THE SOLUBILITY OF APPLIED NUTRIENTS IN MUCK SOILS AND THE COMPOSITION AND QUALITY OF CERTAIN MUCK CROPS AS INFLUENCED BY SOIL REACTION CHANGES AND MOISTURE CONDITIONS

By

WILLIAM S. LIGON

A THESIS

PRESENTED TO THE FACULTY

OF

MICHIGAN STATE COLLEGE

OF

AGRICULTURE AND APPLIED SCIENCE

IN

PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE

DEGREE OF DOCTOR OF PHILOSOPHY

East Lansing

1 9 3 4

ACKNOWLEDGMENTS

The writer wishes to make the following acknowledgments:

(1) To Dr. Paul M. Harmer for the suggestion of the problem and for his encouragement, co-operation, and many helpful suggestions--both in the performance of the work and in the preparation of the manuscript.

(2) To Dr. C. E. Millar and other members of the soils section of Michigan State College for their numerous suggestions and constructive criticisms.

(3) To the N.V. Potash Export MY. Inc., of Amsterdam, Holland, for their generous fellowship thru which this investigation was made possible.

THE SOLUBILITY OF APPLIED NUTRIENTS IN MUCK SOILS AND THE COMPOSITION AND QUALITY OF CERTAIN MUCK CROPS AS INFLUENCED BY SOIL REACTION CHANGES AND MOISTURE CONDITIONS

INTRODUCTION

The muck soils of Michigan have long held a national reputation for the production of various crops. While most Michigan mucks when properly fertilized produce satisfactorily, there are some that possess a reaction unfavorable for the profitable growing of certain crops. Of such mucks there are at least two classes: (1) the "alkali" mucks, or those having an alkaline reaction caused, generally, by the concentration of ash produced from the burning of muck materials of high lime content, and (2) the "very strongly acid" mucks, that are low in lime and have a very high degree of acidity.

Within recent years considerable work has been done by Harmer (12) (13) (14) (15) at this Experiment Station in reclaiming such mucks by means of sulfur applications to the alkaline type and lime applications, together with certain additional treatments, usually copper sulfate, to the very strongly acid type. In many cases the results have been phenomenal (14) (15). Sulfur applications on certain alkaline mucks have in-

HISTORICAL

A large number of studies have been made on soil reaction, availability of plant nutrients, and their relationships to plant composition in connection with mineral soils. In so far as the writer is aware, however, very few investigations of this nature have been reported in regard to muck soils.

Loehwing (24) states that the methods commonly used for the determination of available plant food materials in soils are not adapted to mucks, due to the difficulty in avoiding the adsorptive effects of the organic colloids present in them. He found that soil extracts initially acid to indicators may turn alkaline on standing; and that colloid phenomena such as these were accompanied by great variations in concentration of plant nutrients, especially potassium and calcium. This was in agreement with the observations of Puchner (37). On analyzing crops of corn, oats, wheat, and clover grown on four acid mucks responding differently to potash and lime, Loehwing found that the concentration of potassium or calcium increased in the plant tissues when potassium chloride or calcium carbonate, respectively, were used as fertilizers. He concluded that these results indicated an increased availibility in spite of the tendency of the organic colloids to adsorb mineral bases. Applications of calcium to the soil was found to decrease the potassium content of the plant tissues in all cases. High crop yield was associated with high organic nitrogen and high total carbohydrate content of the plant, while low crop yield correlated with high nitrate and calcium content.

Wilson, Staker, and Townsend (49) found the drainage waters from New York peats to be characteristically alkaline while the reaction of the peats was characteristically acid. Drainage waters were found to be acid only when they were associated with extremely acid soils underlain by non-calcareous materials. No correlation was found to exist between the alkalinity of the water and the acidity or calcium content of the soil thru which it percolated. Altho not stated by the authors, their data indicates that when the deposits were underlain by marl the more acid deposits gave the highest concentration of calcium in the drainage water.

Fleischer (9) found that very heavy applications of lime, even on very lime-deficient peats, were not only unnecessary but actually injurious to crops. Numerous other investigators (1) (2) (13) (14) (47) have warned against improper use of lime on muck soils. Alway and Nygard (2) conclude that on strongly acid peats an actual determination of the per cent of lime is by far the most reliable method so far proposed for detecting lime deficiency. They point out the need of more detailed studies on the relationship of H-ion concentration to lime deficiency in the case of very acid peats.

Loehwing (24) thinks that the injurious effects he obtained by liming acid mucks must be explained by the action of lime on soil nutrients, the net result of which was unfavorable to crops. Tait and Knott (48) also express the opinion that soil reaction has an effect upon the availability of materials in muck soils. These writers have not shown, however, what relationships actually exist between reaction and nutrient solubility in muck soils.

It is clearly recognized that results obtained from studies of mineral soils may be inapplicable to mucks. For this reason, and also because of the fact that several excellent reviews already exist, another review of the large number of investigations that have been conducted on the effects of lime and sulfur additions to mineral soils hardly seemed justifiable here. Of these investigations, the following may be mentioned as among those most pertinent to the present study: Greenhill (11), MacIntyre, et. al. (25) (26), Jenny and Shade (19), Parker and Tidmore (31), Perkins, King, and Benne (32), Robinson and Bullis (38), Ames (3), Shedd (43), Itano and Matsura (18), Stephenson and Powers (46), Powers (36), Kelley and Thomas (21), Kelley and Arany (20), Samuels (40), Fraps (10), McKibbin (28) and Roux (39).

A review of the literature dealing with sulfur and lime applications to mineral soils revealed that the following effects have been attributed to these treatments:

1. Correction of unfavorable soil reaction.

2. Correction of sulfur or calcium deficiency.

3. Changes in concentration of soluble calcium, magnesium, potassium, phosphates, sulfates, carbonates, nitrates, and other soil constituents.

4. Changes in plant composition.

5. Changes in various biological processes.

Many of these effects and numerous others are undoubtedly highly interrelated. Certain of the above points have been noted and studied in the present muck soil investigation.

Crop Quality

Quite frequently a difference in quality between two samples can be seen at a glance; but comparison by means of a scientific measurement that will accurately represent the differences noted by the eye is, in many and probably most cases, a very difficult task. A survey of the literature on crop quality reveals at least two types of standards of measurement that may be possible:

1. Use of some type of scorecard or mechanical defice based on, or designed to measure, such characteristics as color, size, taste, cooking quality, etc.

2. Chemical analysis.

The recent work of Sayre, et. al. (41), in which quality of canning peas was measured by puncture and crushing tests on the one hand, and calcium, starch, and protein changes on the other, illustrates the use of both indices of measurement.

Harmer and Weidemann(17) found that proper fertilization of certain crops on muck land gave notable increases in their sugar content. As a result of their work they suggested the possibility of the use of sugar analysis as a measure for quality of table beets, carrots, onions, turnips, and rutabagas.

As pointed out in the introduction of this paper, lime or sulfur treatment has given enormous improvement of crop quality on certain mucks in Michigan. In this study an attempt was made to compare some of the crop samples of extreme differences in quality as to their content of sugars and certain mineral elements to discover, if possible, any correlations between the crop content of these constituents, the soil treatments, and the yields and quality of the crops.

EXPERIMENTAL

Experiment 1

Effects of Certain Soil Amendments on Nutrient Solubility in the Soil and on Plant Composition.

The object of this experiment was to study, on the same soil under field conditions and thruout a growing season, the effects of lime and sulfur on soil reaction, on the solubility of applied mineral nutrient materials, and on plant composition. It was hoped that in each case a picture might be obtained of the environment under which the plants had grown with respect to the solubility of the added fertilizer nutrients; and that it might be determined whether or not differences thus noted could be correlated with differences in the plants themselves.

Plan and Methods

Description of Soil and Plots. Since sulfur and lime were to be compared on the same soil it was necessary to use a muck not too strongly acid or alkaline. The college muck area was found to be satisfactory in this respect.

In co-operation with Dr. P. M. Harmer, use was made of a series of 12 plots, known as the "reaction plots", being laid out on the college muck, recently fitted for experimental work. This muck had been cleared first about 75 years previously, at which time the growth was chiefly tamarack. After clearing, it had been used mainly as pasture land. In the last 20 years it had developed a scattering growth of poplar. This had been cleared off in 1921. The soil had then been broken about 1924, allowed to go back to sod, and used for pasture until 1930. At this time it was tile drained, broken to a depth of 12 inches, and fitted for the experimental plots, the first crops being grown in 1931.

This muck is somewhat raw--in some parts quite woody--and varies from 10 to 18 ft. in depth where the plots for this study were located. It is a "high-lime" muck (13) and responds markedly to potash and, to a less extent, to phosphate fertilizer. Copper sulfate in small amounts gives good response with many of the crops grown.

All of the plots used in this experiment were fertilized uniformly on May 10 with a broadcast application of 3-9-18 fertilizer at the rate of 800 lbs. per acre. On May 20 to May 22 the plots were given the supplemental treatments shown in table 1. Several crops were seeded on this series of plots at appropriate times; from them onions, carrots, and turnips were chosen for the analytical studies.

Soil Samples

Sampling. Composite soil samples were taken from each plot at approximately two-week intervals from July 7 to Sept. 17. These samples were taken from the surface soil at a 2-3 in. depth, the surface crust having been removed. It was thought that this depth would most nearly represent the environment of the onion bulb and of the carrot and turnip roots throughout the season. The composite samples were made up of twelve or more portions taken from the onion section at different places along each side of the 20-ft. row from which the onion samples were to be obtained.

The soil samples were taken to the laboratory, air-dried, the larger woody pieces screened out, and stored in suitable containers pending analysis. Air-drying of the samples was found by the writer to result in no appreciable differences in pH or water-soluble constituents between tests made six months apart on a num-

Table 1

Plot treatments - Reaction plots (1931).

Plot No.	Treatment[1] (lbs. per acre)
1	Sulfur 500
2	Sulfur 1000
3	None
4	Pulverized limestone 4400
5	Pulverized limestone 4400, sulfur 500
6	Pulverized limestone 8800
7	Pulverized limestone 8800, sulfur 500
8	Pulverized limestone 8800, sulfur 1000
9	None
10	$MnSO_4$ 50[2]
11	$CuSO_4$ 25[2]
12	None

[1] All plots were fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

[2] The $CuSO_4$ and $MnSO_4$ treatments were placed in this series of plots for purposes foreign to this study. Since, however, these treatments have shown decided crop benefits on many Michigan muck soils, presumably due to correction of copper or manganese deficiencies, samplings were taken from these plots along with the others to determine if these treatments exerted any effects at all on the points under investigation here.

ber of the samples. This is in agreement with the findings of Coles and Morison (7) that peat gave no change in pH, upon drying, until all of the water was removed; and also with those of Arnd and Hoffman (4) that drying at room temperature, or even at 105°C., had no appreciable influence on pH.

Analytical Methods.* Hydrogen-ion concentration was determined on all soil samples electrometrically by means of the quinhydrone electrode, the samples having stood over night saturated with water.

One-to-ten soil-water extracts for making the solubility studies were made by the collodion sack method of Pierre and Parker (33) (34). Ten c.c. of toluene were added to each flask along with the 25 g. of muck and 250 c.c. of water to prevent changes in nitrate concentration. After equilibrium was established (4 days), the extracts were withdrawn from around the sacks and stored pending analysis. With the muck under investigation this method of obtaining the extracts was found not to be subject to the difficulties cited by Loehwing (24). This was demonstrated by the following test, the results of which are given in table 2:

Four equal portions were taken from the same soil

\- - - - - - - - - - - - - - - - - - -

* The analytical methods, for both soil and plant, given for Experiment 1 were used in all the experiments presented in this paper.

Table 2

Effect of dialysis period on changes in pH and water-soluble calcium content of 1-10 soil-water extracts.

(pH of soil 6.47)

Flask No.	Days dialyzed	pH		Calcium in 1-10 extract	
		After dialysis	On ninth day	After dialysis p.p.m.	On ninth day p.p.m.
1	1	6.77	6.77	501	509
1a	1	6.77	6.77	489	481
2	4	6.47	6.47	574	570
3	4	6.47		574	
3	9		6.47		570

sample, which had a pH of 6.47. All four portions were set up in collodion sacks at the same time. The soil in flasks 1 and 1a was dialyzed 1 day, after which pH and water-soluble calcium were determined on the dialysate. The extracts were removed from around the sacks and allowed to stand in flasks for 8 days, after which the analyses were repeated. The soil in flask 2 was allowed to dialyze 4 days, pH and calcium were determined on the extract, the extract removed as before, and the determinations repeated on the ninth day. In flask 3 dialysis was allowed to proceed the full 9 days, analyses of the extract being made after 4 days(duplicating flask 2) and on the ninth day. It can be seen from the table that dialysis was not complete after one day, but that there was no change in eight days following removal of the extract from around the collodion sack. Dialysis was complete on the fourth day, and there was no appreciable change from then on to the end of the 9-day test whether the extracts were in contact with the collodion sack or not. The results secured from the acid mucks used in Experiment 2 were more in keeping with Loehwing's findings, their extracts being more alkaline than the mucks themselves and exhibiting some variability in plant food constituents, but not enough to be of significance in comparing the large differences resulting from the different soil treatments.

Potassium was determined by a modification of Kramer and Tisdall's (23) method using sodium cobaltinitrite reagent. The modification consisted in making the precipitation in 50% alcohol, washing with alcohol of like strength, and decanting the supernatant liquid in each case, following centrifuging, rather than siphoning it from the precipitate.

Calcium was determined by precipitating it as the oxalate and titrating the oxalate with standard $KMnO_4$ solution; phosphates, by the blue colorimetric method, using the technique of Parker and Fudge (30); and nitrates, by the phenol di-sulfonic acid method. In those cases in which organic matter in the extract interferred with accurate readings, the procedure of Plice (35), employing the use of ammonia and superoxal, was used with good effect to clear the solutions. Sulfates and chlorides were not determined quantitatively in the water extracts as obtained above but were estimated on several of the samples by the procedures recently published by Spurway (45).

All solubility data are expressed in parts per million in the 1-10 soil-water extracts.

Plant Samples

Sampling. Representative onion samples were taken from the row along the sides of which the soil samples had been taken in each plot. These were removed to the laboratory and each onion quartered. Fifty-gram samples consisting of slices from one quarter piece of each onion were at once placed in pint Mason jars containing boiling alcohol. After boiling for some time on the steam bath the jars were sealed and set aside for sugar analysis. Samples of the carrots and turnips were handled in like manner.

From the remaining plant pieces a sample was made up of quarter pieces from each bulb or root, was weighed, cut into smaller pieces, and allowed to dry somewhat in the air. The samples were then run thru a food chopper and allowed to air-dry completely. This procedure gave practically no loss of sap mineral constituents. The samples were then dried at a uniform temperature of 50°C. in an oven, weighed, finely ground, and bottled pending nitrogen and mineral analysis. All percentages were figured on the weights thus obtained as the dry weights.

Analytical Methods. Nitrogen was determined on the dried samples by the Kjeldahl-Gunning method. The solution for mineral analysis was obtained by the official method (29). In this solution phosphorus and calcium were determined by the official methods and potassium by the cobaltinitrite method. Sugars were determined on the preserved samples by means of the Shaffer and Hartman (42) iodometric method, using the technique given by Cole (6).

Presentation of Results

The data from the separate soil analyses are given in tables 3, 4, 6, 7, and 8 and graphically in figures 1, 3, 5, and 7. The results are summarized in table 9 and figures 2, 4, 6, and 8. Inasmuch as the $MnSO_4$ and $CuSO_4$ treatments did not exert any appreciable influence upon soil reaction or nutrient solubility, the results from plots 10 and 11 are omitted from the graphs and discussions which follow.

Soil Reaction. Table 3 shows that acidity or alkalinity of the soil produced by sulfur or lime additions, respectively, did not change appreciably from the time of the first sampling to the end of the growing season. Altho the determinations showed considerable variation in soil reaction in a few instances, they showed no consistent trend toward more acidity or alkalinity. The variations did not correlate with the rainfall or temperature data for these periods, hence could not be attributed to hydration, dehydration, or movement processes. Apparently the variations noted were largely experimental differences.

Table 3

Effects of sulfur, lime, $MnSO_4$, and $CuSO_4$ on soil reaction - React. plots (1931)

Plot No.	Treatment* (lbs. per A.)	pH July 7	pH July 21	pH Aug. 4	pH Aug. 17	pH Aug. 31	pH Sept. 17	Ave. pH
1	S500	5.0	5.3	5.1	5.2	5.7	5.1	5.23
2	S1000	4.6	4.8	4.6	4.9	5.2	4.9	4.83
3	None	5.7	5.6	5.5	5.5	5.6	5.9	5.63'
4	L4400	6.6	7.2	6.5	6.6	6.2	6.7	6.63
5	L4400 S500	5.9	5.9	5.8	6.0	5.9	6.1	5.93
6	L8800	6.9	7.0	6.9	6.9	7.0	6.9	6.93
7	L8800 S500	6.6	6.7	6.4	6.8	6.6	6.5	6.60
8	L8800 S1000	6.5	6.3	6.3	6.6	6.7	6.6	6.50
9	None	6.0	6.1	6.0	6.4	6.3	6.5	6.22'
10	$MnSO_4$ 50	6.0	6.0	5.9	6.2	6.3	6.2	6.10
11	$CuSO_4$ 25	5.7	6.0	5.8	6.0	6.0	6.2	5.95
12	None	6.0	6.1	5.8	6.0	6.0	6.2	6.02'

*All plots uniformly fertilized with 800 lbs. per A. of 3-9-18 fertilizer.

' Ave. pH of three check plots 5.96.

In the last column of the table the average results for the six different samplings are given. The sulfur lowered the pH about 0.6 for each 500 lbs. applied, while the lime raised it about 0.4 per 2 tons applied.

Water-soluble Phosphate. An examination of fig. 1 together with table 5 reveals some interesting relationships concerning seasonal phosphate solubility. Fig. 1 shows that the samplings 1, 3, and 6 presented wide differences in soluble phosphate content of the soil from the sulfured and limed plots, while in samplings 2, 4, and 5 these differences more or less disappeared. These results were found to correlate quite well with rainfall distribution. Table 5 gives the official daily precipitation and mean temperatures for East Lansing, as compiled by the U.S.D.A. Weather Bureau Station at East Lansing, from June 23, two weeks before the first samples were taken, to Sept. 17, the date of the last sampling.

It should be noted that the first sampling (July 7) was made two days after a heavy rain. The water-soluble phosphate content of the soil from the sulfured plots was found to be considerably higher, and that of the soil from the limed plots lower, than that of the untreated soil; the differences ranged from 20 p.p.m. for the 500 lb. sulfur treatment, thru 10.5 p.p.m. for the

Table 4

Effects of the soil treatments on phosphate solubility - Reaction plots (1931)

Plot No.	Treatment* (lbs. per A.)	Water-soluble PO_4 (p.p.m. in 1-10 extracts)						
		July 7	July 21	Aug. 4	Aug. 17	Aug. 31	Sept. 17	Ave.
1	S500	20.0	6.7	13.8	7.8	1.3	13.8	10.57
2	S1000	17.5	6.3	18.8	5.8	1.4	11.2	10.19
3	None	11.3	8.3	11.6	7.3	2.9	11.4	8.80°
4	L4400	7.0	5.2	5.3	2.2	1.7	6.4	4.63
5	L4400 S500	8.6	8.9	10.6	6.5	5.9	12.1	8.77
6	L8800	2.9	4.7	2.4	3.1	0.8	3.1	2.83
7	L8800 S500	5.7	4.7	6.3	3.6	1.4	5.0	4.45
8	L8800 S1000	4.4	6.6	6.5	4.3	0.8	4.5	4.52
9	None	9.3	6.6	7.0	2.0	1.4	8.0	5.72°
10	$MnSO_4$ 50	7.2	7.3	6.7	2.7	1.0	9.1	5.67
11	$CuSO_4$ 25	9.3	6.6	8.0	3.7	1.3	8.1	6.17
12	None	10.9	9.1	10.0	4.8	3.1	9.5	7.90°

*All plots fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

°Average of three control plots 7.47.

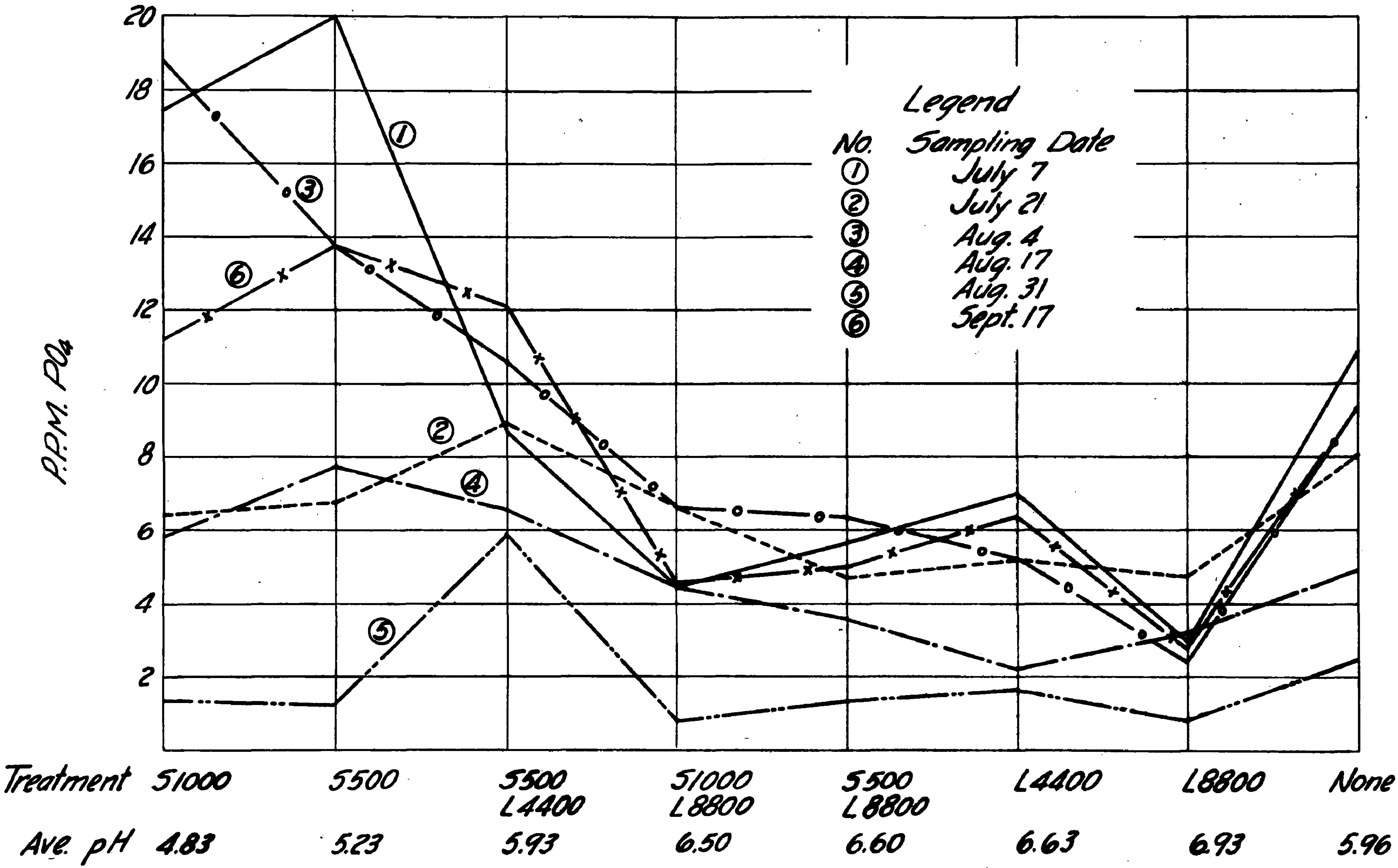


Figure 1. Seasonal effects of lime and sulfur treatments on water-soluble phosphate content in muck soil - Reaction plots (1931).

