SOME EFFECTS OF THE APPLICATION OF SULFUR TO A SOIL.

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INTRODUCTION.

It has been known for many years that sulfur is one of the mineral elements essential for plant growth. Until rather recently,however,little attention has been given this element as it was thot that only very small amounts of sulfur were removed from the soil by plants. This was due in part to the fact that the method for the determination of sulfur in plants had consisted in determining only the sulfur present in the ash of the plants and,as most of the sulfur was in the organic form,it was driven off during ignition.

With the introduction of the more accurate method for the determination of the total sulfur in plant tissue it was found that by using the old method sometimes as much as ninety percent of the sulfur was lost. The knowledge of the larger amounts of sulfur removed by the crops has greatly stimulated interest in the role of sulfur in plant nutrition.

Other work has shown large losses of sulfur thru drainage waters as compared with the known amount of sulfur brought to earth in the rain water so that the need of certain soils for this element has become an important consideration.

HISTORICAL.

Comparison of the analyses of plants made by Hart and Peterson (13) of the Wisconsin Experiment Station with the an-alyses of Wolff, which had been accepted as the true sulfur content of plants, shows conclusively that the sulfur content of these plants had been placed entirely too low.

The following table taken from their works shows some comparisons.

TABLE I. PERCENTAGE COMPOSITION OF SOME COMMON FARM MATERIALS.

CROP	SULFUR	SULFUR TRIOXIDE	WOLFF'S SULFUR TRIOXIDE
Alfalfa hay	.287	.717	.425
Clover (red)	.164	.410	.222
Cotton seed meal	.487	1.217	.092
Oats	.126	.472	.055
Soy beans	.341	.852	.085
Wheat	.170	.425	.007

Shedd (25) of Kentucky using the sodium peroxide method found rather wide variations in the amount of sulfur present in different crops. The amount of sulfur as compared with the amount of phosphorus assimilated also varies widely. The sulfur taken up by leguminous plants is often in excess of the amount of phosphorus, altho usually the amounts are approximately the same. The cereals contain approximately one half as much sulfur as phosphorus, while the Cruciferae contain considerably more sulfur than phosphorus.

Until recently little work had been done toward determining the amount of sulfur in the soil. Hart and Peterson (13) have reported that in normal soils there are about equal quantities of phosphorus and sulfur and have pointed to the fact that approximately two thirds as much sulfur as phosphorus is removed in crops. They found that liberal manuring keeps up the supply of sulfur in a soil.

Ames and Boltz (1) have found that"soils well supplied with organic matter contain more sulfur than soils con taining a smaller amount of organic residue".

TABLE II. SULFUR CONTENT OF A CLYDE CLAY.

Upper 6 inches soil	1,056 pounds per acre.
6 - 12 inches	830 pounds per acre.
12 - 18 inches	686 pounds per acre.

It has been suggested by Berthelot and Andre (2) that the sulfur in soils occurs in at least three general combinations, (1) sulfates and sulfides, (2) ethereal sulfur, and (3)organic compounds. They have pointed out that sulfides would be rapidly changed under normal conditions so that this form would be present in considerable quantities only under poorly aerated conditions.

Shedd (25) has reported analyses of virgin and cultivated soils from different geological areas for both sulfur and phosphorus and has shown that in most cases sulfur has been lost more rapidly thru cultivation than has phosphorus.

As an average of several analyses of"typical soils of that part of the state where they were taken",Swanson and Miller have found considerable loss of sulfur thru cultivation.

Table III. AVERAGE SULFUR CONTENT OF SOME KANSAS SOILS.(26)

	VIRGIN	CULTIVATED
Surface 0 - 7 inches	.046 %	.027 %
Subsurface 7 - 20 in.	.044 %	.022 %
Subsoil 20 -40 in.	.034 %	.026 %

Considering the forty inch depth of soil with a weight of twelve million pounds per acre there has been a loss for the three strata of nineteen hundred and twenty pounds of sulfur. They also found that there was no relation between the amount of sulfur removed by crops and the amount indicated as lost by the analysis of the soils.

Lyon and Bizzell (21) have reported large losses of sulfur thru drainage. In the lysimeter work at Cornell it was found that the sulfur removed"from an unplanted,unlimed soil that had received some farm manure but no commercial fertilizer amounted to forty four pounds per acre annually". Application of lime increased the loss thru drainage.

Data obtained at Rothamsted (15) indicate losses of from about twenty pounds in the case of unmanured plots to as much as eighty pounds per acre annually where the plots were fertilized.

These losses are relatively high and were it not for the replenishing of the supply in the soil,sulfur would certainly become one of the limiting elements in crop production. Without thot of keeping up the sulfur supply in the soil,this element is added in several fertilizers commonly used such as in acid phosphate,potassium sulfate and barnyard manure. Commercial acid phosphate carries approximately one half calcium sulfate,so that two hundred pounds of acid phosphate would add about sixteen pounds of sulfur when this material is applied to soil.

Besides the amounts of sulfur added artificially there is some brought to the soil thru atmospheric precipitation. Kossowich (18) has reported that sulfur falling annually,in rain,varies from about nine pounds per acre in the country to as much as seventy two pounds near towns where there is a large amount of combustion. Data accumulated at Rothamsted and at Madison,Wisconsin,indicate that seven to eight pounds of sulfur per acre is about the true amount that is annually brought to the soil in rain.

The reported results of tests conducted to determine the effect of sulfur upon plant growth are variable. Pfeiffer and Blanck (22) believe that the importance of sulfur as a fertilizer has been exaggerated. In field experiments carried on by them only negative results were obtained,in which they found no increase in plant growth and no effect upon the assimilation of nitrogen.

Hopkins (16),using data secured at the Pennsylvania Experiment Station as a result of twenty four years experiment,has called attention to the fact that"bone black in sulfuric acid(making a product carrying sulfur)increased the value of the crops grown by $4.90 per acre per annum as an average of four plots in each of four series,while the application of the same amount of phosphorus in bone meal not carrying sulfur produced an average increase amounting to $4.96."

Sulfur applied in potassium sulfate did not increase the yield of alfalfa or other crops at the Kansas Experiment Station. In commenting on these results Swanson and Miller (26) have stated that"the reason for this may possibly be that in spite of the large losses of sulfur in cultivated soils,sulfofication still takes place sufficiently rapidly for the needs of the crop. The large loss in excess of that used by the crop makes this inference plausible."

Experimenting with sulfur as a means of combating potato scab,Wheeler,Hartwell and Moore (29) found injurious effects upon the plants where no lime was added. It was thot that the injury was due to a gradually increasing acidity brought about by the oxidation of the sulfur. In order to further test the action of sulfur upon the plants a series of pot cultures was begun. Oats were grown on the pots and this crop was followed by millet. Both crops showed decided injury where sulfur was added. Ammonium sulfate is suggested as the form in which sulfur may be added to the soil,"since ammonia returns its cost by its action as a manure. Sulfur,on the other hand,is much more expensive than sulfate of ammonia and has little,if any,even indirect manurial value."

Bernhard also studying the effects of sulfur on potato scab has found great benefit from sulfur. He believes that it disinfects the soil and puts it into better physical condition,causing quicker and more intensive action of commercial fertilizers and the production of more available food stuff.

Dymond,Hughes and Jupe (10) working with pot cultures found that when the plants were protected from the outside atmosphere they clearly showed the need of sulfur,while those not so protected showed no need of sulfur. Vetch was a possible exception. These workers found that sulfur greatly increased the percentage of albuminoid nitrogen in the crops grown.

Reimer (24) in Oregon,found that the application of sulfur either in super-phosphate or as gypsum increased the yield of alfalfa from twenty five to five hundred percent. The soils used had a relatively high phosphorus content,and rock phosphate gave no increase.

At the Kentucky Experiment Station (25) sulfur fertilizers were found to be beneficial when applied to many different crops. Tobacco gave decided increase in growth when sulfur was applied to a fertilizer containing nitrogen,phosphorus and potassium as compared to the growth where only the last three elements were used. Clover,however,did not show any appreciable effect from the addition of sulfur except in the case of potassium sulfate and this beneficial effect may have been due to the potassium.

Hart and Tottingham (14) in greenhouse work at Wisconsin Experiment Station,obtained increased growth of clover and rape where sulfates were added to a complete fertilizer treatment. In general,calcium sulfate proved more effective than sodium sulfate. Elemental sulfur as a rule gave harmful effects even in the presence"of a generous supply of calcium carbonate". There was a noticeable extension of roots where sulfates were added.

Pitz (23) also of Wisconsin,concluded from pot culture experiments that"it seems safe to say that sulfur increased slightly the yield of clover in Miami silt loam soil".

Duley (9) working at Missouri Experiment Station,found that"flowers of sulfur increased the yield of clover over no treatment". No beneficial effect was noticeable,however,when sulfur was applied along with heavy applications of complete fertilizer containing no sulfur. Increased number of nodules on the roots of the clover grown where sulfur was added was readily apparent. Using rape,sulfur alone was slightly beneficial but this effect was not noticeable where used in connection with a complete fertilizer. No definite conclusions could be drawn from other experiments with corn and soy beans.

The beneficial effect of sulfur was thot by Demolon (7) to be due either to its effect upon bacterial activity or indirectly to the solvent action of the product of the oxidation upon the soil minerals.

Boullanger and Dugardin (4) found a beneficial effect resulting from the use of small amounts of sulfur and believed it was due to the action on bacterial activity. They found that the rate of decomposition of nitrogenous materials resulting in increased production of ammonia is stimulated by sulfur. With small amounts of sulfur the process of nitrification was also benefitted but with larger amounts the process was retard-

-ed. It is interesting to note that they concluded from work with pure cultures of nitrite and nitrate organisms that the nitrite organisms are not noticeably affected by applications of sulfur even in rather large amounts,while the larger amounts retarded the change from nitrites to nitrates. This is not what would naturally be expected as the accumulation of sulfuric acid formed upon the oxidation of the sulfur would be expected to retard the change from ammonia to nitrites more seriously for it is in this change that the medium would tend toward an acidic condition.

Experiments carried on by Shedd (25) showed thatsulfur when applied to the soil was rapidly changed to sulfate and that it furnished readily assimilable sulfur for alfalfa. After four months the amount of sulfur oxidized was generally about sixty percent of the total amount present regardless of whether one hundred or five hundred pounds per acre had been added.

In this connection the work of Brown and Kellogg (6) is interesting. The results of their work show that soils have a definite sulfofying power which is determinable in the laboratory. While some of this oxidation may be due to direct chemical action,it is thot that by far the larger part of that work is brought about by the activity of micro-organisms. The rate of oxidation is of importance as it is a commonly accepted idea that plants obtain their sulfur as sulfate thru their roots. It was found that the rate of oxidation was dependent upon many factors. Organic matter increased the rate as did also good aeration. Mixtures of sand

and soil showed more rapid oxidation of sulfur than soil alone, up to fifty percent sand,at which point there was a slowing up of the process due probably to the lessening of the food supply. The fact that the process is one of oxidation and requires aeration indicates that there is an optimum moisture content for each soil. The optimum moisture content was found to be about fifty percent of complete saturation,which is approximately that best adapted to most plant life. Carbohydrates were found to depress sulfofication,the amount of depression having a direct relation to the amount of the material added. The amount of depression also depended upon the solubility of the carbohydrate,that is,the greater the solubility the greater the depression of the process.

Brioux and Guerbet (5) found that carbohydrates had a retarding effect upon sulfofication but that nitrogenous materials and calcium carbonate increased the rate.

Kappen and Quensell (17) discuss the sulfur cycle. They suggest that the sulfur in organic remains is changed into ferrous sulfide,and finally into free sulfur by the action of the oxygen of the air. They found that sterilization of the soil retarded sulfofication and from this it was concluded that at least part of the oxidation was due to the work of micro-organisms,altho it was thot that the process was to a considerable extent a strictly chemical reaction.

In studying the effect of sulfur upon plant growth Pitz (23)set up a series of treatments of Miami silt loam in one gallon jars. Applications of calcium sulfate and elemental sulfur were made at the rate of .01 %,.05 %,.10 %, .5 %,and 1.0 %. The uncropped jars were kept at a good moisture content,sampled from time to time and determinations of ammonia and nitrates made. It was found that calcium sulfate had no noticeable effect upon either ammonification or nitrification."Elemental sulfur,on the other hand,in concentrations of .5 % and 1 % decreases nitrate formation." The ammonia production was greatly increased by concentrations of .5 % and 1 % of elemental sulfur. Some of his data are recorded below.

