils by application of heaviest rate of superphosphate. In the cases of Bates, Cherokee, and Idana soils some rates of rock phosphate decreased the lime requirement. In each case the heaviest rate of rock phosphate caused the greatest decrease in lime requirement.

With each soil the addition of lime decreased the lime requirement. In the cases of the Cherokee and Idana soils, the application of some rates of rock phosphate with lime reduced the lime requirement more than did application of lime alone.

With each soil the inclusion of the heaviest rate of superphosphate with lime resulted in a greater lime requirement than that which occurred where only lime was applied.

DISCUSSION

There exists abundant evidence that liming of acid soils to pH near neutrality will promote the availability of both native soil phosphorus and of that applied as a soluble fertilizer. This influence might explain some of the increased yields which occurred with each of these soils where lime was applied. Increased yields of alfalfa also may result from other influences. Alfalfa is a heavy feeder of calcium. By comparing Tables 1 and 25, it was possible to observe changes in levels of exchangeable calcium which occurred as a result of liming. Liming effected the greatest increase in exchangeable calcium in the case of Bates fine sandy loam. It also caused considerable change in the cases of Cherokee silt loam and Idana silty clay loam. It appeared, therefore, that both liming and the provision of extra supplies of phosphorus increased alfalfa yields.

Considering total yield data alone for each soil, it was readily apparent that the combination of lime and the heaviest rate of superphosphate consistently produced the greatest yield of alfalfa. This immediately gave rise to the question as to whether phosphate treatment or lime was the most significant factor in effecting these yield increases.

It appeared that addition of phosphorus had slightly greater effect than did addition of lime, in the cases of Parsons silt loam and Cherokee silt loam soils. This was evidenced in yield data (Tables 4 to 6) because the heaviest rate of application of superphosphate alone produced total yields of 27.0 and 27.4 g. per pot, respectively, for these soils. These yield values were slightly greater than those which resulted from addition of lime alone, 25.7 and 25.0 g. per pot, respectively, for the same loam soil, the superiority of lime alone as compared to superphosphate alone was rather clear cut. Somewhat the same situation prevailed insofar as Idana Silty Clay loam was concerned. Even more important than these singular effects, was the more or less additive effect which occurred with each soil when superphosphate and lime were combined.

Certain applications of rock phosphate increased alfalfa yields on each soil. The heaviest rate of rock phosphate, when used without lime, actually increased the total yield of alfalfa produced by each soil. It appeared that rock phosphate application was especially beneficial in the case of the Bates soil. With this soil, combination of the heaviest rate of rock phosphate with lime was especially as effective in producing alfalfa as was the combination of either rate of superphosphate and lime. This particular soil was quite acid (pH = 5.1), high in exchangeable H^{+}(11.2 m.e./100g.) and low in exchangeable Ca^{++}(3.4 m.e./100g). This combination of factors undoubtedly aided in dissolving some of the fluorapatite contained in the added rock phosphate. There was some evidence that rock phosphate, when added alone, actually furnished some Ca^{++} to the exchange complex of this soil. Furthermore there was some evidence that addition of rock phosphate effected a slight increase in the pH value of this soil. This soil, because of certain inherent factors, was especially effective in reacting with rock phosphate in such manner as to yield an increased availability of phosphorus for the production of alfalfa.

Further evidence as to the adaptability of Bates fine sandy loam for application of rock phosphate was provided in the data pertaining to total phosphorus uptake, total calcium uptake, phosphorus content and calcium content.

It was quite apparent that much phosphorus was rendered available from rock phosphate in the case of unlimed Bates soil. Alfalfa produced under such circumstances had very high content of phosphorus at the time of each cutting, especially where the heaviest rate of rock phosphate was applied. Plants accumulated considerable total phosphorus under such circumstances. Actually this particular application of rock phosphate effected an almost four-fold increase in phosphorus accumulation by plants when used alone and it nearly doubled phosphorus accumulation when used with lime.

Rock phosphate treatment was rather effective in the case of unlimed Cherokee silt loam soil. In this case the soil was somewhat less acid than was the Bates fine sandy loam. It apparently was even somewhat more deficient in available phosphorus as evidenced by comparative soil test values. The combination of moderately acid soil conditions and acute phosphorus deficiency permitted alfalfa plants to derive considerable phosphorus from rock phosphate. Inasmuch as rock phosphate treatment did not increase the pH value or exchangeable calcium content of this soil, it did not seem that the fluorapatite molecule was as much affected by reaction with this soil as it was with the Bates soil. Available phosphorus content, as measured by chemical meanes, was affected relatively little by rock phosphate addition to the Cherokee silt loam. Apparently the release of phosphorus from rock phosphate to the plant in the Cherokee soil depended more upon factors which functioned directly between the plant and the rock phosphate system than upon those soil factors which might have aided in dissolution of phosphorus contained in rock phosphate as appeared to be true when such was added to Bates fine sandy loam.