Table 5

Daily rainfall and mean temperature values for East Lansing between dates of sampling. (1931)

June 23 to July 6 (inc.) (Before first sampling)		July 7 to July 20		July 21 to Aug. 3		Aug. 4 to Aug. 16		Aug. 17 to Aug. 30		Aug. 30 to Sept. 16	
Rain. (ins)	Temp.	Rain. (ins)	Temp.	Rain. (ins)	Temp.	Rain. (ins)	Temp.	Rain. (ins)	Temp.	Rain. (ins)	Temp.
.02	69	.0	74	.0	75	.68	76	.27	76	.0	58
T	70	.0	67	.0	70	.0	80	.04	77	.23	66
.0	78	.0	66	.0	68	.0	79	.0	73	T	66
.8	70	.01	66	.0	66	T	77	.0	66	.0	64
.0	76	.0	66	.0	70	.10	78	.0	65	.25	63
.58	80	T	66	.0	76	T	75	.0	64	.0	68
.16	78	.09	68	.0	78	T	70	.0	69	.0	65
.0	82	T	71	.0	80	.0	60	T	74	.0	64
.0	84	.10	80	T	81	.0	62	.0	64	.05	72
.0	80	.0	82	T	74	.0	64	.0	64	.37	78
.0	73	.02	84	.05	72	.0	68	.0	65	T	78
.0	70	T	80	.02	70	.0	71	.05	68	.0	80
.59	74	T	81	.54	80	T	74	T	62	.13	79
.0	69	.06	74	.0	74			.0	58	.40	78
										.54	73
										.06	65
										.07	70
Ave. Temperature and Total Rainfall for each Sampling Period											
2.15	75.2	.28	73.2	.61	73.9	.78	71.8	.36	67.5	2.10	69.8
Average Temperature and Total Rainfall for 6 Days Preceding Sampling											
.59	75.0	.18	80.2	.61	75.2	T	66.5	.05	63.5	1.20	74.2

average of the checks, to 2.9 p.p.m. for the heaviest lime application. No heavy rain occured during the two weeks preceding the second sampling and the soil samples were much more uniform in soluble phosphate content. The third sampling, like the first, followed two days after a heavy rain and the soil of the sulfured and limed plots again showed increase and decrease, respectively, in water-soluble phosphate. There was a heavy rain after sampling on the same day the third sampling was made, then a dry period of twelve days. The fourth sampling, taken at the end of this dry period, gave phosphate data similar to that of the second sampling. This dry period was followed by a light rain and thirteen more dry days, constituting quite a long period of comparative drought prior to the fifth sampling. The soil of all of the plots except that of plot 5 was very low in water-soluble phosphate, and the soil of plot 5 was lower than it had been before. It is possible that some of the surface crust was accidentally included in the samples from plot 5, making them higher than the others. The last sampling was made after a rainy season, as shown by table 5, and the soluble phosphate content was again found to be higher in the sulfured soil and lower in the limed soil than in the checks.

From these data the soluble phosphate content of the sulfured muck is seen to have fluctuated widely, while that of the limed muck was much more constant. A suggested explanation for this relationship is that phosphate was rendered more soluble by the acidity induced by the oxidation of the sulfur. Because of this increased solubility, more of the phosphate was carried upward as the soil moisture moved to the surface and evaporated, the phosphate being deposited in the immediate soil surface. Following a period of drought, samples taken below the surface would be, as a result, relatively low in soluble phosphate, while after a rainy period soluble phosphate would be high, due to its being carried down from the surface into the soil again. On the other hand, the lime, by raising the pH of the soil, fixed the phosphate in a less soluble form, as $Ca_3(PO_4)_2$; hence, it would neither rise to the surface or descend so rapidly as that in the sulfured soil and would be, therefore, more constant in amount. The soil of plot 6, which received the heavy application of lime without sulfur, was very constant in water-soluble phosphate content. This explanation was substantiated by qualitative tests made on the surface crust in which phosphate was found to be more concentrated in the crust of the sulfured plots than in that of the limed plots during a dry period.

Phosphate is usually not thought of as exhibiting much movement in soils; however, the fact that phosphates were found to be low in amount at the 2-3 in. depth at one time, and high at the same depth at a later date, shows that there must have been considerable movement of phosphates. It would not seem logical to attribute such fluctuation to the action of the growing plant in removing soluble phosphate from the soil solution, inasmuch as the variations were by far the greatest in the samples from the plots receiving sulfur alone, whereas plants were growing on all of the plots more or less equally well; also, the water-soluble phosphate content did not become progressively less at each succeeding sampling thruout the growth period.

It is easily seen from fig. 2 that in this soil, considering the data for the entire 12 weeks, phosphate was made more soluble by sulfur and less soluble by lime treatment. There was also very close correlation between soil pH and water-soluble phosphate content, phosphate solubility increasing as the soil acidity increased.

From fig. 1 and the data in table 5 it appears that there was no correlation between the water-soluble phosphate content of the muck and the daily mean temperatures during the growing season.

This series of tests shows strikingly the fallacy of drawing conclusions and basing field recommendations, or

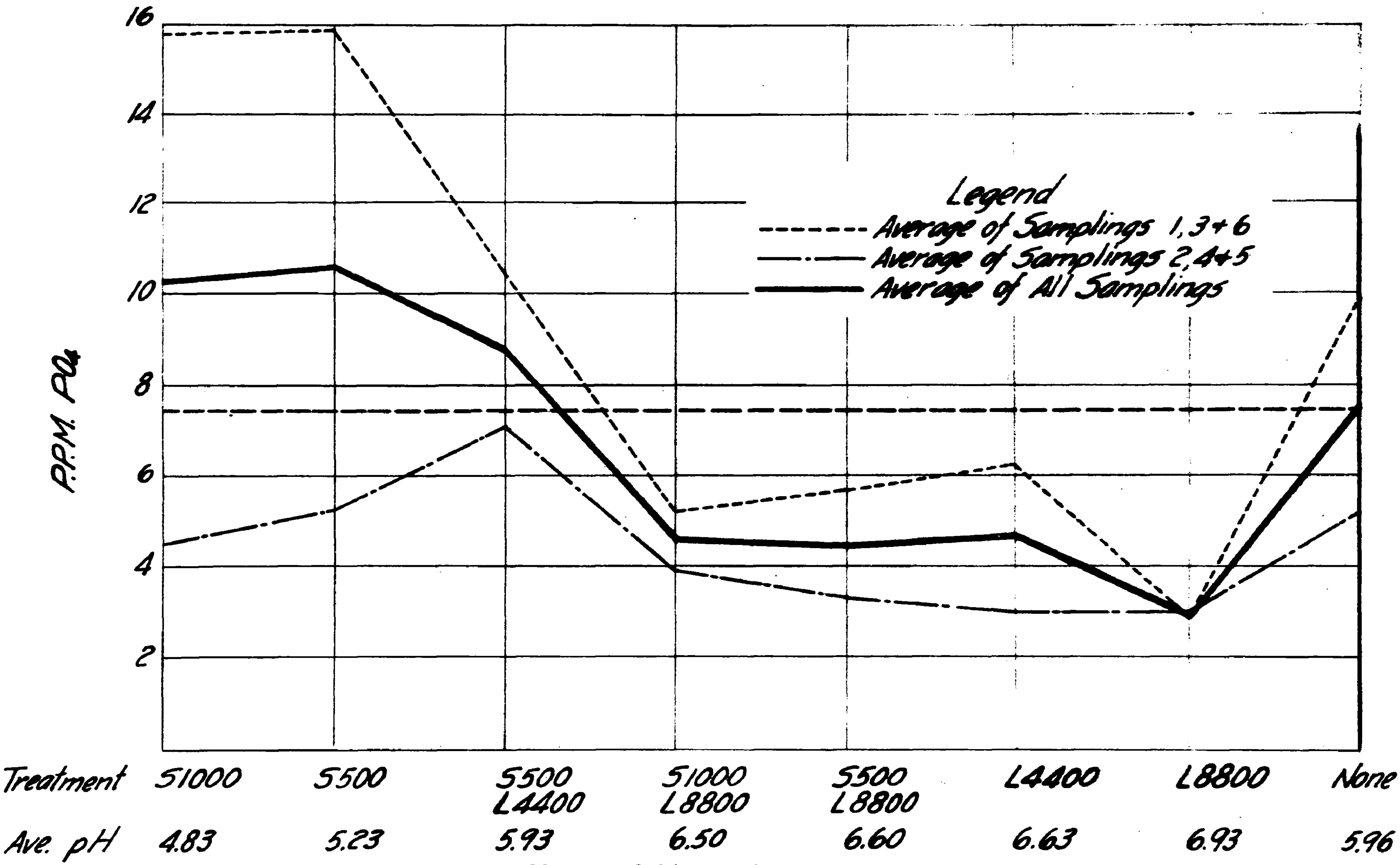


Figure 2. Summary of the effects of lime and sulfur treatments on water-soluble phosphate content in muck soil - Reaction plots (1931). Samplings 1,3, and 6 were made following rains; 2,4, and 5 following dry periods.

attempting to make correlations between water-soluble phosphate and crop yields, on the basis of determinations made on a single sample of surface soil. This is especially true if the treatments under comparison result in soil reaction changes. Under such conditions it is apparent that several such tests should be made at different times, and possibly at different depths, if conclusions are to be drawn correctly. It should be emphasized that in this study all samples were removed from an empirical depth of 2-3 ins., taken as most nearly representing the environment of the bulbs and roots studied. The comparisons probably would vary in degree if made on samples taken at different depths, due to the upward and downward movements of the soluble salts. Sampling at several depths was beyond the scope of this investigation. This same depth of 2-3 ins. was used in the taking of all samples reported on in this paper.

Water-soluble Calcium. The results of the water-soluble calcium determinations are given graphically in figs. 3 and 4. Comparing fig. 3 with fig. 1, it can be seen that the quantities of water-soluble calcium in the samples from the various plots were much more constant thruout the growing season, with respect to one another, than were the quantities of water-soluble phosphate. The explanation for the fact that the third sampling

Table 6

Effects of the soil treatments on calcium solubility - Reaction plots (1931)

Plot No.	Treatment* (lbs. per A.)	Water-soluble Ca (p.p.m. in 1-10 extract)						
		July 7	July 21	Aug. 4	Aug. 17	Aug. 31	Sept. 17	Ave.
1	S500	296	179	389	205	143	148	226.7
2	S1000	413	308	598	280	254	376	371.5
3	None	93	101	179	103	106	64	107.6°
4	L4400	151	119	224	150	114	88	141.0
5	L4400 S500	198	208	415	225	253	169	244.7
6	L8800	138	139	276	168	152	98	161.8
7	L8800 S500	241	241	489	232	224	237	277.3
8	L8800 S1000	380	369	642	292	258	405	391.0
9	None	95	106	213	106	141	73	122.3°
10	$MnSO_4$ 50	107	120	168	98	110	66	111.5
11	$CuSO_4$ 25	99	111	179	88	93	58	104.6
12	None	114	85	159	106	120	61	107.5°

*All plots fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

°Average of three control plots 112.5.

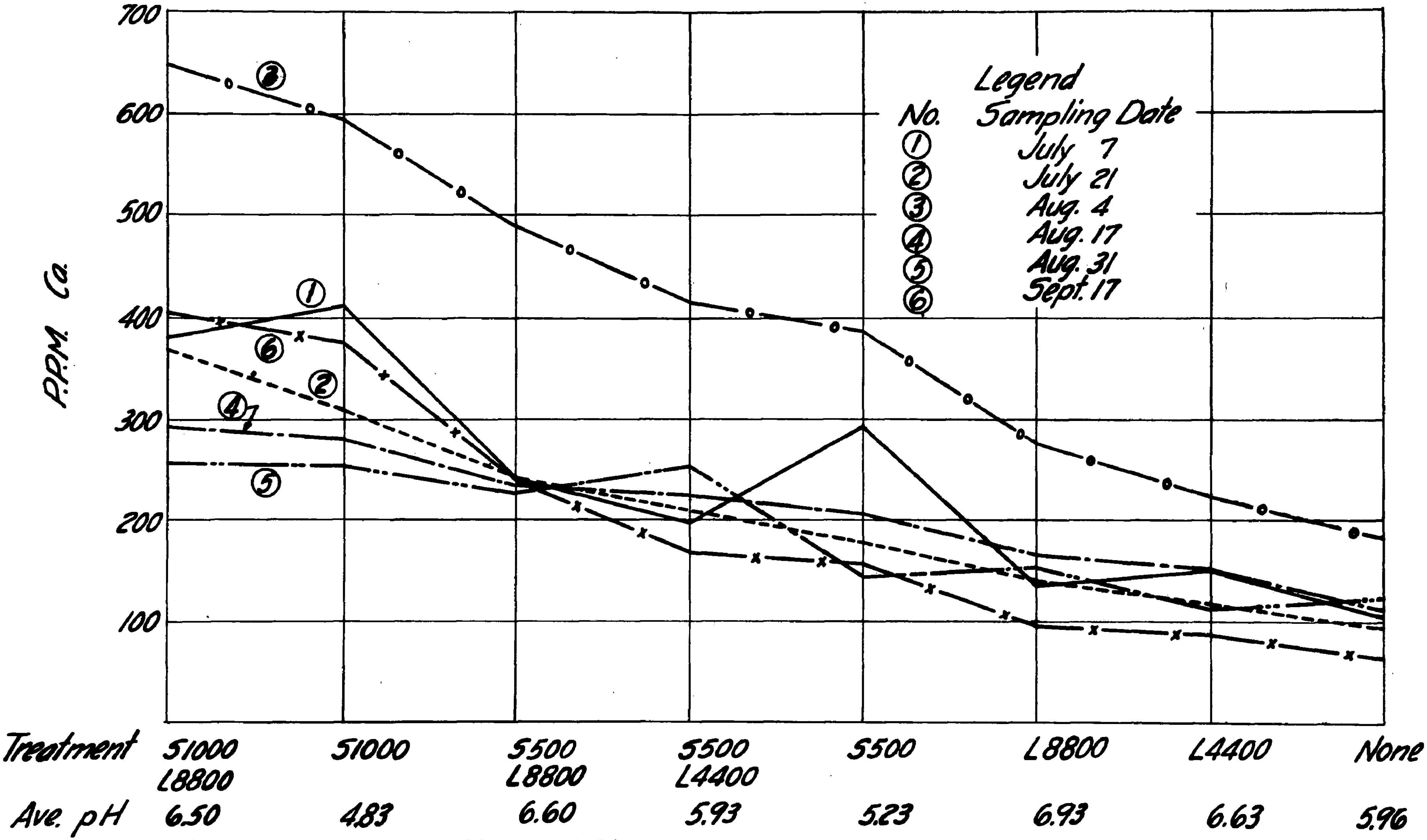


Figure 3. Seasonal effects of lime and sulfur treatments on water-soluble calcium content in muck soil - Reaction plots (1931).

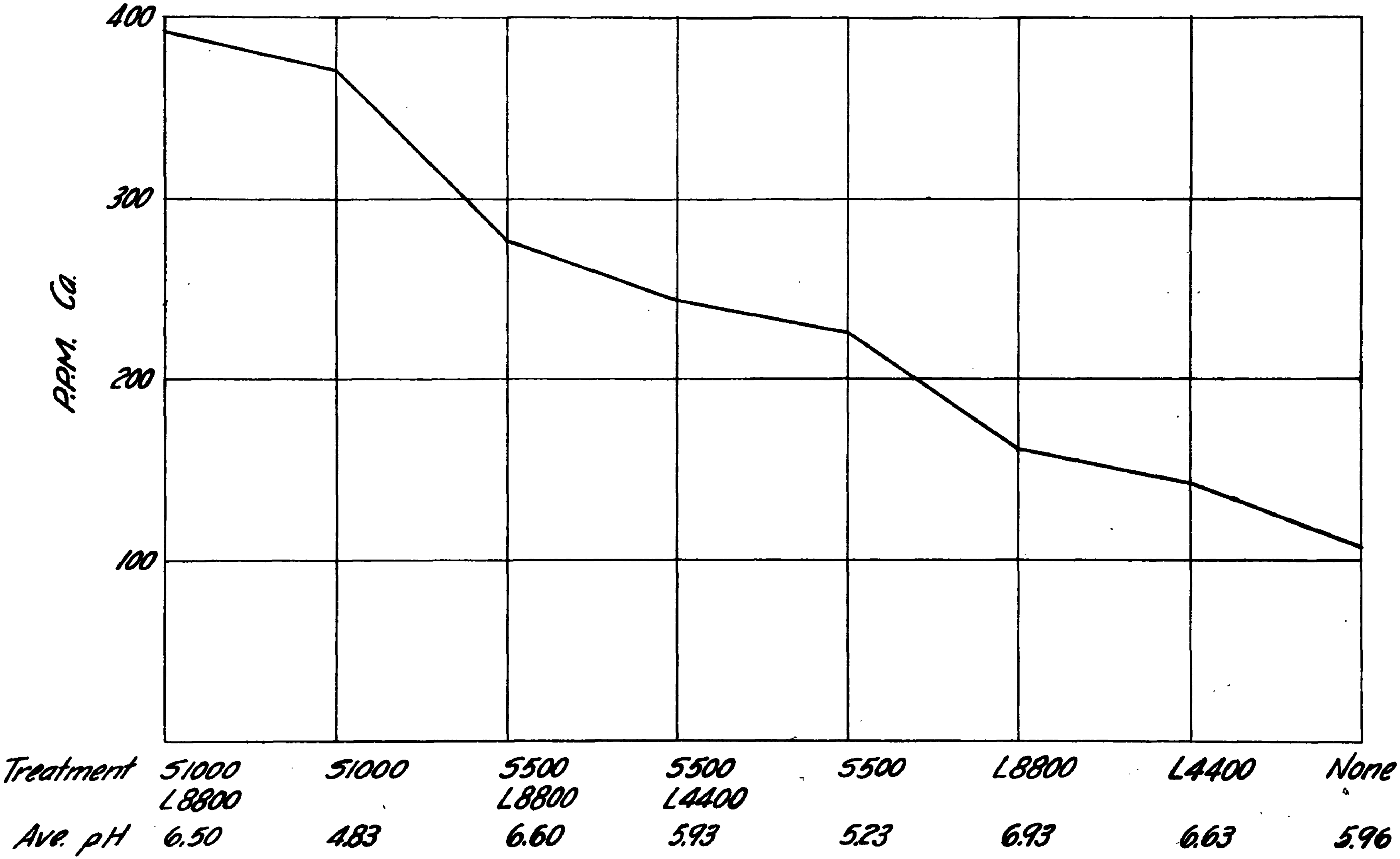


Figure 4. Summary of the effects of lime and sulfur treatments on water-soluble calcium content in muck soil - Reaction plots (1931).

from all plots was much higher in water-soluble calcium than any of the other samplings can not be found in the rainfall or temperature records.

Probably the most striking difference between the calcium and phosphate results is that calcium solubility was increased by application of either lime or sulfur to the soil, whereas phosphate solubility was increased by sulfur and decreased by lime. Altho either lime or sulfur increased the soluble calcium content of the soil, the sulfur was much the more effective. The relationship can best be shown in fig. 4, which gives the averages of the results for the six samplings. The untreated soil showed the lowest soluble calcium content, the light lime treatment gave a slight increase, and the heavy lime application an additional slight increase. The light sulfur application gave a sharper increase in the amount of soluble calcium than did the lime treatments. Lime in addition to sulfur increased the soluble calcium content of the soil slightly with each further lime addition. The heavy sulfur treatment gave a sharper increase in calcium solubility than did any of the above treatments, while the heavy lime-heavy sulfur treatment gave the highest value of all.

From the foregoing, it is apparent that the amount of soluble calcium present in the soil was dependent upon the total supply present and the amount of sulfate ion available to bring it into solution. Furthermore, it is evident that the soil reaction bore no relationship whatever to the water-soluble calcium content of the soil. The heavily sulfured soil had an average pH of 4.83, the lowest of any plot, and the soil of the heavily sulfured and limed plot an average pH of 6.50, one of the highest values; yet these two were the highest of all in soluble calcium content. Similarly, the plot treated with 500 lbs. of sulfur and 4400 lbs. of lime had the same average pH as the average of the three control plots, yet its soluble calcium content was more than double that of the controls.

The explanation for the increased solubility of calcium due to sulfur treatment of the soil doubtless lies in the fact of the much greater solubility of $CaSO_4$ over that of $CaCO_3$. In every case where sulfur was added the dialyzed calcium was found to be associated with the sulfate ion; where sulfur was not added it was found to be associated with the carbonate ion. Furthermore, the dry residues of the extracts from the plots which had received sulfur, both with and without lime, failed to effervesce when HCl was added to them, while those from the plots which received lime effervesced readily. This explanation is in line with Samuels' (40) hypothesis that sulfur, oxidizing to sulfate in contact with $CaCO_3$, forms $CaSO_4$, the organisms concerned utilizing more or less of the CO_2, thus formed, as a source of carbon.

It thus seems safe to conclude that, contrary to the action of phosphate whose solubility depended upon soil reaction, calcium solubility, in this muck at least, depended not on soil reaction but upon the amount of calcium present in the soil and the amount of strong negative radical (SO_4'') available. This conclusion is substantiated by other data presented in this paper.

Doughty (8) has shown that only water-soluble calcium is able to precipitate phosphate in the presence of peat, the calcium in the complex having no effect even upon saturation. He further states that the presence of organic matter, however, prevents some of the water-soluble calcium from uniting with phosphate. This was substantiated in the present study, considerable quantities of calcium and phosphate having been found in the same solution.

Water-soluble Potassium. Comparing fig. 5 with figs. 1 and 3, it will be noted that the water-soluble potassium content of the soil showed more fluctuation and less marked differences attributable to the sulfur or lime treatment than did the phosphate or calcium. The third sampling was, as with calcium, much higher thruout in soluble potassium content than were the other samplings. In other respects the general trend of potassium

Table 7

Effects of the soil treatments on potassium solubility - Reaction plots (1931)

Plot No.	Treatment* (lbs. per A.)	Water-soluble K (p.p.m. in 1-10 extracts)						
		July 7	July 21	Aug. 4	Aug. 17	Aug. 31	Sept. 17	Ave.
1	S500	60.8	31.0	81.5	40.1	23.7	38.9	46.00
2	S1000	57.4	25.4	85.5	26.7	20.7	47.2	43.82
3	None	39.9	26.2	60.8	22.8	14.7	29.8	32.37°
4	L4400	38.0	25.8	58.9	24.6	24.0	27.8	33.18
5	L4400 S500	38.0	44.8	72.9	33.0	33.6	28.8	41.85
6	L8800	25.2	29.4	46.5	28.3	19.0	28.1	29.42
7	L8800 S500	35.7	34.9	57.0	30.4	22.0	28.8	34.80
8	L8800 S1000	36.8	36.7	84.3	32.7	20.4	32.1	40.50
9	None	30.5	22.2	56.5	16.7	22.4	21.2	28.25°
10	$MnSO_4$ 50	33.5	30.2	52.8	21.5	16.0	32.7	31.12
11	$CuSO_4$ 25	30.4	21.2	45.1	15.1	12.7	21.7	24.37
12	None	35.4	22.6	58.6	18.6	22.9	23.5	30.27°

*All plots fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

°Average of three control plots 30.30.

