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RELATION OF SOIL ACIDITY TO COTTON ROOT ROT

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Cotton plants grown in containers of soils varying naturally in hydrogen-ion concentration (a measure of soil acidity) were inoculated with cotton root rot. Incidence of root rot following inoculation, later spread of the disease, and overwintering to following years, were all greater in the more alkaline soils and less in the more acid soils.

Soil materials were adjusted artificially toward acidity by additions of sulphur, sulphuric acid, calcium sulphate, or ammonium sulphate, or toward alkalinity by additions of lime or sodium carbonate. In general, the soils made acid were found to be unfavorable, and the soils made alkaline were found to be favorable, for the disease. The hydrogen-ion concentration of the surface soil seemed of particular importance. A six to twelve-inch surface layer of acid soil caused immediate or final disappearance of root rot, while acidification of the deeper soil, with the surface layer left alkaline, did not eradicate the disease.

Sulphur mixed into soil in field plats reduced the percentage of root rot on cotton plants but did not eradicate it. Sulphur applied in the surface soil finally made the soil acid to depths of more than two feet. The acidity or alkalinity of the surface soil apparently was of special importance in these experiments also. It is impracticable to acidify calcareous soils, and application of soil acidification for control of root rot in other soils is still in the experimental stage.

The experiments summarized in this Bulletin have shown that soils originally acid or made acid by additions of various chemicals are less suitable for infection of plants by the root-rot fungus, and less suitable for continued survival of the fungus from year to year, than are soils originally neutral to alkaline or made so by chemical additions. Unsuitability of acid soils to the root-rot fungus is not necessarily due directly to the hydrogen-ion concentration, but is associated closely with this factor.

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RELATION OF SOIL ACIDITY TO COTTON ROOT ROT

By J. J. Taubenhaus, Chief, and W. N. Ezekiel, Plant Pathologist, Division of Plant Pathology and Physiology; and J. F. Fudge, Assistant Chemist, Division of Chemistry*

The root-rot disease, caused by the fungus *Phymatotrichum omnivorum* (Shear) Duggar, attacks a large proportion of the different kinds of cultivated plants, causing enormous losses not only of field crops grown in Texas and elsewhere in the Southwest but also of orchard trees, ornamental shrubs, and shade trees. For several years, studies have been made on the possible relation of the acid or basic reaction of the soil to Phymatotrichum root rot. Some results of these studies have been published (14, 5). It is the purpose of this Bulletin to present, in brief form, the results of a number of experiments, and to summarize our present knowledge of this important factor as it affects the distribution and prevalence of root rot.

DISTRIBUTION OF PHYMATOTRICHUM ROOT ROT IN TEXAS AS RELATED TO DIFFERENCES IN SOIL ACIDITY

Root rot is much more prevalent in the heavier soils of Central, South, and Western Texas and is less common in the generally lighter soils of East Texas (4). In 1925 and 1926, a survey was made of a number of cotton fields, and composite samples of the upper three inches of soil were taken from each field (17). Root rot was found throughout the range of soils included in this survey—in one of the most acid fields, of pH 5.5, and in the most alkaline, of pH 8.6. However, the percentage of fields with root rot in the neutral to alkaline soils (pH 6.5 to 8.6) was twice that in the acid soils (pH 5.5 to 6.4). Considering the severity rather than merely the presence or absence of root rot, a marked relation of pH to root rot was evident. While the disease was present in a field of which the surface soil had a pH of 5.5, there was only a trace of the disease in this field. In five cases of root rot on soils of pH 5.9, three were only traces. All five fields with root rot at pH 6.0 had only a trace of the disease. All five cases from pH 6.1 to 6.3 were recorded as traces. It was only with soil of pH of 6.5 or higher that the disease was found in destructive abundance. In 10 fields with root rot, selected at random from those between pH 7.1 and 7.9, only two were recorded as having less than 1 per cent of root rot, five had between 10 and 20 per cent, and the other three had from 20 to 70 per cent.

Root rot was thus not only of more frequent occurrence on soils of pH 7.0 to 8.0 than on soils of pH 5.5 to 6.5, but also it was more often of destructive abundance when present on neutral to alkaline soils than when present on acid soils.

Dawson and Collins (3) have reported similarly that heavily infested areas are calcareous and alkaline (pH 7-8.3), while root rot is less prevalent or absent in non-calcareous soil of neutral or slightly acid

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reaction (down to pH 6.0). In later studies (1) it was concluded that while there was this general correlation of prevalence of root rot with pH and calcium carbonate content of the soil, this did not apply within a given soil type of Texas Blackland soils. This was presumably because such soils are almost uniformly favorable for root rot insofar as determined by the soil reaction.

