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AGRONOMY DEPARTMENT

A STUDY OF THE SULPHUR SUPPLY OF SOILS AND ITS RELATION
TO PLANT GROWTH

BY
J. STANLEY COBB

A THESIS
SUBMITTED FOR THE DEGREE
OF
MASTER OF SCIENCE

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Reel 1
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Page 1

INTRODUCTION

The subject of the source of plant growth was one which occupied early investigators for centuries and brought forth numerous theories and explanations. The present problem of the plant physiologist, or more correctly, the agronomist, is to keep the plant supplied with its source of growth in proper amounts and under proper conditions. Our knowledge of the elements necessary for plant growth we owe to the work of some early chemists and plant physiologists.

(1)

Theodore de Saussure in 1804 laid the foundation for future work by his use of the quantitative statistical method. He found that the composition of plant ash is not constant, but varies with the nature of the soil and the stage of growth of the plant. However, he determined that it consists chiefly of alkalis and phosphates. Thus, from the first, phosphates were found to be highly important in plant growth.

Based on this work of de Saussure came the subsequent work of Boussingault, Sprengel, Liebig and Lawes and Gilbert. Up to 1840

(2)

Boussingault had conducted some field experiments which were a great improvement over the pot experiment conclusions of Davy.

(3)

(4) Sprengel had studied the ash constituents of plants. But very little interest or controversy was started until Liebig published his radical theories in 1840 as "Chemistry in its Application to Agriculture and Physiology".

(5)

Liebig held that plant growth is directly proportioned to the amount of mineral plant food constituents in the soil, and that

the nitrogen is obtained from the air. Lawes and Gilbert took exception to Liebig's theory and by experiments, published in the early Rothamsted Memoirs, demonstrated that plants obtained most of their nitrogen from the soil.

Thus by 1855 the fundamental principles of soil fertility as known today were established. Lawes and Gilbert had proved by long continued experiments that crops require phosphates and salts of the alkalis and also a supply of some nitrogenous compounds as nitrates or ammonium salts. Leguminous crops behaved abnormally, the cause of which was not then known. They also showed that the composition of the ash does not afford reliable information as to the amounts of each constituent needed. Turnips were found to require large amounts of phosphates for growth although only a little is present in their ash.

Liebig's list of the elements necessary for plant growth has since been confirmed by plant physiologists and they are known to be potassium, magnesium, calcium, iron, phosphorus, sulfur, carbon, nitrogen, hydrogen and oxygen.

Of these the most important are nitrogen, phosphorus and potassium. Nitrogen is known to aid materially the vegetative growth of the plant and give it size and substance; phosphorus aids in early root growth and in bringing on maturity, and potassium aids materially the formation of chlorophyll and the manufacture of starch.

They are also important from the standpoint of the agronomist as regards soil fertility because they seem to be most often deficient in the soil and must be artificially applied to maintain plant growth. For this reason they are called the primary plant food elements although no more important for plant growth than the others. The fact that they are removed from the soil and the

amounts removed has been learned, as previously stated, by chemical analyses of the plants grown.

The object of this paper is to consider the possibility of sulphur's becoming as important in soil fertilization as the above elements and to discuss some means of supplying any possible deficiency of sulphur in the soil.

The Importance of Sulphur.

In the experiments of plant physiologists sulphur has always been included in mineral plant nutrients but has been added as a salt with some necessary basic element.

(8)
Loew says that sulphur as a mineral element is given no credit as functioning for plant food. Sulphates are used but the base only is considered.

(7)
Duggar states that sulphur is important only as a component of albuminoidal compounds. It is required in such limited quantities that the seed may furnish all needed for normal growth of plant for a considerable period.

Present analyses of crops show it to be present in most crops in as large amounts as is phosphorus. Analyses of the plant ash for sulphur do not give the total amount present in the plant so

that figures given by early investigators are worthless. An improvement in method of analysis has brought out ^{the} real sulphur content of plants. This is shown by the comparison given in ⁽⁶⁾ the table by Hart and Peterson. The percentage in the ash as determined by Wolff is seen to be only one half and less than one half of the real content of the plant as determined by the peroxide method.

This knowledge of the large amounts of sulphur removed from the soil by crops has led to investigations of the possibility of a deficiency of sulphur in the soil. Hart and Peterson published the first important work in this country and other experiment stations have since made investigations.
(9)

Bogdanov in Russia before 1899 made the earliest mention of the possibility of sulphur becoming of practical importance in the soil by the exhaustion of the supply through cropping. He compared the methods of Liebig, Carius, Stoeckhardt and Schraeder for determining sulphur in cereals, leguminous plants and beets. Using Liebig's method as the most accurate and simple he found nearly twelve times as much sulphur in the products examined as in their ash. Having observed beneficial effects of fertilizers containing sulphates, he concluded that sulphur may be of more benefit to plant growth than is usually assumed.

Sulphur Content of Crops.

Phosphorus is well known to be an important mineral plant food constituent in the soil. For this reason a comparison of the amounts of sulphur and phosphorus removed by crops and found in the soil will serve to show the possibility of sulphur's competing with phosphorus as a limiting factor in the yield of some crops.

The following table is taken from the work of Hart and Peterson. (6) It shows well the relative amounts of sulphur trioxide and phosphorus pentoxide removed from the soil by the same farm crops.

Crop	Dry wt. lbs.	SO ₃ lbs.	P ₂ O ₅ lbs.
Wheat grain, 30 bu.	1530	6.4	14.2
Wheat straw	2653	9.3	6.9
Barley grain, 40 bu.	1747	6.6	16.0
Barley straw	2060	7.7	4.7
Oat grain, 45 bu.	1625	7.5	13.0
Oat straw	2653	12.2	6.4
Corn grain, 30 bu.	1500	6.4	10.0
Corn stalk	1877	5.6	8.0
Meadow hay	2822	11.3	12.3
Red Clover hay	3763	15.4	24.9
Alfalfa hay	9000	64.8	39.9
Bean grain, 30 bu.	1613	9.4	22.8
Bean straw	1848	4.9	6.3
Turnips, root	3126	57.8	22.4
Turnips, leaf	1531	34.4	10.7
Sugar beet, root	4320	9.5	20.2
Sugar beet, leaf	1848	20.0	13.1
Potatoes	3360	11.52	21.5
Tobacco leaf	1800	16.0	8.0
Tobacco stalk	3200	5.0	8.0
Cabbage	4800	98.0	61.0

It can readily be seen that different crops vary considerably in their sulphur content. The cereals and some other crops remove less sulphur than phosphorus from the soil. Certain crops such as alfalfa hay, cabbage and turnips remove much more sulphur than phosphorus.

The composition of the plants explains why some remove more sulphur than others. Sulphur is known to make up a large part of the protein compounds of plants and of certain volatile oils. Hence, plants such as the cruciferae and alfalfa are always found to have a high sulphur content. Proteins such as albumen and others are more or less important components of all plants and play a part in the life processes of the plant. In this way sulphur functions in plant life. Therefore, the importance of a supply being kept available to the plant is apparent.

These crops include most of the common ones grown on farms. From the table an idea can be obtained of the relative amounts of asulphur removed by any crop. Plants rich in protein and other compounds such as alfalfa and the cruciferae always require more sulphur for their growth than the cereals and other plants containing less sulphur compounds.

Sulphur Content of Soils.

Numerous analyses of soils show the relative amounts of sulphur and phosphorus contained. Clark states that the average percent of sulphur and phosphorus in the earth's crust is the same, 0.11%, but the percentages in our cultivated and uncultivated fields will vary considerably from that. Interesting data have been obtained from several states and other places, some of which will be quoted.

The average of analyses of thirteen surface soils and sub-soils of the United States gives SO_3 , 0.13% and P_2O_5 , 0.14%.
(15)

Hilgard gives analyses of soils of different types, most of which show a greater content of phosphorus than of sulphur. With some, however, the opposite is true. This goes to show that the sulphur content of a soil depends more on its condition and
(18)

treatment than on any distinct origin or type.

A strong acid solution of the soil was made and the sulphur determined. The percentage of sulphur trioxide is probably low as the acid does not dissolve all the sulphur. The results obtained are as follows :

Soil Class	%SO ₃	%P ₂ O ₅
Heavy clay	.02	.30
Heavy clay	.16	.47
Loam	.12	.11
Loam	.22	.71
Sandy	.01	.35
Average of five Hawaiian soils	.19	.56

(12)

Dymond, Hughes and Jupe found English soils to contain less sulphur than phosphorus, but the method for total sulphur analysis was not used ; so the actual sulphur content may have been higher.

The sulphur and phosphorus content of some Kansas soils is given by Swanson and Miller as follows :

(13)

Total sulphur was obtained by the sodium peroxide fusion method. This method is used in all work hereinafter reported.

Average percentages in 13 virgin soils.

Lbs. per 2,000,000 lbs. soil

	S.	P.	S.	P.
Surface	: 0.046	: 0.046	: 920	: 920
Sub-surface	: 0.044	: 0.033	: 880	: 660
Sub-soil	: 0.034	: 0.035	: 680	: 700

Average percentages in 16 cropped soils.

Lbs. per 2,000,000 lbs. soil

	S.	P.	S.	P.
Surface	: 0.027	: 0.043	: 540	: 860
Sub-surface	: 0.022	: 0.040	: 440	: 800
Sub-soil	: 0.026	: 0.035	: 520	: 700

These figures show that the amount of sulphur and phosphorus is about the same in virgin soil but the amount of sulphur is less in cropped soils, indicating a loss of sulphur through cultivation but no loss of phosphorus. The virgin and cropped soils were not adjacent so no direct conclusions can be drawn regarding the loss of sulphur due to cultivation, but it plainly shows that cultivated soils have a smaller content of sulphur than of phosphorus.