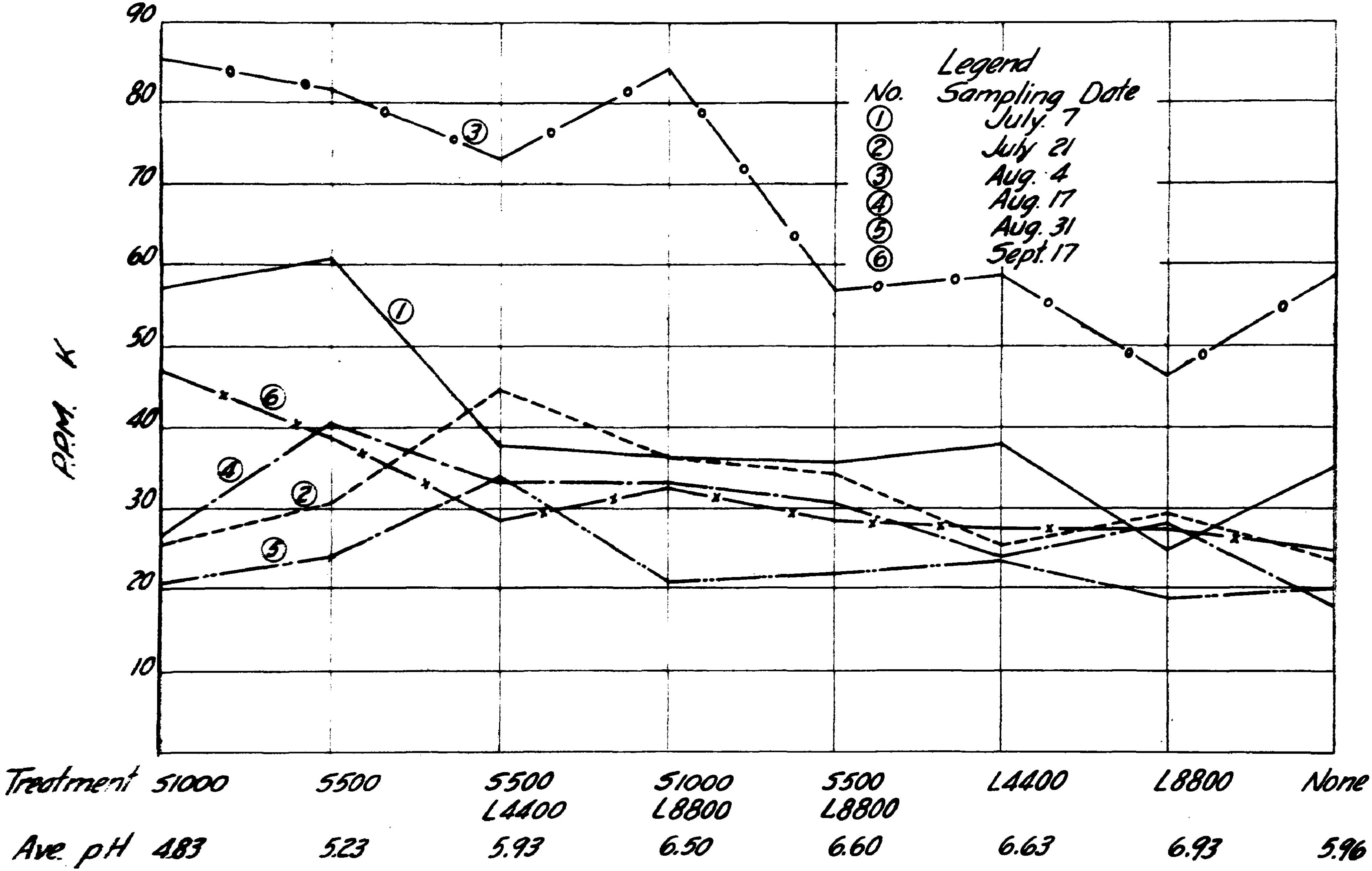


Figure 5. Seasonal effects of lime and sulfur treatments on water-soluble potassium content in muck soil - Reaction plots (1931).

solubility was similar to that of the phosphate, samplings 1, 3, and 6 being proportionately higher in soluble potassium on the more acid plots than were the other samplings. The general effect of the treatments can best be seen from the averages for the six samplings. These are shown in fig. 6. The tendency was toward increase in solubility of potassium as a result of the sulfur additions to the soil. The limestone applications, on the other hand, produced little or no effect on the potassium solubility when no sulfur was applied; but, when applied with sulfur, decreased potassium solubility below that secured with sulfur alone.

Nitrates. Wilson and Townsend (50), sampling the upper 4 ins. of muck soils thruout the season, found no consistent relationship between nitrate-nitrogen and hydrogen-ion concentration. They found, however, that during hot, dry weather the muck soils became more acid in reaction and higher in nitrates at the surface.

Figures 7 and 8 present graphically the results of the nitrate determinations made in this study. Figure 7 shows that the nitrate content of the soil was extremely variable with respect to time of sampling. It was highest in the Aug. 4 and Aug. 17 samplings, despite the growing crop. This was especially noticeable in the samples from the plots receiving the heavy lime and

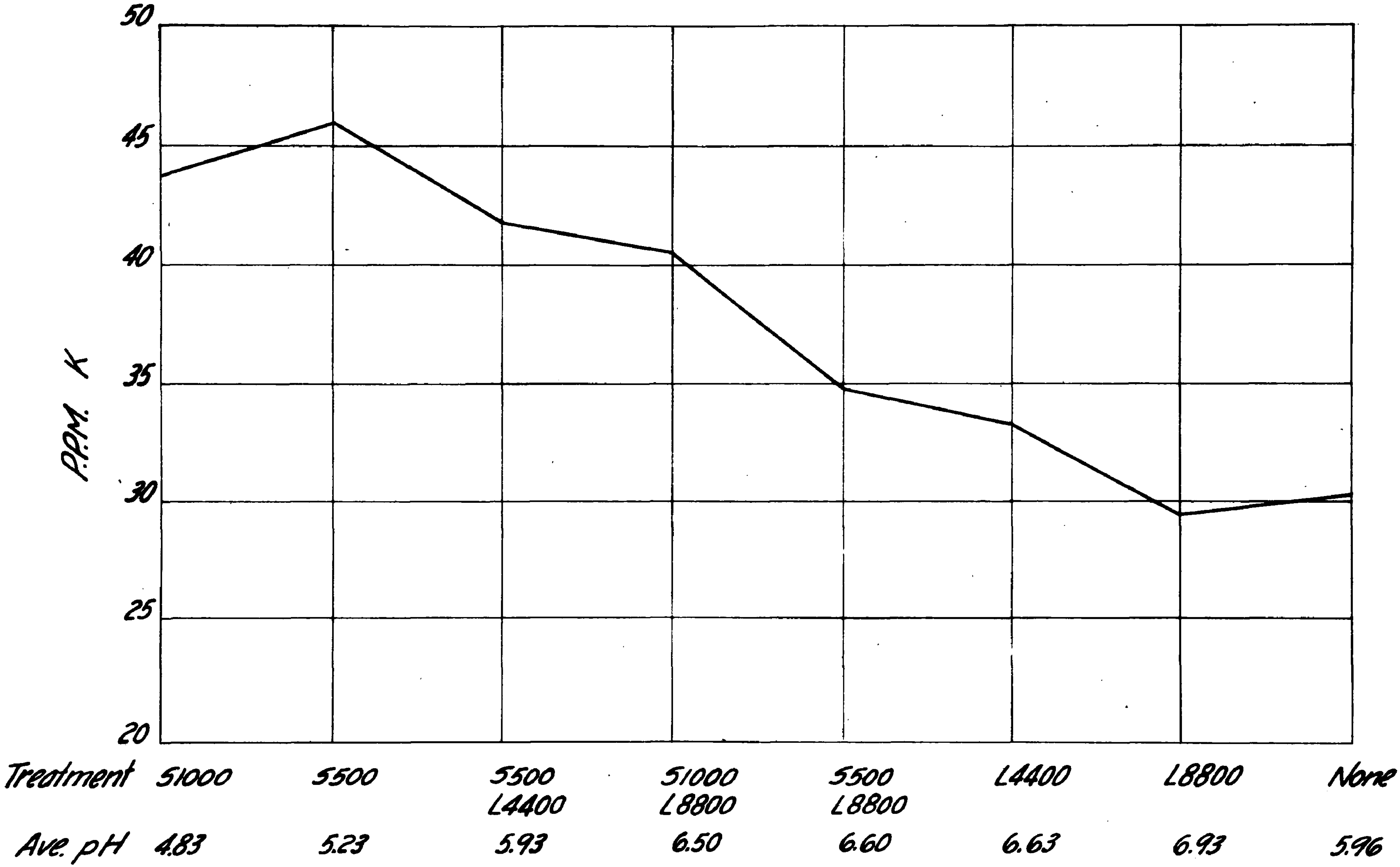


Figure 6. Summary of the effects of lime and sulfur treatments on water-soluble potassium content in muck soil - Reaction plots (1931).

Table 8

Effects of the soil treatments on nitrate supply - Reaction plots (1931)

Plot No.	Treatment* (lbs. per A.)	Available NO_3-N (p.p.m. in 1-10 extracts)						
		July 7	July 21	Aug. 4	Aug. 17	Aug. 31	Sept. 17	Ave.
1	S500	11.0	19.1	24.8	26.3	16.9	2.4	16.75
2	S1000	11.0	15.2	16.9	19.4	10.5	2.5	12.58
3	None	9.9	12.5	29.4	18.8	4.4	4.5	13.25°
4	L4400	10.3	12.5	30.6	19.4	4.0	5.3	13.68
5	L4400 S500	7.0	16.7	23.1	20.0	11.4	3.4	13.60
6	L8800	5.8	5.9	36.3	24.4	3.9	3.0	13.22
7	L8800 S500	7.8	19.7	39.4	26.3	14.0	3.6	18.47
8	L8800 S1000	9.8	15.0	21.3	23.8	12.0	4.2	14.35
9	None	7.5	9.5	25.0	10.0	6.4	3.3	10.28°
10	$MnSO_4$ 50	6.0	8.0	20.3	13.1	4.1	3.0	9.08
11	$CuSO_4$ 25	9.0	2.3	25.0	4.5	3.0	1.5	7.55
12	None	10.0	4.5	16.9	17.5	14.5	2.0	10.90°

*All plots fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

°Average of three control plots 11.47.

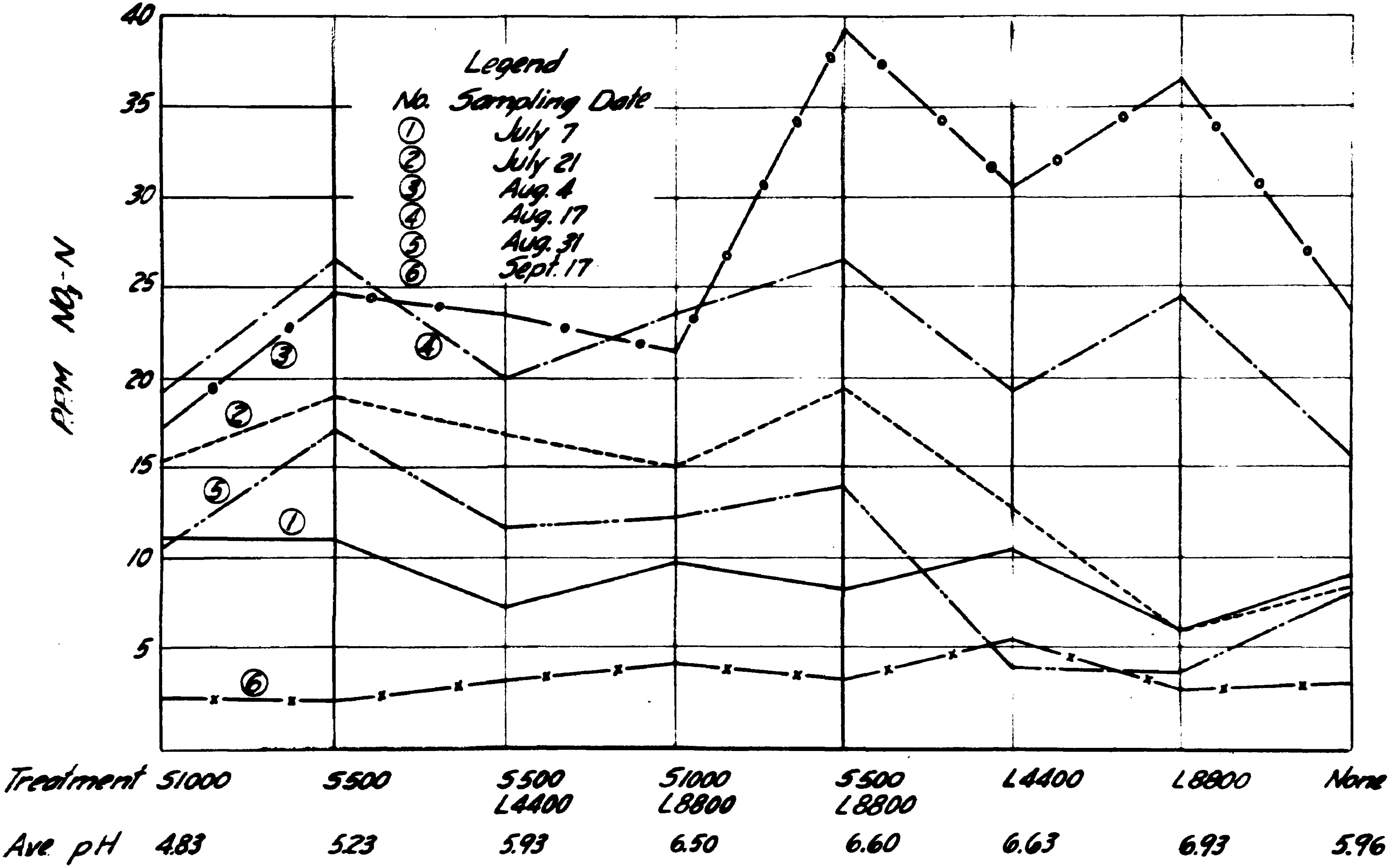


Figure 7. Seasonal effects of lime and sulfur treatments on nitrate content in muck soil - Reaction plots (1931).

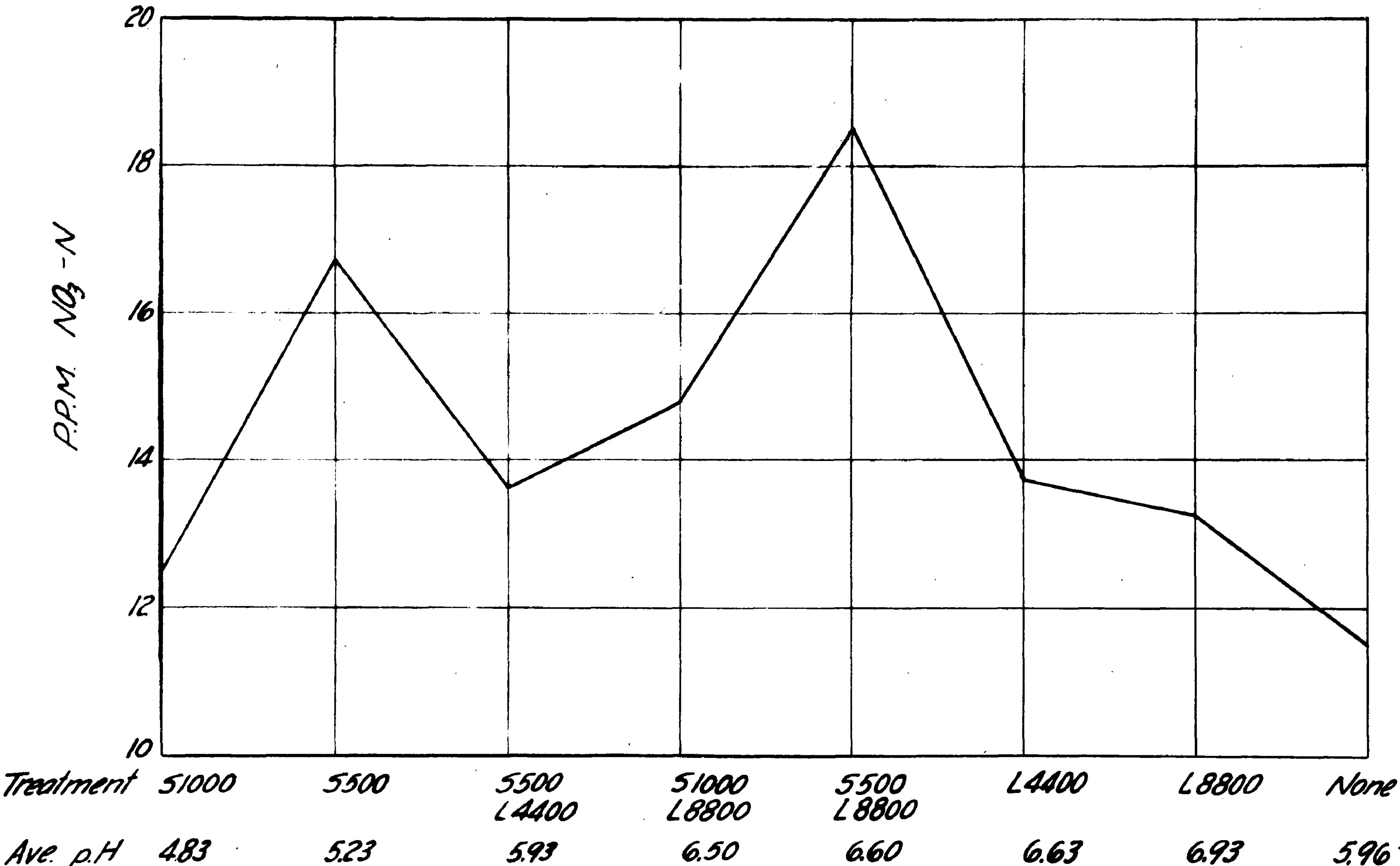


Figure 8. Summary of the effects of lime and sulfur treatments on nitrate content in muck soil - Reaction plots (1931).

and the heavy lime-light sulfur applications. Nitrates were low in the first sampling (July 7), increased in the second, third, and fourth (Aug. 17) samplings, decreased in the fifth (Aug. 31), and were very low in the soil of all plots at the time of the last sampling (Sept. 17). There was no correlation apparent between these results and the temperature or rainfall distribution as given in table 5. Figure 8 shows that the plots which received the light sulfur and the light sulfur-heavy lime applications were highest in soil nitrate content, based on the averages for the six samplings. It also indicates that sulfur application stimulated nitrification in most instances when accompanied by lime, while the heavy sulfur application alone did not. Lime treatment alone did not greatly stimulate nitrification in this muck.

<u>Comparison of Water-soluble Nutrients.</u> The foregoing results show that the lime and sulfur treatments exerted certain definite effects upon the solubility of nutrients in the soil. These results are summarized in table 9 for comparison. They show that in all cases calcium was by far the nutrient element present in largest amount, followed by potassium, nitrate, and phosphate, respectively. Sulfur addition increased the solubility of calcium, potassium, and phosphate in the soil, while lime gave an increase in calcium solubility, a decided decrease in phosphate solubility, and a tendency toward decreased potassium. The nitrate content of the soil

Table 9

Summary of the effects of the soil treatments on pH and water-soluble nutrients -React. plots (1931).

Plot No.	Treatment* (lbs. per A.)	Ave. of six determinations made at two-week intervals				
		pH	PO_4 p.p.m.	NO_3 N p.p.m.	Ca p.p.m.	K p.p.m.
1	S500	5.23	10.57	16.75	226.7	46.00
2	S1000	4.83	10.13	12.58	371.5	43.82
3	None	5.63	8.80	13.25	107.6	32.37
4	L4400	6.63	4.63	13.68	141.0	33.18
5	L4400 S500	5.93	8.77	13.60	244.7	41.85
6	L8800	6.93	2.83	13.22	161.8	29.42
7	L8800 S500	6.60	4.45	18.47	277.3	34.80
8	L8800 S1000	6.50	4.52	14.35	391.0	40.50
9	None	6.22	5.72	10.28	122.3	28.25
10	$MnSO_4$ 50	6.10	5.67	9.08	111.5	31.12
11	$CuSO_4$ 25	5.95	6.17	7.55	104.6	24.37
12	None	6.02	7.90	10.90	107.5	30.27

* All plots fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

was quite variable toward the lime and sulfur treatments.

Crop Yields and Composition. Due to many disturbing factors such as poor stand, extremely dry weather, and an unusual number of insect pests, the crop yields from the reaction plots in 1931 were not at all comparable and are therefore omitted.

In table 10 the results from the moisture, nitrogen, phosphorus, calcium, and potassium analyses of the onions are presented. It is at once apparent that, with the exception of a possible slight increase in potassium due to liming, there were no consistent differences in plant composition due to differences in soil treatment. Comparing the table with the foregoing solubility graphs, it is also evident that no consistent relationship existed between the solubility of any of the soil nutrient elements studied and their percentage in the onion bulbs. The carrots and turnips gave similar results, hence the data for them are not given.

The results of the sugar analyses of the onions, carrots, and turnips are presented in table 11. Altho the sugar content is shown to have varied considerably, there is no general indication of correlation between treatment of the soil and the sugar content of any of the three crops studied. Neither is there any definite difference of ratio between reducing and non-reducing

Table 10

Nitrogen and mineral content of onions from the soil reaction plots (1931).

Plot No.	Treatment* (lbs. per A.)	Per cent Moisture	Per cent in dry matter			
			N	P	Ca	K
1	S500	90.6	2.38	0.182	0.42	1.29
2	S1000	91.0	2.46	0.235	0.44	1.49
3	None	91.0	2.55	0.270	0.59	1.30
4	L4400	91.0	2.59	0.257	0.53	1.50
5	L4400 S500	91.5	2.71	0.266	0.45	1.82
6	L8800	91.5	2.68	0.281	0.54	1.58
7	L8800 S500	90.7	2.74	0.276	0.45	1.58
8	L8800 S1000	91.4	2.54	0.265	0.43	1.50
9	None	90.9	2.43	0.257	0.46	1.35
10	$MnSO_4$ 50	91.4	2.57	0.256	0.46	1.44
11	$CuSO_4$ 25	91.4	2.47	0.263	0.41	1.33
12	None	90.6	2.00	0.234	0.38	1.38

* All plots fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

Table 11

Sugar content° of onions, carrots, and turnips from the soil reaction plots (1931).

Plot No.	Treatment* (lbs. per A.)	Onions % Reducing	Onions % Non-red.	Onions % Total Sugars	Carrots % Reducing	Carrots % Non-red.	Carrots % Total Sugars	Turnips % Reducing	Turnips % Non-red.	Turnips % Total Sugars
1	S500	2.58	1.89	4.47	2.96	1.90	4.86	--	--	--
2	S1000	2.84	1.27	4.11	2.68	2.29	4.97	2.71	0.0	2.71
3	None	2.76	1.54	4.30	2.95	1.94	4.89	2.51	0.0	2.51
4	L4400	2.53	1.81	4.34	2.74	1.28	4.02	2.50	0.0	2.50
5	L4400 S500	2.39	1.84	4.23	2.64	2.33	4.97	2.74	0.0	2.74
6	L8800	2.25	1.51	3.76	2.40	2.66	5.06	2.87	0.0	2.87
7	L8800 S500	2.48	1.95	4.43	2.56	2.43	4.99	2.48	0.0	2.48
8	L8800 S1000	2.43	1.86	4.29	2.15	2.39	4.54	2.47	0.0	2.47
9	None	2.52	2.25	4.77	2.68	2.59	5.27	2.53	0.0	2.53
10	$MnSO_4$ 50	2.52	1.96	4.48	2.65	2.36	5.01	2.39	0.0	2.39
11	$CuSO_4$ 25	2.58	2.07	4.65	3.01	2.04	5.05	2.35	0.0	2.35
12	None	2.78	2.09	4.87	2.83	2.21	5.04	2.52	0.0	2.52

* All plots fertilized uniformly with 800 lbs. per A. of 3-9-18 fertilizer.

° Sugars calculated as per cent dextrose.

sugars.

It should be borne in mind, in considering the crop data presented in this experiment, that the reaction of the soil on which the crops were grown is very satisfactory for plant growth (the muck below the plowed layer is slightly to medium acid), hence neither lime nor sulfur is needed for the production of good crops; and that this experiment was planned primarily for the soil studies presented. The crops which were analyzed, while presenting some characteristic differences such as in degree of maturity, color, etc., did not possess such extreme differences in quality as would be obtained in crops grown on mucks badly in need of either lime or sulfur. For this reason outstanding differences in crop composition probably should not have been expected. This experiment was, therefore, supplemented with the following analytical studies of crops taken from typical alkaline and typical strongly acid muck areas.

Supplemental Data

Results from a Burned-over Muck Area.

Onions. Representative onion samples were taken for analysis from four onion plots located on a burned-over muck area that gave excellent response to sulfur treatment. (This muck had been burned-over about 40 years previously. It was broken in 1927 and gave a crop failure in 1928. The plots were established in 1929, and the onion samples were taken for analysis from the 1930 crop). Each of these samples was graded into four sizes, the number of onions in each size counted, and the percentage of each size in each sample computed. Table 12 presents the plot treatments together with the data obtained. The results show that the sulfur-fertilizer treatment was by far the best for increasing onion size, either sulfur alone or fertilizer alone giving but slight increase.

The onions of each size from each plot were analyzed for moisture, nitrogen, phosphorus, calcium, and potassium content. The results of these analyses are set forth in table 13. From these results it is apparent that the N, P, Ca, or K content did not vary with onion size in any of the samples. The moisture content, however, seemed to show a slight decrease with decrease in onion size in practically all cases. This might be expected, since the smaller the onion the greater the proportionate amount of drier outside surface. Sulfur applications to the soil gave a decided decrease in P, N, Ca, and K content in the onions. Fertilizer applications in addition to the sulfur seemed to increase, slightly, the phosphorus content above that of the onions

Table 12

Relationship of onion size to sulfur and fertilizer applications on an alkaline muck.

Treatment (lbs. per acre)	Percentage of sample (by number)			
	130 g. or over	85-130 g.	40-85 g.	Below 40 g.
None	.0	3.33	38.09	58.57
Sulfur 1000	2.21	9.93	56.98	30.88
4-8-16 1200	2.34	6.25	45.05	46.35
Sulfur 1000 4-8-16 1200	21.35	26.97	39.89	11.80

Table 13

Relationships of onion size and composition to sulfur and fertilizer applications on an alkaline muck soil.