EXPERIMENTS ON THE GENERAL RELATION OF SOIL REACTION TO PREVALENCE AND DESTRUCTIVENESS OF ROOT ROT

The results of the field survey indicated that Phymatotrichum root rot is relatively less destructive in somewhat acid soils than in alkaline soils. It was still necessary to determine whether this was due actually to differences in the soils, or whether it might not have resulted from climatic or regional influences. In order to study this, a variety of experiments has been carried out under partially controlled conditions, usually in containers of various sorts exposed to natural weather conditions. Soils naturally varying in acidity have been transported to College Station and installed side by side in containers. In other experiments, soils have been adjusted toward acidity or alkalinity as desired. In attempts to determine the ions involved in the relation, soils have been made acid with sulphur, sulphuric acid, calcium sulphate, and ammonium sulphate, or made alkaline with lime or sodium carbonate. In some of the experiments the depth to which soil has been acidified has been made a variable.

Comparison of Soils of Naturally Differing Acidity

In this experiment, soil material of seven different types was transported to College Station and placed in long wooden boxes, 12 feet long, 2 feet wide, and 3 feet deep. Each soil was dug to a depth of three feet. Each six-inch layer was sacked separately, and each layer replaced at its original depth in the boxes. Cotton was planted in a row along the middle of each box from 1928 through 1932. During 1928 root rot was introduced at one end of each box, by repeated artificial inoculation with naturally-infected cotton roots (13).

Results for this experiment are given in Table 1. The best relation of root rot to the soil reaction appeared in the initial spread of root rot, following inoculation in 1928. Spread was successively greater with soils of higher pH values. Only one of the inoculated plants succumbed in the Susquehanna soil with pH 5.5, and not one plant in the Tabor soil with pH 5.8, while most of the plants succumbed in the two boxes of more alkaline soils.

In 1929, root rot reappeared in each box in which it had caused any infection the preceding year, and attacked a higher percentage of plants than in 1928. However, a large amount of inoculum added to each box in October, 1928, furnished additional material for possible overwintering. The ability of root rot to survive in these various soils was shown better by the results during the next three years, when its reappearance depended solely on successful overwintering.

With the cessation of inoculation, root rot disappeared from the acid Susquehanna fine sandy loam, and did not appear again during the period of the experiment. No root rot was found at any time in the shallow phase of Tabor fine sandy loam, which became as acid as the Susquehanna soil. The Ochlockonee clay loam, which varied from pH 6.3 to 5.9, supported root rot for only three years, and none occurred after 1930. In the next three soils, varying from about neutrality to slight alkalinity, root rot survived for the period of the experiment.

Special explanation seems necessary for the results in the Houston black clay. This soil was consistently the most alkaline one in the experiment, and it is a type on which root rot is highly destructive in the field. Yet after causing complete loss in this box in 1929, and 93% loss in 1930, root rot did not show up in 1931 and 1932. This is to be interpreted not as resulting from unsuitability of the soil for the fungus, but rather from the fact that the Houston soil was "too favorable" for the fungus, and caused a natural periodicity of root rot such as occurs also under field conditions with soils of the Houston series. As the writers have discussed previously (14), the periodic cumulative increases of root rot in such highly favorable soils, usually followed then by abrupt decreases for several years, may be explained as follows: When many plants become infected and the roots decay early in the season, with resultant death of the vegetative strands on these roots, there are relatively few undecayed portions of roots left on which the fungus can overwinter in a vegetative condition.

Table 1. Spread and survival of root rot on cotton plants growing in soils differing naturally in acidity.

Soil type	Source of soils, county	pH of soil, 0-2 feet deep			Spread of root rot along rows during 1928, feet	Total percentages of plants infected				
		1928	1929	1931		1928	1929	1930	1931	1932
Susquehanna fine sandy loam, shallow phase	Brazos	5.5	5.6	5.2	0	2	8	0	0	0
Tabor fine sandy loam, shallow phase	Robertson	5.8	5.7	5.2	0	0	0	0	0	0
Ochlockonee clay loam	Brazos	6.3	5.9	6.3	4	27	59	20	0	0
Tabor fine sandy loam	Brazos	6.7	7.0	7.7	4	29	34	0	20	30
Kirvin fine sandy loam	Brazos	7.1	7.1	7.3	5½	30	80	44	32	55
Caddo fine sandy loam	Robertson	7.6	7.5	7.8	7½	53	82	31	16	19
Houston black clay	Bell	7.7	7.6	8.1	7½	74	100	93	0	0

Such a sequence of events apparently took place in the box of Houston soil in this experiment. Root rot attacked 93% of the plants by the time notes were taken in the fall of 1930, and presumably "ate itself out" on the few remaining roots before the following season. Under field conditions, root rot would not be entirely eliminated, but it is possible that in the small portion of soil present in the box there happened to be neither living vegetative material nor living sclerotia at this time to carry the fungus along. It is, of course, possible that the fungus may have been present in a dormant condition and merely have failed to cause infection during 1931 and 1932.