Apparently rock phosphate, as applied in this experimental investigation, was less effective with Parsons silt loam and Idana silt loam than with either of the two soils previously discussed. Parsons silt loam was less acid than any of the other soils, it was relatively high in exchangeable Ca^{++} content and was not so deficient in available phosphorus as was either Cherokee or Bates soils. Thus soil properties were not so favorable for the dissolution of phosphorus from rock phosphate. Plants grown upon

Parsons soil accumulated more phosphorus from untreated soil than did plants grown upon untreated cultures of either Cherokee or Bates soil. This same comparison held also for limed cultures. There apparently was less necessity for the plant to derive phosphorus directly from the rock phosphate material than there was in the case of Cherokee soil. Thus rock phosphate was not able to yield available phosphorus quite so effectively under this set of soil-plant relationship.

Considerable phosphorus was rendered available from rock phosphate under certain circumstances associated with Idana soil. This was quite evident in the case of unlimed cultures where alfalfa plants accumulated more phosphorus from the heavy application of rock phosphate than from any other phosphate treatment applied to unlimed soil. Chemical measurements of available phosphorus indicated a marked release of available phosphorus from rock phosphate under these conditions. However, when this soil was limed the effectiveness of rock phosphate was markedly reduced. It would appear, therefore, that release of phosphorus from rock phosphate to available forms was dependent almost entirely upon factors associated with the soil. The plant,because of a fairly high level of available phosphorus in the original soil material, was not forced by necessity to derive relatively such a high proportion of its total phosphorus uptake directly from the rock phosphate material. The soil factors were, however, relatively favorable for the dissolution of phosphorus contained in rock phosphate (pH = 5.2, exchangeable H^+ = 9.6 m.e./100 g. and a lime requirement value of 5,000pounds per acre). Thus considerable phosphorus was rendered available from such and furthermore it was accumulated by the plants.

SUMMARY AND CONCLUSIONS

In answer to the original objectives of this study it was found that:

In the cases of some unlimed soil material, the lowest rate of application of rock phosphate yielded essentially the same amount of phosphorus to alfalfa plants as did the lower rate of application of superphosphate. This was true with Cherokee silt loam and Idana silty clay loam.

The lowest rate of rock phosphate application was appreciably less effective than the lower rate of superphosphate application in the cases of Parsons silt loam and Bates fine sandy loam.

The intermediate rate of rock phosphate application was superior to the lower rate of application of superphosphate in the case of unlimed cultures of Parsons silt loam, Bates fine sandy loam, and Cherokee silt loam. It was of about the same degree of effectiveness with Idana silty clay loam. The intermediate rate of rock phosphate application never was quite as effective as the higher rate of application of superphosphate, even though equivalent total amounts of P_2O_5 were furnished.

The highest rate of rock phosphate application was as effective as the higher rate of superphosphate in the cases of unlimed Parsons and Cherokee soils. It was somewhat superior in the case of Idana soil but slightly inferior in the case of the Bates soil.

Liming apparently reduced the effectiveness of rock phosphate in some instances. This was most apparent where the highest rate of rock phosphate was combined with lime. This tendency did not exist in the case of the Bates soil.

Liming always improved the efficiency with which superphosphate supplied phosphorus to alfalfa. The favorable interaction between lime and superphosphate in this respect enabled this treatment to rank at the top insofar as phosphorus supplying power was concerned. At the same time, rock phosphate compared less favorably with superphosphate on limed cultures than on unlimed ones.

Rock phosphate appeared to be more effective in supplying phosphorus for alfalfa after a period of three months or after the second cutting of alfalfa.

In the cases of some unlimed soil material, rock phosphate was not effective in supplying calcium for the soil. This was true with Parson silt loam, Cherokee silt loam, and Idana silty loam. This was not true with Bates fine sandy loam as there was some calcium supplied to the exchange complex of this soil.