Treatment (lbs. per A.)	Onion size gms.	Per cent Moisture	Percentage in dry matter			
			N	P	Ca	K
None	85-130	90.00	2.16	0.23	0.47	1.69
	40-85	89.72	2.12	0.24	0.43	1.78
	Below 40	89.13	2.22	0.26	0.43	1.79
	Ave.	89.62	2.17	0.24	0.44	1.75
S 1000	Over 130	89.82	1.83	0.17	0.35	1.27
	85-130	89.38	1.74	0.17	0.37	1.21
	40-85	88.64	1.87	--	--	--
	Below 40	88.47	1.80	0.17	0.37	1.03
	Ave.	89.08	1.81	0.17	0.36	1.17
S 1000 4-8-16 1200	Over 130	89.35	1.61	0.19	0.31	1.45
	85-130	89.39	1.77	0.20	0.27	1.65
	40-85	88.82	1.65	0.20	0.28	1.57
	Below 40	88.27	1.79	0.17	--	1.82
	Ave.	88.96	1.71	0.19	0.29	1.62
4-8-16 1200	Over 130	89.37	1.86	0.22	0.29	1.54
	85-130	89.91	2.11	0.24	0.31	1.78
	40-85	88.80	2.02	0.23	0.33	1.72
	Below 40	89.00	2.21	0.25	0.31	1.92
	Ave.	89.27	2.05	0.24	0.31	1.74

whose soil received sulfur alone, but it was still lower than that of the onions grown on the check plots. When no sulfur was applied, fertilizer did not decrease the N, P, or K content of the onions, but did give a decrease in calcium content. Altho the percentages of all of these elements were reduced in the onions by sulfur and fertilizer applications to the soil, the actual amounts removed in the crop were greatly increased by these treatments. Table 14 gives the pounds per acre of N, P, Ca, and K actually removed from each plot by the crop.

Sugar determinations were made on representative onion samples from these four plots. The results are tabulated in table 15. There seems to have been an increase in total sugar content as a result of fertilization but no significant increase attributable to sulfur application. On the unsulfured soil fertilizer seemed to produce a slight increase in content of reducing sugars in the onions, while on the sulfured soil fertilizer increased the content of non-reducing sugars. This may probably have been due to a difference in maturity of the onions.

From the foregoing results it would seem that on this muck combined applications of sulfur and fertilizer to the soil gave onions of slightly higher sugar content and of lower nitrogen and mineral percentages.

Table 14

Amounts of N, P, Ca, and K removed from the soil by onions as affected by sulfur and fertilizer treatments.
(ALKALINE MUCK)

Treatment (lbs. per A.)	Pounds per acre removed by crop			
	N	P	Ca	K
None	6.01	.79	1.17	4.87
S 1000	36.35	3.43	7.27	23.63
4-8-16 1200	20.40	2.32	3.13	18.18
S1000 4-8-16 1200	102.91	11.76	17.64	99.97

Table 15

Effects of sulfur and fertilizer treatments on the sugar content of onions grown on alkaline muck.

Treatment (lbs. per A.)	Per cent sugar (determined as dextrose)		
	Reducing	Non-reducing	Total
None	2.46	2.64	5.10
Sulfur 1000	2.64	2.48	5.12
Sulfur 1000 4-8-16 1200	2.66	2.93	5.59
4-8-16 1200	2.81	2.65	5.46
Ave. sulfur	2.65	2.70	5.38
Ave. no sulfur	2.63	2.64	5.28

Other Crops. Samples of carrots, parsnips, and potatoes were taken from the same alkaline muck from plots fertilized uniformly but receiving differential sulfur treatments. Mineral analyses were made, as with the onions. The results are given in table 16. The small differences in composition obtained were not significant, except possibly in the case of nitrogen. Sulfur additions to the soil seem to have decreased the nitrogen content of all three crops. Again, as was the case with the onions, sulfur applications to the soil increased the actual amount of N, P, Ca, and K removed by the crops. Table 17 presents the calculated amounts of these elements removed per acre by the potatoes, carrots, and parsnips.

Results from a Strongly Acid Muck Area.

Table 18 presents some results, obtained by Harmer, showing the effects of soil applications of lime on the yield of carrots and onions. The differences in quality between some of the samples were very marked. Samples of the carrots and onions from these plots were taken for sugar analysis. The results are set forth in table 19. There was a gradual increase in sugar content of the carrots with each lime addition to the soil, whereas the onions showed no appreciable difference in sugar content between samples from the plots treated with 16000lbs. and 24000 lbs. per acre of lime, respectively.

Table 16

Effect of sulfur on the nitrogen and mineral composition of carrots, parsnips, and potatoes grown on alkaline muck soil.

Sulfur Treatment* (lbs. per A.)	Per cent Moisture	Percentage in dry matter			
		N	P	Ca	K
Carrots:					
No S	89.99	1.54	0.21	0.42	2.48
S 1000	88.39	1.35	0.21	0.40	2.45
S 2000	89.51	1.16	0.22	0.42	2.37
Parsnips:					
No S	80.38	1.22	0.24	0.28	2.30
S 1000	78.12	1.10	0.23	0.27	2.12
S 2000	78.61	1.12	0.27	0.27	2.25
Potatoes:					
No S	78.89	2.18	0.24	0.09	3.14
S 1000	78.06	1.94	0.26	0.10	3.03
S 2000	78.61	1.97	0.29	0.10	3.14

* All plots fertilized uniformly with an 0-8-24 mixture in amount adapted to each particular crop.

Table 17

Amounts of N, P, Ca, and K removed by certain crops as affected by sulfur applications on an alkaline muck soil.

Sulfur Treatment * (lbs. per A.)	Pounds per acre removed by crop			
	N	P	Ca	K
Carrots:				
No S	78.00	10.64	21.27	125.61
S 1000	100.31	15.60	29.72	182.04
S 2000	78.61	14.91	28.46	160.60
Parsnips:				
No S	88.13	17.34	20.23	166.15
S 1000	110.71	23.15	27.17	213.37
S 2000	108.43	26.14	26.14	217.82
Potatoes:				
No S	36.72	4.04	1.52	52.90
S 1000	51.83	6.95	2.67	80.94
S 2000	51.20	7.54	2.60	81.61

* All plots fertilized uniformly with an 0-8-24 mixture in amount adapted to each particular crop.

Table 18

Effect of lime applications on yield of carrots and onions on a very acid muck soil.

(After Harmer)

Plot No.	Treatment* (lbs. per A.)	Yield per acre		
		Carrots (tons)	Onions (bu.)	Onions Per cent Immature
1	No lime	0.0	0.0	- -
2	Lime 8000	1.1	0.3	53.8
3	Lime 16000	2.7	20.4	45.8
4	Lime 24000	4.5	9.4	54.6

* All plots fertilized uniformly with 1000 lbs. per acre of 4-8-24 fertilizer.

Table 19

Effect of lime applications on the sugar content of onions and carrots from a very acid muck soil.

Plot No.	Treatment* (lbs. per A.)	Sugar Content[t]					
		Onions			Carrots		
		Reducing %	non-reducing %	Total %	non-Reducing %	reducing %	Total %
1	No lime	- -	- -	- -	- -	- -	- -
2	Lime 8000	- -	- -	- -	1.68	0.46	2.14
3	Lime 16000	2.44	2.61	5.05	1.68	0.60	2.48
4	Lime 24000	2.37	2.56	4.93	2.04	0.63	2.67

* All plots fertilized uniformly with complete fertilizer.

t Calculated as per cent dextrose.

These results show that differences in sugar content were not great enough to be used as a measure of differences in quality in these crops.

Experiment 2

Effects of Lime and Sulfur Additions to Acid and Alkaline Mucks, Respectively.

In the preceding experiment certain effects on the pH and solubility of applied nutrients were noted in connection with lime and sulfur additions to a slightly acid, high-lime muck. The question naturally arises: would lime and sulfur give these same effects, respectively, on "alkali" mucks and "very strongly acid" mucks? The purpose of this experiment was to obtain information on this question. In addition, the effect of a later application of nitrate following sulfur treatment was compared with the addition of sulfur alone on the alkaline soils.

Plan and Procedure

Bulk samples of six soils were collected from various localities in southern Michigan. Soils M, T, and H were all "very strongly acid" soils from which satisfactory yields of muck crops could not be obtained without the application of lime in considerable quantity. Soil R was from a burned-over muck area on which most crops were known to respond well to sulfur treatment. This sample came from the same field on which the studies reported in pages 27-30 were made. Soil G was an alkaline mineral soil very high in organic matter and which had come from a burned-over muck area. Soil O was a well-decomposed muck nearly neutral in reaction.

These soils were dried and finely screened. Equal quantities of each soil were placed in 2-gallon glazed pots in the greenhouse. On June 1 (1933) the acid mucks were given a uniform treatment of 1200 lbs. per acre of a 3-9-18 fertilizer mixture, and a solution treatment of $CuSO_4$ equivalent to a 100-lb. per acre application. In addition, the three pots of each acid muck received the lime treatment indicated in table 20. On June 15 the other mucks were given the same blanket fertilizer and $CuSO_4$ treatment the acid mucks had received and the sulfur applications indicated in table 20. Each treatment was mixed thoroly with all of the muck in each jar. On Aug. 3, the No. 4 pots of the alkaline soils received a 300-lb. per acre solution application of $NaNO_3$ as a top dressing.

All pots of each muck were brought to a uniform moisture content with distilled water, and were kept thus undisturbed until July 18 to allow equilibrium to be reached. On this date, soil samples were taken at the 2-3 in. depth for analysis, and the pots were seeded to Giant Thickleaf spinach. A suitable and uniform soil moisture content was maintained in the pots of each muck. Shortly after germination, the spinach was thinned to a uniform stand of 7 plants per jar. The crop was harvested Aug. 21.

Presentation of Results

The results of the experiment are presented in table 20.

Soil Reaction and Crop Growth. The acid mucks showed considerable difference in buffering ability toward the lime treatments. For example, the 12-ton lime application raised the pH of soil M from 3.59 to 6.20, while a like application raised that of soil T from 3.84 to only 5.51.

Each of the three acid soils gave an increase in yield with each increase in amount of lime applied. (Plate I)

The sulfur treatments did not bring about as large a change in soil reaction as was expected, especially in the alkaline muck R, which had previously given a much greater change in the field. It is possible that

Table 20

Effects of lime and sulfur treatments on soil pH and nutrient solubility, and on yield of spinach on acid and alkaline soils.

Pot No.	Treatment* (lbs. per A.)	pH	Water-soluble nutrients: Ca ppm	K/Ca ratio	K ppm	PO_4 ppm	NO_3-N ppm	Yield per Plant gms.
M1	None	3.59	24	2.6	63	7.8	11	0.00
M2	L 12000	5.24	33	2.5	84	5.3	22	3.06
M3	L 24000	6.20	44	1.0	42	2.3	44	4.87
T1	None	3.84	36	1.5	54	6.6	7	0.00
T2	L 12000	4.78	32	1.4	46	3.4	17	2.94
T3	L 24000	5.51	40	1.2	49	2.4	26	9.27
H1	None	3.95	33	2.0	67	34.0	4	0.00
H2	L 12000	5.60	45	1.4	62	18.0	15	3.75
H3	L 24000	6.39	75	1.1	84	13.0	17	5.96
R1	None	7.79	128	0.50	64	1.5	12	6.23
R2	S 1000	7.54	172	0.30	52	1.5	10	5.69
R3	S 2000	7.42	210	0.25	53	1.6	9	6.17
R4	S 2000 plus $NaNO_3$ 300 t	7.34	269	0.17	45	1.6	9	7.87
G1	None	7.77	44	0.21	9.2	1.5	8.0	3.44
G2	S 1000	7.30	70	0.14	9.9	1.5	5.5	3.04
G3	S 2000	6.98	78	0.12	9.2	1.5	4.5	2.00
G4	S 2000 plus $NaNO_3$ 300 t	7.08	72	0.12	9.2	1.9	3.5	5.10
O1	None	6.50	70	0.69	48	2.4	18	14.20
O2	S 1000	6.13	89	0.51	45	3.0	15	14.57
O3	S 2000	5.70	181	0.35	64	3.0	16	11.29
O4	S 2000 plus $NaNO_3$ 300 t	5.75	145	0.37	54	3.5	14	11.54

* All pots received a uniform application of 1200 lbs. per A. of 3-9-18 fertilizer mixture and a solution treatment of $CuSO_4$ equivalent to a 100-lb. per A. application.

t Analyses shown were made prior to $NaNO_3$ application.

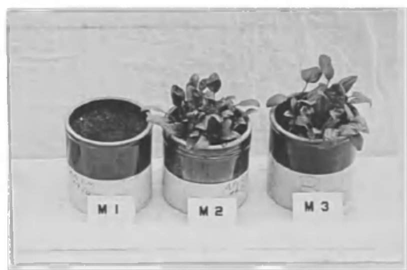


PLATE I

Response of spinach to liming on three strongly acid mucks. Number 1, no lime; 2, 12000 pounds per acre; 3, 24000 pounds per acre. All pots were uniformly fertilized with a 3-9-18 fertilizer mixture, and a solution treatment of $CuSO_4$ equivalent to a 100-pound per acre application.

sufficient time was not allowed for oxidation of the sulfur, or else some of the experimental conditions were such that oxidation was retarded.

The effect of the sulfur treatment on spinach yield was not significant. Some other limiting factor seemed to be involved. The plants in the G and R series gave strong indication of nitrate starvation. Further, the nitrate analyses made on these soils before seeding the spinach showed the nitrate supply to be low, and thus pointed toward lack of sufficient nitrate as the difficulty. An application of nitrate on Aug. 3 to pot 4 of soils R, G, and O proved beneficial to the spinach in soils R and G, especially the latter.

Water-soluble Nutrients. Water-soluble calcium content in the soil, as in Experiment 1, was found to have increased in practically every case with each addition of lime or sulfur.

Potassium solubility in the soil was again found to be quite variable in actual amount with respect to lime or sulfur treatment. The K/Ca ratio showed, however, a very consistent relationship to soil treatment. This ratio decreased with addition of either lime or sulfur. In other words, treatment which increased calcium solubility increased the amount of dialyzable calcium in proportion to the amount of dialyzable potassium, even tho it may have raised or lowered the actual amount of potassium dialyzed. This relationship was found to hold almost perfectly in all of the experiments reported in this paper in which water movement was not a factor.

In each of the three acid soils the soluble phosphate content correlated well with soil reaction. Comparing the three, however, it is apparent that the actual amounts of phosphate in solution at comparable pH values varied considerably. For example, the extract of soil T, pH 3.84, contained 6.6 p.p.m. PO_4 while that of soil H, pH 3.95, contained 34 p.p.m. PO_4. Lime application to the soil lowered the soluble phosphate content in every case.

The sulfur additions showed no noticeable effect upon phosphate solubility in the more alkaline soils. It is very probable that not enough acidity was produced in these soils, especially in soil R, by the sulfur added to reach the point of appreciable increase in solubility of phosphate. Soil R has shown increase in phosphate solubility in the field (16). Even so, it would seem that mucks vary considerably in their ability to fix phosphate at any particular pH value.

The nitrate content in the soil correlated well with the lime additions on the acid mucks. Without exception, each addition of lime gave increased nitrate. With the alkaline soils sulfur treatment showed a tendency toward decreasing the nitrates. As previously pointed out, the nitrates seened to be a limiting factor in the growth of spinach on soils R and G.

Experiment 3.

Comparative Effects of Different Acidity-producing Materials on an Alkaline Muck.

In the preceding experiments sulfur was the only source of acidity employed. It seemed desirable to know whether or not other acidity-producing materials applied to ALKALINE muck soils would prove beneficial to crop growth, and to compare their effects with those of sulfur upon nutrient solubility and plant response. This experiment was designed to secure such information, and also to find out, by comparing the effects of equivalents of sulfur and H_2SO_4, how much of the sulfur added becomes effective in changing the soil reaction within a comparatively short time.

Plan and Procedure

Fourteen clay pots, of 1-gallon capacity, were coated inside with paraffin and filled with equal weighed portions of alkaline muck. On Jan. 18 (1932) the soil of all pots was given a uniform application of 1200 lbs. per acre of a 3-9-18 fertilizer mixture and a solution treatment of $CuSO_4$ equivalent to a 50-lb. per acre application. In addition, the treatments designed to increase soil acidity were applied. These are given in table 21. In the cases of the H_2SO_4, HCl, HNO_3 and $(COOH)_2 \cdot 2H_2O$ treatments, those marked "1" and "2" were chemically equivalent to the 2000 and 4000-lb. sulfur treatments, respectively. The "1" and "2" $Al_2(SO_4)_3$ treatments were, respectively, 700 and 1400 lbs. per acre. Duplicates were run in the case of the checks only, it being felt that two rates of application of each material would be as good a check on its effect as duplication yet furnish additional data as well.

The pots were kept watered with distilled water, in the greenhouse, for three months to allow chemical reaction to proceed and equilibrium to be reached. Soil samples were taken April 10, and the pots seeded to spinach April 12. The spinach was harvested from all but four pots May 24 and soil samples were taken from the pots harvested. The remaining four pots were harvested June 1 and soil samples were taken from them on that date. The soil samples were analyzed for pH and water-soluble nutrients, as in the previous experiments.

Presentation of Results

The complete results of the experiment are presented in table 21.

Effects of certain acids and acidity-producing materials on soil pH and nutrient solubility, and on yield of spinach on an alkaline muck soil .

Pot		pH and nutrient solubility at time of seeding crop					pH and nutrient solubility at time of harvesting crop					Yield
No.	Treatment*	pH	PO_4	NO_3-N	Ca	K	pH	PO_4	NO_3-N	Ca	K	per Plant
11	H_2SO_4 (1)	7.00	0.25	8.13	300	48.0	7.17	0.45	1.5	273	20.4	3.38
12	H_2SO_4 (2)	6.25	0.39	9.06	593	51.7	6.49	0.50	0.0	531	21.3	7.61
13	S 2000	7.17	0.26	4.00	179	44.1	7.26	0.33	0.0	201	20.9	3.31
14	S 4000	6.48	0.26	3.00	417	53.0	6.51	0.45	0.0	446	23.1	2.86
15	HCl (1)	6.88	0.25	4.13	466	46.2	6.97	0.33	0.0	316	16.3	8.75°
16	HCl (2)	6.22	0.27	6.50	703	48.2	6.41	0.48	0.0	305	27.1	2.83°
17	HNO_3 (1)	6.99	0.19	250.00	343	44.3	7.20	0.25	125.00	251	18.0	6.38°
18	HNO_3 (2)	6.27	0.25	600.00	614	42.9	6.55	0.65	210.00	318	27.2	10.50°
19	Oxalic acid (1)	7.80	0.24	7.25	83	27.3	7.70	0.30	2.75	77	14.1	0.74
20	Oxalic acid (2)	7.78	0.27	5.75	101	34.3	7.53	0.35	0.0	115	15.8	1.70
21	Aluminum sulfate (1)	7.55	0.25	3.75	111	37.0	7.54	0.35	0.0	95	16.2	1.80
22	" " " (2)	7.60	0.27	10.50	95	32.2	7.59	0.45	0.0	80	14.2	2.14
23	None	7.53	0.25	3.50	112	41.7	7.58	0.50	0.0	94	14.5	4.87
24	None	7.55	0.27	4.00	108	41.3	7.53	.33	0.0	124	14.6	4.00

* All pots uniformly fertilized with 1200 lbs. per A. of 3-9-18 fertilizer and a solution treatment of 50 lbs. per A. of copper sulfate. For the acids, (1) and (2) are amounts equivalent in acidity to that produced by the complete oxidation of 2000 and 4000 lbs., respectively, of sulfur; for the aluminum sulfate, (1) and (2) are 700 and 1400 lbs. per A., respectively.

°Harvested eight days later than the other pots.

Soil Reaction. Comparing, in table 21, the results of the pH determinations on the samples from the S, H_2SO_4, and check pots, it appears that 70% of the light sulfur application and 80% of the heavy application were effective in producing acidity within a period of three months. There was very little difference in the efficiency of the three strong acids in lowering the pH, the HCl apparently being slightly more effective than the others. The $(COOH)_2 \cdot 2H_2O$ seemed to produce a slight alkalinity while the $Al_2(SO_4)_3$ was evidently not added in sufficient quantity to exert any effect upon the soil reaction.

After the crop of spinach had been harvested the acidity of the soil receiving S or mineral acid treatment was found to have decreased somewhat from that present prior to seeding; in the soil treated with $(COOH)_2 \cdot 2H_2O$ it had increased slightly, while no change was manifested in the others.

Water-soluble Calcium. The water-soluble calcium content of the soil was markedly increased by all of the mineral acid treatments and S. The HCl additions exerted the greatest effect, followed in order by the HNO_3, H_2SO_4, and sulfur treatments. The results are presented graphically in fig. 9.

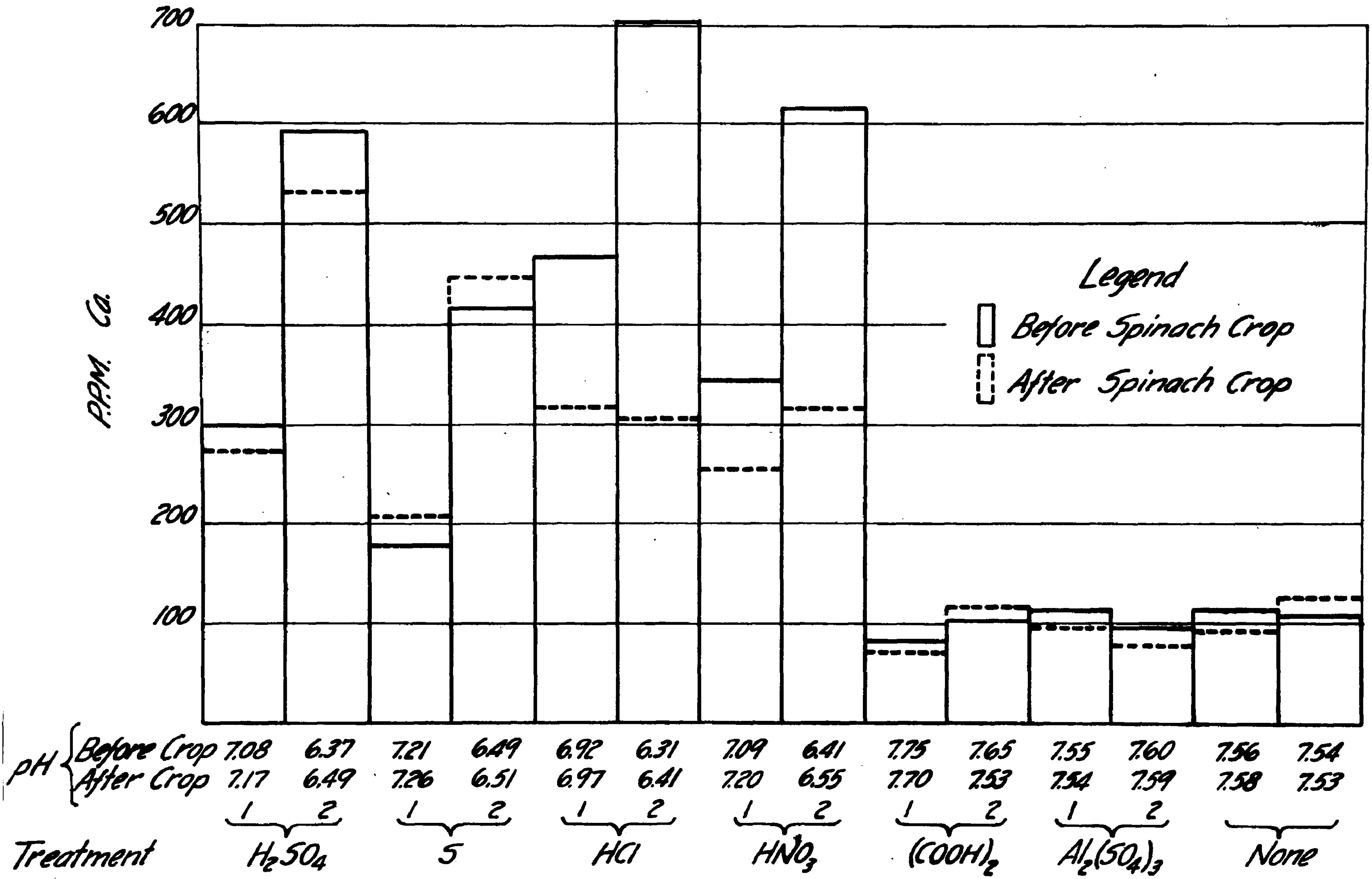


Figure 9. Comparative effects of certain acid materials on calcium solubility in an alkaline muck.