Analyses by the same men of virgin and cultivated soils similar and adjoining give evidence as follows :

% sulphur in virgin soil :	% sulphur in cropped soil :	% loss
0.044	0.027	38.53
0.062	0.036	41.56

They found that the loss of sulphur in cropped soils is greater than that of either nitrogen or carbon. The phosphorus and potash content tends to be higher in cropped than in virgin soils.

(14)

Shedd reports comparative sulphur and phosphorus analyses of soils from several areas of the State of Kentucky. His work shows higher amounts of phosphorus than of sulphur in all cases except one in both surface soil and sub-soil of virgin and cultivated soils. The loss due to cultivation is almost always greater in the case of sulphur than phosphorus and while the phosphorus content is sometimes increased by cultivation, the sulphur content is always decreased except in the case of a changing river alluvial soil.

(16)

Brown and Kellogg give analyses of five soil areas which show greater amounts of phosphorus than of sulphur as follows :

Sulphur Lbs. per A. Phosphorus

Soil	Surface	Sub-Surface	Subsoil	Surface	Sub-Surface	Subsoil
Missouri						
Loess	755	1239	1363	1538	2697	3892
Mississippi						
Loess	719	1073	1047	1361	2204	3003
Southern						
Iowa Loess	770	1105	1055	1368	2089	2972
Wisconsin						
Drift	938	1528	1327	1395	2217	3253
Iowan						
Drift	893	1207	855	1289	2207	2889

(6)

Hart and Peterson give analyses of soils of known history as compared with virgin soils. The cultivated soils show a decrease in sulphur content even though light manuring had been practised on the various crops.

(17)

Soil analyses from rotation plots by Ames and Boltz show a slight decrease in sulphur content due to cultivation even when some sulphur carrying fertilizers are used. A soil unfertilized for sixteen years shows a loss of sixty pounds of sulphur per acre for that period. Other differences are not so marked but indicate a decrease in sulphur where crops have been grown.

(18)

The following analyses are of soil from plots of known treatment in the Pennsylvania and Rothamsted fertility tests.

Pennsylvania Plots			
Plot No.	Treatment	% SO_3	Lbs. per 2,000,000 lbs. soil
14	(Blank	.054	1080
16	(		
9	(Acid phosphate		
17	(Muriate of potash	.965	1300
	(Blood		
12	(Ground bone		
35	(Muriate of potash	.061	1220
	(Blood		

Here the no-treatment plots are found to be low in sulphur content and the plot receiving acid phosphate as a sulphur carrier is higher in sulphur content than the one receiving other phosphate carriers.

Broadbalk Wheat Plots.		Rothamsted.			
Plot:	Treatment	% SO_3			
No.:		1881:	1893:	1904:	1911
		:	:	:	"
3	Unmanured every year	.054:	.050:	.044:	
10	Irregular 1844-1850. In 1851 and since 200 lbs. muriate of ammonia and 200 lbs. sulphate of ammonia.	.076:	.068:	.041:	
11	Irregular 1844-1848. In 1849 and since $3\frac{1}{2}$ cwt. superphosphate, 200 lbs. sulphate of ammonia and 200 lbs. muriate of ammonia.	.058:	.072:		
19	Irregular 1844-1847. 1848-1878 $3\frac{1}{2}$ cwt. superphosphate lime made with muriatic acid, 200 lbs., sulphate of ammonia 300 lbs., rape cake 500 lbs., 1879-1882 rape cake alone 1700 lbs., 1883 and since 1889 lbs. rape cake.	.064:	.072:		.093
	Virgin soil.				.091

These analyses show a tendency for the percent of SO_3 in the soil to decrease through cultivation without manure. With the use of some fertilizers the SO_3 content of the soil is seen to increase even above that of virgin soil.

From the above works the general conclusion may be drawn that soils are found to be deficient in sulphur even more than they are in phosphorus. Also, a decrease in the total sulphur content of the soil is seen to be brought about by cultivation and cropping. And, when properly fertilized, the sulphur content of the soil is maintained. This, then, may be a general warning ; that sulphur may become a limiting factor in crop production unless supplied to the soil in fertilizers of some sort.

Forms of Sulphur in the Soil.

It is one of nature's wisest provisions that plant food should be stored in the soil in an insoluble condition and have to undergo changes before becoming soluble and available to the plant. Sulphur is no exception to this rule and, along with nitrogen, phosphorus and potassium exists in the soil both in a soluble and insoluble state.

(19)

Berthelot and Andre state that sulphur exists in the soil chiefly in three forms, sulphates and sulphides, ethereal sulphur, and organic compounds.

The sulphates are more or less soluble in the soil solution. Sulphides exist mostly in the form of pyrites and are slowly oxidized to sulphates. The organic matter resulting from manure applied to the soil and crop residues undergoes decay and oxidation of the sulphur present. Ethereal sulphur compounds probably reach the soil in manure from the urine of animals. The sulphur of organic matter reaches the soil in the form of complicated organic compounds.

(20)

Peterson states that sulphur occurs in plant and animal tissue chiefly in the form of proteins, volatile compounds, as the mustard oils, and sulphates. He found that the amount of sulphates in plant tissue varies with the soil supply and a vigorous growth may be made where no sulphates are found in the tissue. Therefore, the amount of sulphates furnished to the soil in organic matter is negligible and the other forms of sulphur require changing.

Just what form or forms of sulphur are used by the plant has not been definitely proven but the evidence of experiments indicates

that the sulphate form is necessary for sulphur assimilation by the plant. Sulphates are the final soluble form of sulphur available to the plant. Applications of elemental sulphur have been shown by Shedd (10) to give greater increases in plant growth than some sulphites and sulphates. But he also shows that elemental sulphur is rapidly oxidized to sulphates in the soil. It may be true that the intermediate forms, before the sulphate form is reached, are taken up to a limited extent by plants, but probably not sufficiently to be important. Analogous to this is the well known formation and use of nitrates in the soil. The intermediate forms, as ammonia and organic compounds, are thought to be used by the plant to a limited extent.

The action of bacteria in the transformation of sulphur is very important and has been shown by numerous investigators to be the chief source of sulphate formation.

(21)
Kapppen and Quensell concluded from investigations that the sulphur, released through putrefaction and the action of bacteria on organic matter, and any in the elemental form, is changed to sulphates. All the sulphur of organic matter and sulphides must first be changed to the elemental form. The finely divided sulphur is so easily oxidized that the intermediate steps are not noticed. They also found that the form of sulphur affects the rapidity of change but that the change was quicker in soil than in air and in natural soil than in sterilized soil. All the action is not attributed to microorganisms because sterilizing the soil may also destroy a certain chemical action. They found that in all soils the change to sulphates took place so quickly that the sulphites or sulphides formed exercised no injurious effect on germination or future growth of the plant.

(22)
Brioux and Guerbet proved the bacterial nature of sulphur

oxidation in the soil and showed the influences of various substances on it. The addition of calcium carbonate greatly accelerated oxidation, but sterilization of the soil almost entirely prevented it.

(23)

Kossovich says the sulphur cycle is rather complicated, being made up of a change from organic to inorganic form and vice versa, and oxidation and reduction principally through the activity of microorganisms.

(24)

Demelon studied the rate of transformation of sulphur in soil by adding 5 grams of sulphur to 100 grams portions of soil. He found that the sulphur was partially oxidized to sulphuric acid. He also found that the reaction was most rapid in non-sterilized soil.

(25)

Lint, in his work on the effect of the addition of free sulphur on soil acidity, found that sulphur increased the lime requirement of the soil considerably. This, he concluded, was due to the oxidation of the sulphur to sulphuric acid, since after the seventh week the lime requirement remained the same probably because all the sulphur had been oxidized.

(25)

Lipman has demonstrated the production of sulphuric acid by mixing elemental sulphur and insoluble tri-calcium phosphate in compost heaps. He found that the insoluble phosphate was rendered partly soluble by its bases taking up the acid formed.

(10)

Shedd found by determining the sulphate sulphur present before and after incubating soil with elemental sulphur, that about 60% was oxidized in four months. This was true whether 100 or 500 pounds per acre had been added. He also found that oxidation is more rapid in fine soil than in sand. The organic sulphur in manure alone was slowly oxidized. In the case of both soil and manure the addition of calcium carbonate did not seem to increase

the oxidation.

(26)

Brown and Kellogg have made an extensive study of the production of sulphates in the soil by bacteria and the effect of various substances on this process. They state that there are numerous organisms in the soil which cause sulfification, and these are grouped under the name of sulfifying bacteria. The sulphur cycle in the soil is explained as being made up of several stages. First, organic compounds are broken down with the production of hydrogen sulphide which is changed to free sulphur deposited as granules in the cells of the bacteria. This free sulphur is oxidized to sulphates in which form it is available to plants. During the process of the work it was found that some oxidation of sulphur to sulphates in the soil takes place as a purely chemical action independent of bacteria. This was discovered through an increase in sulphates present after shaking samples of soils with sulphides added in water for seven hours.

The method used for determining sulfification in soils was as follows : 100 gram samples of fresh soil were placed in tumblers, 0.1 grams of various sulphur materials added and this incubated five days at room temperature. The sulphates present before and after incubation were determined by shaking samples of the air-dry soils with twice their weight of water in bottles for seven hours and determining the sulphates by precipitating with BaCl_2 and using the sulphur photometer.

The conclusions reached were that sodium sulphide and free sulphur are the best forms of sulphur to use for determining sulfification. The sulfifying power of soils was found to vary with different treatments. The use of stock manure or green manure on soils increased their production of sulphates and in general it appeared that soils poor in organic matter were low in

sulfofication.

The optimum moisture condition for sulfofication was found to be 50% of saturation. This is also the best condition for plant growth, which may correlate optimum sulphate production and plant growth.