Taken together, the results of this experiment showed a close relation of pH of the soil with extent of spread of root rot in the boxes, and close relation also of pH to the percentage of original incidence of root rot following inoculation and to the overwintering (with the exception of the Houston soil as explained above). As in other experiments, root rot could be started even in the more acid soils, but did not survive for many years, even in the marginal Ochlockonee soil.

Preliminary Experiment with Lufkin Fine Sandy Loam Soil Adjusted by Various Additions

An experiment was set up in 1927 in a series of 120 earthenware cylinders (drain tiles), each 2 feet deep and 18 inches in diameter. These were sunk upright in the ground, nearly to the ground level, and filled with Lufkin fine sandy loam soil material. Various materials specified in Table 2 were worked into the surface soil to a depth of four to six inches. These applications were made partly in 1927 and partly early in the spring of 1928, but the entire amounts had been applied before cotton was planted in 1928. Six cylinders were used for each set of treatments. The cotton was thinned to five plants per cylinder, making the total about 30 plants for each of the series. The plants were inoculated artificially with Phymatotrichum root rot in 1928 and again in 1929, by the method previously described (13).

It will be noted from table 2 that the pH of the soil in some of the series changed greatly in response to the treatments. This shift from neutrality was generally greater in 1928 than in 1929. In 1928, the changes were confined largely to the surface layer (about 0-8 inches) of the soil. By the end of the second year, the pH was approximately uniform in most of the cylinders to about 12 inches deep; the soil at 12 to 18 inches was usually intermediate between the pH of the upper foot and the original value; and the soil at 18-24 inches had often shifted slightly from neutrality. That is, during the second year the changes due to the treatments were less intense, but extended to greater depths.

The results are summarized by individual series in Table 2. It is to be noted that root rot was introduced successfully and killed some of the plants in all series except the one in which the extreme acidity killed all the cotton plants. A general relation of the soil acidity or alkalinity to the incidence and destructiveness of root rot is evident. Additions of pure calcium carbonate, hydrated lime, or sodium carbonate made the soil alkaline and were in general favorable to root rot. Additions of ammonium sulphate produced little change in pH and no definite changes in root rot as compared with the check. Sulphuric acid, powdered sulphur, and soda alum made the soil more acid, and reduced the incidence of root rot. Root rot overwintered in some of the containers of each series in the winters of 1927 and 1928, appearing on plants of the succeeding crop prior to the inoculation.

The correlation is more evident in Table 3, in which the different series are grouped by the pH of the soil without regard to the different treatments. The differences in pH were associated more significantly with changes in the mortality from root rot than in the incidence of the disease.

Table 2. Effect of surface applications of various materials to Lufkin fine sandy loam soil material on incidence of root rot.

Treatments, pounds per acre	Mean pH, 0-6 inches		Plants attacked by root rot, * percentages		Plants killed by root rot, percentages	
	1928	1929	1928	1929	1928	1929
Calcium carbonate, 32,000	7.8	7.6	67	55	43	39
" " 16,000	7.8	7.5	80	79	37	79
" " 4,000	7.7	7.4	97	97	61	81
Sodium carbonate, 3,000, plus calcium carbonate, 16,000	8.0	7.8	100	85	47	77
Sodium carbonate, 3,000	7.4	7.0	50	57	33	39
Sodium chloride, 2,000, plus calcium carbonate, 16,000	7.7	7.5	87	77	57	54
Hydrated lime, 4,000	7.6	7.3	80	86	40	51
None, check	7.0	6.9	73	90	27	69
Dry sheep manure, 10,000	6.9	6.7	83	31	37	6
" " " 20,000	6.9	6.7	83	61	30	36
Ammonium sulphate, 400	6.5	6.7	83	78	40	53
Sulphuric acid, 3,400	5.4	6.0	100	63	37	43
" " 4,000	5.0	6.1	77	25	40	13
" " 5,000	5.0	6.1	63	50	30	20
Soda alum, 2,000, plus sulphuric acid, 3,000	5.3	6.0	43	50	10	33
Soda alum, 8,000, plus sulphuric acid, 3,000	4.5	5.7	61	28	16	22
Sodium sulphate, 2,000, plus sulphuric acid, 5,000	5.0	6.1	47	53	13	47
Powdered sulphur, 1,000	5.4	5.9	67	49	23	27
" " 2,000	4.7	5.8	64	47	23	31
" " 10,000	2.9	3.8	†	...	...	...