Qualitative tests showed the calcium in the extract to be associated with the acid radical added; for example, in the soil extracts from pots 15 and 16 the calcium was found to be in the form of $CaCl_2$, a much more soluble form than compounds of calcium with the naturally occuring acid radicals in the check soil.

The oxalic acid treatments did not have any appreciable effect on the soil content of water-soluble calcium. It would seem that a heavy application of exalic acid would reduce calcium solubility by precipitating the soluble calcium as the oxalate. The greatest amount of oxalic acid applied, 13,500 lbs. per A., is sufficient to precipitate slightly more than 5000 lbs. of calcium. Since calcium solubility was not reduced, it is evident that the oxalic acid applied was either destroyed by biological activity and did not precipitate the calcium or, if it did, the resulting salt was broken down soon afterward.

Following the spinach crop, the water-soluble calcium content was found to be considerably reduced in the soil treated with HCl or HNO_3, especially with the heavier treatments, while in that of the other pots it had suffered but little change. Thus the solubility effect resulting from the S or H_2SO_4 additions appeared to be more permanent than that from the HCl or HNO_3 treatments. With all of these acid materials, however, the water-soluble calcium in the soil was still much higher than in the untreated soil or in that receiving the $(COOH)_2 \cdot 2H_2O$ or $Al_2(SO_4)_3$ treatments.

Water-soluble Potassium. Figure 10 shows the amounts of water-soluble potassium in the extract from the soil of each pot, both preceding and following the spinach crop. The increases in potassium solubility due to mineral acid treatment of the soil, while positive, were but slight in comparison with those in calcium solubility, as shown in the preceding figure.

The striking thing shown by fig. 10 is that the soil of every pot, regardless of treatment, showed a large decrease in soluble potassium following the spinach crop. Since the soil of some of the pots gave practically no spinach crop and since that of pot 18, which produced the largest yield, was also highest in soluble potassium following the crop, it is apparent that the decrease in soluble potassium was due largely to its becoming fixed by the soil rather than its being removed by the plants. It is thus seen that altho the mineral acid treatments tended toward increasing the water-solubility of the potassium added to the soil, they did not prevent its gradual fixation by the soil. This fixation of potassium by an alkaline muck was not observed in the field studies with the slightly acid, high-lime muck in Experiment 1.

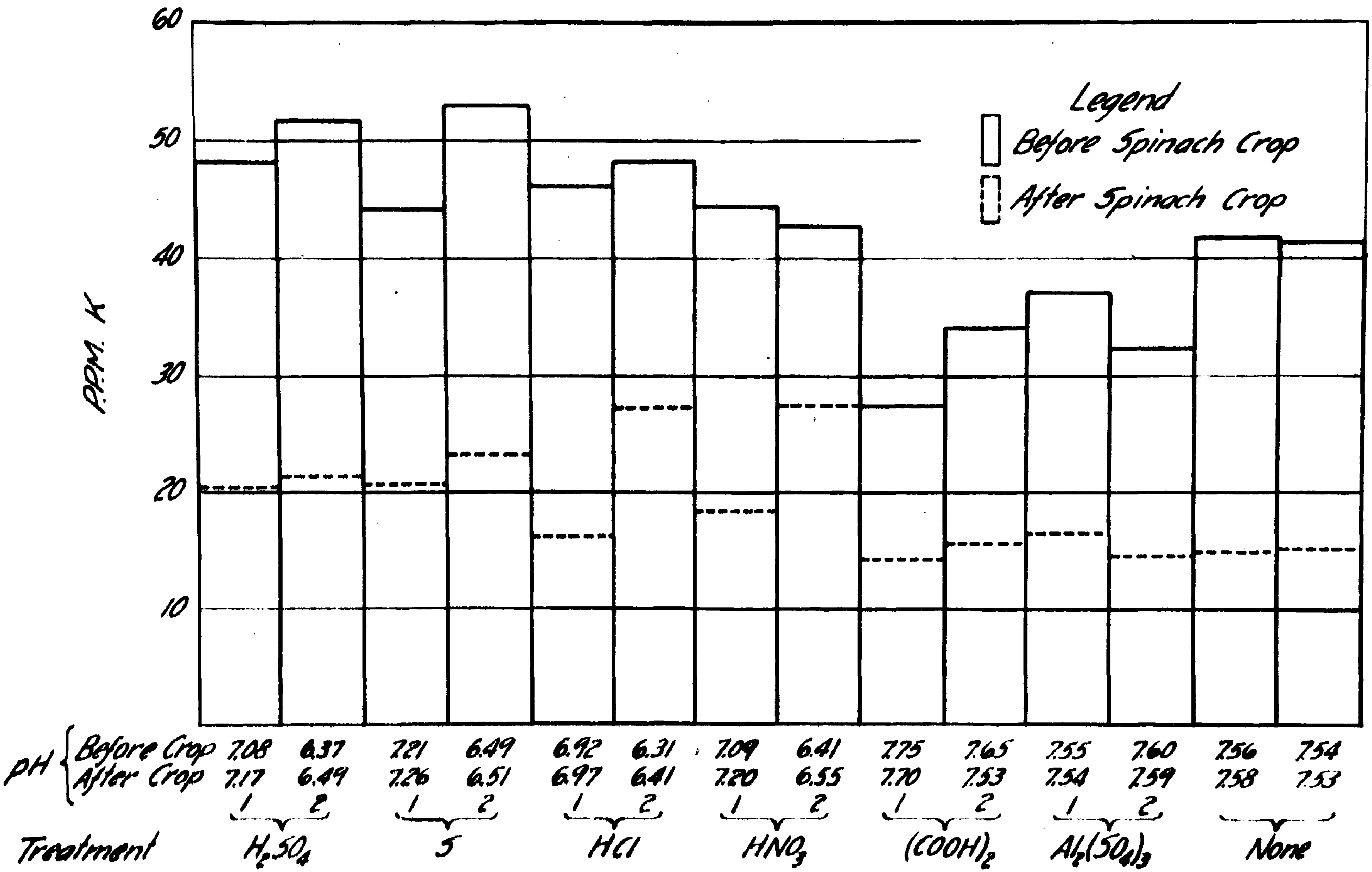


Figure 10. Comparative effects of certain acid materials on potassium solubility in an alkaline muck.

Water-soluble Phosphate. None of the treatments gave any changes in water-soluble phosphate content in this muck (table 21). It will be noted, however, that the lowest soil pH obtained by virtue of any of the treatments was 6.22, which is still quite high for notable increase in phosphate solubility to occur. This soil has shown increase in soluble phosphate in the field (16) as a result of sulfur treatment. Even so, it apparently has more retentative ability for phosphate than the more acid soils studied in Experiments 1 and 2, at similar pH values.

Nitrates. The soil nitrate content was not consistently affected by any of the treatments except HNO_3 (table 21). Nitrate supply was probably a limiting factor in the growth of the spinach in most of the pots. The HNO_3 pots were the only ones whose soil showed more than a trace of nitrate following the crop,and in these large amounts remained.

Crop Growth. Table 21 shows that there was no correlation between total yield of spinach and water-solubility of any of the soil nutrients studied except nitrates. There were, however, marked differences in the growth of the crop due to the different soil treatments.

The untreated soil and the sulfur and sulfuric acid-treated soil were the first in which the spinach germinated. In them, the plants made a very vigorous early growth. The spinach in the ~~whose~~ soil receiv~~ed~~ing the oxalic acid and aluminum sulfate also germinated fairly well but grew much more slowly, being poor and stunted, and never attaining any appreciable size thruout the experiment.

In the soil treated with HNO_3 or HCl, the seeds were extremely slow in germinating--so slow, in fact, that it was thought they had died. When the spinach in these pots finally came thru the soil, the plants in the S and H_2SO_4-treated soils were almost ready to harvest; however, when these seeds did germinate the plants grew exceedingly rapidly, had a much darker green color, and were of superior quality to all the others.

As previously stated, all the plants with the exception of those in pots 15, 16, 17, and 18 were harvested May 24. At that time the plants in pots 11, 12, 13, and 14 were beginning to form seed stalks, while those in pots 15, 16, 17, and 18 were growing very rapidly, and it was apparent that harvesting them at that time would not give a true representation of their possible yield. They were not harvested until June 1, eight days later than the others; hence, the yields are not strictly comparable to the yields of the other pots. These plants were of excellent quality altho those in pot 16 were quite variable in size, there being three large plants and four very small ones, resulting in a rather low yield per plant.

The foregoing results show that the particular material used in changing the reaction of an alkaline muck soil to a lower pH has considerable influence on the solubility of soil nutrients and on the type of spinach growth obtained. Of the various acidity-producing materials studied, sulfur is the only one of practical importance. As pointed out, insufficient nitrate for the crop evidently prevented the increases expected from sulfur application.

Experiment 4

Nutrient Solubility and Spinach Growth in Mixtures of Acid and Alkaline Mucks.

In the foregoing experiments some form of chemical was used to bring about more acid or more alkaline conditions within the soils studied. These additions were shown to have resulted in various changes in nutrient solubilities, some of considerable magnitude. It seemed desirable to know what effects the natural soil acids or alkalis would have upon the solubility of fertilizer nutrients. By mixing strongly acid muck and alkaline muck in different proportions a gradation in reaction between two extremes would be obtained. In such mixtures the soil would, of course, be different in each case; but the acidity or alkalinity present would be of natural occurence and in proportionate amount. If these mixtures were fertilized uniformly a study of the solubility of the added nutrients would show, to some extent at least, the influences of the soil materials themselves, undisturbed by the addition of a reaction-changing chemical as sulfur or lime. The present experiment deals with this situation.

Plan and Procedure.

Bulk samples of a very strongly acid muck (pH 3.43) and an alkaline muck (pH 7.26) were secured. Each sample was finely screened and thoroly mixed. On Jan. 8 (1932) a series of 9 2-gallon pots of these soils was prepared: one of each alone and seven of the two intimately mixed in as many definite proportions by volume. On Jan. 11 the pots were given a uniform treatment of 2000 lbs. per acre of a 3-9-18 fertilizer mixture, the same being mixed thoroly with the upper 4 inches of the soil. Distilled water was ~~then~~ added to the pots containing acid muck only and alkaline muck only until the apparent optimum water content for each had been reached. From their weights the amount of water to be added to the other pots was calculated according to their proportionate content of each muck. All of the pots were then brought to proper weight with distilled water and kept there thruout the experiment. More than a month was allowed for equilibrium to take place, samples for analysis being removed Feb. 17. The pots were ~~then~~ seeded to spinach Feb. 19. The spinach was harvested and soil samples taken again April 9. The pots were then refertilized with

1000 lbs. per acre of 3-9-18 fertilizer mixture on April 14 and allowed to stand until May 10, at which time soil samples were taken as before and spinach seeded a second time. The second crop of spinach was harvested and soil samples taken on June 16. Determinations of pH, water-soluble potassium, calcium, phosphate, and of nitrates were made on the four sets of soil samples according to the methods previously described.

Presentation of Results

The complete results of the experiment are presented in table 22.

Soil Reaction. The pH determinations show that practically a perfect correlation existed between soil reaction and the smounts of each muck present. Moreover, these reactions remained fairly constant thruout the experiment, during which time two crops of spinach were harvested. These relationships are best seen from fig. 11.

Solubility of Nutrients. Figure 12 presents, graphically, the solubility results from the first

Table 22

Effects of varying mixtures of acid and alkaline muck on soil pH and nutrient solubility, and on yield of spinach.

Pot No.	Muck Mixture *	pH and nutrient solubility at time of seeding crop					pH and nutrient solubility at time of harvesting crop					Weight per Plant
		pH	PO_4 ppm	NO_3-N ppm	Ca ppm	K ppm	pH	PO_4 ppm	NO_3-N ppm	Ca ppm	K ppm	gms.
						First Crop						
1	Acid Muck	3.43	15.0	2.75	32	94.5	3.53	14.4	2.25	34	62.5	0.0
2	7Ac-1Al	4.03	10.6	3.12	89	92.2	4.40	10.6	0.0	33	31.9	4.28
3	6Ac-2Al	4.51	7.5	3.50	94	87.5	4.76	6.9	0.0	35	33.9	10.10
4	5Ac-3Al	4.82	6.3	4.00	94	75.1	4.89	6.3	0.0	34	25.1	19.31
5	4Ac-4Al	5.26	4.7	9.75	117	66.9	5.47	4.5	0.0	39	22.5	19.65
6	3Ac-5Al	5.61	2.1	7.50	148	82.9	5.81	3.3	0.0	55	26.9	19.33
7	2Ac-6Al	6.23	1.3	15.00	186	75.3	6.43	1.6	0.0	52	20.2	23.91
8	1Ac-7Al	6.70	0.75	7.50	164	80.4	7.05	0.99	0.0	54	20.2	17.02
9	Alkaline Muck	7.26	0.75	7.50	151	75.8	7.49	0.91	0.0	115	36.6	15.45
						Second Crop						
1	Acid Muck	3.46	11.6	2.25	32	70.0	3.45	11.9	1.50	28	62.4	0.0
2	7Ac-1Al	3.81	6.9	1.50	33	89.7	4.20	8.4	1.50	49	48.6	0.088
3	6Ac-2Al	4.37	5.2	3.50	112	47.8	4.47	5.2	5.00	117	33.0	1.46
4	5Ac-3Al	4.73	4.5	4.50	145	43.7	4.83	4.5	0.00	141	37.1	0.53
5	4Ac-4Al	5.05	3.1	6.00	150	46.3	5.20	2.3	0.00	188	20.8	8.46
6	3Ac-5Al	5.64	2.0	8.00	148	50.2	5.84	1.1	0.00	97	15.8	9.08
7	2Ac-6Al	6.19	0.70	2.75	145	40.0	6.42	0.63	T	74	14.6	10.62
8	1Ac-7Al	6.68	0.70	2.00	208	52.1	7.17	T	5.50	47	18.8	12.78
9	Alkaline Muck	7.41	0.63	3.88	174	56.4	7.51	T	7.00	70	21.1	14.66

* All pots received a uniform application of 2000 lbs. per A. of 3-9-18 fertilizer mixture.

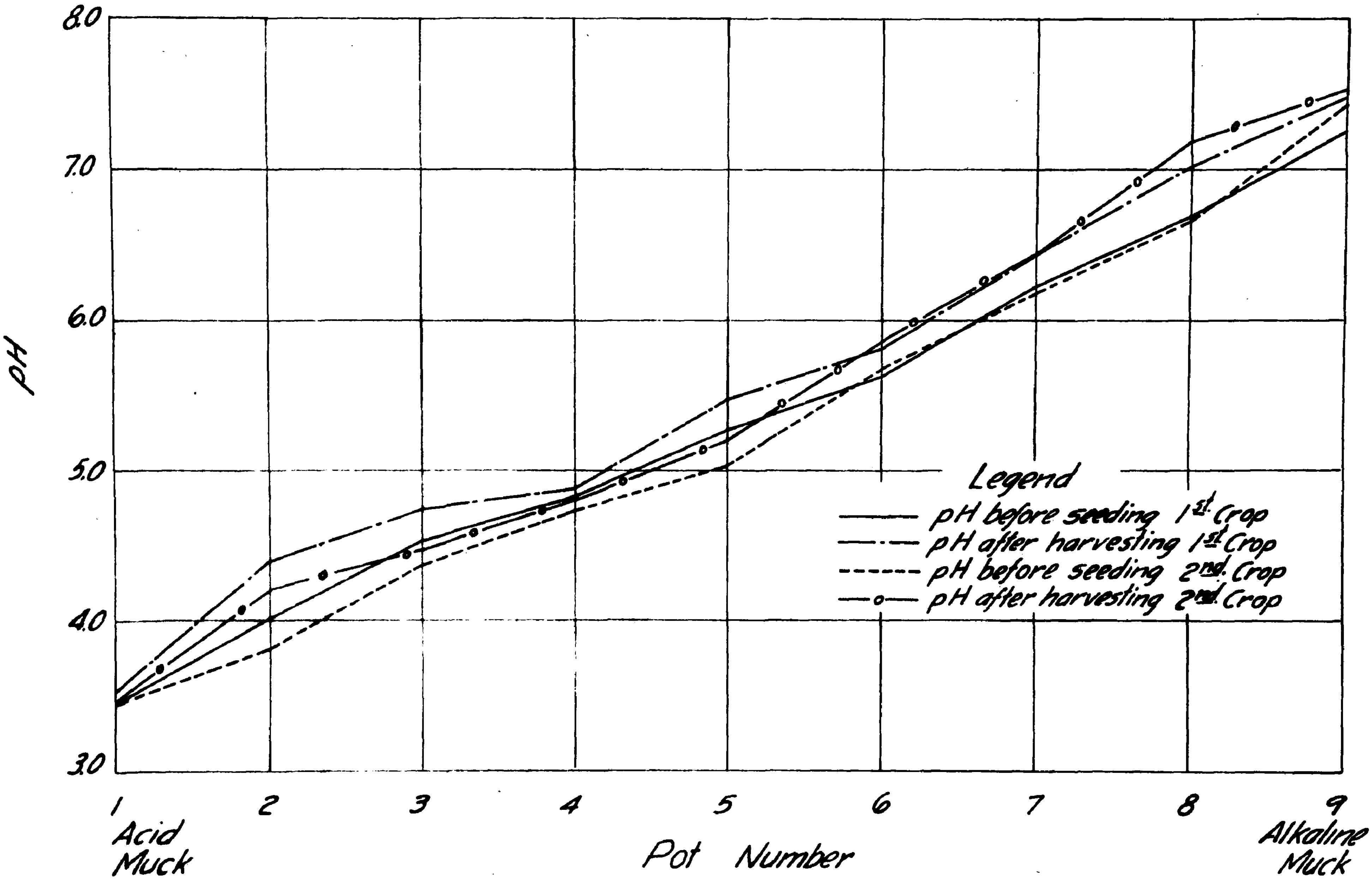


Figure 11. pH of acid-alkaline muck mixtures as influenced by the growth of two spinach crops.

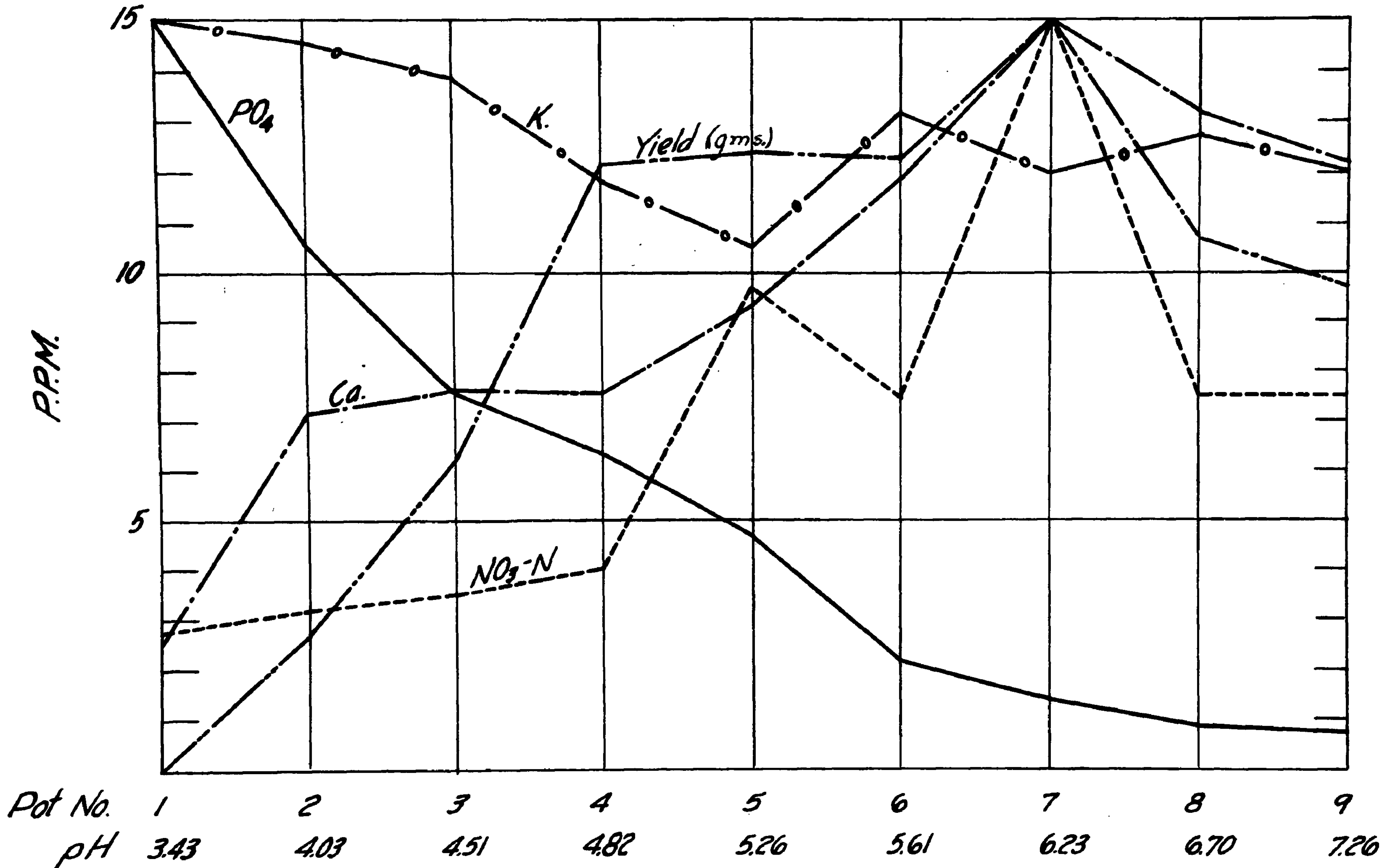


Fig. 12. Relationships between yield of spinach and nutrient solubility in mixtures of acid and alkaline muck. Pot 1 contained acid muck only, pot 9 alkaline muck only. (To reduce the results to the same scale the actual amount of Ca was divided by 12.4; K by 6.3; and yield in grams by 1.59).

sampling of the soils -- that made before the seeding of the first spinach crop -- together with the yield per plant of the first crop.

The calcium curve shows that the water-soluble calcium content of the soil decreased, generally, with increasing acidity, the acid muck being very much lower in soluble calcium than the alkaline muck or any of the mixtures. This result is in sharp contrast to that obtained when acidity was introduced into alkaline muck by means of sulfur or other chemical treatment. This result lends support to the argument previously advanced that calcium solubility is not dependent upon pH but rather upon the amount of calcium present and the acid radical with which it is associated.

The calcium determinations for the other three samplings (table 22) show, in general, the same results as those of the first sampling, remembering, of course, that the water-soluble calcium content of the soil may have been decreased through the removal of calcium by the growing crop.

The phosphate curve (fig. 12) shows that phosphate solubility increased in the soil as pH decreased. This is in line with the findings of the preceding experiments, except in the cases of the alkaline soils whose reactions were not brought low enough by the treatments to reach the point at which appreciable change in soluble phosphate would occur. The phosphate-solubility curve in this case is especially worthy of note. Its relationship to pH is very definite and consistent, the first measurable increase in soluble phosphate being at pH 6.23 and becoming greater at an increasingly rapid rate as acidity increases. Its similarity to an ordinary titration curve suggests a definite chemical reaction as its basis. Austin (5) obtained such curves by titration of $CaH_4(PO_4)2$ with $CaCO_3$ and CaO, altho he found appreciable increase in phosphorus to take place at a higher pH than that shown here. Spurway (44) noted, however, that in dilute solutions concentration of the liquid phase was a factor in determining at what reaction precipitation would take place. Doughty (8) has shown that precipitation and physical adsorption both function in the removal of phosphate from a phosphate solution by a peat soil. Since the different mixtures of necessity var~~y~~ied proportionately in adsorption material, it is possible that the curve represents a resultant of these two factors. Preceding experiments showed, however, that increased phosphate solubility occured with addition of acid material on the same muck, in which case the adsorption material was uniform. This would lead to the belief that phosphate fixation and liberation was largely chemical.

This relationship between pH and phosphate solubility in the soil holds very consistently thruout the experiment (table 22), being unaffected by the growing of two spinach crops or the application of additional fertilizer. This, again, indicates that the action is chemical and that the form which the phosphate takes is dependent, primarily, on the acidity present. On the other hand, it was shown in Experiment 2 that altho phosphate solubility was decreased in acid mucks in every case by lime addition, the actual amounts in solution at a particular pH value varied with each individual soil. This indicates that both adsorption and chemical fixation influence phosphate solubility.