Increased aeration up to a mixture of 50% fine soil and 50% sand also increased sulfofication. With higher percents of sand sulfofication decreased which may have been due to a lack of organic matter.

The effect of the addition of carbohydrates was found to be detrimental in direct proportion to the amounts added. Also the detrimental effect varied in the inverse ratio to the solubility of the carbohydrate material.

In order to correlate sulphate production with crop growth, greenhouse tests were carried out in pots of soil sown to timothy. Thirty pounds of soil were weighed out in each pot and kept at the optimum moisture content of 50% saturation. One series of duplicate pots was kept bare and bacteriological tests made from them, while the other series was seeded to timothy.

The treatments were as follows :

1. Nothing.
2. 25 T. horse manure per acre.
3. 25 T. cow manure per acre.
4. 4 T. clover hay per acre.
5. $\frac{1}{2}$ T. CaS per acre.
6. $\frac{1}{2}$ T. CaSO_4 per acre.

The sulphates present were determined at irregular intervals by the method described above and sulfofication tests were also carried out as described above.

From the results it was found that the application of calcium

sulfide, cow manure, horse manure and clover hay to the soil increased to a considerable extent the sulphate content of the soil. This increase was greatest in the case of the material containing the largest amount of sulphur. This shows that the sulphur in insoluble, unavailable form in the soil is changed quite readily to sulphates. The sulphide was oxidized very quickly and the other materials only slightly less rapidly. Thus, under optimum moisture and temperature conditions in a fairly fertile soil sulfification undoubtedly occurs very readily.

Also, the presence of sulphates in the soil was found to increase to a large extent the sulfofying power of the soil. The greater the amount of sulphate the greater was the sulfification up to a certain limit which was not determined.

The results of the crop yields indicate that the cow and horse manure treatments gave the largest increase over the check pots, the clover and calcium sulphate a slightly smaller increase and the calcium sulphide no increase. The calcium sulphide was rapidly oxidized to sulphate and more sulphate was formed than was applied in the sulphate treatment. This larger amount of sulphate must have caused the smaller yields than those obtained by the sulphate treatment.

It is shown that both manures and calcium sulphate in small amounts had the same effect on crop yield and on sulfification. The effects of calcium sulphate on crop yield and sulfification are the same up to a certain amount of sulphate, beyond which the crop is not affected but sulfification is still increased.

This review of investigations on the changes which sulphur undergoes in the soil quite strongly establishes the fact that insoluble forms of sulphur are converted to soluble sulphates in the soil and that this action is mostly bacterial. The sulphates

then are the source of sulphur for plant food.

As long as the total sulphur content of a soil is sufficiently large to supply sulphur compounds for bacteria to work upon under good physical conditions of the soil there will probably be sufficient sulphates furnished to the plant. In this way the total sulphur content of the soil is diminished. This decrease has been shown from soil analyses already given. The remedy, then, may be to furnish sufficient sulphur bearing materials to the soil for the bacteria to work upon and thus prevent an exhaustion of the supply.

Effect of Sulphur on Plant Growth.

The real value to the plant of any form of fertilizer must be determined by growing the plant in soil with applications of the fertilizer in question. Numerous experiments of this nature have been carried out with sulphur fertilizers. The results have been somewhat conflicting as a brief review of the more important experiments, conducted especially for this purpose, will show.

(27)

Hart and Tottingham grew various crops in boxes of 33 pounds of soil under greenhouse conditions. The fertilizer applications were heavy, as follows :

Control (no fertilizer),

Complete fertilizer, 26.5 grams,

Complete fertilizer, 26.5 grams + Na_2SO_4 12 grams,

Complete fertilizer, 26.5 grams + CaSO_4 12 grams,

Na_2SO_4 12 grams,

CaSO_4 12 grams,

Sulphur(flowers) 5 grams.

The results were as follows :

Sulphur alone produced a decrease in growth and yield of

beans, clover, pea seed, radishes, rape, oats and barley.

The sulphates increased the yield of clover, pea seed, radishes, rape and barley and oat seed. None of the sulphates affected the growth of oat and barley straw. Calcium sulphate produced a decrease in beans.

An analysis of clover tops and rape grown with the various treatments showed that the sulphur content is increased by the presence of sulphates in the soil. It is known, however, that the sulphur content of seed varies little.

The above results indicate that plant members of the Cruciferae and Leguminosae which contain large amounts of sulphur are affected most by sulphur fertilizers. The gramineae show no increase in straw though seed production is markedly increased.

In this experiment certain results may be due to other factors than plant food, since very heavy applications of fertilizer were used and the effect of different amounts of sulphates were not tried out. The deleterious effect of sulphur alone may have been due to the large amount applied or to poor soil conditions for its rapid oxidation to sulphates.

(17)
Ames and Boltz found, from pot and plot tests, that, in general, fertilizers containing sulphates gave higher crop yields of soy beans and rape than similar fertilizers not containing sulphates. The sulphur content of these crops was also increased. Millet hay and seed gave opposite results from the above two crops as to yield, but the sulphur content of the hay was increased, and that of the seed decreased.

(10)
Shedd conducted some pot experiments with different forms and amounts of sulphur and grew several kinds of crops. The influence of the sulphur fertilizers on the growth of the crop was

determined and, in some cases, also the effect on the sulphur content of the plant.

In all cases poor results were obtained unless the sulphur was added to a rich soil or along with a complete fertilizer.

Tobacco was increased in yield 24% by the use of 500 pounds of sulphur per acre or of 536 pounds of CaSO_4 per acre.

Soybeans were increased in yield and sulphur content by the use of various forms of sulphates.

The yield of clover was not influenced by any form of sulphur due probably to the high sulphur content of the soil used. Similarly, the yield of turnips was not affected.

Cabbage was decreased rather than increased in yield by the use of large and small amounts of various forms of sulphur.

Mustard and radishes following the cabbage showed gains from some of the sulphates. They were especially beneficial in the case of mustard, and all showed an increase in yield over their corresponding carbonates.

Alfalfa grown in sand cultures gave good increases from the use of elemental sulphur, and in nine out of fifteen cases, the sulphates used gave better yields than their corresponding carbonates.

(28)

F. L. Duley in some sand and soil cultures found that flowers of sulphur partly took the place of a soluble sulphate in a nutrient solution when used in a sand medium, and had a marked effect on the production of chlorophyll in corn plants. In soil cultures flowers of sulphur used alone was slightly beneficial to the growth of corn and rape and still more beneficial to the yield of red clover. The production of nodules on the roots of the clover was very markedly increased.

Reimer in one publication shows evidence of a beneficial effect of sulphur on alfalfa production and in a later publication (30) gives conclusive evidence from data of large increases of alfalfa from applications of sulphur fertilizers.

The results given in the second publication are as follows : Alfalfa was grown on plots receiving varying amounts of ground phosphate rock, flowers of sulphur, iron sulphate and superphosphate. The ground phosphate rock plots gave no increase over the check plots. The other plots with treatment of 300 pounds per acre gave an increase of slightly more than 100% over the check plots.

Other plots were treated with superphosphate, iron sulphate, flowers of sulphur, gypsum, ground phosphate rock, mono-calcic phosphate, and steamed bone meal. Alfalfa, red clover and vetch were grown. The mono-calcic phosphate, ground phosphate rock and steamed bone meal plots produced no increase in yield. The other treatments at the rate of 300 pounds per acre all gave increases, some as high as 200% - 300% over the check plot yields.

An analysis of the soil tends to throw some light on the results obtained in the above experiments.

Soil Type	Lbs. per acre ft. of soil.	
	Phosphorus	Sulphur
Medford fine sandy loam	3357	882
Tolo loam	2334	616
Medford clay loam (fertile soil)	3747	1650

On the last soil applications of superphosphate produced no increase in yield. All the soils are rich in phosphorus so that is not a limiting factor. But where sulphur is deficient the crop was shown to be benefited by applications of sulphur fertilizers.

On the same soil types observations of the effect of lime sulphur spray on alfalfa, red clover, vetch and Canada field peas under sprayed fruit trees showed larger, healthier and darker green growth under the trees where the spray drippings had fallen than on the outside. This was not due to the lime because the soil was naturally rich in lime. The sulphur in the spray may have been the cause of the better growth.

The results of four years of plot experiments at the New Jersey Station, using ferrous sulphate and gypsum, show no definite effects on plant growth unless a stimulating effect. The authors state that any increase in yield with excessive applications of sulphur materials are due to its stimulating action and not to its value as a plant food.

The sulphate of iron, 100 pounds per acre, gave the largest increases in dry matter and total nitrogen of crops, but 200 pounds per acre gave the least increase. Gypsum applied at the rate of 1000 pounds per acre gave an increase with one corn crop. The other crops showed no appreciable gain.

(32)

Pitz gives the following results on the effect of elemental sulphur and CaSO_4 on certain of the higher and lower forms of plant life. Tests were made in agar medium and in soil. Calcium sulphate has a more beneficial effect on bacterial and plant growth than elemental sulphur. Calcium sulphate, 0.01% and up, does not increase the number of bacteria on agar plates but does increase the growth of legume bacteria. Amounts up to 0.05% increase yield and root growth of clover.

0.01% elemental sulphur and above increased but slightly the yield of clover and root growth and nodule formation. It increased ammonification but decreased nitrification and the total number of soil organisms.

(33)

Brown and Johnson in their studies on sulfification used soil which was too rich in sulphur to draw any conclusions as to the effect of applications of sulphur on plant growth. It contained per 2,000,000 pounds surface soil, 911 pounds of phosphorus and 2487 pounds of sulphur.

They found that the sulfofying power of the soil was increased by applications of calcium sulphate, mono-calcium phosphate, acid phosphate, rock phosphate and rock phosphate plus calcium sulphate. The sulphate and phosphate alone had greater effects than combinations as in acid phosphate. All the treatments increased the ammonifying power of the soil to practically the same extent.