*Total of plants killed by root rot and of those infected but not yet killed.
†No plants, all killed by acidity.

Table 3. Rearrangement of results in Table 2, with the series grouped by mean pH values, without regard to the treatments.

Mean pH of surface soil	1928 Results			1929 Results		
	Number of series in the soil-reaction group	Percentages of plants attacked by root rot	Percentages of plants killed by root rot	Number of series in the soil-reaction group	Percentages of plants attacked by root rot	Percentages of plants killed by root rot
7.0–8.0	8	79	43	7	77	60
6.0–6.9	3	83	36	9	56	36
5.0–5.9	6	66	26	3	41	27
4.5–4.7	2	63	20	0	..	..
2.9–3.8	1*	..	..	1*	..	..

*No plants, all killed by acidity.

Most of these cylinders were devoted after 1929 to another experiment, but five of the more acid series were continued through the seasons of 1930, 1931, 1932, and 1933, to find whether root rot would disappear. The cotton plants in these cylinders were inoculated again in 1930, but were not inoculated in 1931, 1932, or 1933. Therefore root rot appeared during these last years only as a result of overwintering successfully either in these cylinders or beneath them. As shown in Table 4, the surface layers of soil in all except the most acid series had by this time shifted back to pH 6.0 or beyond. There was a gradual decrease in percentages of plants with root rot, but this trend occurred in the series in which the soil was approaching neutrality as well as in the one that was still somewhat acid. The acidity obtained in these cylinders was evidently insufficient to prevent the incidence of root rot following inoculation, and the acidity prevailing after 1930 in these cylinders evidently could not prevent the disease from overwintering. The sole exception was the series treated with the highest rate of sulphur. No cotton plants could be grown in these cylinders during the early years of the experiment, and the plants that were grown in 1930 and later years did not succumb to root rot from the inoculations made in 1930.

In this experiment, root rot was definitely eliminated only in the one series of cylinders with a soil reaction of pH 4.2-4.4. It survived in soils adjusted by various treatments to around pH 5, and was favored by treatments that changed the reaction toward alkalinity.

Table 4. Incidence and survival of root rot in Lufkin fine sandy loam soil material plus surface applications of various materials. (Cotton plants inoculated 1928, 1929, and 1930; 6 cylinders per series.)

Treatments, pounds per acre	Mean pH of soil, 0-6 inches					Percentage plants attacked by root rot					
	Sept. 1928	Mar. 1930	Dec. 1931	Nov. 1932	Jan. 1934	1928	1929	1930	1931	1932	1933
Sodium sulphate, 2,000, plus sulphuric acid, 5,000	6.2	6.1	6.8	6.9	7.6	47	53	42	39	7	13
Sulphuric acid, 5,000	5.9	6.1	6.6	6.9	7.5	63	50	74	33	36	47
Sulphur, 1,000	5.9	6.0	6.6	6.8	7.4	67	49	53	25	22	18
Sulphur, 2,000	4.8	5.7	6.0	6.3	7.0	64	47	67	49	35	30
Sulphur, 10,000	3.2	3.8	4.4	5.0	5.5	*	*	0	0	0	0

*No plants, all killed by acidity.

Lufkin Fine Sandy Loam Soil Adjusted to Different Hydrogen-ion Concentrations with Lime, Sulphur, and Sulphuric Acid

A uniform soil was adjusted to the entire depth of the cylindric earthenware containers to fairly precise hydrogen-ion concentrations, in series providing sufficient replication to furnish reasonably large numbers of plants at each pH. Lufkin fine sandy loam surface soil material, from 0-12 inches deep only, was used. This was a brownish-gray fine sand, naturally slightly acid, of pH 6.2 to 6.3. The method developed by Fraps and Carlyle (7) was used to determine the amount of sulphuric acid needed to adjust this soil to various acidities. Additions were made directly on this basis in the sulphuric acid series, and with one and one-half times the calculated amounts in the sulphur series. Since the soil used was already slightly acid and only slightly buffered, only small additions, as indicated in Table 5, were required to develop fairly intense acidity. The sulphur, sulphuric acid, or limestone were added to weighed amounts of soil material (the additions being calculated on the air-dry soil weight) and incorporated thoroughly into the soil by mixing in a large box. The mixed soil was then placed in earthenware cylinders, 2 feet deep and 18 inches in diameter, set upright in the soil so that the tops were only two to three inches above the surface. Twelve of these

Table 5. Changes in pH of soil following additions made in April, 1930, to the entire depth of Lufkin fine sandy loam soil material in cylinders.