TABLE IV.

EFFECT OF ELEMENTAL SULFUR ON PRODUCTION OF AMMONIA

	Ammonia nitrogen(mgs) per 100 grams soil				
	12 days	30 days	44 days	72 days	93 days
Untreated	3.97	3.19	3.12	2.97	3.40
.01 % sulfur	3.91	2.38	3.19	2.72	3.23
.05 % sulfur	3.19	2.29	3.06	2.46	3.23
.10 % sulfur	3.06	2.21	3.23	2.55	3.16
.50 % sulfur	3.82	2.89	5.95	7.31	8.26
1.00 % sulfur	3.95	2.89	6.80	7.31	9.52

TABLE V.

EFFECT OF ELEMENTAL SULFUR ON NITRATE PRODUCTION

Nitrate nitrogen (mgs) per 100 grams soil

	12 days	30 days	44 days	72 days	93 days
Untreated	1.53	1.66	2.93	3.93	4.35
.01 % sulfur	1.80	1.99	2.65	3.13	4.13
.05 % sulfur	2.17	1.88	2.29	3.20	4.53
.10 % sulfur	1.38	1.69	2.92	4.13	4.93
.50 % sulfur	1.24	.54	1.41	1.14	.89
1.00 % sulfur	.94	.54	.64	.95	.85

That acidity is rapidly developed from the oxidation of sulfur in the soil has been shown by a number of workers. Lint (19) has shown a decided rise in the acidity of a soil due to the oxidation of sulfur added and this acidity was easily detected a year after application. Several men have hinted of possible solvent action of the sulfuric acid resulting from the oxidation of sulfur added to a soil.

Ames and Boltz (1) concluded from rather discordant data that there is some solvent action upon rock phosphate in a mixture of soil,rock phosphate and sulfur. In their experiments the cultures used were under anaerobic conditions which must necessarily work toward vitiation of the results.

Lipman,McLean and Lint (20) have shown that the oxidation of sulfur in a mixture with soil and rock phosphate can make phosphorus soluble. They believe that the results obtained "justify the claim that compost heaps in which sulfofication is active may be utilyzed for the production of available phosphoric acid out of insoluble phosphates". In view of the above results Lipman has suggested that the time may be near when regular applications of elemental sulfur will be made,the sulfur being used to supply the needs of the plant as a food and also to aid in making available other plant foods. He also has suggested that pure cultures of sulfofying bacteria may find a place in scientific agriculture.

Since the work reported in this thesis was undertaken,Lipman,McLean and Lint have reported further work on the availability of rock phosphate as affected by the oxidation of sulfur. From a large amount of work they have obtained results which substantiate the theory that the oxidation of sulfur"is of value in making available the phosphorus of mineral phosphates".

Fred and Hart (12) have reported comparative tests of the effects of sulfates and phosphates on the rate of ammonification,carbon dioxide evolution and upon bacterial numbers,in both solution and soil. Insoluble tri-calcium phosphate in the form of bone ash did not hasten ammonification in a peptone solution. The addition of monobasic potassium phosphate to the same solution caused a great increase in the production of ammonia. In soil,both phosphates showed favorable effect upon ammonification. The corresponding sulfates slightly increased ammonification. The potassium sulfate gave the larger increase and this effect was probably due to the potassium,altho the action of monobasic potassium phosphate as compared with that of potassium sulfate shows that the potassium does not materially effect ammonification.

It was also found that the sulfates of calcium,magnesium and potassium increased carbon dioxide production to some extent. The authors concluded that "the sulfates,altho as low in amount in most soils as phosphates,will not,in all probability,have the same general crop producing power as the phosphates".

OBJECT OF THIS EXPERIMENT.

Data have accumulated showing that as much as forty pounds of sulfur per acre are lost annually in drainage water, while only about one fifth of this amount is brought to the soil in rain and snow. With this loss so far in excess of the addition,it seems that eventually an essential element like sulfur must become a limiting element in crop production.

Rather recently interest has been aroused in the use of sulfur as a soil amendment and attempts have been made to determine its effect upon plant growth. A common form used in many of these tests was elemental sulfur altho it was a commonly accepted idea that plants take up the sulfur in the form of sulfates. The results thus far obtained with elemental sulfur may not necessarily be due to the need of the plants for this element but it seems probable that some of its effects have come about indirectly. The influence of sulfur upon the transformations of nitrogen in the soil or its effect upon the solubility of phosphorus,potassium and other essential elements may bring about marked results. Information that may throw light on the behavior of sulfur in the soil should prove valuable.

PLAN OF THE EXPERIMENT.

The work consisted of pot culture and biochemical studies of the effects of the various treatments upon the soil. By previous work Duley (9) had shown that, so far as known, the Eldon silt loam was one of the soils lowest in sulfur content in the state of Missouri, having only about three hundred pounds of sulfur per two million pounds surface soil, as determined by the strong acid digestion method. As he had done some work similar to the present work, it seemed wise to use the same soil.

The Eldon silt loam is a brown silt loam of good texture for pot culture work, fairly well supplied with organic matter and very slightly acid. A partial analysis follows.

TABLE VI.	%	Pounds per 2000000
Total nitrogen	.1959	3918
Total phosphorus	.0327	654
Total sulfur	.0206	412
Total potassium*	1.469	29380

*Average of two analyses of this type secured by the Missouri Experiment Station.

POT CULTURE WORK.

The soil was sifted thru a four mesh screen and thoroly mixed. The three gallon earthenware pots were weighed and an amount of soil representing ten kilograms of dry soil was weighed into each pot.

The materials for the different treatments were weighed on an analytical balance. In turn the soil from the different pots was placed on an oilcloth,the proper fertilizing materials added and the whole thoroly mixed. The soil was then returned to the pot and a watering device,patterned after that of Briggs and Shantz built up,using chert,which had been treated with hydrochloric acid,as the material thru which the water was to percolate.

After the watering device was put in,the pots were all reweighed and from this weight,the standard weight of each pot at the proper moisture content was calculated. An attempt was made to keep all cultures at a moisture content of twenty two percent. The pots were weighed each week and enough water added to bring the weight up to standard. Water was also added from time to time during the week,the amount being based on the quantity used the previous week. Toward the latter part of the growing season,water was added five and six times per week. Distilled water was used to water all cultures.

Additional water was added to all cultures where additions were made to the soil. Thus for every gram of organic matter added,two cubic centimeters of water was added in calculating the standard weight. For inorganic materials one fourth of their weight of water was added but this amount was almost negligible.

Four series of pots with the following treatments were assembled.

No.1 None

No.2 Sulfur

No.3 Calcium carbonate

No.4 Calcium carbonate + sulfur

No.5 Organic matter

No.6 Organic matter + sulfur

No.7 Organic matter + calcium carbonate

No.8 Organic matter + calcium carbonate + sulfur

No.9 Nitrogen + phosphorus + potassium

No.10 Nitrogen + phosphorus + potassium + sulfur

In later discussion the terms,lime will frequently be used to refer to calcium carbonate,O.M.to organic matter and the chemical symbols N,P,K,and S to nitrogen,phosphorus, potassium and sulfur.

The different materials were applied at the following rates:

Sulfur - 300 pounds per 2000000 pounds soil or enough to double the amount of sulfur in the soil as shown by the official method.

Calcium carbonate - Sufficient to neutralize the total acid formed if all of the sulfur added were oxidized.

Organic matter - Five tons ground clover hay per 2000000 pounds soil,clover being a common nitrogenous farm product.

Nitrogen - 80 pounds per 2000000 pounds soil,applied in sodium nitrate,this being the average amount of nitrogen found in two tons clover.

Phosphorus - 30 pounds per 2000000 pounds soil applied in mono-calcium phosphate,this being the average amount found in six tons of clover.

Potassium - 60 pounds per 2000000 pounds soil applied in potassium chloride,this being the amount found in two tons of clover.

"C.P." chemicals were used.

Representatives of two families of plants,Cruciferae and Leguminosae,were planted in the pots. The Cruciferae show a high sulfur content and for this reason they might be expected to respond to sulfur treatment. Purple topped,strap-leafed turnips were used. Red clover(Trifolium pratense) also has a fairly high sulfur content,is a good greenhouse plant and being a legume,might indicate interaction of sulfur with protein formation. Two series were sown to turnips and two series to clover.

BIOCHEMICAL.

For the biochemical studies , three hundred gram portions of the Eldon silt loam with treatments similar to the treatments in the various pots,were placed in pint Mason jars. Enough jars were set up so that two jars of each of the various treatments could be taken down every two weeks for a period of sixteen weeks and the contents analyzed for ammonia,nitrates,sulfates and easily soluble phosphorus. The jars,loosely capped,were kept in the original pasteboard containers in the greenhouse under conditions similar to the pots. The jars were each weighed at the start and were kept at approximately twenty two percent moisture content by adding distilled water from time to time as needed.

Later,in order to intensify the action of the sulfur, another series of no-crop cultures was set up, in which larger amounts of different additions were used, and treated in a way similar to the first no-crop series.

BIOCHEMICAL METHODS.

The 300 grams of soil were thoroly mixed and halved on a balance. One half was again divided into equal portions, to be used for the determination of ammonia and nitrates respectively.

The other half of the original sample was used for the determination of sulfates and easily soluble phosphorus.

The 75 gram portion for the ammonia determination was placed in an 800cc. Kjeldahl flask, about 10 grams of heavy magnesium oxide added together with 50 - 75 cc. ammonia-free water. The ammonia was then distilled into standard sulfuric acid using a mixture of steam and air to drive the ammonia over, the distillation being continued until 175 - 200 cc. of distillate was obtained. The excess acid was titrated with standard sodium hydroxide using sodium-alizarin-sulfonate as indicator. The distillation required from 40 - 50 minutes.

The 75 gram portion for nitrate determination was immediately placed in an electric oven and dried at a temperature of 100°- 105° C. It was then shaken up with 300 cc. of N/18 hydrochloric acid, allowed to settle, whereupon 200 cc. of the supernatant liquid was blown off and placed in a 500 cc. Kjeldahl flask. Six cc. of sodium hydroxide (200 grams per liter and free from nitrates) were added and the solution boiled until concentrated to less than one half the original volume. One hundred and seventy five cubic centimeters of ammonia-free water were added,which was followed by DeVarda metal and over a low flame distillation was begun. As the distillation proceeded the flames were turned higher. The ammonia from the reduction of the nitrates was distilled into standard sulfuric acid and the excess acid titrated with standard sodium hydroxide using rosalic acid as indicator. The distillation should require at least 40 minutes.

The one half of the original sample was placed in a shaker bottle,350 cc. of N/18 hydrochloric acid was added and shaken in a shaker for 2 hours. The sample was allowed to stand over night and the solution was filtered thru a folded filter. From the clear filtrate an aliquot representing 100 grams of soil was taken and run to dryness on the water bath. The residue left upon dehydration was taken up with water and a little hydrochloric acid and the silica filtered off. The filtrate from this filtration was heated to boiling and the sulfates were then precipitated by barium chloride. After standing over night the barium sulfate was filtered off,ignited and weighed.

A few cubic centimeters of nitric acid were added to the filtrate from the barium sulfate determination and the solution concentrated to about 10 cc. The acid was neutralized with ammonium hydroxide and the solution again made slightly acid with nitric acid. A few grams of ammonium nitrate were then added and the phosphorus precipitated by ammonium molybdate at a temperature of 50°C. After standing over night the ammonium-phospho-molybdate was filtered on a double filter, washed first with dilute nitric acid, then with .1 % ammonium nitrate until free from acid, and finally washed twice with cold water. The precipitate was then dissolved in standard potassium hydroxide and the excess alkali titrated with standard nitric acid using phenolphthalein as indicator.

In extracting the sulfates and phosphorus from the soil by the use of distilled water, a clear filtrate could not be obtained. Accordingly N/18 hydrochloric acid was used, as this was found to be the strength of dilute acid which most completely flocculated this soil.

TURNIP CROP.

The soil in all pots was made up to twenty two percent moisture content on December first. The pots were covered with oilcloth and allowed to stand until December fourth, when they were seeded.