The crop yields, sulfification and ammonification results did not always run parallel. Acid phosphate gave the greatest increase in the crop of oats, probably due to lack of phosphoric acid in the soil and its ready availability in the acid phosphate.

(34)

Pfeiffer and Blanck conclude from their experiments that sulphur does not benefit plant growth nor increase nitrogen availability in the soil. It seems to produce a very small harmful effect in some cases. A certain beneficial effect is due to the action of sulphur on fungous diseases.

(35)

Pfeiffer and Simmermacher conducted experiments on the action of sulphur in plant nutrition. They conclude from their results that sulphur fertilization is wholly ineffective on the soils used and that a recommendation for the general use of sulphur is not justified.

(36)

E. B. Fred worked on the possibility of carbon bisulphide furnishing sulphur as a plant food. He found that the addition of carbon bisulphide to the soil produced a temporary reduction in the number of micro-organisms and then a decided increase.

This was due to the disinfecting action. The amount of soluble compounds of nitrogen and sulphur were increased.

The action on plant growth varied with different soils and different crops. Using a loam soil, buckwheat, oats and mustard were most benefited. The growth of red clover in peat soil was increased. The yield of mustard was increased in all experiments in non-acid soils, showing sulphur to be most beneficial there.

(12)

Dymond, Hughes and Japo report both plot and pot experiments with sulphur fertilizers. In plot experiments comparing muriate and sulphate of ammonia the yield of cabbage and clover was increased by the sulphate while that of oats, barley and swede was not benefited.

Analyses of the crops showed that under favorable conditions the presence of sulphates increased the albuminoid content as well as the total weight of the crop, showing that the sulphate has a direct effect on the plant. This was true of vetch and maize grown.

The conclusion was made that the supply of sulphur already in the soil or brought down in the rain is not sufficient for heavy yielding crops rich in albuminoids, either for the production of greatest yield or the highest feeding value, and for such crops a sulphate should be included in the artificial manure. For cereal crops and for permanent pasture the soil and rain provide all the sulphuric acid necessary.

In some cases effects have been noted from the application of sulphur for other purposes than as a fertilizer. Such has been the case in applying sulphur to potatoes for scab prevention.

(37)

Sherbakoff found that in general the application of about 100 pounds sulphur per acre somewhat increased the yield, but 300 pounds and over materially decreased the yield. Applications of

lime decreased the injurious after effect of large applications of sulphur for scab.

No definite results were obtained as to the fertilizing value of sulphur on potatoes.

(38)

Wheeler, Hartwell and Moore grew crops in pots of soils from the treated plots. They found the yield of oats and millet less where sulphur had been used for potato scab. The decreased yield was not so great where lime was used.

In both the above experiments the injurious after-effects were probably due to the acidity caused by the oxidation of large amounts of sulphur. This was partly corrected by applications of lime. An excess of sulphates was undoubtedly present so that no difference in plant growth could be noted if the acidity had not been deleterious.

All important evidence concerning the direct effect of sulphur on plant nutrition must be obtained from experiments planned especially for that purpose. The long standing field fertilizer experiments at college stations and in other countries were planned for determining the effect on crops of the three essential plant food elements only. However, there is some evidence which may be said to point toward the favorable influence of sulphur on crop growth.

(39)

In some Rhode Island Station experiments the double superphosphate gives somewhat poorer results than three acidulated phosphates. This, Hopkins states, is probably due to the stimulating action of the large amounts of calcium sulphate in the acid phosphate. In this case that must be true since sufficient sulphur for plant growth is applied to all plots in the uniform treatment of 398 pounds of potassium sulphate per acre.

A comparison of ground bone and dissolved bone black as a

fertilizer in some Pennsylvania Station experiments seems to give no evidence for the beneficial action of sulphur fertilizers, though this may be due to other stronger factors.

In some five and three year rotation experiments at the Ohio Station the following results are shown :

Five year rotation. Av. yields per A., bu. and lbs.

Plot:	Treatment	:15 yrs.: : Corn : : bu.	:15 yrs.: : Oats : : bu.	:15 yrs.: : Wheat : : bu.	:13 yrs.: : Clover: : lbs.	:13 yrs.: : Timothy : lbs.
	:N.76,P.20,K.108. P. :added in 220# raw	:	:	:	:	:
26	:ground bone	: 46.9	: 46.7	: 23.5	: 3290	: 3680
	:N.76,P.20,K.108. P. :added in 280# acid	:	:	:	:	:
27	:bone black	: 48.2	: 49.3	: 26.4	: 2890	: 3490

Three year rotation.

:	:	:15 yrs.: :Potatoes: : bu.	:14 yrs.: : Wheat : : bu.	:14 yrs.: :Wheat straw: : lbs.	:13 yrs.: : Clover : lbs.
	:N.38,P.20,K.83. P. :added in raw bone meal:	: 176.0	: 35.6	: 3350	: 3420
	:N.38,P.20,K.83. P. :added in acid bone	:	:	:	:
27	:black	: 185.8	: 37.0	: 3630	: 3250

The acid bone black gives larger average yields than the bone without the sulphuric acid.

A comparison of alfalfa yields on sulphate of potash and ⁽⁴³⁾urate of potash plots at the Massachusetts Station show yields markedly in favor of the sulphate plots. This agrees with results ⁽³⁰⁾ shown previously though in this case the sulphur content of the soil is not known. Also, the alfalfa seen growing presented a vigorous green healthy appearance on the sulphate plots and a weaker yellowish appearance on the no-sulphate plots.

1/8 acre plots. Fertilizer treatment.

For 21 years, 600 pounds fine ground bone annually.

No manure. In 1910, 2 tons lime per acre.

Since 1900, 250 pounds per acre annually of KCl or K_2SO_4 .

Two year average yields.

Tons per acre.

	: KCl plots	: K_2SO_4 plots
Grimm Alfalfa	: 3.734	: 4.231
Common Alfalfa	: 2.886	: 3.636

* Manurial treatment.

Alfalfa yields.

Tons per acre.

	: Field O.	: North Field
1911	: 2.72	: 2.80
1912	: 2.99	: 3.58
1913	: 3.89	: 4.97

* Field D. 1910-1912 inclusive, Bone meal, 600 lbs.
 KCl 200 lbs.
 1913, Basic slag meal, 1000 lbs.
 Not previously manured, KCl 200 lbs.

North Field. 1912-1913, Basic slag meal, 1000 lbs.
 K_2SO_4 100 lbs.
 Previously manured annually.

Experiments such as the above do not show conclusive results regarding the value of sulphur as they were not planned for that purpose. Many uncontrolled factors exist, such as the indirect effects of different materials and different solubilities of different forms of plant food. But at least some experiments, such as the last given, show such definite results in one direction that the influence of the sulphate fertilizer seems probable.

Direct and Indirect Effect of Sulphur on Plant Growth.

With any material added to the soil to benefit plant growth there is a possibility of a direct or indirect benefit unless one action only has been proven to be important. On this point there are conflicting opinions in the case of sulphur fertilizers.

(44)

Hopkins states that calcium sulphate acts as a crop stimulant but supplies no plant food of value.

(45)

Liebig states that in France sulphuric acid has been poured upon the fields after the removal of crops and has been found to form a good manure. This he ascribes to the formation of gypsum in the soil. Gypsum, he states, serves a two-fold function : first, that of decomposing carbonate of ammonia and of fixing the ammonia, which may be performed by other salts of calcium; and second, it acts as a sulphate which cannot be supplied by any salt of lime not containing sulphuric acid.

In regard to one possible indirect effect of elemental sulphur applied to the soil, Lipman shows experimentally that its oxidation to sulphate will not make insoluble phosphates soluble unless in a more concentrated mixture than can be made in the soil.

(25)

(46)

Hopkins has stated that the high sulphur content of plants does not represent their needs but denotes the presence of an abundance of sulphates in the soil. This statement is also true of phosphates when an abundant supply is present in the soil. It is probably the case with sulphates in the stems and leaves of plants but not in the seed, which has been shown by Peterson to maintain a fairly constant percentage of sulphur.

(20)

(47)

Fred and Hart have shown a much more beneficial effect of phosphates than of sulphates on soil bacteria. Sulphates, therefore, do not function indirectly in this way as much as phosphates.

The character of the compounds in different plants show a varying demand for sulphur. For the manufacture of some of these organic compounds, such as the albuminoids, large amounts of sulphur must be used directly by the plant. This is shown by the wide difference in sulphur content of the cruciferous plants and the cereal plants.

Thus, the sulphates in the soil must have a direct food relation to the plant, and considering the amounts removed by some plants and the decreased sulphur content shown in some soils, it would seem that sulphur may become as direct a limiting factor in crop production as nitrogen, phosphorus or potash.

Numerous other investigations on sulphur fertilization besides those already mentioned have been published. The following abstracts are from articles to which previous references have not been made.

(48)

Demelon found that sulphur was oxidized to sulphate in the soil. He obtained an increased yield from flowers of sulphur, (10 grams per square meter of soil) applied to rutabagas, beets and parsnips.

(49)

Later the same man found that potatoes were benefited the most by applications of sulphur but that the action diminished when large amounts of organic matter and mineral fertilizers were added at the same time.

(50)

F. Grannetto obtained an increased yield of potatoes from sulphur applied at the rate of 400 pounds per acre with other fertilizers. When applied alone a decrease in yield was obtained.

(51)

Takeuchi found that gypsum decreased crop yield when used with acid fertilizers but increased it when used with alkalin fertilizers.

(52)

W. Janicaud from some pot experiments with tomato plants showed that 2 grams of sulphur alone per kilogram of soil had a deleterious effect on growth. When used with ammonium sulphate or a complete fertilizer a beneficial effect was secured.