Series	Materials added per 100 pounds of air-dry soil	pH desired	pH obtained (mean of all cylinders, entire depth)			
			Dec. 1930	Dec. 1931	Nov. 1932	July 1933
a	250 cc., 2.83 N. H_2SO_4..............	4.0	4.8	5.0	5.2	5.7
b	200 " " "	4.5	4.9	5.0	5.5	6.3
c	150 " " "	5.0	5.4	5.3	5.9	7.0
d	100 " " "	5.5	5.8	5.5	5.9	7.0
e	None............................	6.0	7.0	6.3	7.0	7.3
f	90.7 gm. ground limestone..........	...	8.5	8.0	8.5	8.6
g	907 " " "	...	8.5	8.0	8.4	8.4
h	17.007 gm. sulphur, velvet sublimed flowers............................	4.0	4.4	4.6	5.1	5.4
i	13.608 gm. sulphur, velvet sublimed flowers............................	4.5	4.4	4.6	5.2	5.6
j	10.206 gm. sulphur, velvet sublimed flowers............................	5.0	4.7	4.9	5.6	6.1
k	6.804 gm. sulphur, velvet sublimed flowers............................	5.5	5.1	5.3	6.1	6.3

Table 6. Incidence and persistence of Phymatotrichum root rot on cotton plants grown in Lufkin fine sandy loam surface soil material adjusted to the entire depth of the containers to different pH values.

Series	Numbers of plants				Percentages plants attacked by root rot				Percentages plants killed by root-rot			
	1930	1931	1932	1933*	1930	1931	1932	1933	1930	1931	1932	1937
a	164	116	173	101	8	0	0	0	0	0	0	0
b	201	115	188	75	28	0	0	0	6	0	0	0
c	177	114	183	70	71	4	3	0	21	2	1	0
d	148	108	165	111	78	16	15	34	44	11	10	27
e	172	111	184	115	81	51	40	16	40	28	24	11
f	203	105	165	82	97	82	72	66	64	61	60	48
g	199	107	128	76	78	72	61	58	39	52	39	38
h	135	95	145	82	18	0	0	0	8	0	0	0
i	197	93	134	62	28	0	0	0	12	0	0	0
j	190	91	140	77	41	2	0	12	24	2	0	12
k	220	93	128	85	46	26	16	7	32	19	9	7

*In 1933, only 6 of the 12 cylinders of each series were available for this experiment.

cylinders were used for each of the eleven series of soil treatments. As indicated in detail in Table 5, the treatments were planned to provide the following: 4 series treated with sulphuric acid to obtain various acidities; a similar set of 4 series treated with sulphur planned to reach the same range of acidities; an untreated series; and two series in which were incorporated respectively 0.2% and 2% of finely ground limestone, to obtain definitely alkaline and calcareous soils to compare with the acidified soils.

Periodic pH determinations were made on soil samples taken by 6-inch depths to the bottoms of the containers. At first the pH was fairly uniform at all depths. By the end of three years, however, the deeper samples averaged usually about 0.5 pH more acid than the 0-6 inch samples. Thus in series *a* samples from 0-6 inches deep averaged pH 6.1; from 6-12 inches deep, pH 5.8; from 12-18 inches deep, pH 5.5; and from 18-24 inches deep, pH 5.5. Differences between the replicate containers were usually less than 0.5 pH. The values given in Table 5 are averages for all depths and all containers in the various series. It will be noted that in both the sulphur and sulphuric acid series the soil was most acid the first year, becoming less acid during the course of the experiment. The sulphuric acid treatments failed to secure the desired acidities, while the sulphur additions (made in excess of the theoretical requirements) produced greater acidity in three of the four series than was desired, but soon drifted toward neutrality. During the period of the experiment, the sulphur series maintained greater acidity than the corresponding sulphuric acid series.

Cotton was grown in these cylinders from 1930 through 1933. Root rot was introduced into the containers by copious artificial inoculation during the summer of 1930; naturally-infected cotton roots were used as inoculum (13). No inoculations were made in the succeeding years. Notes were taken each year on the incidence of root rot, including observations on the appearance of above-ground symptoms of the disease and also, at the end of the season, of symptoms on the roots even of those plants that appeared normal. Exhaustive microscopic study eliminated certain small plants, particularly in the more acid series, that succumbed early in the season, usually to damping-off, which was favored by the soil conditions. These plants were not considered in calculating the percentages of root rot in the various series (Table 6).