Germination was uniform and strong except where organic matter was added. Within a few days after sprouting it was noticeable that where organic matter had been added the seedlings were not growing so well as where this material was not present. Fred (11) has found that green manures may seriously injure germination of certain seeds especially oily ones such as soy bean and cotton seed, altho peanuts, mustard and clover are somewhat affected. The injury appeared to be due to the action of certain fungi. While the clover added in the present work was dry, it is possible that the poor germination on the O.M. pots was due to the addition of this organic material.

After three weeks the plants on the pots where organic matter alone had been applied began damping off and this proceeded until there were fewer plants remaining than it was desired to grow. It was thot that with a crop like turnips, in the greenhouse, little root development would be obtained. It was planned to have a rather large number of plants in each pot with the idea that the greater portion of the plant weight would be in the top. Accordingly the turnips were gradually thinned to twenty plants per pot, except in the case of Nos. 25 and 35 (O.M. alone) in which the plants damped off until only nine remained in pot No. 25 and eighteen in pot No. 35, all of which grew to maturity. No plants died after six weeks from time of seeding.

As early as three weeks after planting, the plants in the pots treated with nitrogen, phosphorus and potassium were noticeably better than those in the pots with any other treatment, and this difference became more and more marked as growth continued. After two months from time of seeding, the plants that had survived in the "O.M. alone" pots were decidedly better than any other except where nitrogen, phosphorus and potassium had been added. The plants in the other O.M. treatments were becoming pale, the color being easily noticed in contrast with the color of the plants under N.P.K. treatment. The addition of lime appeared to be responsible for a slight retardation of growth as compared with no treatment.

As growth continued it became apparent that the paler plants, on the pots where treatments in addition to organic matter were applied,were not producing as much top growth as the plants on the other treatments. Toward the close of the experiment,however,as the roots began to enlarge,it was noticeable that root development under the O.M.treatment was proceeding with equal if not faster rate than under the other treatments,except the treatment with nitrogen,phosphorus and potassium. Shortly before harvesting the crop the leaves began to fall,but these were saved and weighed at the close of the experiment. The turnips were harvested March fourteenth,which was one hundred and one days from time of seeding. Plate No.I shows the appearance of the plants a few days before harvest.

TABLE VII. THE EFFECT OF SULFUR ON THE TURNIP CROP.

Amount of water used and weight of dry material.

Pot	Treatment	Water used. cc.	Total water used. cc.	Wt.roots, (grams)	Total wt. roots. (grams)	Wt. tops. (grams)	Total wt. tops. (grams)	Total wt. plants.(grams	
21	No treatment	18696		5.33		17.48			
31	No treatment	18610	37306	3.59	8.92	17.12	34.60	43.52	
22	Sulfur	18715		6.45		17.37			
32	Sulfur	18836	37551	3.96	10.41	17.58	34.95		45.36
23	Lime	16830		4.03		15.55			
33	Lime	16785	33615	3.00	7.03	14.75	30.30	37.33	
24	Lime + sulfur	17260		3.50		17.07			
34	Lime + sulfur	17656	34916	5.10	8.60	17.37	34.44		43.04
25	Organic matter	16520		10.80		12.63			
35	Organic matter	17774	34294	7.20	18.00	14.36	26.99	44.99	
26	O.M.+ S.	17410		6.73		13.90			
36	O.M.+ S.	16974	34384	4.06	10.79	10.59	24.49		35.28
27	O.M.+ lime	17054		5.15		14.18			
37	O.M.+ lime	17070	34124	4.95	10.10	11.48	25.66	35.76	
28	O.M.+ lime + S.	16134		3.45		9.77			
38	O.M.+ lime + S.	17006	33140	5.84	9.29	12.23	22.00		31.29
29	N.P.K.	24500		18.50		34.03			
39	N.P.K.	24440	48940	20.80	39.30	32.69	66.72	106.02	
30	N.P.K.S.	23980		15.25		29.30			
40	N.P.K.S.	24420	48400	18.90	34.15	33.27	62.57		96.72
								267.62	251.69

The data obtained concerning the effect of sulfur on the turnip crop is rather inconclusive. Sulfur appeared to be slightly beneficial when used alone, the increased growth being found in the roots rather than in the tops. Lime alone decreased the yield of turnips but the addition of sulfur to the lime counteracted this effect, this combination resulting in a yield approximately that obtained on the check. Sulfur in connection with organic matter, organic matter and lime, and soluble nitrogen, phosphorus and potassium, showed a decrease in dry matter produced as compared with these treatments alone.

Thus two treatments with sulfur show a slight increase while three treatments show a slight decrease in dry matter produced. The total dry weights of turnips obtained on the ten pots, where no elemental sulfur was added, was 267.62 grams and the corresponding weight where sulfur was added was 251.69 grams. These differences as to the effect of sulfur would seem to be within experimental error. However, it appears that even under greenhouse conditions where there is no addition of sulfur thru rainfall, there is sufficient soluble sulfur present in this soil to produce large crops of turnips.

It was to be expected that if sulfur in available form was lacking in this soil, the effect of the sulfur on the crop would be most marked where soluble plant foods other than sulfur were added, as the addition of these elements would throw the plant foods still more out of balance. However no increase was obtained when sulfur was added to the N.P.K.

treatment. The failure of sulfur to increase the crop when used in addition to nitrogen,phosphorus and potassium,was not due to its being unavailable,for tho added as flowers of sulfur,an unavailable form,it was rapidly oxidized to a soluble form. This was shown in a no-crop series to be discussed later,where added sulfur gave seven times as much soluble sulfate at the middle of the experiment,and eighteen times as much at the close as was found in soil where no sulfur was applied. It is probable that the rate of oxidation of sulfur was more rapid where plants were grown than in the no-crop series so that even larger amounts of sulfates were available for the crop than these figures show. It would therefore seem that if sulfur were the deficiency in the plant foods,where nitrogen,phosphorus and potassium alone were added,its effects on the crop should have been marked when it was applied along with these elements.

In view of the fact that sulfur gave no increase when used in connection with soluble plant foods,it seems probable that the slight beneficial effect of sulfur,obtained where used alone and in connection with lime,was due to indirect action upon other plant foods in the soil. Where large amounts of the three frequently deficient plant foods were added in soluble form the slight effect of the sulfur would be overshadowed. From the work published by Lipman andco-workers (20) and work reported later in this thesis,some action of sulfur upon the solubility of phosphorus in soil is shown. It is reasonable to expect similar solvent action ipon the potassium in the soil but this effect would likely not be so noticeable since in normal soils there is usually a greater deficiency of available phosphorus than potassium.

It is probable that somewhat different results would have been obtained if fewer plants had been grown. In the case of the treatments of organic matter and different additions, there seemed to be strong indications of insufficient quantities of available plant food for twenty plants,for where fewer plants were grown,as in Nos.25 and 35,the plants made a much better growth. Where soluble plant foods were added the number of turnips was none too many for a vigorous growth.

The element lacking in these O.M.treated pots would appear to be nitrogen for the clover crop on the same treatments showed no harmful effects and appeared to be benefitted. The inherent qualities of the clover plant would make it less susceptible to lack of available nitrogen. Chemical studies carried on in connection with this work,which will be discuss-ed later,showed less nitrate nitrogen where organic matter was added than in the corresponding treatments where organic matter was not added. Doryland,as well as others,has shown that the addition of energy material may cause a reduction of nitrates thru assimilation by micro-organisms. This may explain the results here noticed.

After harvesting the turnip crop,samples were taken from the soil in series 31 - 40 and nitrates present were determined. It was found that the nitrates varied within experimental error averaging eleven and two tenths pounds nitrate nitrogen per two million pounds soil,except in the case of pot No.35,which showed fourteen and eight tenths pounds present on the same basis,this being only three and six tenths pounds more than the average of the other pots. The work in the no-crop series,which will be discussed later, showed a nitrate nitrogen accumulation at the time of harvest of the turnips of about one hundred and fifteen pounds per two million pounds soil as an average of the four pots where neither organic matter nor N.P.K were added,one hundred and three pounds where organic matter was added and two hundred pounds where soluble plant foods were supplied. But where plants were grown these rather large and widely differing amounts of nitrates were reduced to the common level of eleven and two tenths pounds per two million pounds soil, which may be near the lower limit of concentration at which plants under these conditions may obtain nitrogen in sufficient quantities for sustained growth.

CLOVER CROP.

The pots in the clover series were seeded on December fourth and recieved the same treatment already described.

The germination was good altho just a trifle retarded where organic matter was added,this retarding effect of the organic matter persisting until after six weeks from date of seeding.

Three weeks from date of seeding the soluble plant foods were having noticeable effect,the plants in the pots containing added nitrogen,phosphorus and potassium being much stronger and of a better color than the other plants. This effect of soluble plant foods was not so noticeable, however,as was the case with the turnips in the other series. At six weeks it could be distinctly seen that lime was retarding growth as compared to no treatment,but sulfur when added to the lime appeared to overcome most of this depressing effect. Little difference could be noted between the different organic matter treatments. The soluble plant foods were producing the most growth and no difference was noticeable as a result of the addition of sulfur to the N.P.K.treatment.

After two months the sulfur alone appeared to be slightly better than no treatment. The retarding of growth where lime had been added was quite noticeable,while sulfur added to the lime increased the growth,altho the growth did not seem equal to that produced by the no treatment or sulfur alone. The plants where organic matter had been added had overcome their backwardness and now were better than the treatments where no organic matter was applied,except where soluble plant foods were added. With the N.P.K.treatments and sulfur in connection,pot No.9 appeared to be slightly better than No.10 (containing added sulfur), while pot No.20 (with sulfur) seemed slightly better than pot No.19.

Four months from time of seeding the same general effects as were noticeable at two months continued to be apparent. The crop was harvested April twentieth,which was one hundred and thirty eight days after seeding.

TABLE VIII. THE EFFECT OF SULFUR ON THE CLOVER CROP.

Amount of water used and weight of dry material.

Pot	Treatment	Water used. cc.	Total water used. cc.	Wt.tops. (grams)	Total wt. tops. (grams)	Wt.roots. (grams)	Total wt. roots. (grams)	Total wt. plants. (grams)	
1	No treatment	18740		17.87		22.78			
11	No treatment	18430	37170	17.23	35.10	22.92	45.70	80.80	
2	Sulfur	18130		18.15		23.40			
12	Sulfur	18275	36405	19.03	37.18	24.05	47.45		84.63
3	Lime	15760		15.80		21.50			
13	Lime	15409	31169	14.95	30.75	20.55	42.05	72.80	
4	Lime + sulfur	16339		18.20		24.72			
14	Lime + sulfur	16020	32359	16.40	34.60	22.05	46.77		81.37
5	Organic matter	19414		22.48		29.50			
15	Organic matter	19296	38710	21.57	44.05	28.22	57.72	101.77	
6	O.M.+ S.	19504		24.05		29.17			
16	O.M.+ S.	19116	38620	24.00	48.05	27.05	56.22		104.27
7	O.M.+ lime	18698		21.01		28.38			
17	O.M.+ lime	19266	37964	21.88	42.89	27.08	55.46	98.35	
8	O.M.+ lime + S.	18678		22.35		30.31			
18	O.M.+ lime + S.	19400	38078	22.45	44.80	31.45	61.76		106.56
9	N.P.K.	22365		33.29		37.60			
19	N.P.K.	22060	44425	31.64	64.93	37.10	74.70	139.63	
10	N.P.K.S.	22795		31.30		36.22			
20	N.P.K.S.	22885	45680	32.86	64.16	33.47	69.69		133.85
								493.35	510.68

Sulfur,when applied at the rate of three hundred pounds per two million pounds soil,increased the yield of clover,when used alone or in combination with lime,organic matter,and organic matter and lime,as compared with these treatments without sulfur. When used along with soluble nitrogen,phosphorus and potassium,addition of sulfur resulted in a decrease in the yield of clover. The largest increases due to sulfur were obtained where it was used in connection with lime. Lime alone,and in combination with organic matter, depressed the yield of clover but where sulfur was added to a treatment containing lime,the yield was considerably increased. Organic matter increased the yield of clover when compared with the corresponding treatments containing no organic matter. Soluble nitrogen,phosphorus and potassium gave a decided increase in growth.