(53)

E. Rabate found that a sulphuric acid solution, when applied for the destruction of weeds in a wheat field, had a fertilizing action on the soil.

(54)

Chanerlin and Desriot used sulphur at the rate of about 223 to 446 pounds per acre with superphosphate, potassium sulphate and sodium nitrate on potatoes and beets. The yields were increased and disease reduced.

(55)

In another work these men found that 178 to 355 pounds of sulphur per acre gave increases in yields of potatoes and beets.

(56)

B. Heinze concluded from experiments that the action of sulphur is similar to that of carbon bisulphide but is not entirely biological and is not well understood.

(57)

V.V. Sabasknikov obtained a better growth of barley and rye from the application of 10 grams of sulphur per square meter of soil.

(58)

E. Boullanger added 70 grams of sulphur to 30 kilograms of soil. The influence of the sulphur was favorable to the growth of carrots, beans, celery, lettuce, sorrel, endive, potatoes, onions and spinach in natural soil but not in sterile soil.

(59)

E. Boullanger and M. Dugardin concluded that the favorable influence of small doses of sulphur was due to an activating effect on ammonifying and nitrifying bacteria.

(60)

Daikuhara found from pot experiments with three soils that even less than 0.02% sulphur trioxide in the soil was sufficient to meet the requirements of barley plants for sulphur.

(61)

Bernhard claims that sulphur disinfects the soil, puts it in a

better physical condition, causes a quicker and more intensive action of the commercial fertilizers applied, makes more available the foodstuffs already present in the soil and plays a greater role in plant nourishment than has hitherto been ascribed to it.
(62)

Bernhard later applied sulphur at the rate of 44 pounds per plot of 600 square yards and obtained a beneficial effect on hoed crops, potatoes and mangolds.

(63)
Magnien shows that sulphur at the rate of 2-3 grams per square meter placed in the rows at planting time apparently doubled the yields of turnips and beets.

(64)
Tritschler found that sulphur increased the yield and sugar content of mangel wurzels.

(65)
H. von Feilitzen found that out of five varieties of potatoes all but one yielded more on plots receiving 356 pounds of sulphur per acre in addition to normal fertilizers than on plots receiving no sulphur.

(66)
Suchting shows that ammonium sulphate increased the yield of potatoes more than did sodium nitrate.

(67)
Carlier demonstrated that manganese sulphate does not have a high manurial value. He also demonstrated that the high opinion of the fertilizer value of magnesium sulphate was unwarranted.

(68)
D. Zolla found that the fertilizing action of sulphur on vines was increased when mixed with organic matter and used in large amounts.

(70)
Maizeres found that 250-500 kilograms of sulphur per hectare increased the yields of potatoes and beets.

(71)
Herlinger reported higher yields of potatoes in sulphured rows.

(72)
F. Gianitto found that sulphur alone at the rate of 400 pounds per acre decreased the yield of potatoes, but when combined with

other fertilizers, it increased the yield.

(73)

Lierke observed that fertilizers containing sulphates gave better results than other fertilizers with fruits.

(74)

Josef Urban found that sulphur used at the rate of 178 pounds per acre with ammonium sulphate and Chili saltpeter slightly increased the yield of sugar beets.

(75)

W. Thalan reports some experiments with different forms of sulphur. Most were oxidized to sulphates in the soil.

(76)

M. Cercelet obtained increased yields of beans, peas, onions, potatoes and asparagus from applications of sulphur.

(77)

Chauzit found sulphur to have a favorable influence on the yield of grapes, especially when applied with fertilizers high in organic matter.

(78)

Liechti found from experiments that an increase of sulphur in fertilizers and soils tends to produce an increase in the amount in crops.

(79)

Vermorel and Dantony found organic matter to be important in obtaining beneficial results from applications of sulphur.

(80)

Degrully obtained large increases in yields of beets and turnips from sulphur applied at the rate of 109 grams per square meter. He concluded that this might be due to the sulphates formed or to a direct stimulating action of sulphur on the plant.

Losses of Sulphur from the Soil.

A consideration of the sources and amount of loss of sulphur from the soil is important in determining how much effort must be made to offset this loss and maintain an adequate supply for plant growth.

There are two sources of loss, namely, drainage and cropping. The nature of sulphur compounds in the soil is such that loss by drainage is considerable. The sulphates formed in the soil, like nitrates, are readily leached out. For this reason, there may be no accumulation of a supply but those not used by the plant are leached out and more must be formed from insoluble sulphur compounds. Accordingly, the addition of small amounts of sulphates in fertilizers will not permanently increase the amount in the soil. (82) Work done by Professor Morse of the Massachusetts Experiment Station shows just as much loss of calcium from the soil in the form of a sulphate as in the form of a chloride. This was determined by soil analysis from plots treated with muriate and sulphate of potash for twenty-two years. Though calcium chloride is known to be more soluble than calcium sulphate, he shows by figures that the average annual rainfall for a humid region is more than sufficient to dissolve out all the calcium sulphate formed from an ordinary application of potassium sulphate.

(83)

Lyon and Bizzell show that the loss of sulphates in drainage water varies considerably with the soil treatment and cropping. Their results from lysimeter tests are as follows :

Treatment	Loss of sulphates per acre annually
Manure, light application, no lime, uncropped.	44 lbs.
Manure, light application, no lime, cropped.	51.8 lbs.
Manure, light application, lime, uncropped.	53.1 lbs.
Sulphate of potash, 200 lbs. per acre, no lime, cropped.	56.4 lbs.
Sulphate of potash, 200 lbs. per acre, lime, cropped.	62.0 lbs.

It may be seen that the addition of lime increases the loss, probably due to the ready formation of calcium sulphate. An application of a sulphur carrying fertilizer also increases the loss. More sulphates are lost when no crop is present than when one is present with similar treatment.

(84)

Ruprecht and Morse have shown a greater loss of sulphur in the drainage water from plots treated with ammonium sulphate than from plots treated otherwise.

(85)

Hall gives figures on the loss of sulphur in drainage water. He states that 50 pounds of sulphur trioxide is lost annually per acre from unfertilized Rothamsted plots and 85 to 220 pounds annually per acre from fertilized plots.

(12)

Dymond, Hughes and Jupe give the loss of sulphur trioxide in drainage water from Barn Field, Rothamsted as 71.4 pounds per acre annually, a loss to the soil of .001 %.

That sulphates are not as stable compounds in the soil as phosphates is seen from any complete analysis of drainage waters. Sulphates have been compared with phosphates as possibly becoming of equal importance in soil fertilization. The large amount of

sulphur lost in drainage waters seems to indicate that the soil supply may become exhausted quicker than in the case of phosphorus. This is seen in the compilation of drainage water analyses from some Rothamsted plots as given by Hall. (86)

Analyses were made of the drainage water from various plots with different treatments.

	:Parts per million	
	:Maximum	:Minimum
Phosphoric acid	: 1.66	: 0.17
Sulphuric acid	: 99.70	: 21.90

Added to the loss of sulphur from the soil by drainage is the large amounts taken up by crops. This is shown in the following table from Shedd. (14)

Pounds of sulphur and phosphorus removed per acre by average crops.

	Lbs. Dry weight	Lbs. Sulphur	Lbs. Phosphorus
Wheat grain, 30 bu.	: 1530	: 2.6	: 6.2
Wheat straw	: 2653	: 3.7	: 3.0
Total crop	: 4183	: 6.3	: 9.2
Corn grain, 30 bu.	: 1500	: 2.6	: 4.4
Stover	: 1877	: 2.2	: 3.5
Total crop	: 3377	: 4.8	: 7.9
Bean grain, 30 bu.	: 1613	: 3.8	: 10.0
Bean straw	: 1848	: 2.0	: 2.8
Total crop	: 3461	: 5.8	: 12.8
Turnips, root	: 3126	: 23.1	: 9.8
Turnips, leaf	: 1531	: 13.8	: 4.7
Total crop	: 4657	: 36.9	: 14.5
Tobacco leaf	: 1800	: 6.4	: 3.5
Tobacco stalk	: 3200	: 2.0	: 3.5
Total crop	: 5000	: 8.4	: 7.0
Potatoes	: 3360	: 4.6	: 9.4
Meadow hay	: 2822	: 4.5	: 5.4
Glover hay	: 3763	: 6.2	: 10.9
Alfalfa hay	: 9000	: 26.0	: 17.4
Cabbage	: 4800	: 39.2	: 26.6

Sources of Sulphur Supply to the Soil.

To offset the constant removal of sulphur from the soil there are numerous sources of supply. It has been shown that virgin soil contains a fairly large amount of sulphur. This probably came originally from mineral compounds such as pyrites and from decayed vegetation. Another natural supply of sulphur is the rainfall. There is considerable sulphur gas in the atmosphere, chiefly in the form of the trioxide. The amount varies with the nearness to some source of sulphur gas such as decaying organic matter or burning coal. Thus, near towns and factories more sulphur trioxide is present to be washed from the atmosphere than is found in the open country.

The amount of sulphur brought to the soil by rainfall has been determined by various investigators.

(23)

Kossovich found that the sulphur falling with the rain annually per acre varied from 9 pounds in the country to 72 pounds in the neighborhood of towns. He concluded that a continuous introduction of sulphur from the atmosphere is essential to vegetation and for maintaining a supply to offset the rapid depletion from the soil by leaching.

(12)

Dymond, Huges and Jupe found the annual rainfall to bring down 18.5 pounds sulphur per acre in the country, and 50 pounds per acre near towns.

(6)

Hart and Peterson quote Hall as showing the average annual precipitation at Rothamsted to be $18\frac{1}{2}$ pounds of sulphur trioxide. They also give determinations of sulphur trioxide in the rainfall near Madison, Wisconsin. For five months of the year the rainfall was 11.14 inches and 10.70 pounds of sulphur trioxide per acre were brought down. Their figures are incomplete for a year

but show that there is a monthly and probably a seasonal variation in the amount of sulphur trioxide furnished the soil by rainfall.