The results in 1930, when the plants in each cylinder were inoculated with the disease, agreed with previous results in showing the possibility of introducing root rot even in acid soils by artificial inoculation. In the six series of cylinders with soil less acid than pH 5.0, there was more than 40% of root-rot infection, while only one of the five series with soil more acid than 5.0 had as much as 40% infection. However, Phymatotrichum root rot resulted from the inoculation in at least some of the cylinders of every series, even those with soil at pH 4.4, and some of the plants even in this definitely acid soil were killed by the disease.

In succeeding years, root-rot infection could occur only as the result of successful overwintering of the disease. There was a sharp decrease of root-rot infection in the more acid soils. In 1931, the disease did not reappear in the two more acid of the sulphuric acid series, which averaged approximately pH 4.8 and 4.9, nor in the two more acid of the sulphur series, which averaged pH 4.6. No infection with root rot was found in these series in the following years, although the soil became less acid.

Meanwhile, the disease diminished progressively in all the series, but only to a small degree where lime had been added. In 1933, three years after the original inoculation, more than half of the plants in the limed series, *f* and *g*, showed symptoms of root rot, and more than a third of the plants were killed by root rot.

There were several intermediate series, in which root rot was still present after several years, but in which it had decreased greatly in abundance. This group included series *c*, with a decrease from 71% to 3% in 1932 and 0 in 1933; *d*, from 78% down to 34% in 1933; *j*, from 41% down to 12%; *k*, from 46% down to 7%; and the check series *e*, from 81% down to 16%. In these series the soil varied originally from about neutrality to slight acidity, except *j* in which the initial pH was 4.7.

Within the period of this experiment, the following occurred: (1) In the most acid soils, root rot was obtained by the inoculation, but the percentage was low and the disease could not overwinter in these soils and did not reappear in following years. (2) In less acid soils, higher percentages of root rot were obtained by the inoculation in 1930; there were great decreases in the percentage of infection in the following year; but the disease had not disappeared completely in three years. These soils were evidently too acid for favorable overwintering and seasonal development of root rot. Whether the disease would disappear completely in such soils in a few additional years is not indicated by these results. (3) In the calcareous, alkaline soils, still higher initial infections were secured. Only slight progressive decreases in percentages of root rot occurred in the three following years.

Because of the progressive decrease in soil acidity in these series, it would be difficult to decide on a limit to the pH that would be expected to yield the results mentioned for these several groups. The calcareous soil of pH 8.0 to 8.5 is obviously definitely in the range favorable for root rot. Soil more acid than pH 5.0 is probably definitely unfavorable. Between about pH 6.0 and pH 7.0, the conditions are apparently unfavorable for root rot, but not so unsuitable as to cause rapid disappearance of the disease.

Experiment with Four Soil Types with the Hydrogen-ion Concentration Adjusted by Various Additions

In this experiment, four types of soil were employed, each soil material being used untreated and also with various additions. Some of the additions were planned to change the acidity, and other additions to change the plant nutrient content of the soils. The soils were installed in large boxes, planted to cotton, root rot was introduced by artificial inoculation, and the effect of the treatments was observed both on incidence of the disease and on final survival under the various conditions. The 63 boxes used for the experiment, each 12 ft. long, 2 ft. wide, and 3 ft. deep, were set up during the winter of 1928-29. Each box was put in place by removing the original soil, inserting the box, and then filling with the new soil. The soils used are described below:

Tabor fine sandy loam, shallow phase, from an old field in permanent pasture. Surface soil: 0-10 inches, grayish-yellow fine sand, pH 5.9-6.2. Subsoil: 10-18 inches, yellowish-red clay, pH 5.8-6.0; 18-25 inches, reddish-yellow to yellow clay, pH 5.6-5.8; 25-32 inches, dense yellow clay, pH 5.8-6.4; 32-36 inches, heavy yellow clay, pH 6.9-7.4.

Susquehanna fine sandy loam, virgin soil from woods. Surface soil: 0-3½ inches, brownish loamy sand, pH 6.5-6.9; subsurface, 3½-10 inches, yellow fine sand, pH 6.1-6.5. Subsoil: 10-16 inches, red clay, pH 5.4-5.9; 16-26 inches, red mottled with gray clay, pH 5.3-5.7; 26-36 inches, gray clay mottled with red, pH 5.5-6.0.

Kirvin fine sandy loam, deep phase, virgin soil but heavily pastured. Surface layer: 0-6 inches, light brown loamy fine sand, pH 6.8-7.1; 6-12 inches, brownish-yellow fine sand, pH 6.9-7.1; 12-24 inches, yellow fine sand, pH 7.0-7.1. Subsoil: 24-36 inches, red heavy clay, pH 5.7-6.2.