No significant difference in the number of nodules under the different treatments was noticed. Plants under all treatments showed nodules,which indicated that the nodular organisms were present and not appreciably affected by the various treatments.

The results are,to some extent,in accord with those obtained by Duley,who used the same soil and crop. In both experiments,it was found that sulfur alone increased the yield of clover over no treatment,while lime alone depressed the yield. However,in the previous experiment,sulfur resulted in still further depression of the yield when added to the lime,but in the present work,sulfur in connection with lime produced a yield equal to that obtained under no treatment, and where lime and sulfur were used with organic matter the yield produced was larger than where organic matter alone was used, altho lime and organic matter gave less growth than organic matter alone. Sulfur in connection with the soluble plant foods gave a depression in yield in both experiments.

On the whole, there was a marked difference in the growth of plants in the two experiments. In the previous work, soluble nitrogen, phosphorus and potassium increased the total yield of clover on two pots from 6.98 grams on no treatment, to 68.83 grams where used in connection with lime, when lime alone gave a yield of 5.78 grams. In the present work, the increase due to the addition of these soluble plant foods was not nearly so marked. However, the elements were applied at somewhat different rates. In the previous work these elements were applied at the rate of eighteen pounds nitrogen, sixty pounds phosphorus and twenty-four pounds potassium per acre, while in the present work these elements were applied at the rate of eighty pounds nitrogen, thirty pounds phosphorus and sixty pounds potassium.per acre seven inches. In the previous work twenty plants were grown per pot as compared with twenty-two plants in the present experiment. The growing period was two weeks longer in the previous experiment than in the present one. The slow rate of growth in the previous experiment is thus apparent, since the no treatment in the present work gave a larger yield than was obtained on the complete fertilizer treatments in the previous work, even when the period of growth was shorter in the present experiment.

The effects of elemental sulfur on the clover crop in both experiments would appear to be the result of indirect action upon other plant foods rather than as a food for the plants. In both experiments the sulfur gave increased growth when used alone, but when used along with soluble nitrogen, phosphorus and potassium, where its effect as a plant food should have been more pronounced, no increase from its use resulted.

NO-CROP.

A no-crop series, involving the same treatments as were used in the pot cultures, was assembled in order to study the periodic changes taking place under these treatments, without the plant as a disturbing factor. It seemed that the more important effects of the sulfur treatment would be upon the solubility of mineral plant foods and upon the biological changes of soil nitrogen, especially upon nitrification. Accordingly determinations of soluble sulfates, soluble phosphorus and ammonia and nitrate nitrogen were made at intervals during the growing period. The results of analyses reported are (except in a few instances) the average of two different jars under the same treatment.

TABLE IX. SOLUBLE SULFATES.

Sulfur as sulfate per 2000000 pounds soil (pounds)

Treatment	*Start.	2 wk.	4 wk.	6 wk.	8 wk.	10 wk.	12 wk.	15 wk.	18 wk.
None	7.0	7.6	7.4	6.7	7.2	5.3	6.3	5.4	7.3
Sulfur	7.0	17.0	40.6	61.8	68.0	87.3	98.7	95.7	108.3
Lime	7.0	7.5	7.8	6.9	8.2	6.4	4.2	4.8	7.9
L.+ S.	7.0	28.0	40.7	51.9	69.7	86.0	97.6	100.9	108.8
O.M.	7.0	7.4	6.9	6.9	7.1	5.1	4.8	4.9	6.9
O.M.+ S.	7.0	20.4	38.1	49.6	73.9	83.9	89.8	88.2	105.1
O.M.+ L.	7.0	6.1	6.7	6.9	7.1	4.7	5.0	3.7	6.7
O.M.+L.+S.	7.0	37.6	54.4	67.2	72.3	91.3	89.8	102.5	116.0
N.P.K.	7.0	8.6	6.0	7.0	9.0	7.1	5.7	4.7	7.4
N.P.K.+ S.	7.0	19.3	27.6	40.1	56.6	83.8	88.4	94.5	108.9

* Average of all.

Sulfur was rapidly oxidized to sulfate when added to Eldon silt loam,altho the rate of oxidation appears to be less rapid than that found by some investigators. This may be due to the inherent qualities of this soil as Brown and Kellogg (6) have found that each soil has a definite sulfofying power. At the end of eighteen weeks more than one-third of the amount of sulfur applied was in the sulfate form and capable of being extracted by N/18 hydrochloric acid. Organic matter, lime,and nitrogen,phosphorus and potassium,in the amounts here used,had little effect upon the rate of oxidation,altho the treatment,organic matter + lime + sulfur,resulted in the largest production of sulfates.

It is of interest to note that where no elemental sulfur was added there was no measurable oxidation of sulfur. Where organic matter was added, carrying approximately sixteen pounds of sulfur per two million pounds soil, there was no noticeable increase of soluble sulfates, even after eighteen weeks.

TABLE X. AMMONIA ACCUMULATION.

Ammonia nitrogen per 2000000 pounds soil (pounds)

Treatment	Start.	2 wk.	4 wk.	6 wk.	8 wk.	10 wk.	12 wk.	15 wk.	18 wk.
None	28.7	28.2	26.3	36.8	37.9	38.5	43.5	38.4	31.2
Sulfur	28.7	29.9	28.9	38.8	41.9	32.9	42.4	37.1	33.1
Lime	28.7	31.4	23.3	39.5	35.2	35.5	44.2	35.8	35.9
L.+ S.	28.7	31.1	24.3	36.7	36.1	36.8	38.2	37.4	34.7
O.M.	28.7	42.0	31.6	35.7	41.6	41.7	47.4	36.8	37.4
O.M.+ S.	28.7	36.8	30.3	34.3	42.9	39.7	46.5	39.8	37.1
O.M.+ L.	28.7	40.3	32.5	30.8	39.0	45.5	48.0	39.8	38.3
O.M.+L.+S.	28.7	43.6	35.4	30.1	34.0	35.0	48.1	40.1	36.9
N.P.K.	28.7	41.7	32.9	22.5	35.6	40.0	46.2	36.2	34.3
N.P.K.+ S.	28.7	51.9	44.4	39.5	43.3	48.0	48.6	37.2	33.6

Sulfur, when applied at the rate of three hundred pounds per two million pounds soil, had little measurable effect upon ammonification. On the whole, there was an indication of an increase in distillable ammonia where sulfur was applied, but only where sulfur was used in connection with soluble nitrogen, phosphorus and potassium was there positive evidence of this increased accumulation of ammonia. With soluble plant foods there was an increase in distillable ammonia when sulfur was added,and this increase was maintained beyond ten weeks,after which the effect became less marked and at the close of the experiment had disappeared.

In allcases the greater variations in the amount of ammonia present were found toward the first part of the experiment. It will be remembered that it was during the first ten weeks that the rate of sulfur oxidation was most rapid. It would seem that the increased ammonia production was connected with the oxidation of the sulfur.

TABLE XI. NITRATE ACCUMULATION.

Nitrate nitrogen per 2000000 pounds soil (pounds)

Treatment	Start.	2 wk.	4 wk.	6 wk.	8 wk.	10 wk.	12 wk.	15 wk.	18 wk.
None	47	69	96	99	102	90	100	113	112
Sulfur	45	62	85	97	99	96	111	110	117
Lime	47	75	99	92	103	101	103	116	119
L.+ S.	43	69	95	91	104	94	106	120	119
O.M.	42	38	51	67	73	71	78	97	113
O.M.+ S.	45	35	56	73	74	81	94	100	108
O.M.+ L.	43	33	53	78	67	82	91	104	107
O.M.+L.+S.	48	49	65	84	71	88	102	110	113
N.P.K.	111	143	107	175	178	187	196	198	197
N.P.K.+ S.	108	133	103	163	169	170	185	201	201

The results obtained indicate a slight decrease in nitrates present in the soil under sulfur treatment. This decrease in nitrates was noticeable at the beginning of the experiment but as the rate of oxidation of the sulfur decreased this depression of the nitrates disappeared and the nitrates, in some instances where sulfur was added, increased beyond where no sulfur was applied.

This disappearance of the first effect of the sulfur and the final increase in the nitrates under sulfur treatment may be due to several causes. As a result of probable stimulation of bacterial activities under sulfur treatment, larger amounts of nitrates may have been used by the organisms and this would have caused a decrease, but as the rate of sulfur oxidation became slower the nitrates began to accumulate and the effect that the sulfur had exerted on the solubility of plant food elements was responsible for the increased accumulation. Then too the acidity developed upon oxidation of the sulfur may have had a slight retarding action on the nitrifying organisms but as the experiment was continued the organisms may have become accustomed to the presence of the slightly increased acidity or the reaction of the soil may have become better adjusted.

Where sulfur was added in connection with lime, the depressing effect was not so noticeable and when used along with organic matter, both with and without lime, it appeared to slightly increase nitrate accumulation. In connection with soluble nitrogen, phosphorus and potassium the depressing effect of the sulfur upon nitrate accumulation was most noticeable altho here again as the rate of oxidation of the sulfur decreased this effect of the sulfur disappeared.

The slow rate of nitrate accumulation under organic matter treatments was readily apparent. Until after ten weeks there was a decidedly smaller amount of nitrates present where organic matter was added,even tho this material was clover hay,a nitrogenous substance. It is also of interest to note the effect of soluble plant foods upon nitrate accumulation. The total nitrates present was always larger where nitrogen,phosphorus and potassium were added and up to the twelfth week these elements,and probably the element largely responsible was phosphorus,accelerated nitrate production more than any other treatment.

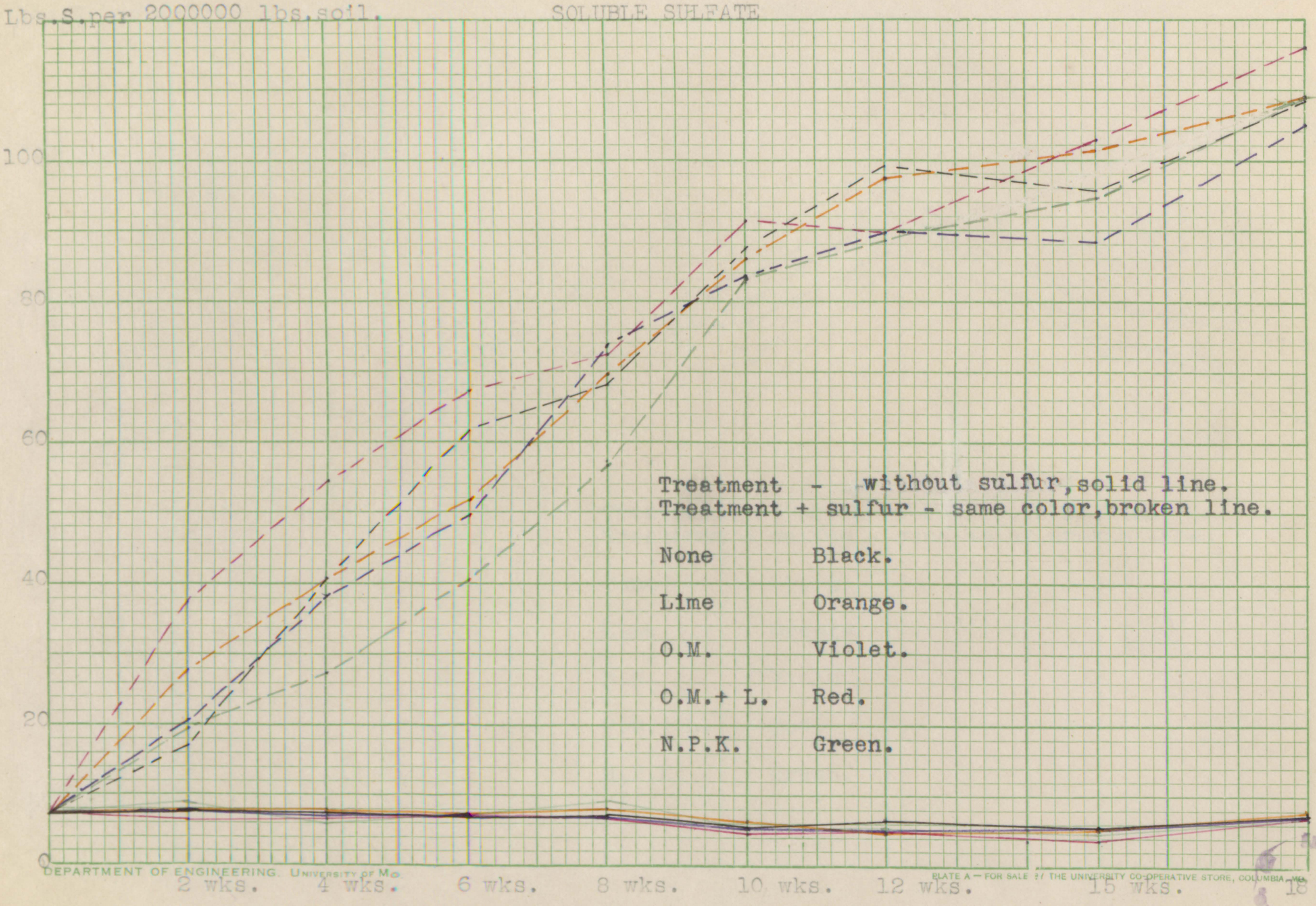
TABLE XII. EASILY SOLUBLE PHOSPHORUS.