It is undoubtedly safe to conclude from the data given that the annual loss by leaching much more than offsets the supply of sulphur brought down by the rain, and since this leaches from the soil so rapidly, there is no accumulation from this source for the use of the plant. Therefore, to furnish an available supply of sulphur, some other means must be employed than the transitory amounts in the rainfall and the natural supply in the soil which will not replenish itself.

Stock manures contain sulphur as well as other plant food materials. This is undoubtedly an important source of sulphur to the soil in regions where sufficient is produced to be of value. As to the per cent of sulphur in different stock manures, no average data has been obtained. It is known from a study of physiological chemistry that a greater amount of sulphur is excreted from the body in the urine than in the undigested solid matter. It gets into the urine from the oxidation of protein material in the body. Analyses of human urine give about 3.3% total sulphur. This would probably be about the same for farm animals. Since a large proportion of the urine is apt to be lost, the per cent of sulphur in the manure pile would be considerably less than in the urine.

(16)

Brown and Kellogg state that 10 ton applications of horse manure and cow manure return to the soil 12.28 and 16.02 pounds of sulphur respectively. Assuming this to be a general average for manures, the amount of sulphur returned is seen to be small.

Besides stock manures there are numerous commercial fertilizers used which contain sulphur. The most common of these with

the average amounts of sulphur carried are as follows :

100 lbs. acid phosphate	8 lbs. sulphur
100 lbs. ammonium sulphate	24 lbs. sulphur
100 lbs. potassium sulphate	18 lbs. sulphur.

Kainit contains considerable sulphur. Basic slag also contains some sulphur. Organic fertilizers such as dried blood, tankage, etc. contain varying amounts of sulphur, mostly in organic combination. Sodium nitrate, potassium chloride and calcium cyanamid probably contain no appreciable amount of sulphur.

Thus it is seen that there are numerous sources of sulphur supply commonly in use without considering the use of elemental sulphur alone.

Maintaining the Sulphur Supply.

Different sections of the country support different types of farming. Within these types the method of fertilization must be adapted to conditions. One system of fertilization, then, will not fit all types of farming. However, a broad question such as the sulphur supply may be worked out for a few closely related types of farming under similar soil and climatic conditions. Thus, all types of farming as found in Massachusetts or, more broadly, in the New England States, may be considered as similarly affecting the above question. This would not include types under different conditions of soil as found in the Middle West.

The chief farming practises in Massachusetts may be classed as dairying, truck farming and intensive tobacco, onion and potato raising.

First, we will consider dairy farming. Can the sulphur supply of the soil be maintained alone by the manure produced ? According to Warren's "Farm Management", the larger stock on a farm

will produce about one ton of manure per month per 1000 pounds live weight. For a 150 acre farm, then, with 15 cows and 4 horses about 21 tons of manure might be produced per month. During four months of the year, 15 tons of this might be lost from the cows at pasture. This would leave an average yearly production of about 200 tons. The amount produced by other stock than cows and horses would be negligible.

Supposing the chief crops raised are 40 acres of hay, including 20 of clover, 15 acres of corn, 10 acres of other grains and 1 acre of potatoes. The rest of the land might be pasture and waste land to which no manure is applied. This would remove annually about 400 pounds of sulphur in crops while the maximum amount of sulphur applied in 200 tons of manure would not exceed 350 pounds, according to the few figures we have. Green manure crops and crop residues would return only what sulphur they had removed.

Thus, from theoretical figures, it is seen that the sulphur supply cannot be maintained even on dairy farms by stock manure alone.

In the other two types of farming, little manure is produced. Considerable is purchased from cities where possible but it is generally impossible or too expensive to purchase sufficient to be used alone. What amounts are used will not furnish sufficient sulphur for intensive cropping over long periods of time.

For all types of farming in Massachusetts, large amounts of commercial fertilizers must be and are used. This practice over the state varies and the amounts used cannot be accurately stated.

Director Brooks of the Massachusetts Experiment Station has recommendations which are followed to a certain extent throughout the state. These recommendations, as Director Brooks states, are

designed to supply the optimum amounts of plant food so that the maximum returns may be secured for all labor expended on the crop. The amounts are probably somewhat in excess of those commonly used by the farmers but, nevertheless, they indicate what the average practice through the state may be.

Some of these fertilizers though applied primarily to supply other plant foods contain generous amounts of sulphur. Some figures comparing the amounts of sulphur supplied in this way with the amounts removed by the crop will show whether there is likely to be any necessity of applying sulphur alone for maintaining fertility in Massachusetts soils.

Crop	:Sulphur carrying: :fertilizers re- :commended :	lbs. per: : acre : with : manure :	lbs. : : sulphur : added : per acre :	lbs. : : sulphur : removed : by acre : of crop :	excess : sulphur : over crop : demands
Corn	:Acid phosphate	: 400	: 32	:	:
	:Basic slag*	: 500	: —	: 4.8	: 27.2
Hay	:Ammonium sulphate*	: 100	: 24	:	:
	:Acid phosphate	: 300	: 24	: 6.2	: 41.8
Onions	:Tankage	: 200	: —	:	:
	:Basic slag	: 800	: —	:	: 101.2
	:Acid phosphate	: 1000	: 60	: 23.8	:
	:Sulphate of	:	:	:	:
	: potash*	: 250	: 45	:	:
Potatoes	:Am. sulphate	: 80	: 14	:	:
	:Acid phosphate	: 1200	: 96	:	:
	:Sulphate of	:	:	:	:
	: potash*	: 560	: 134	: 4.6	: 239.4
Tobacco	:Cotton seed meal	: 1700	:	:	:
	:Am. sulphate	: 200	: 48	:	:
	:Acid phosphate	: 500	: 40	: 8.4	: 79.6

*Seldom actually used.

The above table shows a very large excess of sulphur over that used by the crop. In actual practice much of this would be leached out but undoubtedly more than the crop needs is retained in the soil by adsorption. A more permanent supply is

given to the soil in slowly decomposing organic matter from manures. All the preceding figures have been based on the assumption that the loss of sulphur by leaching equals or exceeds the amount brought down by rainfall.

Thus, under systems of farming as found in New England there seems to be little danger of sulphur's ever becoming a limiting factor in crop production. Such may not be the case, however, in regions such as the Middle West where crops are produced extensively from the natural fertility of the soil or with the aid only of green manures, crop residues and limestone.

Sulphur in Acid Phosphate.

It has been pointed out that many commercial fertilizers commonly used for the purpose of supplying nitrogen, phosphorus or potassium also furnish considerable sulphur and that they thus aid in maintaining the sulphur supply in the soil. Acid phosphate is one of the most extensively used of these sulphur carrying fertilizers. Its high efficiency as a fertilizer has been demonstrated in comparison with other phosphorus manures and largely attributed to the ready availability of its phosphoric acid. Some have claimed that the calcium sulphate contained in it also aids by a stimulating action on plant growth. The question also arises as to whether part of the beneficial action of acid phosphate is not due to the use of the sulphur as a plant food.

The following work was planned to determine the effect, if any, of the sulphur in acid phosphate on plant growth:

Method of Procedure.

Oats, turnips and clover were grown for about three months in three-gallon glazed earthen ware jars in the greenhouse. No drainage was allowed from the jars. Watering from the bottom was

practised almost exclusively through a glass tube in the center of each jar as shown in the photograph. The optimum moisture content of the soil was determined and each pot was kept up to this by frequent applications of tap water.

The oats were thinned to ten plants per pot, the turnips to five and the clover to thirty-five. At the end of the growing period the crops were harvested and oven-dried and these weights taken for the calculation of results.

The fertilizer treatment per pot was as follows :

Pot No. :	Treatment and amounts
:	:
O	:Nitrate of soda, 400 lbs. per A. (0.2264 grams). :Muriate of potash, 300 lbs. per A. (0.17 grams).
A	:Same as above plus double superphosphate, free from : sulphur, 0.411 grams.
B	:Same as O plus acid phosphate, 1000 lbs. per A. : (0.566 grams)
C	:Same as A plus sulphuric acid, 0.2009 grams.
D	:Same as A plus flowers of sulphur, 0.0656 grams.
E	:Same as A plus calcium sulphate, 0.3528 grams.
LO	:Same as O plus 2000 lbs. lime per A. (1.132 grams Ca(OH)_2)
LA	:Same as A plus 2000 lbs. lime per A. (1.132 grams Ca(OH)_2)
LB	:Same as B plus 2000 lbs. lime per A. (1.132 grams Ca(OH)_2)
LC	:Same as C plus 2000 lbs. lime per A. (1.132 grams Ca(OH)_2)
LD	:Same as D plus 2000 lbs. lime per A. (1.132 grams Ca(OH)_2)
LE	:Same as E plus 2000 lbs. lime per A. (1.132 grams Ca(OH)_2)

The object of the fertilizer treatment as given was to determine the effect on plant growth of the sulphur contained in an application of 1000 pounds of acid phosphate per acre. This is done by comparing treatments of acid phosphate and other forms of sulphur, of the same amount as found in the acid phosphate, with

treatments of a double superphosphate carrying an equivalent amount of water and citrate soluble phosphoric acid but no sulphur. Equal amounts of nitrogen and potash were added to each pot. The effect of lime was determined by adding equal amounts of calcium hydrate to one duplicate set of each treatment. Duplicate pots were used in all cases.

The double superphosphate was made by treating finely ground rock phosphate with pure phosphoric acid. The fine ground rock was found to contain a small amount of sulphur. This was practically eliminated by soaking in oxygenated water and decanting repeatedly. A trace of sulphur still remained, probably in the mineral pyrites, but the amount was negligible.