Lufkin fine sandy loam. Surface layer: 0-12 inches, homogeneous brownish-gray fine sand, pH 5.9-6.1. Subsoil: stiff gray clay, apparently uniform; 12-18 inches, pH 6.0-6.1; 18-24 inches, pH 5.8-6.1; and 24-36 inches, pH 6.0-6.4.

The soils were dug out in the layers mentioned and sacked, the sacks were transported to College Station and weighed, and samples were taken to determine the dry weight of the soil. Additions were made to these soil materials, in filling the boxes, on the basis of the weight of oven-dry soil. The various layers of the soils were placed in their new locations in the boxes at the same depths as those from which they had been dug. Additions to the soil materials, unless otherwise specified, were made to the entire depth of the boxes. The materials added were mixed in as the soils were placed in the boxes.

All treatments were made to duplicate boxes. For the Tabor, Susquehanna, and Kirvin soils, limestone was used at 1% and 5% of the dry weight of the soils, and sulphuric acid was added in various amounts estimated to reach the acidities indicated in Table 7. Soils of certain other boxes were given special treatments as summarized in Table 8. The Lufkin soil material was used in another set of boxes (Table 9) in which the upper soil layers were made acid by addition of sulphuric acid to reach an estimated pH 5.0, while the deeper layers were made alkaline by addition of 1% of limestone. The relative depth of these two layers was the variable. Pairs of boxes were made acid respectively to 6 inches, 12 inches, 18 inches, and 24 inches deep, with the soil below this depth in each case alkaline. Two other boxes were made acid to the entire depth, and two were made alkaline to the entire depth.

All the treatments had been completed by May, 1929. Startex variety (Texas Station No. 7000) cotton was grown in a single row down the center of each box from this year until 1933. The plants were thinned usually to distances of about four inches apart, leaving about 36 plants to the 12-foot row. More plants were left during some seasons, bringing

Table 7. Incidence and persistence of Phymatotrichum root rot in boxes of soil materials, of various soils, adjusted by additions of lime or of acid.

Soil types and treatments	Box No.	Average pH of soil, for 0-2 feet deep					Percentages of plants attacked by root rot				
		1929	1930	1931	1932	1933	1929	1930	1931	1932	1933
Tabor fine sandy loam											
checks, untreated.	1	5.7	5.9	5.7	5.9	5.9	51	100	53	31	0
	2	6.2	5.8	5.8	6.0	6.1	38	95	38	6	0
lime added, 1%...	7	7.4	7.3	7.7	7.8	7.9	44	65	74	26	67
	8	7.3	7.5	7.9	7.7	8.0	48	97	36	50	90
" " 5%...	9	7.7	7.6	7.9	8.1	8.2	38	91	32	0	9
	10	7.5	7.5	8.0	8.1	8.2	43	92	33	36	95
acid, to estimated pH 5.5.........	15	5.2	5.1	5.1	5.3	5.9	49	78	32	0	0
	16	5.3	5.5	5.2	5.6	5.3	24	29	13	0	0
acid, to estimated pH 4.5........	17	4.9	5.0	5.0	5.3	5.6	0	9	0	0	0
	18	5.1	5.0	5.0	5.4	5.6	8	3	0	0	0
Susquehanna fine sandy loam											
checks, untreated.	19	6.3	6.2	5.7	5.8	6.3	3	7	10	0	0
	20	6.1	6.2	5.9	5.7	6.4	3	6	21	0	0
lime added, 1%...	21	7.4	7.5	7.5	7.7	7.9	49	91	69	11	55
	22	7.6	7.4	7.8	7.7	8.1	28	76	50	6	79
" " 5%...	23	7.8	7.7	8.1	7.7	8.1	44	48	60	67	100
	24	7.7	7.7	8.0	7.8	8.1	42	66	45	56	100
acid, to estimated pH 5.5........	29	5.5	5.5	5.2	5.5	5.9	31	57	15	0	25
	30	5.3	5.4	5.3	5.5	5.8	30	52	3	0	25
acid, to estimated pH 4.5........	31	5.1	5.1	5.1	5.4	5.6	24	30	8	0	39
	32	5.2	5.1	5.4	5.3	6.0	50	36	14	0	16
Kirvin fine sandy loam											
checks, untreated.	33	6.9	6.8	7.2	7.5	7.4	61	88	24	0	100
	34	7.0	7.0	7.7	7.6	8.0	47	97	94	0	39
lime added, 1%...	39	7.4	7.4	8.5	8.4	8.5	64	93	40	8	33
	40	7.6	7.5	8.6	8.6	8.8	47	95	0	0	29
" " 5%...	41	7.7	7.7	8.2	8.5	8.6	53	97	71	0	10
	42	7.7	7.6	8.4	8.6	8.5	73	98	81	90	84
acid, to estimated pH 6.5........	43	6.5	6.8	7.9	7.2	8.0	56	98	0	3	49
	44	6.3	6.4	7.5	6.6	7.4	59	95	18	0	16
acid, to estimated pH 5.5........	45	6.4	6.1	7.2	7.0	7.4	17	11	14	0	18
	46	6.1	6.3	7.2	6.3	7.6	58	92	10	17	4
acid, to estimated pH 4.5........	47	5.8	5.9	6.6	6.0	6.4	44	70	44	44	90
	48	6.0	6.3	6.9	6.3	7.2	8	15	14	8	28
Lufkin fine sandy loam											
check, untreated..	63	6.1	6.1	6.9	6.3	...	44	57	0	0	...
lime added, 1%...	51	7.4	7.6	7.8	8.0	8.2	46	68	4	3	0
	52	7.4	7.5	7.9	8.0	8.1	26	33	17	11	50
acid, to pH 5.0...	53	5.5	5.6	6.0	5.5	...	13	2	0	0	...
	54	5.2	5.6	5.6	5.4	...	0	2	0	0	...