Phosphorus per 2000000 pounds soil
(pounds)

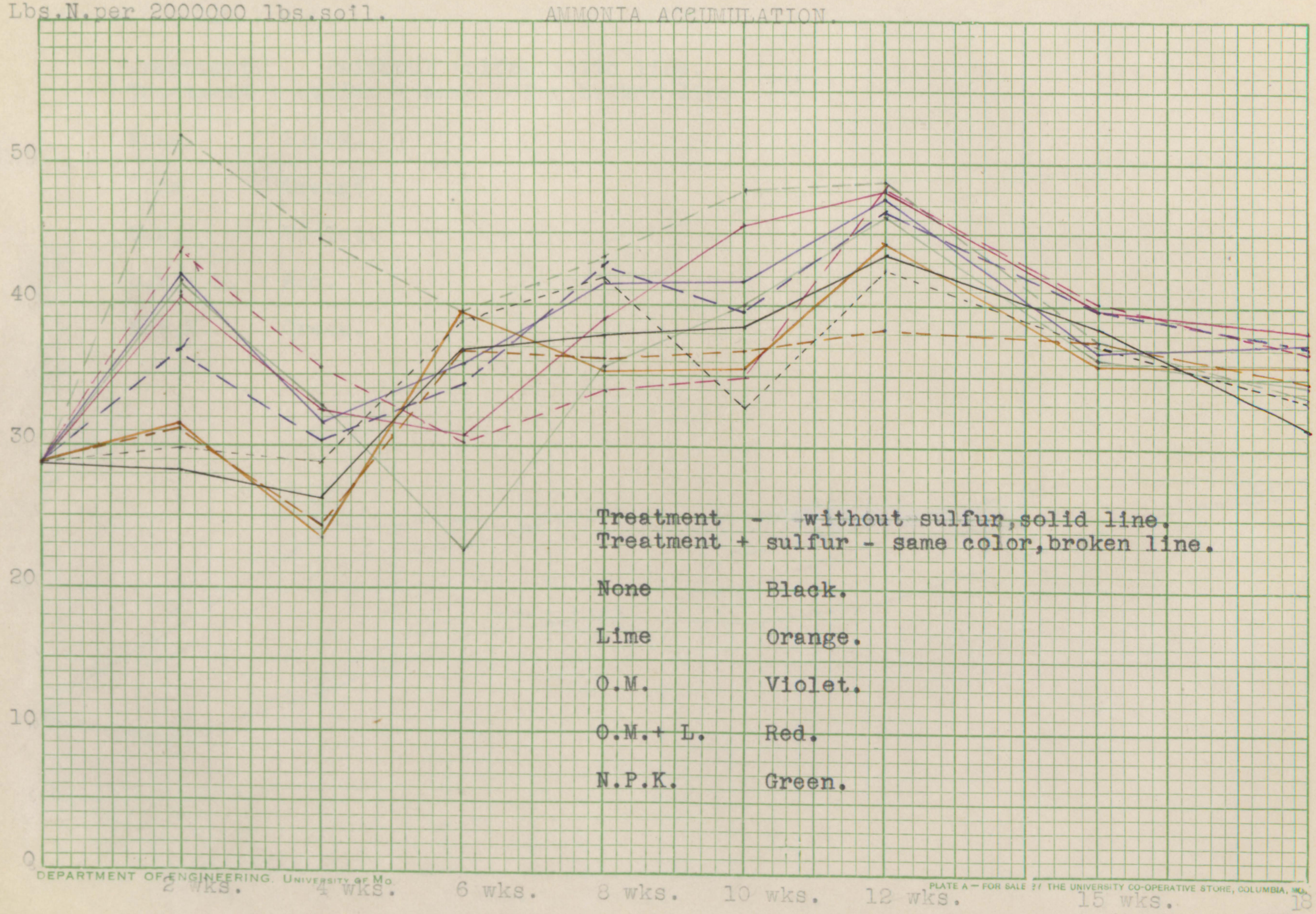
Treatment	Start.	2 wk.	4 wk.	6 wk.	8 wk.	10 wk.	12 wk.	15 wk.	18 wk.
None	7.2	6.2	6.5	4.1	6.6	6.4	5.3	5.2	4.9
Sulfur	6.9	7.7	6.8	4.7	7.3	7.9	5.3	5.7	5.5
Lime	7.2	6.5	6.2	4.1	6.6	5.9	5.0	4.6	5.2
L.+ S.	6.9	6.8	6.1	4.0	7.3	7.2	4.7	4.6	5.2
O.M.	11.3	8.6	6.9	5.2	7.6	6.6	6.4	4.8	6.0
O.M.+ S.	11.0	8.6	6.8	6.2	8.7	7.7	6.6	5.6	6.7
O.M.+ L.	11.8	8.9	6.9	5.3	7.8	6.8	6.2	5.0	5.3
O.M.+ L+S.	11.6	9.5	9.6	6.9	8.6	8.5	7.6	5.5	6.5
N.P.K.	12.3	11.0	10.3	7.2	8.5	9.3	8.6	6.7	7.3
N.P.K.+ S.	12.0	10.4	10.2	8.4	10.5	10.3	9.6	8.0	8.8

The amount of phosphorus that is soluble in eighteenth normal hydrochloric acid fluctuates from time to time under the same treatment. It is noticeable,however,that in all cases there is less phosphorus soluble in eighteenth normal hydrochloric acid at the close of the experiment than there was at the beginning. This decrease is most marked in the treatments where organic matter and soluble phosphorus in monocalcium phosphate were used. It is interesting to note that there is a relatively large amount of phosphorus in clover that is soluble in this strength acid,in fact almost as much is extracted from the soil when treated with clover as is recovered from the soil after an application of mono-calcium phosphate,which carried phosphorus at the rate of thirty pounds per two million pounds soil.

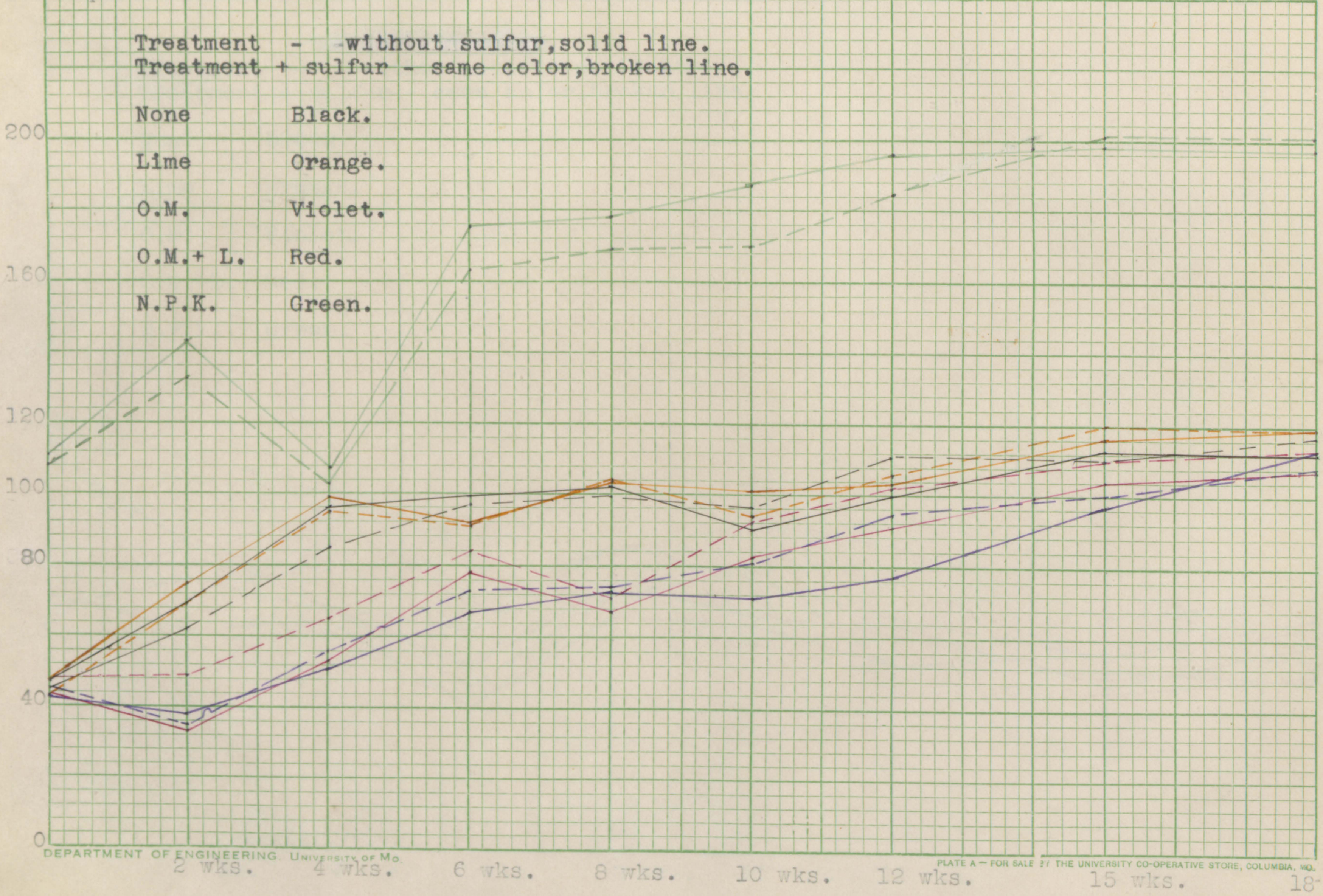
On the whole there is an indication that sulfur increased the amount of easily soluble phosphorus. This solvent effect of sulfur or the products resulting from its oxidation, is best seen where sulfur was used alone and in combination with soluble nitrogen,phosphorus and potassium or calcium carbonate. With organic matter the effect is somewhat masked for here other agencies are at work. The decomposition of the organic matter results in the increase of many different products,those having most important bearing on this point being ammonia,which would have a tendency to revert soluble phosphorus,and different acids such as carbonic,nitrous and nitric acids,which would exert a solvent action upon the soil minerals. These products may have greater effects upon the solubility of