The solubility of potassium in the soil, as noted in previous experiments, showed considerable variation. No consistent trend was in evidence with the exception of a noteworthy increase in solubility in the more acid mixtures, the two most acid pots being considerably higher than the others. Comparing the results of the four determinations of water-soluble potassium in the soil of pot 1 (which grew no crop), fixation of potassium is again shown to have taken place.

The nitrate content was highest in the soil of pot 7 at the beginning of the experiment. This jar also gave the highest yield in the first crop. The yield curve and nitrate curve show good correlation beyond the point at which extreme acidity influenced the yield. The yield curve parallels the calcium curve also, but soluble calcium was present in all pots thruout the experiment, as shown by the data in table 22, while nitrates were absent in the soil of all pots except pot 1 at the time the spinach was harvested. Apparently, as in Experiment 3, deficiency of nitrate was one of the limiting factors, if not the most important one, except in the extremely acid pots. This is emphasized in the results for the second crop. Even after an application of 1000 lbs. per acre of 3-9-18 fertilizer previous to the seeding of the second crop, the soils of pots 4, 5, and 6 showed no nitrates at the time the spinach was removed, and pot 7 showed only a trace. The yields of the second crop checked consistently thruout with the nitrate supply, except in the first three, highly acid, soils; and pot 9 gave the highest yield, whereas pot 7 had given the highest in the first crop. Thus it seems that again, as in previous experiments, the available nitrate supply (natural and applied in the fertilizer) was insufficient for the crop being produced, so that it, rather than the supply of available phosphate, potash, and calcium became the limiting factor in the growth of the crop.

Experiment 5

It has long been recognized that crop failures are common on mucks that are too wet or that are overdrained. (1) (27) (12) (13). In Experiment 1 of this study, the apparent influence of such water relationships as rainfall, evaporation, and the resulting soil water movements on the solubility of phosphate and probably of other nutrient materials in the soil was noted. Apparently but little work with muck soils under experimental conditions has been done on the effect of controlled moisture supply on plant growth and composition, and none on its effect on the solubility of plant ~~food~~ nutrients in the soil.

Alway (1) reports that heaviest yields were obtained from mucks having the water table at a depth of 20 to 40 ins. He recommends 40 ins. as generally the best for small grains and cultivated crops, and 20 to 30 ins. for hay crops. McCool and Harmer (27) recommend a water level of about 3 ft. during the summer months for most general farm crops and root crops, altho it may be somewhat higher in the early part of the season. For hay and pasture they recommend a 2-ft. level in most cases. They also point out the importance of maintaining a fairly uniform water level. Harmer (13) makes similar recommendations for onions but states, in addition, that better yields may be secured with the water table at a depth of only 2 ft. if the muck is so well tiled or ditched that heavy rains produce little or no fluctuation in water level. More recently, he (15) recommends improving the drainage, if needed, as the first step in the reclamation of "alkali" mucks. On the other hand, he advises maintaining the water level on very acid mucks as high as is consistent with the root-habits of the crop being grown. Knott (22) states that the water table for onions may be at the 18-in. level early in the season, but later a depth of 2 to 3 ft. is more desirable.

In connection with the studies on the effects, on soil and crop, of sulfur and lime additions to muck soil, it was felt that water level might be found to exert some influence on the results obtained. This experiment was undertaken, therefore, to obtain information on the following questions:

(1) What effects, if any, does the height of the water table have upon the solubility of fertilizer nutrients in the soil, with and without sulfur and lime addition?

(2) What influence does height of water table exert on plant response to sulfur or lime applications to the soil?

(3) Are differences in crop quality resulting from differences in water level in the soil, with and

without soil treatments of sulfur and lime, reflected in the mineral or sugar content of the crop?

(First Year)

Plan and Experimental Procedure

For this study a group of 36 lysimeter cans of 42" depth and 24" diameter were employed. This set of cans, previously prepared for another study, were constructed of heavy galvanized sheet iron, painted on the inside with duco paint and set into the ground so that the tops were about 4 ins. above the land surface. Figure 13 illustrates the set-up of the cans and the device by which the water level was regulated. Water poured into the funnel rises in the soil until the top of the overflow pipe is reached, it being adjusted to within 6, 18, or 36 ins. of the soil surface in the various cans. These three water levels were taken in this study to represent, as nearly as possible, what under field conditions would be poor, fair, and good drainage, respectively, for most of the crops grown. Rain water caught from a building roof was used for watering the soil. The cans were exposed to natural rainfall also.

All of the cans were filled to within 18 ins. of the top with subsoil muck from the area on which the college muck plots are located, then filled to the top with surface muck from the same source. This 18 ins. of

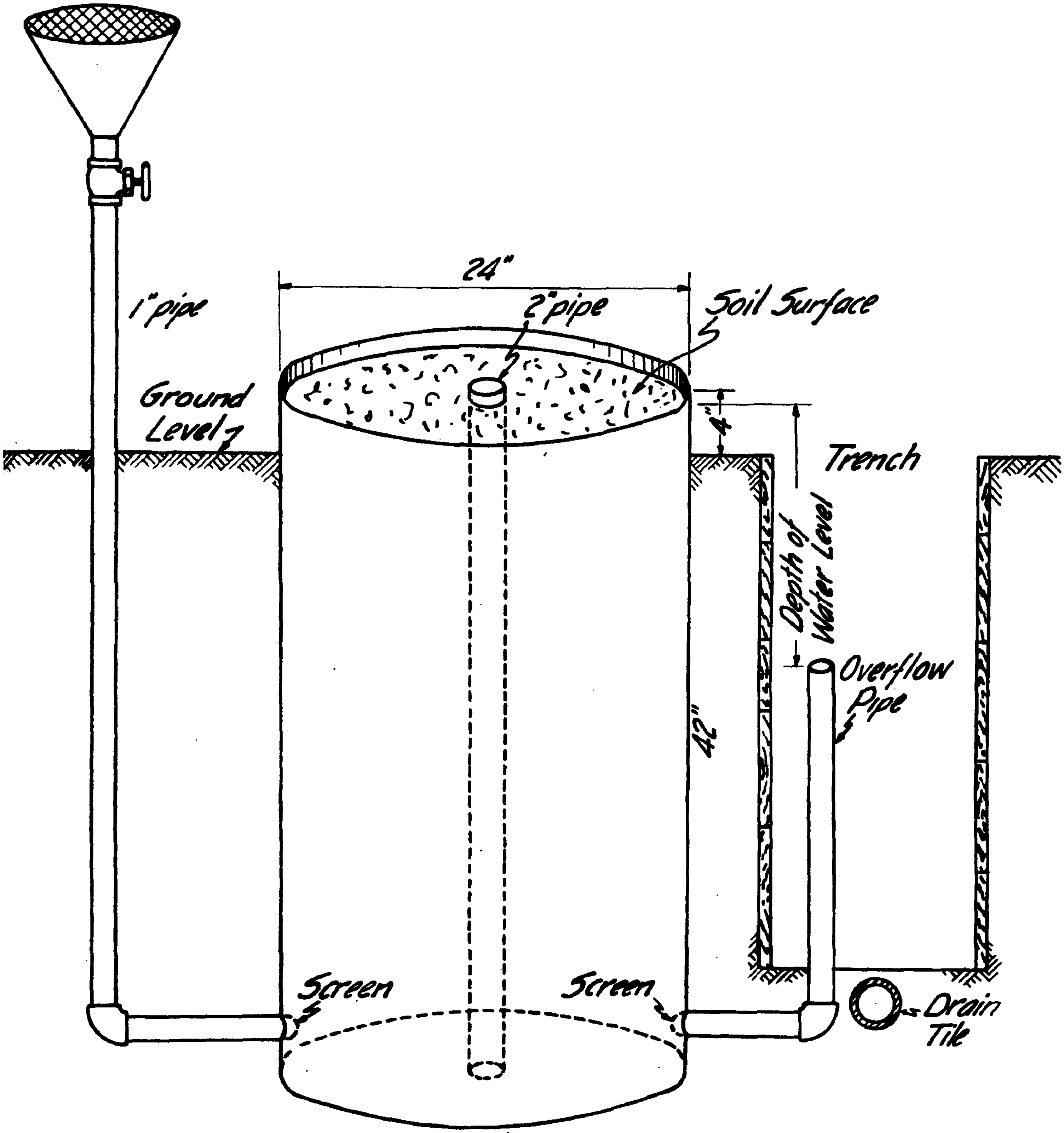


Figure 13. Diagram of soil can showing method used for controlling water level. (The 2" pipe was used for testing water depth.)

surface soil was screened thru a 1-in. screen to remove all large woody pieces and was mixed thoroly in four batches, a weighed amount being put into each can from each batch. The last 6-in. layer put into each can was given a uniform treatment of 1200 lbs. per acre of 3-9-18 fertilizer containing the equivalent of a 60-lb. per acre application of $CuSO_4$. On the same date, April 29 (1932), the soil of certain of the cans was given lime and sulfur treatments, alone and in combination (table 23). All soil treatments and water levels were in duplicate except in the case of some of the 6-in. water level cans. These were meant to be duplicates but it was found impossible to maintain all of the 6-in. levels, due to leaks in some of the pipe connections; hence, the levels shown (table 23) as 7, 9, or 12 ins. were approximated. In those cases in which duplication of water level was not secured the results obtained are given for each can; in the others, the results given are averages of the duplicates. Also, due to the variability of the high water levels, only the results obtained at the 18" and 36" levels are included in the general averages.

Onions were seeded May 1, all water levels being 18" below the surface at that time in order to give all of the seeds a uniform germination in each can. The water table in each can was brought to proper level after the onions had reached a height of approximately 2 ins. Soil samples were taken for analysis from the 2-3 in. depth and the onions thinned to fifty per can, June 16. Seven celery plants were transplanted, on July 1, to the center portion of each can. They were re-set several times in the soil of low water level, due to its extreme dryness. The onions were harvested Aug. 31 and allowed to cure until Sept. 2, at which time they were weighed, counted, and sampled for analysis.

After removal of the onions, an application of 300 lbs. of $NaNO_3$ per acre was added in solution to one of each set of duplicate cans in order to make certain that the lack of sufficient nitrate to produce a good yield of celery would not be a limiting factor in the crop's response to the sulfur and lime applications. A yellowing of the plants at the higher soil water levels, especially the 6" level, had indicated that such might be the case. The celery was harvested Oct. 8.

Presentation of Results

The complete results of the soil analyses are presented in table 23.

Soil Reaction. Based on the one sampling made June 16, it appears that water level had no significant

Table 23

Influence of water-level height on the effects of sulfur and lime on soil pH and nutrient solubility - College muck (1932)

Treatment * (lbs. per A.)	Water-level Height (ins)	pH	In 1-10 soil-water extract June 16			
			PO_4 p.p.m.	Ca p.p.m.	K p.p.m.	NO_3-N p.p.m.
L 5000	6	5.96	13.4	93	56	8.0
L 5000	12°	5.92	14.2	103	43	14.0
L 5000	18	5.84	16.1	128	52	12.2
L 5000	36	6.01	15.0	77	33	11.0
Ave. 18"- 36"	levels	5.93	15.6	103	43	11.6
L 10000	12°	6.45	9.4	127	55	8.8
L 10000	18	6.64	9.4	105	51	8.3
L 10000	36	6.62	9.9	80	35	3.9
Ave. 18"-36"	levels	6.63	9.7	93	43	6.1
S 500	6	5.04	26.2	132	40	4.3
S 500	9°	5.05	25.0	142	61	3.8
S 500	18	5.06	23.1	147	47	2.9
S 500	36	5.10	20.6	115	33	2.8
Ave. 18"-36"	levels	5.08	21.9	131	40	2.9
S 1000	7°	4.90	25.3	198	58	9.8
S 1000	18	4.88	26.3	207	62	6.5
S 1000	36	4.93	23.8	181	40	6.5
Ave. 18"-36"	levels	4.91	25.1	194	51	6.5
L 10000, S 1000	6	6.14	10.0	207	50	3.1
L 10000, S 1000	18	6.15	10.0	242	60	6.5
L 10000, S 1000	36	6.09	10.4	192	37	4.0
Ave. 18"-36"	levels	6.12	10.2	217	49	5.3
None	7°	5.26	25.0	106	37	7.0
None	18	5.40	23.0	87	39	7.3
None	36	5.50	20.0	70	31	4.7
Ave. 18"-36"	levels	5.45	21.5	79	35	6.0
AVE. ALL 18" LEVELS		5.67	17.98	152.7	51.8	7.28
AVE. ALL 36" LEVELS		5.71	16.61	119.2	34.8	5.48

* All cans fertilized uniformly with 1200 lbs. per A. of 3-9-18 fertilizer containing 60lbs. per A. of $CuSO_4$.

° 6 in. level not maintained; values given are approximate.

effect on the changes in soil pH obtained by sulfur or lime addition. There is indication that in the untreated soil acidity decreased very slightly with decreasing water level, but the differences are so small that they may not be of significance.

Water-soluble Phosphate. Figure 14 shows that soil water level exerted no consistent influence on the effects of lime and sulfur additions on phosphate solubility in the soil samples taken. In general, the soil of 36" water level was somewhat lower in soluble phosphate content at the 2-3 in. soil depth than that having a higher water level. The soil treated with the heavy lime application, both with and without sulfur, did not show this relationship.

It would seem that the degree of moisture saturation in the soil is the most logical explanation for the results obtained. For example, where the water level was near the surface the soil was very wet, and the zone of salt accumulation resulting from evaporation was shallow--probably not over an inch or two in depth; hence, samples taken at a 2-3 in. depth might be in or out of this zone. On the other hand, the soil of 18" water level was much less saturated with moisture, with the result that the zone of salt accumulation accruing from evaporation was thicker, and the samples taken were probably in this

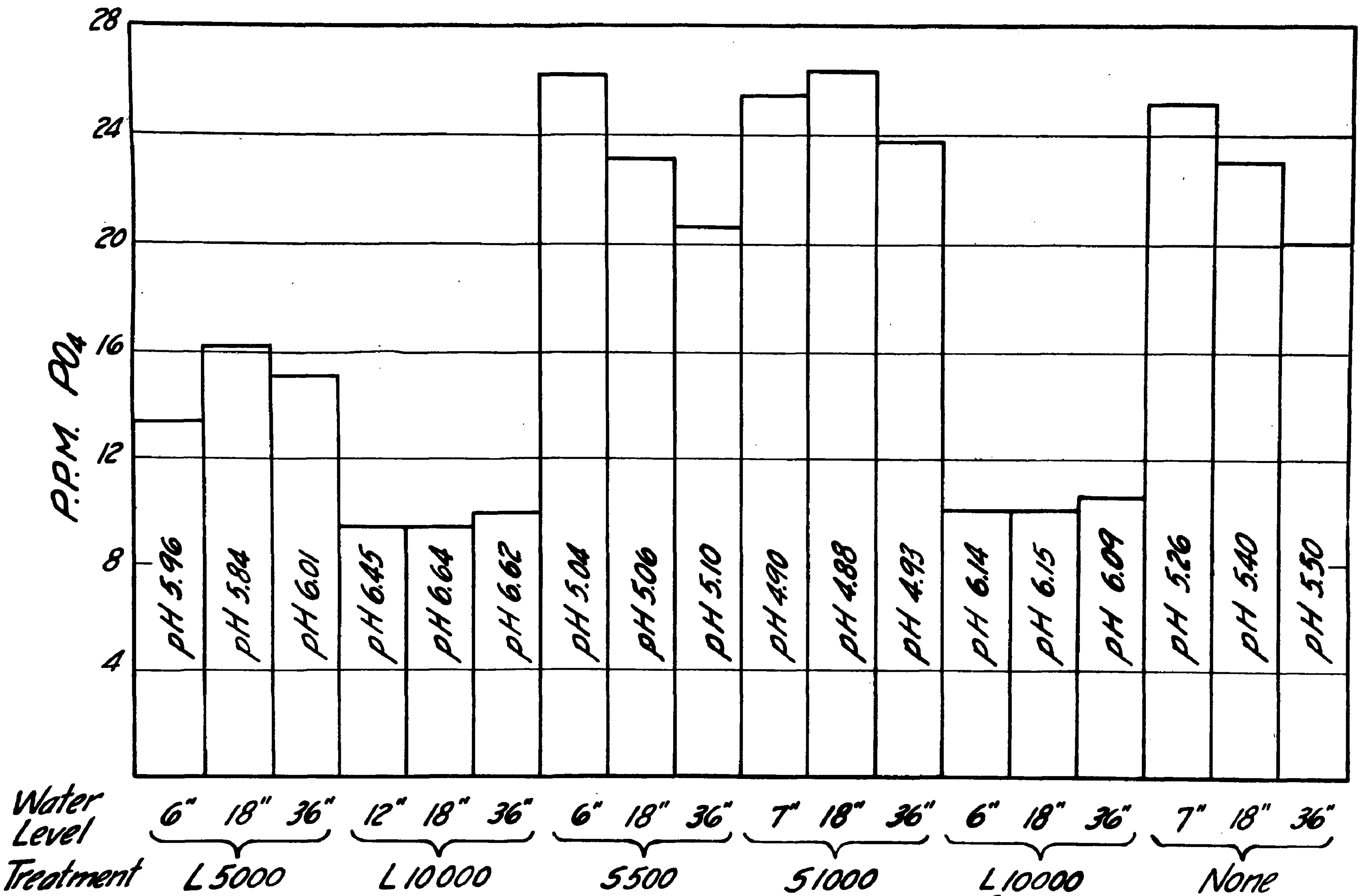


Figure 14. Influence of water level on the effects of lime and sulfur treatments on water-soluble phosphate content in muck soil - College muck (1932).

zone. Similarly, the soil of 36" water level had a much thicker zone of accumulation than the others, so that the salt accumulation was not so localized near the surface; hence, samples taken from the 2-3 in. soil depth were lowest in soluble phosphate in the soil of lowest water level. When the heavy lime applications were added, however, the phosphate was rendered much less soluble, resulting in little movement of phosphate and, consequently, no differences in soluble phosphate at the 2-3 in. soil depth under varying moisture conditions. This explanation regarding the effects of water level on phosphate solubility is, of course, speculative since the sampling was made at one depth only. It is substantiated, however, by its applicability to both the calcium and potassium results which follow.

The fertilizer application evidently furnished enough phosphate at the 2-3 in. depth to maintain fairly well the concentration of water-soluble phosphate in the soil permitted by its reaction in each case, even after different amounts of phosphate had been moved in the soil, due to different rates of evaporation. Qualitative tests of the surface crusts of the sulfured soil showed the phosphate content to be considerably highest in that of the soil with the highest water level.

An examination of fig. 14 reveals that a very close correlation existed between pH and water-soluble phosphate in the soil. This is in line with the results of the previous experiments.

Water-soluble Calcium. Figure 15 shows that, with only two exceptions, the 18" water level resulted in greater solubility of calcium at the 2-3 in. soil depth than did the higher levels. The exceptions were the untreated soil and that receiving the heaviest lime application. In the latter case the high water level was 12 ins. below the surface instead of 6 or 7 as in the other high water-level cans. The soil of the low water-level cans was uniformly lowest in water-soluble calcium at the 2-3 in. soil depth. Again, these results seem best explained on the basis of the relationship of depth of sampling to the thickness of the zone of accumulation resulting from the degree of moisture saturation in the soil and its attendent rate of evaporation.

The effects of the lime and sulfur additions on soluble calcium content in the soil are in agreement with those noted in the field plot studies in Experiment 1. Also, as before, there was no correlation between soil reaction and water-soluble calcium content.

Water-soluble Potassium. The results of the water-soluble potassium determinations are presented graphically in fig. 16. Again, the soil with the 36" water level was uniformly lowest in water-soluble potassium regardless of lime or sulfur treatment. In

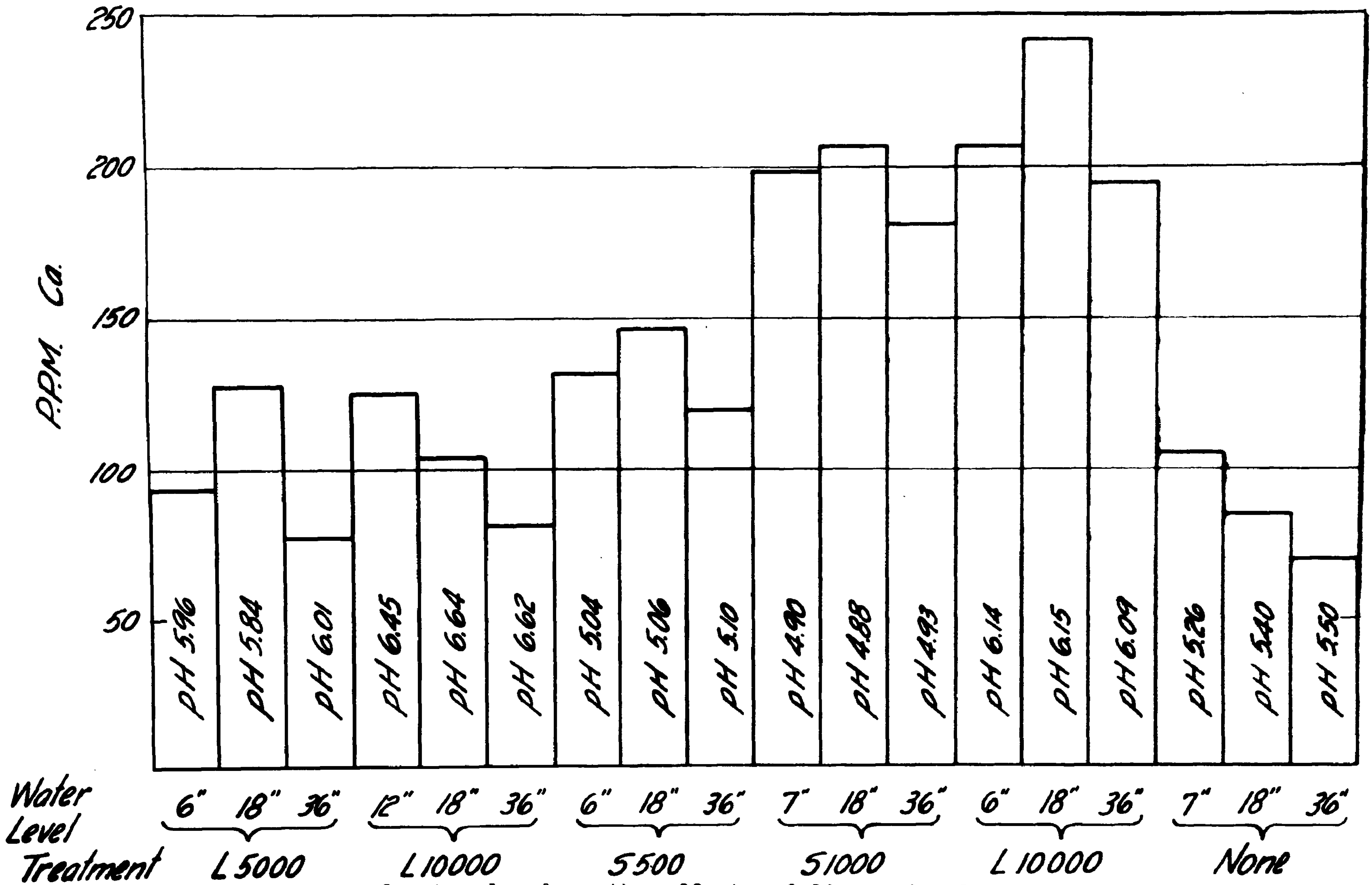


Figure 15. Influence of water level on the effects of lime and sulfur treatments on water-soluble calcium content in muck soil - College muck (1932).