A phosphate was finally obtained which gave nearly the same per cent of water and citrate soluble phosphoric acid as the acid phosphate used. The amount of double superphosphate for each treatment was then calculated so as to give the same total quantity of water and citrate soluble phosphoric acid as the amount of acid phosphate used contained.

To obtain similar sulphur treatments the acid phosphate was analyzed and found to contain 29% sulphur trioxide. The same amount of sulphur was added in the form of sulphuric acid, flowers of sulphur and calcium sulphate as was added in the acid phosphate.

The soil used was obtained from an experimental plot on which crops had been grown, but no fertilizer applied, for the last twenty-six years. It thus represents an average fine sandy loam soil of very low fertility. This was partially air dried and then sifted to get rid of all large pebbles and foreign material. After being well mixed to insure uniformity in the pot, 11681 grams was added to each jar.

The fertilizers were well mixed with the upper half portion of

the soil in each pot before it was poured in. The sulphuric acid was added in dilute solution to the top of the soil just before the seeds were sown.

An analysis of the soil for total sulphur by the sodium peroxide fusion method as outlined by Hart and Peterson gave 0.05% sulphur trioxide. An adjoining soil which had grown the same crops but had received an annual application of a complete fertilizer, including dissolved bone black as a sulphur carrier, was found to contain 0.059% sulphur trioxide. This confirms the work of Hart and Peterson and others showing a decrease in total sulphur content of the soil due to cropping and lack of fertilization.

Results obtained.

The results as shown by the growth of each crop were as follows :

Series 1. Oats.

(Seed sown January 26th. Crop harvested May 11th.)

When harvested the grain was not mature but the heads were well formed. This is shown on Plate 1a and 1-b. The photographs also show that there were no apparent differences in the growth of the oats from the different treatments. During the early growth of the crop a slight stimulation was noticed in the pots receiving phosphoric acid as compared with the check pot receiving only nitrogen and potash, but this was soon equalized, probably due to the fact that oats are coarse feeders and could obtain considerable plant food from the soil itself after once getting started. The addition of lime had no effect.

The dry weights given in Table I show no uniform variations due to fertilizer treatment since any differences shown may be due to natural variations in growth.

Table I.

Series 1.		Oats	Oven-dry weights in grams	
Pot No.	Wt. of : duplicates :	Av. wts. of : duplicates :	Increase + or decrease - : as compared with : check pot : (no phosphorus) :	no sulphur pot
O ₁	34.30			
O ₂	34.45	34.375	00.00	00.00
A ₁	37.00			
A ₂	35.60	36.30	+ 1.925	00.00
B ₁	33.25			
B ₂	32.50	32.875	- 1.5	- 3.425
C ₁	37.50			
C ₂	34.40	35.95	+ 1.575	- 0.35
D ₁	30.30			
D ₂	33.20	31.75	- 2.625	- 4.55
E ₁	33.35			
E ₂	36.10	34.225	- 0.15	- 2.075
LO ₁	33.90			
LO ₂	31.60	32.75	00.00	00.00
LA ₁	31.75			
LA ₂	30.30	31.025	- 1.725	00.00
LB ₁	31.30			
LB ₂	33.10	32.20	- 0.55	+ 1.175
LC ₁	37.95			
LC ₂	33.10	35.525	+ 2.775	+ 4.5
LD ₁	32.90			
LD ₂	34.85	33.875	+ 1.125	+ 2.85
LE ₁	35.50			
LE ₂	31.85	33.675	+ 0.925	+ 2.65

Oats do not seem to be affected by applications of sulphur fertilizers. This agrees with the conclusions of other investigators. The sulphur content of oats is known to be low so that only small amounts of sulphur are used in plant growth. Also, since the oat plant is a coarse feeder it is probably able to get sufficient sulphur from most any soil on which growth will take place at all.

Series 2. Turnips.

(Seed sown January 29th. Crop harvested May 9th.)

From Plate 2 there appears to be very little difference in the growth of the turnip plants under different treatments. This was true throughout their growing period.

But from Table II-b there are seen to be fairly constant variations in favor of some of the sulphur treatments. Where no lime was applied all the sulphur treatments gave increased yield of both tops and roots. The calcium sulphate in the acid phosphate and the calcium sulphate added separately gave larger increases than the sulphuric acid or flowers of sulphur. This may have been partly due to the need of the soil for lime, but probably as much lime was added in the double superphosphate as in the acid phosphate, and so the increase must have been due in greater part to the sulphur added. The combined sulphur of the acid phosphate seems to be the most beneficial form.

The irregular results from the addition of lime were partly due to injuries from aphids and partly to the effect of the lime on the soil. The addition of lime evidently was needed by the soil and improved it to such an extent that the check pots and no sulphur pots gave large yields themselves and so cut down any increase due to the other treatments. This does not destroy the evidence in favor of the effect of sulphur on plant growth but

Table II-a.

Series 2.		Turnips		Oven-dry weights in grams			
		:Av.Wt. of :Wt.Roots:		:Av.Wt. of :Wt.Tops:		:Av.Wt. of	
Pot No.:	Wt.Tops:	duplicates:		duplicates:	& Roots:	duplicates	
O ₁	6.90		6.90		13.80		
O ₂	7.65	7.275	11.60	9.2	19.15	16.475	
A ₁	7.30		12.00		19.30		
A ₂	7.75	7.527	9.70	10.85	17.45	18.377	
B ₁	10.45		14.30		24.75		
B ₂	9.15	9.8	13.80	14.05	22.95	23.95	
C ₁	8.65		11.60		20.25		
C ₂	10.03	9.34	11.10	11.35	21.13	20.69	
D ₁	8.70		10.00		18.70		
D ₂	8.25	8.475	12.50	11.25	20.75	19.725	
E ₁	9.70		12.50		22.20		
E ₂	13.40	11.55	9.75	11.125	23.15	22.675	
LO ₁	8.50		11.35		19.65		
LO ₂	10.45	9.375	12.45	12.9	22.90	22.275	
LA ₁	10.20		13.35		23.55		
LA ₂	9.65	9.925	12.20	12.775	21.85	22.7	
LB ₁	11.20		12.80		24.00		
LB ₂	8.15	9.675	12.05	12.425	20.20	22.1	
LC ₁	9.45		12.40		21.85		
LC ₂ *	8.15	8.8	9.10	10.75	17.25	19.55	
LD ₁ *	8.00		7.30		15.30		
LD ₂ *	7.45	7.725	8.85	8.075	16.30	15.8	
LE ₁ *	8.20		10.85		19.05		
LE ₂	9.15	8.675	9.15	10.00	19.30	18.675	

*Injured by aphids.

Table II-b.

Series 2.		Turnips					
		Increase + or decrease - as compared with					
		Check Pot. (No phosphorus)::			No Sulphur Pot		
Pot No.:		Roots	Tops	Roots and Tops::	Roots	Tops	Roots and Tops
O ₁							
O ₂		00.00	00.00	00.00	00.00	00.00	00.00
A ₁							
A ₂		+1.65	+0.25	+1.902	00.00	00.00	00.00
B ₁							
B ₂		+4.85	+2.525	+7.375	+3.20	+2.273	+5.47
C ₁							
C ₂		+2.15	+2.065	+4.215	+0.50	+1.813	+2.31
D ₁							
D ₂		+2.05	+1.20	+3.25	+0.40	+0.948	+1.35
E ₁							
E ₂		+0.925	+4.275	+5.20	+0.275	+4.023	+4.298
LO ₁							
LO ₂		00.00	00.00	00.00	00.00	00.00	00.00
LA ₁							
LA ₂		-0.125	+0.55	+0.425	00.00	00.00	00.00
LB ₁							
LB ₂		-0.475	+0.30	-0.175	-0.35	-0.25	-0.60
LC ₁							
LC ₂		-2.15	-0.575	-2.725	-2.025	-1.125	-3.15
LD ₁							
LD ₂		-4.825	-1.65	-5.475	-4.70	-2.20	-6.90
LE ₁							
LE ₂		-2.90	-0.70	-3.60	-2.775	-1.25	-4.025

shows that an improved condition of the soil due to liming may allow the plant to obtain sufficient from the soil alone.

Turnip plants are known to be high sulphur consumers and this work shows that the sulphur contained in acid phosphate, or added in like amount, when used as a fertilizer is an aid in causing increased growth.

Series 3. Clover.

(Seed sown January 31st. Crop harvested May 15th.)

The growth of clover plants did not show much variation due to different fertilizer treatments as can be seen from Plate 3. A slightly heavier growth is noticeable, however, in some of the pots receiving lime. This shows that the soil was in need of lime.

However, the variation in dry weights does show a constant increase over the checks due to the various sulphur treatments on both the limed and unlimed soils. This is seen from the figures in Table III.

The different forms of sulphur applied in amounts equal to that in the acid phosphate do not show any constant differences in their effect on plant growth. For clover the combined sulphur in the acid phosphate does not seem to be the best while for turnips it does. Calcium sulphate and sulphuric acid seem to be the best for clover where no lime was used. With lime the flowers of sulphur gave the largest increase. The balance of the evidence seems to be in favor of the sulphur combined as calcium sulphate in the acid phosphate. Calcium sulphate added separately is next in beneficial effect. This is probably because the flowers of sulphur need to be oxidized to sulphates before they are of use to the plant and the sulphuric acid must be taken up by a base. The calcium sulphate applied as such is

Table III.