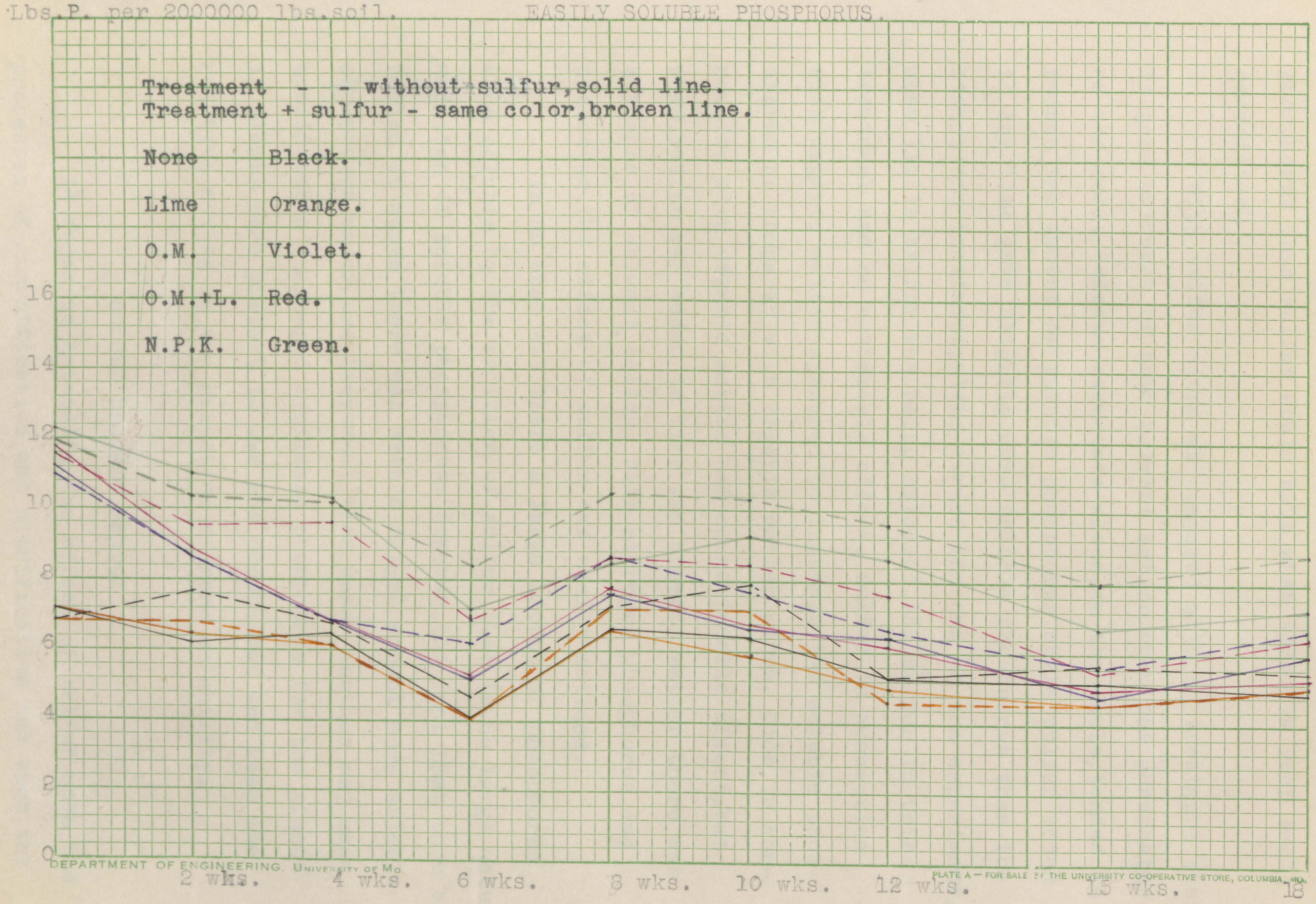


Lbs.S.per 2000000 lbs.soil.
SOLUBLE SULFATE
100
80
60
40
20
0
Treatment - without sulfur,solid line.
Treatment + sulfur - same color,broken line.
None Black.
Lime Orange.
O.M. Violet.
O.M.+ L. Red.
N.P.K. Green.
DEPARTMENT OF ENGINEERING. UNIVERSITY OF MO.
PLATE A — FOR SALE BY THE UNIVERSITY CO-OPERATIVE STORE, COLUMBIA, MO.
2 wks.
4 wks.
6 wks.
8 wks.
10 wks.
12 wks.
15 wks.
18


Lbs.N.per 2000000 lbs.soil.
AMMONIA ACCUMULATION.
50
40
30
20
10
0
2 wks.
4 wks.
6 wks.
8 wks.
10 wks.
12 wks.
15 wks.
18
Treatment - without sulfur,solid line.
Treatment + sulfur - same color,broken line.
None Black.
Lime Orange.
O.M. Violet.
O.M.+ L. Red.
N.P.K. Green.
DEPARTMENT OF ENGINEERING. UNIVERSITY OF MO.
PLATE A — FOR SALE BY THE UNIVERSITY CO-OPERATIVE STORE, COLUMBIA, MO.

Lbs.N.per 2000000 lbs.soil. NITRATE ACCUMULATION.




Lbs. P. per 2000000 lbs. soil.
EASILY SOLUBLE PHOSPHORUS.
Treatment - - without sulfur, solid line.
Treatment + sulfur - same color, broken line.
None Black.
Lime Orange.
O.M. Violet.
O.M.+L. Red.
N.P.K. Green.
16
14
12
10
8
6
4
2
0
2 wks.
4 wks.
6 wks.
8 wks.
10 wks.
12 wks.
15 wks.
18
DEPARTMENT OF ENGINEERING. UNIVERSITY OF MO.
PLATE A — FOR SALE BY THE UNIVERSITY CO-OPERATIVE STORE, COLUMBIA, MO.

4

phosphorus than sulfur would have when added in such small quantities.

With sulfur alone as compared with no treatment there is good evidence of some solvent action upon the phosphates of the soil. Calcium carbonate alone,on the whole,tended to reduce the amount of soluble phosphorus,while sulfur added to the lime gave slightly more solùble phosphorus than the lime alone treatment,altho toward the end of the experiment, when little sulfur was being oxidized,the sulfur in this treatment had no noticeable effect. Sulfur in connection with organic matter appeared to increase the soluble phosphorus as compared with organic matter alone. Lime in connection with organic matter had no noticeable effect,but when sulfur was added to lime and organic matter there was evidence of solvent action. With nitrogen phosphorus and potassium,the effect of sulfur was easily noticed.

In no case was there a large amount of phosphorus made soluble by the addition of sulfur,that is,no large accumulation of soluble phosphorus. However,the fact that thru a period of weeks there was even a slight amount more soluble phosphorus under one treatment than under another may mean considerable increased available phosphorus for the plants if plants were present to use the phosphorus and keep the reaction moving in the direction of more solubility.

SECOND NO-CROP SERIES.

In order to intensify the effect of sulfur upon the processes of ammonification and nitrification and upon the solubility of mineral phosphates,a series of pint jars was assembled,with the following treatments represented.

No.1 Soil + rock phosphate

No.2 Soil + alfalfa

No.3 Soil + rock phosphate + alfalfa

No.4 Soil + rock phosphate + sulfur

No.5 Soil + rock phosphate + alfalfa + sulfur

No.6 Soil + alfalfa + sulfur

No.7 Soil + rock phosphate + alfalfa + sulfur + calcium carbonate

No.8 Soil + rock phosphate + alfalfa + calcium sulfate

The different additions were applied at the following rates.

Rock phosphate	- 3 grams per 100 grams soil. (Commercial Tennessee brown rock,14% phosphorus.)
Sulfur - -	- 1 gram per 100 grams soil.
Alfalfa - -	- 2 grams per 100 grams soil. (Finely ground)
Calcium carbonate	- 1.042 grams per 100 grams soil,or the calculated amount sufficient to neutralize one third of the sulfur added,which was shown to be the amount of sulfur oxidized in twelve weeks in work previously reported.
Calcium sulfate	- 1.794 grams per 100 grams soil,carrying sulfur as sulfate equivalent to one third of the elemental sulfur added.

Three hundred grams of dry soil were placed in each jar in the first five treatments but only one hundred and fifty grams were used in the case of the last three treatments,where ammonia and nitrate accumulation only were to be determined. Thus the last three treatments are not entirely comparable with the first five as differences resulting from the effect of better aeration may have come about,altho the same general effect should be the same.

The jars were loosely capped,returned to the original paste board boxes and placed in the greenhouse. The soil was kept at about twenty two percent moisture by weighing the jars from time to time and adding distilled water as needed. The methods used in making chemical determinations in connection with this series were similar to those used in the work previously reported,changed only to adapt them to the increased amounts of the materials added. The results reported are averages of analyses of separate jars under the same treatment, except in the cases indicated.

TABLE XIII. SOLUBLE SULFATES.

Sulfur as sulfates per 100 grams soil (milligrams)

Treatment	Start	2 wks.	4 wks.	7 wks.	10 wks.	13 wks.
Rock phosphate(R.P.)	6.64	5.64	5.80	6.34	7.20	10.10
Alfalfa (O.M.)	1.98	1.26	1.10	1.56	2.80	5.10
O.M. + R.P.	7.94	6.28*	6.40	7.04	7.60	9.90
R.P + S.	8.14	17.46	31.40	48.90	75.30	81.60
O.M.+ R.P.+ S.	9.64	38.89	58.80	119.30+	90.20	98.50

* One determination. + Evidently too high.

At the end of thirteen weeks,about one twelfth of the sulfur added to a mixture of soil and rock phosphate was oxidized to sulfate and a still larger portion was oxidized when alfalfa was added to this mixture. This increase of the rate of oxidation when organic matter is present is in accord with work of others previously reported. There was little increase of soluble sulfates in treatments where no elemental sulfur was added.

TABLE XIV. AMMONIA ACCUMULATION.

Ammonia nitrogen per 100 grams soil (milligrams)

Treatment	Start	2 wks.	4 wks.	7 wks.	10 wks.	13 wks.
Rock phosphate(R.P.)	2.31	3.08	2.17	1.58	1.13	1.60
Alfalfa (O.M.)	2.71	3.85	2.63	1.98	1.24	2.00
O.M.+ R.P.	2.81	3.47	2.83	1.63	1.55	2.19
R.P.+ sulfur	2.07	4.04	4.77	4.69	5.30	6.17
O.M.+ R.P.+ sulfur	2.64	7.38	13.02	15.58	18.38	20.09
Alfalfa + sulfur	2.96	8.86	17.66			
O.M.+ S.+ R.P.+ lime	2.99	7.72	15.66			
O.M.+ R.P.+ $CaSO_4$	2.89	3.35	2.31			

Sulfur, when added to a mixture of soil and rock phosphate, increased ammonia accumulation as compared with a mixture of soil and rock phosphate. Rock phosphate only slightly increased ammonia accumulation when added to a mixture of alfalfa and soil as compared to the alfalfa treatment alone, but when sulfur was added to a mixture of soil, rock phosphate and alfalfa, the ammonia accumulation was greatly increased.

That this increase in ammonia accumulation was not due to the indirect action of the sulfur upon the rock phosphate is shown in the results obtained with the mixture of alfalfa and sulfur, which produced amounts of ammonia equal to those found under the alfalfa, rock phosphate and sulfur treatment. That the oxidized form of sulfur is not responsible for the increase is shown by comparing the amount of ammonia found under the treatment with alfalfa, rock phosphate and calcium sulfate with the amounts found under the treatments with alfalfa, rock phosphate and sulfur, and alfalfa, rock phosphate, sulfur and lime. In fact, calcium sulfate along with rock phosphate and alfalfa gave no increase of distillable ammonia over the treatment rock phosphate and alfalfa.

It is probable that the organisms responsible for the oxidation of the sulfur, use large quantities of organic matter and that considerable quantities of the nitrogen of the organic matter, in excess of the requirements of the organisms, is thrown off as ammonia.

TABLE XV. NITRATE ACCUMULATION.

Nitrate nitrogen per 100 grams soil
(milligrams)

Treatment	Start	2 wks.	4 wks.	7 wks.	10 wks.	13 wks.
Rock phosphate(R.P.)	2.46	3.79	3.50	4.42	5.41	5.69
Alfalfa (O.M.)	2.91	2.34	3.70	7.75	9.10	10.97
O.M.+ R.P.	2.96	1.26	3.86	7.05	8.54	8.70
R.P.+ sulfur	1.95	2.28	1.48	1.65	2.27	2.12
O.M.+ R.P.+sulfur	2.81	.70	.60	.72	.26	.12
Alfalfa + sulfur	2.81	.56	1.02			
O.M.+ S.+ R.P.+lime	2.91	2.17	3.64			
O.M.+ R.P.+ $CaSO_4$	2.91	1.89	9.51			

Elemental sulfur,in all cases,caused a decided decrease in nitrate accumulation,altho when calcium carbonate was added to a mixture of alfalfa,rock phosphate and sulfur the depression was not so marked as where lime was not added. The rate of nitrate accumulation was increased when sulfur was added to a mixture of alfalfa and rock phosphate,in the form of calcium sulfate. This decided increase was unexpected but time did not permit verification of this result. Pitz(23) found that gypsum had little effect upon nitrification when applied to soil but no large accumulations of nitrate nitrogen were obtained in his experiment.