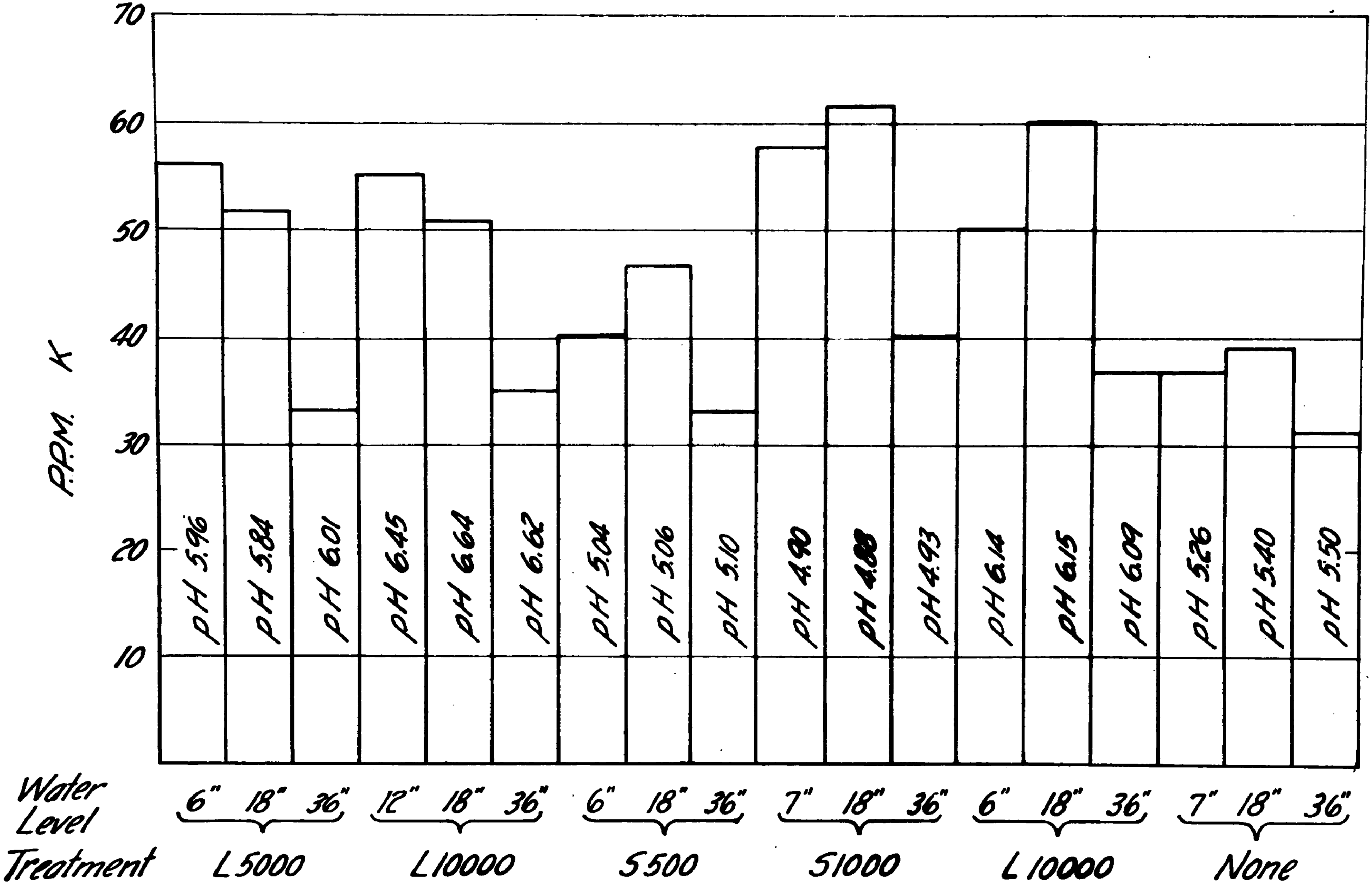


Figure 16. Influence of water level on the effects of lime and sulfur treatments on water-soluble potassium content in muck soil - College muck (1932).

the soil receiving lime only, water-soluble potassium was slightly higher in the 6 and 12 in. water-level cans, while in that receiving sulfur alone or in combination with lime it was slightly highest in the 18" water-level cans. Sulfur increased the water-soluble potassium in the soil, as in Experimentl; lime also increased it, whereas under field conditions (Experiment 1) it had given no increase. There was no correlation between soil acidity and water-soluble potassium content.

Nitrates. The results of the nitrate determinations are presented graphically in fig. 17. It will be noted that the soil of low water level was generally lowest in nitrate. In most cases the soil samples from the 18" water-level cans were higher in nitrates than those from the high-level cans, the only exceptions being those from the cans whose soil received sulfur alone. The increase in nitrate content of the soil following light sulfur application observed in Experiment 1 under field conditions was not noted in this study, the soil receiving 500 lbs. per acre of sulfur being lowest of all in nitrates. Since the heavier application of sulfur did not decrease soil nitrate supply, it is apparent that the nitrate results from the one sampling in this study are too variable to permit of drawing conclusions from

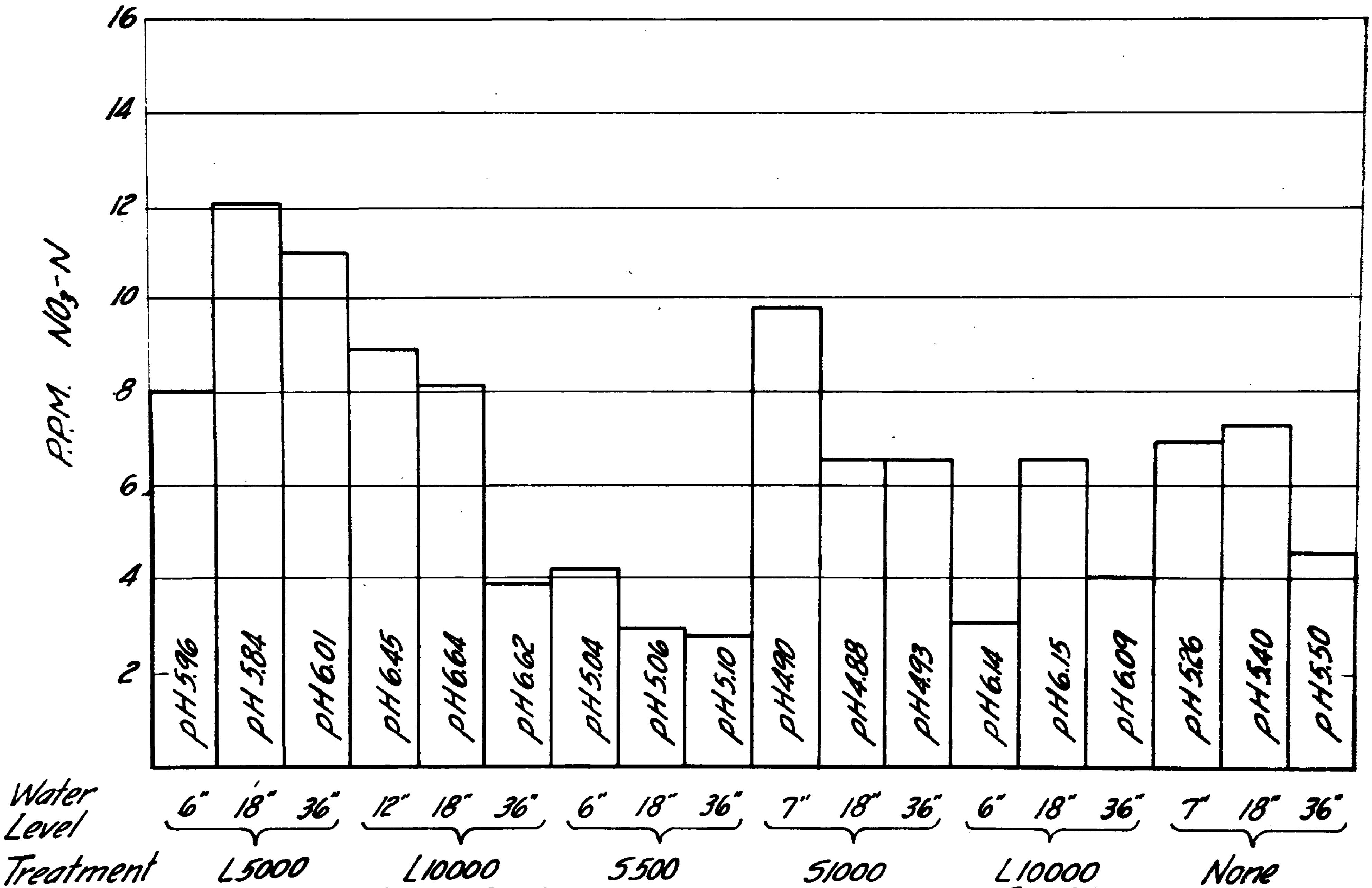


Figure 17. Influence of water level on the effects of sulfur and lime treatments on nitrate content in muck soil - College muck (1932).

them with respect to the influence of sulfur or lime application.

Yield, Growth, and Composition of Onions. The onion yield and analytical results are presented in table 24. Since different numbers of onions occured in the cans, due to some loss thru wireworm and cutworm injury, both total yield and yield per plant are given.

The table shows that soil water level exerted a very important influence on the growth of the onions. Maximum yield was obtained in all cases, regardless of sulfur or lime treatment, in the soil having a water table 18" below the surface. The onions on the limed soil seemed to be more susceptible to injury from excessive moisture conditions than were those on the untreated or sulfured soil (Plate II). The 6" water level caused the muck to be very much too wet for the crop, but in certain of the cans wherein it was impossible to maintain a 6" water level it was found that a slight lowering from this height resulted in a marked increase in yield above that of the 6" level. Fair yields were obtained with 9-12" levels. The soil having a water level 36" below the surface was much too dry for onions, those in the sulfured soil being espeacially injured by the low water level. This experiment confirms the conclusions reached by field investigators (1) (27) (12) (13)

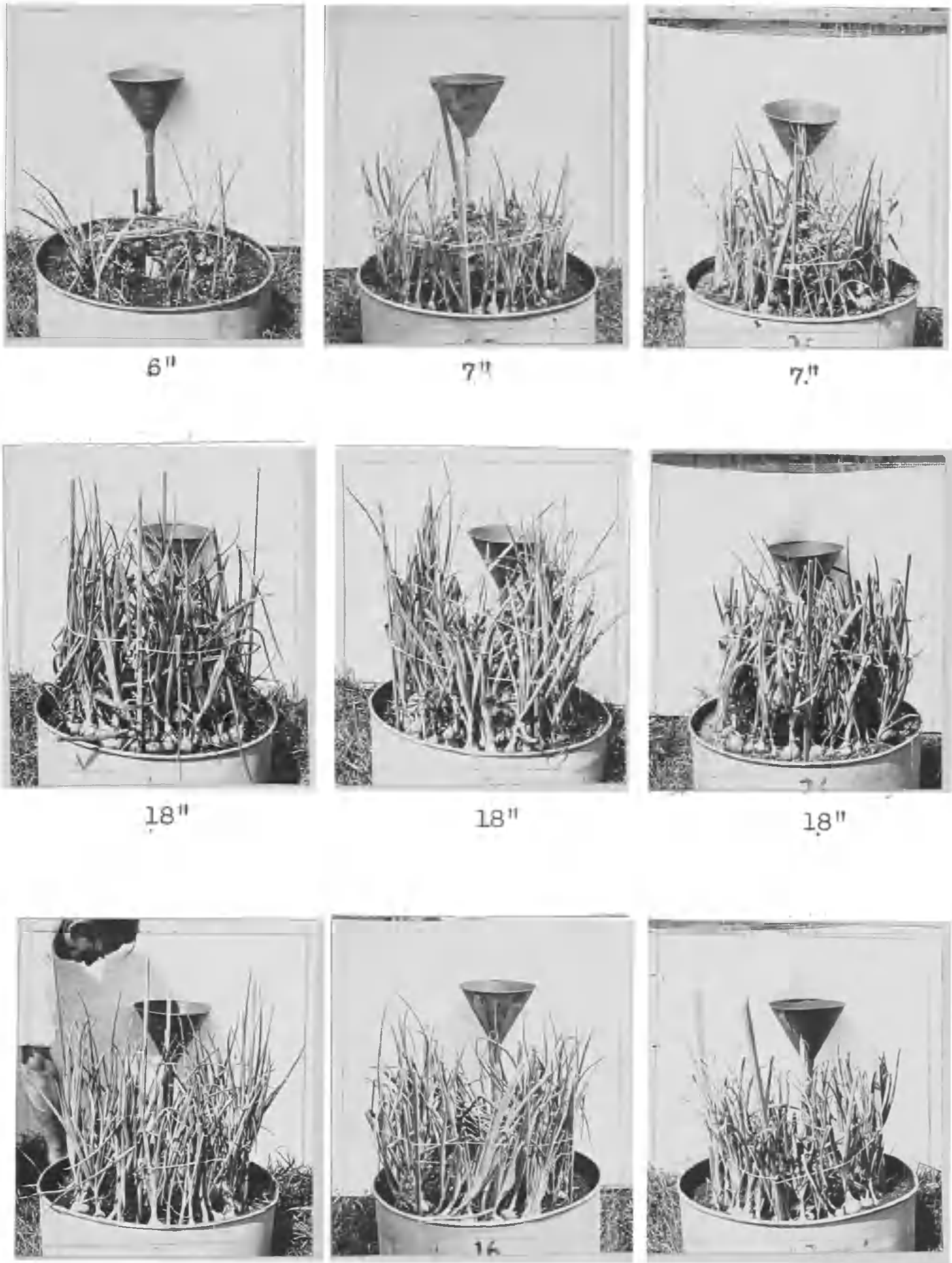
Table 24

Influence of height of water table on the effects of sulfur and lime soil treatments on yield and composition of onions - College muck (1932)

Treatment* (lbs. per A.)	Water Level ins.	pH	Onion Yield Total gms.	Onion Yield Per Onion gms.	N and Mineral Content of Onions (dry basis) N %	Ca %	K %	P %
L5000	6	5.96	311.5	11.54	1.90	0.26	2.01	0.31
L5000	12°	5.92	1189.5	34.99	1.52	0.29	1.71	0.39
L5000	18	5.84	2317.3	60.08	1.94	0.30	1.26	0.27
L5000	36	6.01	1401.0	43.78	2.60	0.33	1.63	0.28
Ave. 18"-36" levels		5.93	1859.2	51.93	2.27	0.32	1.45	0.28
L10000	12°	6.45	1741.3	46.94	1.60	0.33	1.58	0.28
L10000	18	6.64	2119.5	51.79	2.31	0.36	1.39	0.28
L10000	36	6.62	1366.3	35.12	2.76	0.32	1.71	0.28
Ave. 18"-36" levels		6.63	1742.9	43.46	2.54	0.34	1.55	0.28
S500	6	5.04	767.5	19.68	1.29	0.28	1.62	0.33
S500	9°	5.05	1449.0	46.71	1.50	0.31	1.75	0.31
S500	18	5.06	1544.0	44.10	2.18	0.31	1.60	0.35
S500	36	5.10	855.3	29.69	2.81	0.32	1.89	0.40
Ave. 18"-36" levels		5.08	1199.7	36.90	2.50	0.32	1.75	0.38
S1000	7°	4.90	1131.5	31.58	1.44	0.30	1.74	0.33
S1000	18	4.88	1472.3	37.45	2.30	0.31	1.70	0.37
S1000	36	4.93	764.3	24.94	2.84	0.32	2.07	0.46
Ave. 18"-36" levels		4.91	1118.3	31.20	2.57	0.32	1.89	0.42
L10000 S1000	6	6.14	783.0	24.48	1.55	0.30	2.21	0.43
L10000 S1000	18	6.15	1734.0	58.81	2.08	0.33	1.43	0.28
L10000 S1000	36	6.09	1187.3	40.28	2.67	0.33	1.67	0.26
Ave. 18"-36" levels		6.12	1460.7	49.55	2.38	0.33	1.55	0.27
NONE	7°	5.26	728.5	19.17	1.60	0.25	1.87	0.35
NONE	18	5.40	1928.0	59.94	2.19	0.31	1.60	0.34
NONE	36	5.50	1340.3	33.88	3.57	0.32	1.72	0.37
Ave. 18"-36" levels		5.45	1634.2	46.91	2.38	0.32	1.66	0.36
AVE. ALL 18" LEVELS		5.67	1852.5	52.03	2.17	0.32	1.50	0.32
AVE. ALL 36" LEVELS		5.71	1152.4	34.62	2.71	0.32	1.67	0.34

* All cans fertilized uniformly with 1200 lbs. per A. of 3-9-18 fertilizer containing 60 lbs. per A. of $CuSO_4$; S is sulfur, L is pulverized limestone.

° 6 in. level could not be maintained; values given are approximate.



6" | 7" | 7"

18" | 18" | 18"

36" | 36" | 36"

Lime 5000 pounds per acre | No lime or sulfur | Sulfur 1000 pounds per acre

PLATE II.

Effects of lime and sulfur soil applications on onion growth at different soil water levels. All received uniform fertilization. College muck (1932) that excessive as well as poor drainage is likely to decrease yeilds.

On the soil of 18" water level the onions gave good growth over a considerable range of acidity, the best three yields being at pH 5.84, pH 6.64, and pH 5.40 respectively.

The onions showed distinct differences in appearance due to the different soil water levels. Those grown on the soil having a high water table were small, had a very dark brown color, a sickly appearance, and large lateral-running roots. Their growth was arrested at an early stage, altho most of them managed to survive until harvested. The soil of 18" water level yielded the quality onions thruout. They were of good size, on the whole, and of excellent yellow-brown color. The onions from the 36" water-level cans were smaller than those from the 18" water-level cans and of a lighter color.

Nitrogen content of the onion bulbs correlated excellently with water level in the soil, the bulbs from the 36" water-level cans being quite uniformly higher in nitrogen than those from the 18" water-level cans, which were, in turn, higher than those from the cans of high water level. Since onion color also correlated with soil water level it is possible that differences in onion color were due to differences in nitrogen content of the bulbs. This is in agreement with the results of the analyses of the onions from the alkaline muck in Experiment 1 (table 13) wherein the onions from the soil receiving sulfur and fertilizer treatment were lower in nitrogen than were the poorer colored bulbs from the untreated muck.

The results from the potassium determinations show that potassium content of the bulbs correlated very closely with total yield, decreasing in every case, save one, with increase in yield. This was true regardless of lime or sulfur treatment. The calcium content of the bulbs was fairly constant thruout, while phosphorus content showed a tendency to increase with increase in water table depth when sulfur alone was applied to the soil, but to decrease when lime was applied alone or in combination with sulfur. Sugar determinations were made on the onions but as the method employed was subsequently found to be in error the results are not presented.

Celery Yield and Growth. The celery yields are presented in table 25. It is at once apparent, from the large increases in yield due to the application of nitrate about six weeks before harvesting, that the absence of sufficient nitrate may have prevented proper response of the celery to the sulfur and lime soil treatments.

Some important differences in celery growth due to differences in soil water level were noted. When the

Table 25

Influence of height of water table on the effects of sulfur and lime on yield of celery - College Muck (1932)

Can No.	Reaction Treatment x	H_2O Level (in.)	Celery Yield Total (gms.)	Celery Yield Per Plant (gms.)	% Increase per plant from $NaNO_3$ addition
1	L 5000	6	204.1	34.02	
5	L 5000 o	12*	385.6	64.27	88.92 t
6	L 5000	18	567.0	94.50	
2	L 5000 o	18	907.2	151.20	60.00
3	L 5000	36	317.5	79.38	
7	L 5000 o	36	612.4	122.48	54.30
13	L10000	12*	385.6	64.27	
17	L10000 o	12*	567.1	94.52	47.07
18	L10000	18	589.7	98.28	
14	L10000 o	18	861.8	143.63	46.14
15	L10000	36	362.9	60.48	
19	L10000 o	36	363.0	90.75	50.05
12	S500	6	68.0	11.33	
31	S500 o	9*	294.8	49.13	333.62 t
11	S500	18	567.0	94.50	
30	S500 o	18	862.0	143.67	52.03
29	S500	36	544.3	90.72	
10	S500 o	36	1247.4	207.90	129.17
25	S1000	7*	136.2	22.70	
34	S1000 o	7*	453.6	75.60	233.04
36	S1000	18	453.8	75.63	
26	S1000 o	18	975.2	162.53	114.90
27	S1000	36	839.2	139.87	
33	S1000 o	36	1043.2	208.66	49.18
28	L10000 S1000	6	68.1	11.35	
24	L10000 S1000 o	6	136.1	22.68	99.82
32	L10000 S1000	18	703.1	140.62	
22	L10000 S1000 o	18	1111.3	185.62	32.00
20	L10000 S1000	36	568.2	94.70	
21	L10000 S1000 o	36	929.9	154.98	63.65
23	None	7	272.2	45.37	
8	None	18*	997.9	166.37	266.70 t
4	None	18	725.8	120.97	
35	None	18	998.0	166.33	37.50
9	None	36	725.8	181.45	
16	None	36	521.6	86.93	—108.73

x All cans fertilized uniformly with 1200# per A. of 3-9-18 fertilizer containing 60 lbs. of $CuSO_4$ per acre. , S is sulfur, L is pulverized limestone.

o 300# per A. of $NaNO_3$ added to celery August 29, 1932.

* 6 in. level could not be maintained. Values given are approximate.

t due in part to differences in water level height.

plants were first set out those at the highest water levels made the best growth followed in order by those at the 18" and 36" levels. Gradually this relationship changed, the plants in the 6" water-level cans beginning to yellow and those in the 18" cans rapidly overtaking and surpassing them in growth. Toward the latter part of the summer the plants in the 18" water-level cans in turn ceased rapid growth and began to yellow, while the very dark green, tho smaller, plants in the low water-level cans began to gain on them. At this stage the $NaNO_3$ treatment was made to the soil in one set of the cans, as previously noted.

The yields with respect to water level and soil treatment were somewhat variable, being highest, generally, in the cans with an 18" water level except in those to which sulfur was applied. In general, the application of sulfur to muck soil in these studies resulted in decreased nitrification. Since nitrification in a muck soil is confined to the amount of muck above the water level ( ) it is probable that the celery with the 36" soil water level actually had a greater total amount of available nitrate than did that with the higher water levels. This is further indicated by the onion analyses (table 24) and by the celery color differences already mentioned. With a satisfactory supply of nitrogen to balance the increased supply of phosphorus, potassium and calcium resulting from the sulfur applications, the plants were able to make a more gradual growth, with the late application of nitrate serving as a final impetus in late growth. Without the application of nitrate the plants, during their late growth in cool weather, were apparently unable to utilize the excess of mineral nutrients made available by the sulfur applications. Without the nitrate application the effect of the light sulfur application was to decrease the celery yields to 78 and 75 per cent of those secured without sulfur for the 18" and 36" water levels, respectively. The heavy sulfur applications produced 63 and 116 per cent yields for the 18" and 36" water levels, respectively, as compared with the same water levels without sulfur. The nitrate analyses from samples taken June 16 at a depth of 2-3 ins. probably were no measure of the total available nitrate, especially in the cans of 36" water level, with their dry surface layers. It is unfortunate that additional nitrate determinations were not made in later growth and at different depths.

Depressing effects on the yield of celery were evident with both the lighter and heavier lime applications. Comparing the averages from the cans having the same lime application and the same water level, it is evident that the greater depressions resulting from the lime occured in the cans with the 36" water level. With the 5000 and 10000-lb. per acre lime applications, the yields with the 18" water level averaged 85 and 84 per cent, respectively, of the yields from the cans having the same water level but no lime, while with the 36" water level they averaged 74 and 58 per cent. The yields from the muck receiving sulfur in addition to the lime were increased over those redeiving the lime alone by averages of 125 and 206 per cent for the 18" and 36" water levels, respectively.

(Second Year)

A survey of the results of the first year's work with different soil water levels showed it desirable to continue the experiment for another year for the following reasons: (1) the 6" water level was not accurately maintained in all cases, (2) the sugar determinations of the onions were not satisfactory, and (3) sufficient lime was not applied to the soil to give as wide differences in soil reaction in the various cans as was desired. It also seemed desirable to include other crops in the study.

Plan and Procedure.

The upper 6 ins. of soil were removed from each can, fertilized with 1200 lbs. per acre of 3-9-18 fertilizer containing the equivalent of a 60-lb. per acre application of $CuSO_4$, and returned to the can. In addition, all cans previously receiving lime were given another lime treatment identical with the one given the previous season. The pipes to the cans in which it had been found impossible to maintain the 6" water level were put in order, so that this difficulty was eliminated. The duplicate cans were divided into two series, as they had been upon addition of nitrate to the celery the season before, table beets and celery being grown in the set of cans which had received the extra nitrate and onions, carrots, and parsnips being grown in the other set.

The lime applications were made May 22 (1933). The cans to be seeded to onions, carrots, and parsnips were fertilized on the same date. Onions and parsnips were seeded May 28. The soil of the celery-beet cans was fertilized June 20. Carrots were seeded June 21; beets, June 23; and the celery set, June 30. The water tables were adjusted July 10. Each crop was thinned to a uniform number of plants per can, but due to various causes the numbers were not uniform at time of harvesting. An application of 300 lbs. per acre of $NaNO_3$ in solution was added to the celery following removal of the beets. The harvesting dates of the various crops were: beets, Aug. 3; onions, Oct. 7; carrots and parsnips, Oct. 11;

and celery, Oct. 20. Samples of the beets, onions, and carrots were preserved in alcohol for sugar analysis.