Series 3. Pot No.:	Clover.		Over-dry weights in grams.	
	Wt. of duplicates:	Av. wts. of duplicates:	Increase + or decrease - as compared with	
			check pot (no phosphorus):	no sulphur pot
O ₁	14.30			
O ₂	15.30	14.80	00.00	00.00
A ₁	14.20			
A ₂	15.85	15.025	+0.225	00.00
B ₁	15.45			
B ₂	16.25	15.65	+1.05	+0.825
C ₁	15.95			
C ₂	16.55	16.15	+1.35	+1.125
D ₁	17.60			
D ₂	12.85	15.225	+0.425	+0.20
E ₁	18.65			
E ₂	16.10	17.375	+2.575	+2.35
LO₁				
LO ₁	15.85			
LO ₂	15.75	15.80	00.00	00.00
LA ₁	17.80			
LA ₂	15.30	16.55	+0.75	00.00
LB ₁	17.65			
LB ₂	17.05	17.35	+1.55	+0.80
LC ₁	17.45			
LC ₂	17.00	17.225	+1.425	+0.675
LD ₁	19.75			
LD ₂	18.50	19.125	+3.325	+2.575
LE ₁	17.85			
LE ₂	17.15	17.50	+1.70	+0.95

Plate 1-a.

Plate 1-b.

Plate 2.

Plate 3.

ready at once for solution and absorption by the plant.

Clover is known to contain a medium percentage of sulphur, chiefly in its protein compounds. The above evidence shows definitely that the sulphur contained in acid phosphate when applied to clover as a fertilizer aids the phosphoric acid in giving increased yields. It is therefore important to such crops that an adequate supply of available sulphate should be maintained.

Water Soluble Sulphates in the Soil.

In an effort to determine to what extent soluble sulphates are formed in the soil and used by the plant, an analysis of the differently treated soils was made for water soluble sulphates. This was done for each treatment of the turnip and clover crops. Two analyses were made one month apart to ascertain any exhaustion of the sulphate supply through use by the plant.

The method of analysis was similar to that outlined by Brown (26) and Kellogg. Fifty grams of oven dry soil were placed in a shaker bottle with 100 c.c. of distilled water and shaken for seven hours in a shaking machine. This was filtered and 1 c.c. of conc. hydrochloric acid added to flocculate the colloids and to make the solution acid. After settling, this was filtered and the filtrate made up to 500 c.c. in a volumetric flask. An aliquot of 300 c.c. was taken from which the sulphates were precipitated as barium sulphate in a hot solution by the addition, drop by drop, of 10 c.c. of hot barium chloride. The hot solution was allowed to stand over a hot water bath for about twenty-four hours. The precipitate was then filtered through a Gooch crucible of known weight. The crucible and precipitate was allowed to dry and then heated to a red heat over a bunsen flame for about a half hour. After cooling in a dessicator, it was

weighed and the amount of barium sulphate determined by subtraction. This amount was calculated as sulphur trioxide and expressed as parts per 100,000 of dry soil.

A composite soil sample for analysis was taken from each of the duplicate pots.

The results obtained for the turnip pots are given in Table IV. The figures do not seem to be uniform, due probably to variations in sampling. Also, the differences between amounts of sulphates obtained were so small that difficulty was experienced in filtering and weighing them accurately.

There seems to be but little correlation between amount of water soluble sulphates and plant growth. In some cases the amount obtained where no sulphate fertilizers were applied exceeds the amount from sulphate treated soils. This may have been due to optimum conditions in the soil for the formation of sulphates but not for a good crop growth, due to the lack of phosphorus. For this reason, a smaller amount of sulphates would be taken up by the plant.

The water soluble sulphate content of the original soil is seen to be much less than that of the pot soil after growing a crop for some time. This is probably due to the lack of drainage from the pots and the prevention of loss by leaching which would occur in the field. Some sulphates were also added in the tap water but the amount was negligible. A composite sample of all the tap water used analyzed 0.2777 parts sulphur^{trioxide} per 100,000 parts of water. This gives a total addition to each of the turnip pots of about 0.039 grams sulphur^{trioxide} and to each of the clover pots of about 0.041 grams.

A decrease in amount of water soluble sulphates is plainly apparent after a months growth of turnips. This month's growth

Table IV.

Water soluble sulphates. Expressed as SO_3 parts per 100000 of soil

Series 2. April 10.				Series 2. May 8.			
: Excess + or deficiency:				: Excess + or deficiency:			
: - as compared with :				: - as compared with :			
Pot: SO_3	: No Sul-		Pot: SO_3	: No Sul-			
No.:	Check Pot	phur Pot	No.:	Check Pot	phur Pot		
O*	:11.09:	00.00	: 00.00	:O	:12.90:	00.00	: 00.00
A	:14.29:	+3.20	: 00.00	:A	: 6.10:	-6.80	: 00.00
B	:11.09:	00.00	: -3.20	:B	: 8.20:	-4.70	: +2.10
C	:12.12:	+1.03	: -2.17	:C	:10.50:	-2.40	: +4.40
D	: 4.80:	-6.29	: -9.49	:D	: 7.10:	-5.80	: +1.00
E	:14.63:	+3.54	: +0.34	:E	: 4.46:	-8.44	: -1.64
LO	: 9.26:	00.00	: 00.00	:LO	: 5.15:	00.00	: 00.00
LA	: 6.75:	-2.51	: 00.00	:LA	: 1.21:	-3.94	: 00.00
LB	:12.90:	+3.64	: +6.15	:LB	: 2.86:	-2.29	: +1.65
LC	:11.09:	+1.83	: +4.34	:LC	: 5.70:	+0.55	: +4.49
LD	:13.50:	+4.24	: +6.75	:LD	: 4.80:	-0.35	: +3.59
LE	:13.70:	+4.44	: +6.95	:LE	: 2.63:	-2.52	: +1.42

*4.23 parts per 100000 originally contained in soil used.

Table V.

Water soluble sulphates. Expressed as SO_3 parts per 100000 of soil

Series 3. April 12.				Series 3. May 15.			
: Excess + or deficiency :				: Excess + or deficiency :			
: - as compared with :				: - as compared with :			
Pot: SO_3 :	: No Sul-		Pot: SO_3 :	: No Sul-		: No Sul-	
No.:	: Check Pot :	phur Pot	No.:	: Check Pot :	phur Pot	: phur Pot	
O* : 9.72:	00.00	00.00	O : 10.50:	00.00	00.00	00.00	
A : 5.60:	-4.12	00.00	A : 2.50:	-9.00	00.00	00.00	
B : 5.15:	-4.57	-0.45	B : 11.20:	+0.70	+6.70	+6.70	
C : 14.29:	+4.57	+8.66	C : 17.70:	+7.20	+15.20	+15.20	
D : 6.90:	-2.82	+1.30	D : 2.28:	-8.22	-0.22	-0.22	
E : 9.35:	-0.37	+3.75	E : 8.00:	-2.50	+5.50	+5.50	
LO : 7.54:	00.00	00.00	LO : 5.10:	00.00	00.00	00.00	
LA : 9.35:	+1.81	00.00	LA : 7.40:	+2.30	00.00	00.00	
LB : 16.40:	+3.86	+7.05	LB : 4.10:	-1.00	-3.30	-3.30	
LC : 9.72:	+2.18	+0.37	LC : 6.97:	+1.87	-0.43	-0.43	
LD : 8.80:	+1.26	-0.55	LD : 13.60:	+8.50	+6.20	+6.20	
LE : 16.00:	+3.46	+6.65	LE : 3.88:	-1.22	-3.52	-3.52	

*4.22 parts per 100000 originally contained in soil used.

took place during maturity when the greatest demand for sulphates would come from the plant. It seems then that a crop, such as turnips, containing a high percent of sulphur, does use up the readily available supply of sulphates in the soil.

Table V shows very little correlation between the growth of the clover plants and the amount of water soluble sulphate present from different treatments. As in the case of the turnips, some pots without any sulphate treatment show as high soil content of water soluble sulphates as those receiving treatments with sulphates.

The clover pots do not show as decided a decrease in the content of water soluble sulphates at the end of the month as the turnip pots do. There is, however, a slight decrease. This shows that a crop such as clover, containing a medium percent of sulphur, does use up the readily available sulphates but not to as great an extent as the turnip crop.

SUMMARY AND CONCLUSIONS.

The possibility of sulphur's becoming an important limiting factor in crop production has but recently come prominently to the attention of agricultural investigators. The work of various men has brought out numerous points.

1. Improved methods of sulphur analysis for crops and soils show that large amounts of sulphur are removed by crops and that the total per cent in soils is gradually decreased by continual cropping.

2. Sulphur exists in the soil in various forms which are changed to the sulphate form by bacterial and chemical action. It is chiefly in this form that sulphur is taken up by the plant.

3. Crops vary in their demand for sulphur according to their composition. Experiments have shown that especially those crops having a high sulphur content are benefited by applications of sulphur fertilizers.

4. Sulphur may have an indirect as well as a direct effect on plant growth but the direct effect as a plant food is important.

5. Aside from the loss of sulphur from the soil by removal in crops, the ready solubility of sulphates allows a large loss in drainage waters.

6. The chief sources of supply of sulphur to the soil are rainfall, stock manure and commercial fertilizers.

7. Figures show that the stock manure produced in any type of farming is not sufficient to maintain a permanent sulphur supply in cropped soils.

8. Commercial fertilizers, as applied in common practice on

New England farms, are shown to furnish a large excess of sulphur for crop use. Therefore, there is no danger of sulphur's becoming a limiting factor in crop production where commercial fertilizers are commonly used.

From the experiments performed, the following conclusions may be drawn:

1. The sulphur in acid phosphate when applied to soil of a low sulphur content has a beneficial influence on the growth of clover and turnips but produces no effect on the growth of oats.

2. Sulphur is most likely to be beneficial to the growth of crops containing a medium or high percentage of sulphur.

3. The data obtained indicate that the supply of water soluble sulphates in the soil is decreased as the plant grows.

4. Acid phosphate has a beneficial action on plant growth, due to the use of its sulphur as a plant food.

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