The cause of the increased ammonia and decreased nitrate accumulations under sulfur treatments is likely complex. The addition of sulfur may have increased one class of organisms (sulfofiers) to the partial exclusion of another class (nitrifiers). The increased ammonia accumulation may have retarded nitrification,but this is not probable as it is commonly believed that a much larger accumulation of ammonia than here obtained is required to retard nitrification. Due to the stimulated bacterial activity under sulfur treatment, the soil organisms may have used larger quantities of nitrates. It seems probable that at least part of the reduction of the nitrate accumulation where sulfur was added was the result of the action of micro-organisms for even the nitrates present at the beginning of the experiment gradually tended to disappear. It appears,however,that the factor,which affected the nitrate accumulation the most,was the acidic condition of the medium brought about as the result of the oxidation of the sulfur to sulfuric acid. This is indicated in the results obtained where organic matter,rock phosphate and sulfur, and organic matter,rock phosphate,sulfur and calcium carbonate were used,as the treatment with lime gave more nitrates present than the treatment where no lime was added. As is usually the case,the increase of nitrates is accompanied by a reduction of ammonia,since it is the ammonia,which is oxidized to nitrites and then to nitrates.

While elemental sulfur has decidedly decreased the amount of nitrates formed,it has increased the total amount of mineral nitrogen present. This is clearly shown in the following table.

TABLE XVI.MINERAL NITROGEN PRESENT AT THE END OF THIRTEEN WEEKS.

Nitrogen (mgs.) per 100 grams soil

Treatment	Ammonia nitrogen	Nitrate nitrogen	Total mineral nitrogen	
Rock phosphate(R.P.)	1.60	5.69	7.29	
R.P.+ alfalfa(O.M.)	2.19	10.97	13.16	20.45
R.P.+ sulfur	6.17	2.12	8.29	
R.P.+ O.M.+ S.	20.09	.12	20.21	28.50

With this rapid ammonia production and practically no accumulation of nitrates,where elemental sulfur was added, it is possible that there is some loss of ammonia nitrogen from the soil,altho the sulfuric acid resulting from the oxidation of the sulfur should fix most of the ammonia formed.

TABLE XVII. EASILY SOLUBLE PHOSPHORUS.

Phosphorus per 100 grams soil
(milligrams)

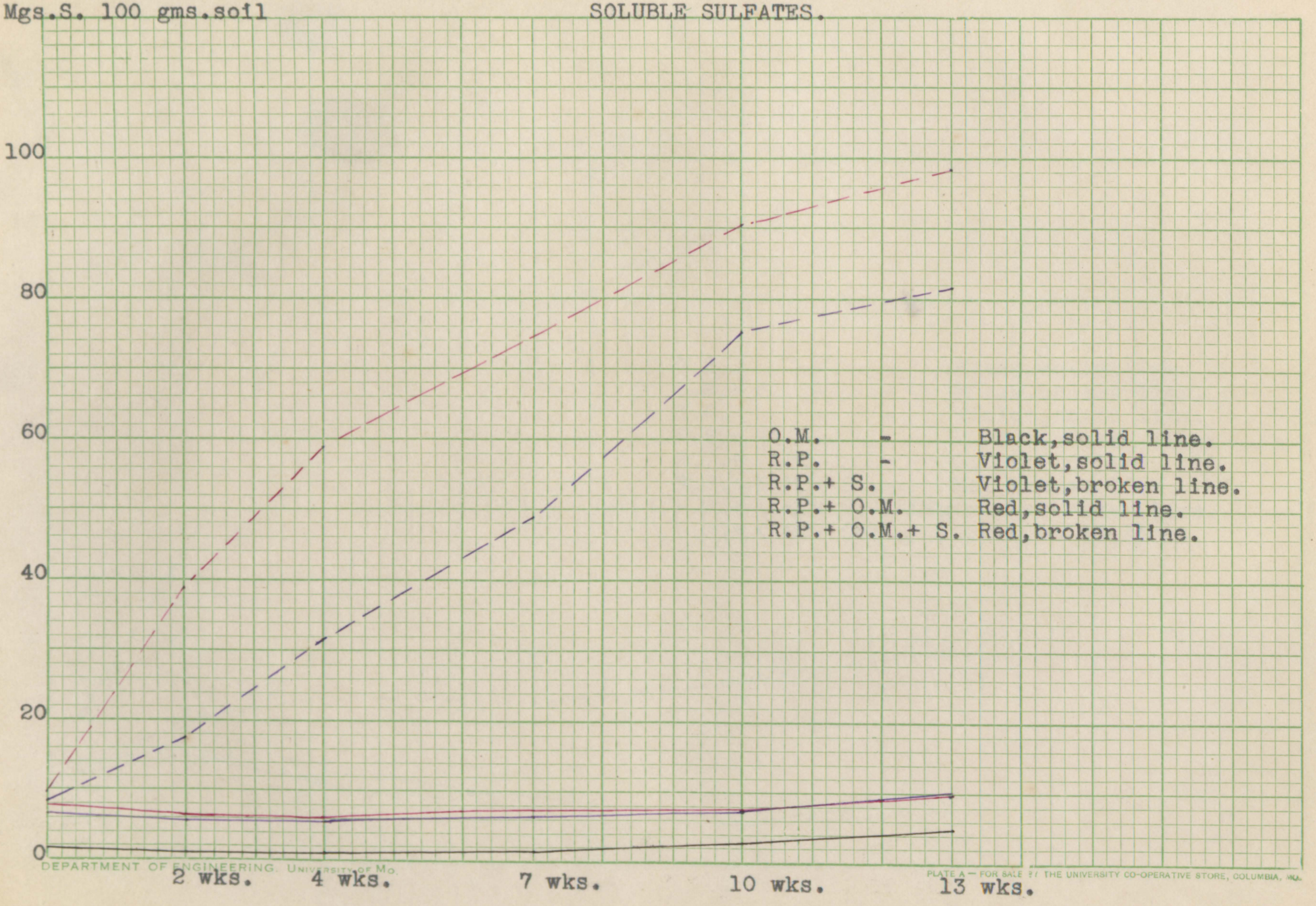
Treatment	Start	2 wks.	4 wks.	7 wks.	10 wks.	13 wks.
Rock phosphate(R.P.)	110.3	93.9	115.3	96.5	100.0	120.8
Alfalfa (O.M.)	2.3	.9	1.6	1.1	1.5	1.4
O.M.+ R.P.	96.8	85.5	106.0	87.4	93.0	113.8
R.P.+ sulfur	109.4	97.2	119.0	103.8	110.8	132.8
O.M.+ R.P.+ S.	99.9	94.2	115.3	96.8	109.0	129.0

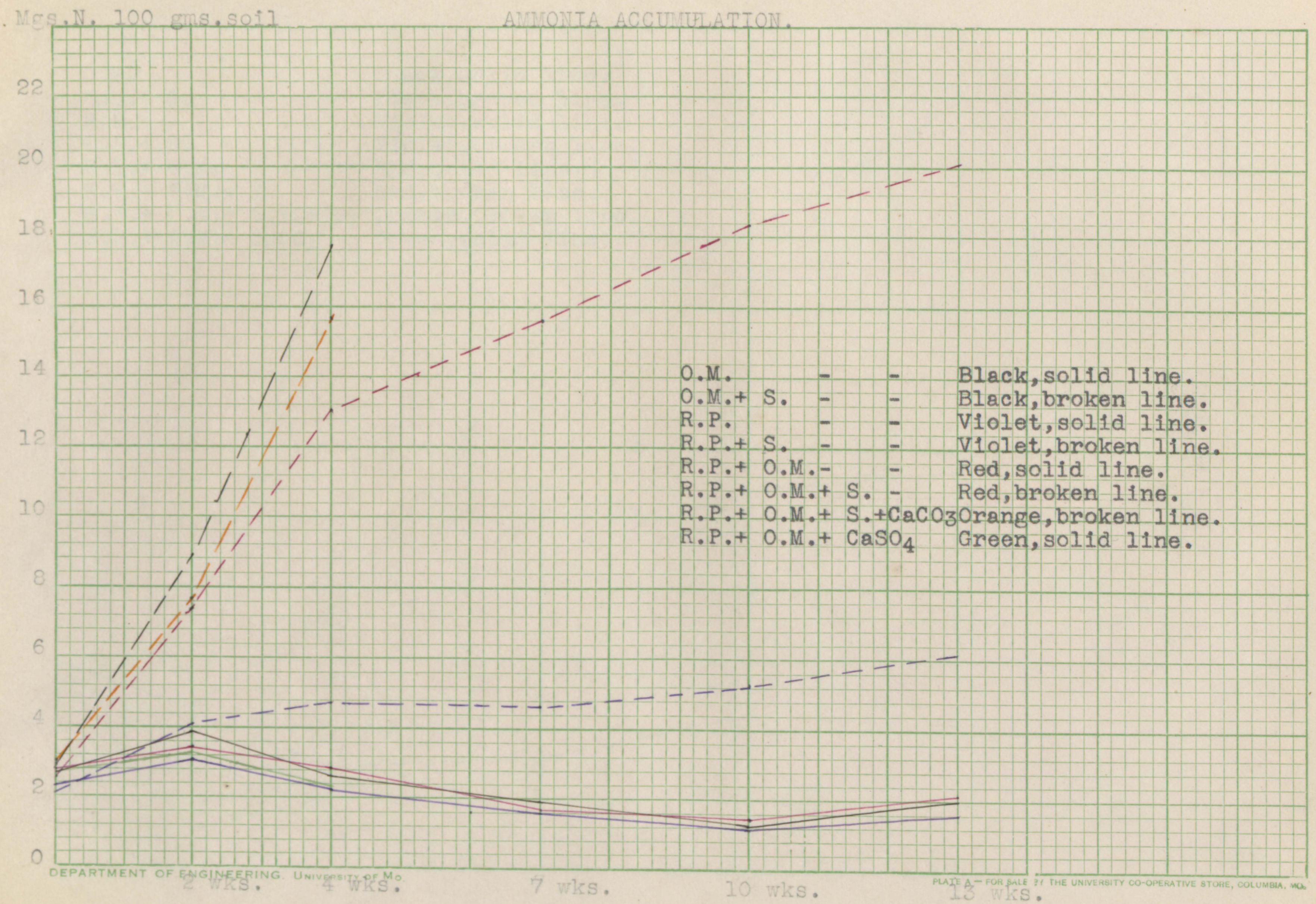
The amount of easily soluble phosphorus may vary from time to time as a result of the activity of soil organisms,but it would seem that slight differences in the manipulation of the different sets of determinations had much to do toward producing the fluctuation in amounts found under the same treatment at different periods. Variations such as these can hardly be avoided when an attempt is made to make such measurements.

The addition of elemental sulfur to a mixture of soil and rock phosphate and also to a mixture of soil,rock phosphate and alfalfa,increased the amount of easily soluble phosphorus. There appears to be a somewhat greater solvent action exerted when used along with organic matter than when used alone. This is probably due to the fact that organic matter increased the rate of oxidation of the sulfur as was shown by previous results, and the increased accumulation of sulfuric acid resulted in increased solubility of the phosphorus.