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SUPERPHOSPHATE AND ROCK PHOSPHATE AS
SOURCES OF PHOSPHORUS AND CALCIUM FOR ALFALFA

by

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This investigation was designed first to compare rock phosphate and superphosphate as sources of phosphorus for alfalfa under both acid and essentially neutral soil conditions and secondly to compare rock phosphate and calcium hydroxide with respect to effectiveness in neutralizing soil acidity and/or supplying calcium both to the exchange complex of the soil and to the plants.

Surface samples of four naturally acid soils were obtained from the Thayer Experiment Field (Parsons silt loam), the Columbus Experiment Field (Cherokee Silt loam), a site south of Dennis, Kansas (Bates fine sandy loam), and a farm south of Wakefield, Kansas owned by Donald and Stanley Thurlow (Idana silty clay loam). Each soil material was screened, dried and distributed among 48 pot cultures. These cultures were employed in a greenhouse experiment.

One-half of the pot cultures was limed with calcium hydroxide at a rate which was in accordance with the previously determined lime requirement. In addition to the application of the liming material, two rates of superphosphate and three rates of rock phosphate were applied to each soil material, both the acid and the limed portions. The heaviest rate of application of rock phosphate was such as to supply approximately the same amount of calcium as was furnished by the application of calcium hydroxide. The lowest rate of application of rock phosphate was equal to one-sixteenth the heaviest rate. The intermediate rate of rock phosphate corresponded to one-fourth the heaviest rate and was four times the amount furnished by the lowest rate. In the case of the superphosphate treatments, the heavier rate furnished the same quantity of P_2O_5 as did the intermediate rate of rock phosphate. The lower rate of superphosphate was equal to one-fourth the heavier rate of the same material. Each of these treatments was replicated four times as was the control culture for each soil material. All of the soil amendments were mixed with the entire quantity of soil used in a given pot.

Alfalfa was planted in March, 1957. Each of the four cuttings was harvested at about the full bloom stage. Yields of plant material, total phosphorus and calcium accumulations by plants and actual phosphorus and calcium contents of the alfalfa were determined for each cutting. Data for these investigations were analyzed statistically.

After the completion of the fourth cutting, determinations upon each soil culture were made with respect to pH, exchangeable calcium content, available phosphorus content, and lime requirement value.

Yields were increased consistently by application of lime alone, by application of superphosphate alone and by heaviest rate of application of rock phosphate alone. The most pronounced effect upon yield resulted from combined application of lime and superphosphate. Combination of lime and rock phosphate was especially effective in the cases of Bates fine sandy loam. In this case the combination of the heaviest rate of rock phosphate with lime produced essentially the same effect as the combination of either rate of superphosphate with lime. With this particular soil, it appeared that both soil factors and plant factors were involved in the release of phosphorus from fluorapatite in rock phosphate to available forms.

Rock phosphate was least effective in the case of Parsons silt loam. Here it appeared that soil factors were less favorable for the release of phosphorus from rock phosphate to an available form. Furthermore the plants were not so dependent upon this source of phosphorus since the soil was relatively richer in available forms of this element.

Satisfactory performance of rock phosphate was noted in certain instances with each of the Cherokee silt loam soil and the Idana silty clay loam soil. In the case of the former, rock phosphate yielded available phosphorus most satisfactorily under unlimed conditions. Factors associated with the plants seemed especially effective under these conditions since alfalfa, because of necessity, had to derive phosphorus from the rock phosphate sources. The necessity of this extraction occurred because the original soil was quite low in content of available phosphorus. Unlimed Idana silty clay loam was especially favorable to the release of phosphorus from rock phosphate presumably because this soil was relatively acid in reaction and high in its content of exchangeable hydrogen. Plant factors was believed less important in this latter case since the soil was originally rather well supplied with available phosphorus. Liming of this material seemed to eliminate the plants' dependence upon rock phosphate as a source of available phosphorus.

Plant uptake of calcium was increased more by liming than by any other single addition of amendment. Superphosphate addition alone induced significant increases in calcium uptake in the case of these soils. Rock phosphate addition was thus effective with only two of the soils.

Exchangeable soil calcium was increased consistently as a result of liming but not as a result of rock phosphate treatment. Minor increases in exchangeable soil calcium as a result of rock phosphate treatment were noted only in the case of Bates fine sandy loam soil.

Chemically "available" phosphorus increased more as a result of superphosphate application than as a result of rock phosphate application. "Available" soil phosphorus was increased very little when lime and rock phosphate were combined as the soil treatment.