Presentation of Results

The best beet yields (table 26) were obtained in the cans whose soil received the heavy lime-heavy sulfur treatment and had 18" and 6" water levels (pH 6.58 and pH 6.70, respectively). The beets from these cans likewise gave the most narrow ratio between the weights of their tops and roots. Very good yields were also obtained on the untreated soil and on that receiving the 10000-lb. lime application, ranging in pH from 5.90 to 6.76. The heaviest lime treatment, 20000 lbs., seemed too much, especially with the high water level, when not accompanied by sulfur. With the heavy sulfur application added to the heavy lime, the depressive effects of the latter were entirely overcome. Both light and heavy sulfur applications alone gave a decided decrease in yields regardless of water level. From these results it would seem that this variety of beet (Detroit Dark Red) can stand relatively wet conditions in the soil if other factors are favorable.

The celery seemed to be affected more, in most cases, by the high water table than were the beets. As before, despite a nitrate application, the celery in the high

Table 26

Influence of height of water table on the effects of sulfur and lime soil treatments on yield of beets and celery - College muck (1933)

Treatment* (lbs. per A.)	Water Level ins.	pH	Beets			Celery	
			Total Roots gms.	Per Root gms.	Ratio Tops/ Roots	Total Weight gms.	Per Plant gms.
L10000	6	6.76	201.3	15.49	2.78	606	67.33
L10000	18	6.50	236.7	23.67	2.79	1010	112.22
L10000	36	6.70	234.9	19.58	2.56	820	82.00
Ave.		6.65	224.3	19.58	2.71	812	87.18
L20000	6	6.90	37.6	3.14	7.75	367	36.70
L20000	18	6.92	192.6	19.26	2.84	1255	114.09
L20000	36	6.76	220.3	20.03	2.99	879	109.88
Ave.		6.86	150.2	14.10	4.53	834	86.89
S500	6	5.87	4.6	0.46	6.17	268	26.80
S500	18	5.46	94.3	7.86	4.73	945	94.50
S500	36	5.61	86.3	9.59	4.52	1000	125.00
Ave.		5.65	61.7	5.97	5.14	738	82.10
S1000	6	5.34	47.1	3.14	5.76	249	24.90
S1000	18	5.10	114.5	9.54	3.73	803	89.22
S1000	36	5.44	78.2	4.89	5.33	577	96.17
Ave.		5.29	79.9	5.86	4.94	543	70.10
L20000 S1000	6	6.70	340.0	28.33	2.18	792	72.00
L20000 S1000	18	6.58	375.7	34.15	2.14	1346	103.54
L20000 S1000	36	6.57	168.5	15.32	3.52	1130	125.55
Ave.		6.62	294.7	25.93	2.61	1089	100.36
NONE	6	5.90	207.7	17.31	2.91	309	30.90
NONE	18	5.94	246.2	16.41	3.30	612	61.20
NONE	36	5.70	210.9	16.22	3.46	809	269.67
Ave.		5.85	221.6	16.65	3.22	577	120.59
AVE. ALL 6 IN. LEVELS		6.25	139.7	11.31	4.59	432	42.93
AVE. ALL 18" LEVELS		6.08	210.0	18.48	3.26	995	95.80
AVE. ALL 36" LEVELS		6.13	166.5	14.27	3.73	869	134.71

* All cans fertilized uniformly with 1200 lbs. per A. of 3-9-18 fertilizer containing 60 lbs. per A. of $CuSO_4$; S is sulfur, L is purverized limestone.

water-level cans showed considerable yellowing, it becoming worse as the season advanced; thus no very satisfactory yields were obtained at the higher water levels. As in the previous season, the celery yields were somewhat inconsistent with respect to sulfur and lime treatment of the soil. In general, the less acid soil gave the best celery.

Table 27 gives the yields of onions, carrots, and parsnips. The relative yields of onions in the various cans agreed fairly well with those of the previous season, altho that from the sulfured soil was somewhat higher in proportion to the others. This might be expected inasmuch as the season was not so dry as before, and one of the effects of sulfur is to hasten maturity; also, the soil pH in these cans had increased somewhat during the growing of the previous crop. The onions seemed to be less affected by the lime or sulfur treatment than were the beets. The low yields of onions secured with the 6" water level on the limed soil substantiates Harmer's contention (   ) that a poorly drained muck with an alkaline reaction is almost certain to produce an onion crop failure. The carrots and parsnips were also very severely injured by the 6" water table, especially on the heavily limed soil. The main tap roots of the plants which did manage to survive the excess moisture were covered with a large number of very

Table 27

Influence of height of water table on the effects of sulfur and lime on yields of onions, carrots, and parsnips - College muck (1933).

Treatment* (lbs. per A.)	Water Level ins.	pH	Onions Total gms.	Onions Per Onion gms.	Carrots Total gms.	Carrots Per Carrot gms.	Parsnips Total gms.	Parsnips Per Parsnip gms.
L10000	6	6.46	109.8	4.58	79.2	15.84	33.4	6.68
L10000	18	6.72	1647.4	49.92	263.5	43.92	312.5	62.50
L10000	36	6.60	1221.0	29.78	426.2	42.62	365.0	24.33
Ave.		6.59	992.7	28.09	256.3	34.13	236.9	31.17
L20000	6	6.97	121.5	4.50	1.5	0.50	0.0	0.00
L20000	18	6.97	1703.5	38.72	690.5	86.31	349.8	69.96
L20000	36	6.92	1413.5	32.87	230.5	19.21	447.5	49.72
Ave.		6.95	1079.5	25.36	307.5	35.34	265.8	39.89
S500	6	5.87	788.6	18.78	32.1	4.59	62.3	10.38
S500	18	5.46	1976.0	53.41	467.1	58.39	213.1	26.64
S500	36	5.38	1231.7	32.41	330.4	30.04	379.6	47.45
Ave.		5.57	1332.1	34.87	276.5	31.01	218.3	28.16
S1000	6	5.28	168.7	8.44	224.8	22.48	16.2	4.05
S1000	18	5.07	1460.2	40.56	247.1	30.89	223.2	44.64
S1000	36	5.14	1649.0	36.64	253.1	23.01	322.0	40.25
Ave.		5.16	1092.6	28.55	241.7	25.46	187.1	29.65
L20000 S1000	6	6.57	728.0	25.10	38.4	6.40	1.5	0.75
L20000 S1000	18	6.67	971.5	28.57	780.8	86.76	403.5	80.70
L20000 S1000	36	6.67	971.2	22.59	568.6	47.39	444.5	29.63
Ave.		6.64	890.2	25.42	462.6	46.85	283.2	37.03
NONE	6	5.83	1444.2	36.11	28.4	14.20	46.6	5.82
NONE	18	5.99	1888.5	38.54	275.9	55.18	228.7	28.59
NONE	36	5.74	1420.7	33.83	439.0	43.90	234.3	33.47
Ave.		5.85	1584.5	28.27	247.8	37.76	169.9	22.63
AVE ALL 6" LEVELS		6.16	560.1	16.25	67.4	10.67	26.7	4.61
AVE ALL 18"LEVELS		6.15	1607.9	41.62	454.2	60.24	288.5	52.17
AVE ALL 36"LEVELS		6.08	1317.9	31.35	374.6	34.22	365.5	37.48

* All cans fertilized uniformly with 1200 lbs. per A. of 3-9-18 fertilizer containing 60 lbs. per A. of $CuSO_4$.
S is sulfur; L is pulverized limestone.

fine roots and, in addition, the tap roots of the parsnips were much branched. The best yields of carrots were obtained in the soil having an 18" water level and receiving the heavy lime-heavy sulfur treatment (pH 6.67). The parsnips gave the best yields in the soils having a 36" water level, but under these conditions the tap roots were very much elongated.

Sugar Content of Beets, Onions, and Carrots.

The results of the sugar analyses of the beets, onions, and carrots are presented in table 28. Comparison of the sugar content of the beets with the soil treatments and beet yields reveals that the best beets ran somewhat higher in sugar content. With the onions the differences were more marked. Sugar content was found to correlate very closely with onion size and was, therefore, highest in the onions from the 18" water-level cans thruout. Correlation between sugar content and onion size was not obtained in the supplementary studies of Experiment 1, in which increased size of onion was obtained by means of sulfur applications on alkaline muck or lime applications on acid muck. In this experiment, there seemed to be a definite decrease in both reducing and non-reducing sugars resulting from lime application with the 6" water level. The sulfur treatments appear to have slightly decreased the content of reducing sugars in the onions, while the heavy sulfur treatment increased

Table 28

Influence of height of water table on the effects of sulfur and lime on sugar content of beets, onions, and carrots - College muck (1933)

Treatment* (lbs. per A.)	Water Level ins.	Sugar Content°								
		Beets			Onions			Carrots		
		Reducing	non-red.	Total	Reducing	non-red.	Total	Reducing	non-red.	Total
		%	%	%	%	%	%	%	%	%
L 10000	6	0.04	4.46	4.50	3.15	3.03	6.18	3.05	2.81	5.86
L 10000	18	0.05	4.31	4.36	3.62	5.11	8.73	4.15	3.72	7.87
L 10000	36	0.04	3.89	3.93	3.42	3.79	7.21	2.59	3.35	5.94
Ave.		0.04	4.22	4.26	3.40	3.98	7.37	3.26	3.29	6.56
L 20000	6	0.04	3.00	3.04	3.21	2.05	5.26	--	--	--
L 20000	18	0.04	3.44	3.48	3.50	4.57	8.07	3.72	2.42	6.14
L 20000	36	0.04	3.94	3.98	3.72	3.23	6.95	3.72	2.26	5.98
Ave.		0.04	3.46	3.49	3.48	3.28	6.76	3.72	2.34	6.06
S 500	6	--	--	--	3.99	3.52	7.51	5.15	2.55	7.70
S 500	18	0.00	3.52	3.52	3.62	4.48	8.10	2.94	3.11	6.05
S 500	36	0.04	3.96	4.00	3.48	3.68	7.16	3.62	2.45	6.07
Ave.		0.02	3.74	3.76	3.70	3.89	7.59	3.93	2.70	6.61
S 1000	6	0.04	4.26	4.30	3.52	4.28	7.80	2.88	2.72	5.60
S 1000	18	0.00	4.14	4.14	3.57	4.50	8.07	4.79	2.47	7.26
S 1000	36	--	--	--	3.36	4.69	8.05	3.53	2.83	6.36
Ave.		0.02	4.20	4.22	3.48	4.49	7.97	3.73	2.67	6.41
L 20000 S 1000	6	0.00	4.91	4.91	3.40	4.02	7.42	4.09	3.32	7.41
L20000 S 1000	18	0.00	4.07	4.07	3.57	4.53	8.10	3.51	3.92	7.43
L 20000 S 1000	36	0.00	4.18	4.18	3.86	4.06	7.92	3.68	2.48	6.16
Ave.		0.00	4.39	4.39	3.61	4.20	7.81	3.76	3.24	7.00
NONE	6	0.05	4.02	4.07	4.06	3.90	7.96	4.68	2.36	7.04
NONE	18	0.04	4.60	4.64	3.74	4.21	7.95	3.64	2.34	5.98
NONE	36	0.04	4.38	4.38	3.84	3.78	7.62	3.25	2.89	6.14
Ave.		0.04	4.33	4.36	3.88	3.96	7.84	3.86	2.53	6.39
AVE. ALL 6 IN LEVELS		0.03	4.13	4.16	3.55	3.47	7.02	3.97	2.75	6.72
AVE. ALL 18 " LEVELS		0.02	4.01	4.03	3.60	4.57	8.17	3.79	3.00	6.79
AVE. ALL 36 " LEVELS		0.03	4.07	4.10	3.61	3.87	7.48	3.40	2.71	6.11

*All cans fertilized uniformly with 1200 lbs. per A. of 3-9-18 fertilizer containing 60 lbs. per A. of $CuSO_4$.

°Calculated as per cent dextrose.

the non-reducing sugars.

While a considerable variation in sugar content was found in the carrots, no consistent differences appeared. A possible explanation for the irregularity of the carrot results lies in the fact that two varieties, the Danver's Half-long and the Oxheart, were used in each can for purposes of comparison with reference to root branching at the 6" water level. In several of the cans, especially those whose soil had a high water level, good growth of both varieties was not secured, so that it was impossible to sample from one variety exclusively thruout the series; hence, differences in sugar content might be attributable, in part, to varietal differences, thereby rendering the results unsuitable for the comparisons intended.

From the foregoing results it appears that sugar content is not a satisfactory criterion for measurement of quality in the crops studied, in so far as quality may have been raised or lowered as a result of changes in the soil reaction or moisture supply.

SUMMARY AND CONCLUSIONS

This investigation consisted of field, greenhouse, and lysimeter studies dealing with the relationships existing between soil reaction and solubility of plant nutrient materials in muck soils, and the chemical composition and quality of some typical muck crops grown on these soils. The method of attack was as follows:

1. Sulfur and lime additions were made to a slightly acid, high-lime muck in the field. Their effects on soil reaction and on the water-solubility of fertilizer nutrients were studied by means of dialysis of samples taken at two-week intervals from the 2-3 in. soil depth, thruout the growing season. Their effects on the mineral and sugar content of the crops grown were also investigated. Similar crop studies were made on certain muck crops grown on typical alkaline and very strongly acid muck soils treated with sulfur and lime, respectively.

2. Greenhouse investigations were conducted in which the changes in soil pH, nutrient solubility, and in plant growth resulting from applications of sulfur, HCl, HNO_3, H_2SO_4, $(COOH)_2 \cdot 2H_2O$, $Al_2(SO_4)_3$, and lime to certain alkaline or strongly acid soils were compared, as well as those resulting from mixing alkaline and very strongly acid muck in different proportions.

3. The influence of moisture supply, as measured by depth of water level, on the effects of sulfur and lime additions to the soil on soil pH, nutrient solubility, and crop composition was investigated.

The following conclusions seem warranted by the foregoing experiments:

(1) The addition of sulfur to fertilized muck soils results in an increase in soil acidity, a large increase in soluble calcium content, a slight increase in potassium solubility, a frequent decrease in nitrification and, if added in sufficient quantity to produce a fairly acid reaction, a large increase in phosphate solubility.

(2) The addition of lime in sufficient amounts to fertilized muck soils results in a decrease in soil acidity, a decrease in phosphate solubility, an increase in soluble calcium content, and, if the muck is strongly acid, an increase in nitrification.

(3) The degree of solubility of the various nutrients at the 2-3 in. soil depth is also influenced by water relationships such as precipitation and height of water table. Soil reaction appears not to be appreciably affected by moisture supply.

(4) Phosphate solubility in muck soils is greatly influenced by soil reaction, being much higher under acid conditions, especially below a pH of 6.0-6.2. On the other hand, calcium solubility is entirely indepen-

dent of soil reaction, being governed instead by the amount of calcium present and THE acid radical with which it is associated.

(5) HCl and HNO_3 exert, in the soil, effects similar to those of sulfur or H_2SO_4 on soil reaction and on the solubility of calcium, potassium, and phosphate. Their effect on spinach growth is much different, however, germination being a great deal slower and later growth more rapid.

(6) Acidity resulting from addition of strongly acid muck to alkaline muck does not result in a large increase in calcium solubility, as happens when chemical treatment is used to produce acidity. Phosphate solubility, however, increases consistently with each addition of strongly acid muck.

(7) Oxalic acid and aluminum sulfate were found to be unsatisfactory materials for altering the reaction conditions of the muck soils studied.

(8) No correlation was apparent between the soluble potassium, calcium, or phosphate content in the soil and its percentage in any of the crops analyzed.

(9) Sulfur and lime applications to the soil affect the growth, mineral composition, and sugar content of certain muck crops in various degree, depending, at least in part, upon the individual soil, the water level, and the crop in question.

(10) In general, with onions, beets, and carrots, better quality may be accompanied by higher sugar content, especially with onions; however, the differences are not of sufficient magnitude that they can be utilized as a basis for measurement of differences in crop quality.

(11) There seems to be no one effect to which the benefits of sulfur or lime treatment on certain Michigan mucks can be attributed. The soil reaction changes resulting from these treatments are accompanied by many other changes in the soil. Restoration of proper soil equilibrium is apparently the most logical explanation.

LITERATURE CITED

(1) Alway, F. J. Agricultural value and reclamation of Minnesota peat soils. Minn. Agr. Exp. Sta. Bull. 188, 1920.

(2) Alway, J. and Nygard, I. J. Differentiation between acidity and lime-deficiency in the case of peat soils. Proc. First Int. Congr. Soil Sci. Com. II: 22-44, 1927.

(3) Ames, J. W. Solvent action of nitrification and sulfofication. Ohio Agr. Exp. Sta. Bull. 351, 1921.

(4) Arnd, Th. and Hoffman, W. Die Bestimmung des Reaktionszustandes von Moorböden. Zeit. Pflanze. Düng. u Bodenk. 10A: 219-232, 1918.

(5) Austin, R. H. Some reactions between mono-calcium phosphate and soils. Soil Sci. 24:263-269, 1927.

(6) Cole, Ralph C. The diurnal and seasonal changes in the sugar content of the sap and tissue of potato plants as affected by soil fertilization. Soil Sci. 33:347-362, 1932.

(7) Coles, H. G. and Morison, C. B. T. Dehydration and soil acidity. Soil Sci. 28:59-70, 1930.

(8) Doughty, J. L. The fixation of phosphate by a peat soil. Soil Sci. 28:23-35, 1930.

(9) Fleischer, M. Die Anlage und die Bewirtschaftung von Moorwiesen und Moorweiden. Auf. 2 Berlin, 1913. (Original not seen; quoted from Alway (1)).

(10) Fraps, G. S. Possibilities of sulfur as a soil amendment. Tex. Agr. Exp. Sta. Bull 414, 1930.

(11) Greenhill, A. W. The availability of phosphatic fertilisers as shown by an examination of the soil solution and of plant growth. Jour. Agr. Sci. 20: 559-572. (1930).

(12) Harmer, Paul M. The management of Michigan muck soils for the production of onions. Mich. Agr. Exp. Sta. Spec. Bull. 168, 1927.

(13) Harmer, Paul M. Muck soil management for onion production. Mich. State Coll. Ext. Bull. 123, 1932.

(14) Harmer, Paul M. Recent developments in fertilizing muck soils. Better Crops v.19, No. 6, p.5-, 1934.

(15) Harmer, Paul M. Unpublished data.

(16) Harmer, Paul M. Personal interview.

(17) Harmer, Paul M. and Weideman, A. G. Fertilization and quality of muck crops. Mich. State Coll. Expt. Sta. Quart. Bull. 8:130-134, 1926.

(18) Itano, A. and Matsura, A. Influence of sulfur on the nature of soils. Zeit. Cfr. Nr. 1138:163-170. (Original not seen; quoted from Chem. Abs.)

(19) Jenney, Hans and Shade, E. R. The potassium-lime problem in soils. Jour. Amer. Soc. Agron. 26: 162-170, 1934.

(20) Kelley, W. P. and Arany, Alexander. The chemical effect of gypsum, sulfur, iron sulfate, and alum on alkali soil. Hilgardia 3:393-420, 1928.

(21) Kelley, W. P. and Thomas, E. E. Reclamation of the Fresno type of black-alkali soil. Calif. Agr. Exp. Sta. Bull 455, 1928.

(22) Knott, J. E. Growing onions on the muck soils of New York. Cornell Agr. Exp. Sta. Bull. 510, 1930.

(23) Kramer, Benjamin and Tisdall, Frederick F. A clinical method for the quantitative determination of potassium in small amounts of serum. Jour. Biol. Chem. 46:339-349, 1921.

(24) Loehwing, W. F. Effects of lime and potash fertilizers on certain muck soils. Bot. Gaz. 80:390-409, 1925.

(25) MacIntire, W. H., Shaw, W. M., and Sanders, K. B. The influence of liming on the availability of soil potash. Jour. Amer. Soc. Agron. 19:483, 1927.

(26) MacIntire, W. H., Shaw, W. M., and Young, J. B. The repressive effect of lime and magnesia upon soil and subsoil potash. Jour. Agr. Sci. 20:499-510, 1930.

(27) McCool, M. M. and Harmer, Paul M. The muck soils of Michigan. Mich. Agr. Exp. Sta. Spec. Bull. 136, 1925.

(28) McKibbin, R. R. The effect of sulfur on soils and on crop yields. Md. Agr. Exp. Sta. Bull. 296, 1928.

(29) Methods of Analysis. The Assoc. of Official Agr. Chemists, Washington, D. D.

(30) Parker, F. W. and Fudge, J. F. Soil phosphorus studies: I Colorimetric determination of organic and inorganic phosphorus in soil extracts and the soil solution. Soil Sci. 24:109-117, 1927.

(31) Parker, F. W. and Tidmore, J. W. The influence of lime and phosphatic fertilizers on the phosphorus content of the soil solution and of soil extracts. Soil Sci. 21:425-441, 1926.

(32) Perkins, Alfred T., King, H. H., and Benne, E. J. Effect of exchangeable base and soil treatments on phosphorus solubility. Soil Sci. 34:385-392, 1932.

(33) Pierre, W. H. and Parker, F. W. The use of collodion sacks in obtaining clear soil extracts for the determination of the water-soluble constituents. Soil Sci. 23:13-32, 1927.

(34) Pierre, W. H. and Parker, F. W. The use of collodion sacks in soil investigations. Proc. First Int. Congr. Soil Sci. Com.II:396-406, 1927.

(35) Plice, M. J. The determination of nitrates in soils containing soluble organic matter. Soil Sci. 33: 213-215, 1932.

(36) Powers, Wilbur L. Studies of sulfur in relation to the soil solution. Univ. Calif. Pubs. in Agr. Sci. 5:119-166, 1927.

(37) Puchner, H. Hysteresis bei Wässerigere Torfauscheidungen. Kolloid Zeit. 25:196-207; 26:159-168, 1919, 1920.

(38) Robinson, R. H. and Bullis, D. E. Acid soil studies: III The influence of calcium carbonate, calcium oxide, and calcium sulfate on the soluble soil nutrients of acid soils. Soil Sci. 13:449-459, 1922.

(39) Roux, E. The fertilizer action of sulfur. Recent experiments of the Institute of Agronomic Research. Compt. rend. Acad. Agr. France 14:616-621, 1928. (Original not seen; quoted from Chem. Abs. 23: 3769, 1929.)

(40) Samuels, Charles Danziger. The oxidation of sulfur in alkali soil and its effect on the replaceable bases. Hilgardia 3:1-26, 1927.

(41) Sayre, C. B., Willaman, J. J., and Kertesz, Z. I. Factors affecting the quality of commercial canning peas. N. Y. (Geneva) Agr. Exp. Sta. Tech. Bull. 176, 1931.

(42) Shaffer, P. A. and Hartman, A. F. The iodometric determination of copper and its use in sugar analysis. Jour. Biol. Chem. 45:349-390, 1921.

(43) Shedd, O. M. Influence of sulfur and gypsum on the solubility of potassium in soils and on the quantity of this element removed by certain plants. Soil Sci. 22:335-354, 1926.

(44) Spurway, C. H. The effect of the nature of the exchangeable bases upon the retention of anions by soils. Jour. Amer. Soc. Agron. 18:497-505, 1926.

(45) Spurway, C. H. Soil testing. A practical system of soil diagnosis. Mich. Agr. Exp. Sta. Tech. Bull. 132, 1933.

(46) Stevenson, R. E. and Powers, W. L. Influence of sulfur oxidation on solubility of soil minerals. Soil Sci. 18:317-321, 1924.

(47) Tacke, Br. Das Kalkbedürfnis kalkarmer Moorböden. Zeit. pflanze. Düng. u. Bodenk. 9B:216-234, 1930.

(48) Tait, G. M. and Knott, J. E. Correcting the unproductiveness of acid and alkaline muck soils for the growing of vegetable crops. Cornell Agr. Exp. Sta. Bull. 572, 1933.

(49) Wilson, B. D., Staker, E. V., and Townsend, G. R. Reaction and calcium content of drainage water from peat deposits in New York. Jour. Amer. Soc. Agron. 24:589-593, 1932.

(50) Wilson, B. D. and Townsend, G. R. Some nitrogen relationships in muck soils. Cornell Agr. Exp. Sta. Memoir 137, 1931.