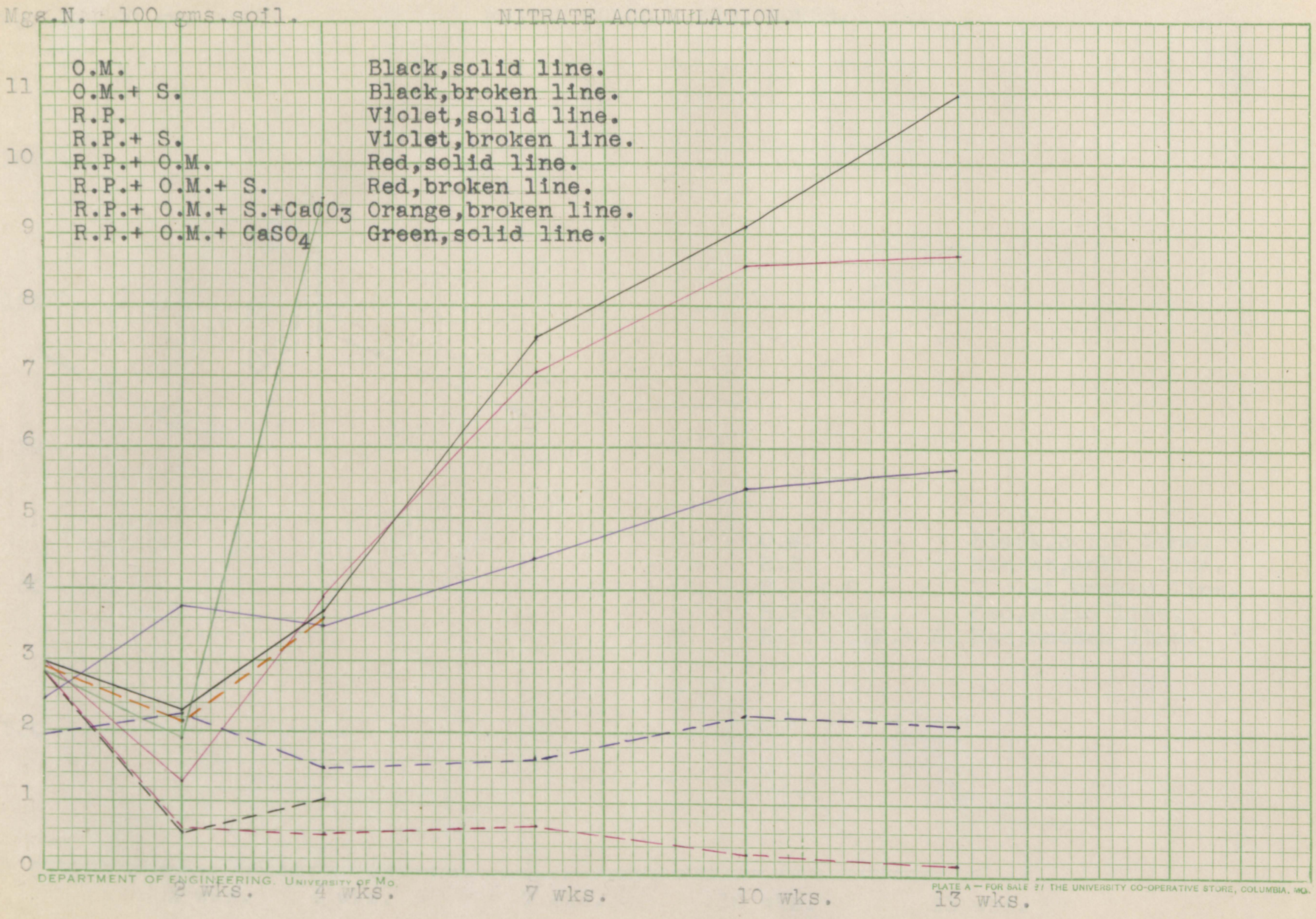
Organic matter,when added to a mixture of soil and rock phosphate, decreased the solubility of the phosphorus. This result is in accord with results reported by Truog(28) and Tottingham and Hoffman(27). However, from the results obtained it would seem that this decrease was not due to increased bacterial activity, but to a purely physical action. At the start (dry materials) a larger amount of phosphorus in rock phosphate was with-held from solution by the addition of organic matter than at any other time during the thirteen weeks, in fact, the difference between the amounts of phosphorus soluble in weak acid under the treatments rock phosphate alone, and rock phosphate and alfalfa decreased as the experiment was continued. The reduction of the amount of easily soluble phosphorus at the start of the experiment could not have been the result of micro-organic activity. However, the lessening of the difference between the amounts of phosphorus soluble under treatments of organic matter and rock phosphate and rock phosphate alone, may be due to the decomposition of the organic matter, which might result in less adsorptive power or in increased solubility of the mineral phosphates brought about by the decomposition products. It is thus possible that some of the solvent action which was found where sulfur and organic matter were used in combination was due to the products resulting from the decomposition of the organic matter.

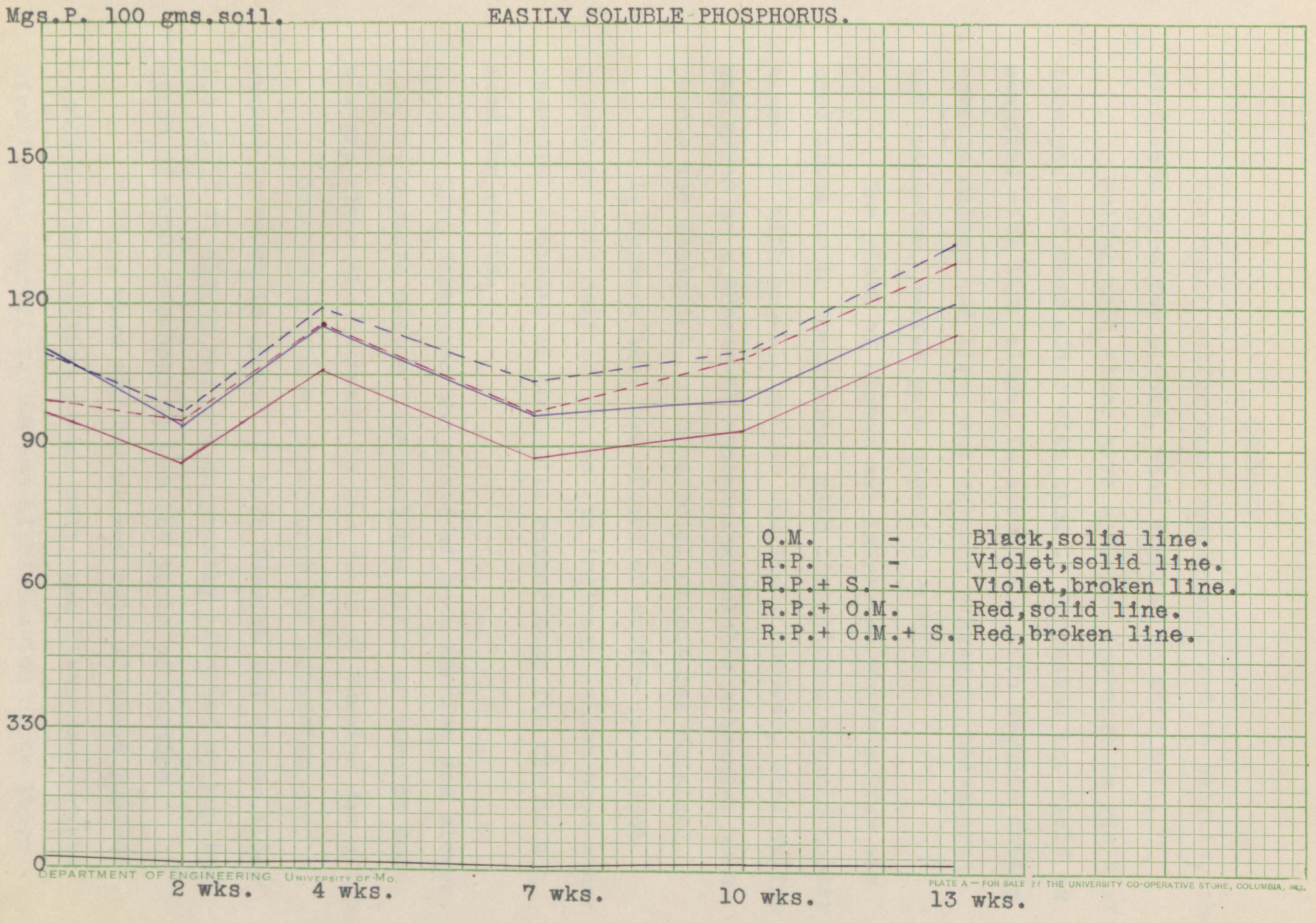
SOLUBLE SULFATES.





Mgs.N. 100 gms.soil
AMMONIA ACCUMULATION.
22
20
18
16
14
12
10
8
6
4
2
0
O.M. - - Black,solid line.
O.M.+ S. - - Black,broken line.
R.P. - - Violet,solid line.
R.P.+ S. - - Violet,broken line.
R.P.+ O.M.- - Red,solid line.
R.P.+ O.M.+ S. - Red,broken line.
R.P.+ O.M.+ S.+CaCO3 Orange,broken line.
R.P.+ O.M.+ CaSO4 Green,solid line.
2 wks.
4 wks.
7 wks.
10 wks.
13 wks.
DEPARTMENT OF ENGINEERING. UNIVERSITY OF MO.
PLATE A — FOR SALE BY THE UNIVERSITY CO-OPERATIVE STORE, COLUMBIA, MO.


Mgs.N. : 100 gms.soil.
NITRATE ACCUMULATION.
O.M. Black,solid line.
O.M.+ S. Black,broken line.
R.P. Violet,solid line.
R.P.+ S. Violet,broken line.
R.P.+ O.M. Red,solid line.
R.P.+ O.M.+ S. Red,broken line.
R.P.+ O.M.+ S.+CaCO3 Orange,broken line.
R.P.+ O.M.+ CaSO4 Green,solid line.
11
10
9
8
7
6
5
4
3
2
1
0
2 wks.
4 wks.
7 wks.
10 wks.
13 wks.
DEPARTMENT OF ENGINEERING. UNIVERSITY OF MO.
PLATE A — FOR SALE BY THE UNIVERSITY CO-OPERATIVE STORE, COLUMBIA, MO.


Mgs.P. 100 gms.soil.
EASILY SOLUBLE PHOSPHORUS.
150
120
90
60
330
0
O.M. - Black,solid line.
R.P. - Violet,solid line.
R.P.+ S. - Violet,broken line.
R.P.+ O.M. Red,solid line.
R.P.+ O.M.+ S. Red,broken line.
2 wks.
4 wks.
7 wks.
10 wks.
13 wks.
DEPARTMENT OF ENGINEERING. UNIVERSITY OF MO.
PLATE A — FOR SALE BY THE UNIVERSITY CO-OPERATIVE STORE, COLUMBIA, MO.

SUMMARY.

Elemental sulfur was readily oxidized to sulfate, the available form for plants, when applied to this soil.

Sulfur used alone gave a slight increase in yield of turnips, and when added with lime it increased the yield as compared with lime alone. In connection with organic matter, organic matter and lime, and soluble nitrogen, phosphorus and potassium, sulfur gave negative results.

The yield of clover was increased where sulfur was used alone or in combination with lime alone, organic matter alone, or with organic matter and lime; however, when sulfur was added to a treatment containing soluble nitrogen, phosphorus and potassium, no beneficial effect was obtained.

It appears that the effect of sulfur upon plant growth on this soil is due to its indirect action upon other essential elements in the soil, rather than its use as a food for plants.

Lime depressed the yield of both turnips and clover.

Organic matter increased the yield of turnips and clover, altho the increase in the yield of turnips was slight.

Soluble nitrogen, phosphorus and potassium gave a marked increase in growth of both turnips and clover, altho the yield of clover was not so greatly affected by application of these elements as was the yield of turnips.

Sulfur, when applied at the rate of three hundred pounds per two million pounds soil, had little measurable effect upon ammonification and nitrification altho there

was an indication of an accelerated rate of ammonification and a depressed rate of nitrification. A slight solvent action upon the phosphates in the sôil was also indicated.

When sulfur was used in much larger quantities in connection with rock phosphate,and with rock phosphate and alfalfa,the rate of ammonification was greatly increased. Nitrification in these same mixtures,where sulfur was added, was decidedly depressed.

Oxidized sulfur in calcium sulfate did not affect these processes in such manner. Calcium sulfate had little effect upon ammonification but increased the rate of nitrification,when added to a mixture of soil,rock phosphate and alfalfa.

Soluble plant foods increased the rate of nitrate accumulation in a no-crop series. Clover hay applied at the rate of five tons per two million pounds soil decreased the rate of nitrate accumulation.

Some solvent action of sulfur upon mineral phosphates was shown when sulfur was added to a mixture of soil containing rock phosphate.

Organic matter decreased the amount of phosphorus that could be extracted from a mixture of soil and rock phosphate and this decrease appeared to be due not to the action of micro-organisms but to a purely physical action.

PLATE I.

TURNIP CROP.

TWO WEEKS BEFORE HARVEST.

SERIES 21 - 30.

SERIES 31 - 40.

PLATE II.

CLOVER CROP.

EIGHTY NINE DAYS AFTER SEEDING.

SERIES 1 - 10.

SERIES 11 - 21.

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