the number of plants per box up to around 50. In 1929, root rot was introduced at one end of the row of cotton in each box by inoculation with naturally-infected cotton roots (13). Again in 1930, the boxes in which the disease had not already developed as a result of successful over-wintering were reinoculated. Thereafter, no further inoculations were made. The results for 1929 and 1930 therefore show the effect of the various soils and treatments on the incidence of root-rot only; while the 1931, 1932, and 1933 results are indicative of the effect of these con-

Table 8. Incidence and persistence of Phymatotrichum root rot in boxes of soil materials, of various soils, into which the additions specified were made.

Soil types and treatments	Box No.	Average pH of soil, for 0-2 feet deep					Percentages of plants attacked by root rot				
		1929	1930	1931	1932	1933	1929	1930	1931	1932	1933
Tablor fine sandy loam											
checks, untreated.	1	5.7	5.9	5.7	5.9	5.9	51	100	53	31	0
	2	6.2	5.8	5.8	6.0	6.1	38	95	38	6	0
manure, 20 tons per acre*......	4	6.1	6.2	5.6	6.0	6.1	47	94	54	0	5
	5	6.2	5.9	6.2	6.0	6.4	39	46	69	0	22
fertilizer, 4-8-4, 1 ton per acre, N as nitrate of soda*..........	3	6.2	6.0	5.9	5.9	6.3	53	96	44	0	0
	6	6.0	5.9	5.7	5.7	5.8	45	87	13	0	0
sodium carbonate, 0.1%..........	11	7.4	6.4	6.6	6.5	6.5	8	0	0	0	0
	12	7.3	6.4	6.6	6.8	6.7	6	0	0	0	0
gypsum, 1%......	13	5.0	4.9	4.9	4.9	5.7	57	95	29	3	0
	14	5.0	5.0	4.9	5.4	5.5	56	89	68	29	46
Susquehanna fine sandy loam											
checks, untreated.	19	6.3	6.2	5.7	5.8	6.3	3	7	10	0	0
	20	6.1	6.2	5.9	5.7	6.4	3	6	21	0	0
sodium carbonate, 0.1%..........	25	6.8	6.9	6.6	6.7	6.7	41	83	3	7	79
	26	6.8	6.7	6.8	6.4	6.5	6	8	54	8	69
gypsum, 1%......	27	5.6	5.5	5.4	5.5	6.0	47	94	76	48	86
	28	5.5	5.6	5.5	5.5	5.9	43	79	17	18	31
Kirvin fine sandy loam											
checks, untreated.	33	6.9	6.8	7.2	7.5	7.4	61	88	24	0	100
	34	7.0	7.0	7.7	7.6	8.0	47	97	94	0	39
manured, 40 tons per acre*.......	35	7.2	6.9	7.5	7.5	7.6	6	12	24	0	7
	36	6.9	7.0	7.8	7.8	7.8	35	76	72	0	32
fertilizer, 4-8-4, 1 ton per acre, N as cottonseed-meal*.........	37	7.1	6.5	7.4	7.5	7.7	56	91	72	0	70
	38	7.0	6.8	7.0	6.9	7.3	69	92	38	0	29
borax, 2 lb., manganese sulphate 50, potassium iodide 5, iron sulphate 50, nickel sulphate 5, copper sulphate 10 lb. per acre*.........	49	6.8	7.1	7.8	7.5	7.9	53	90	58	88	82
	50	6.9	7.0	7.4	6.8	7.8	44	87	18	13	8

*Applications at the rates mentioned made twice, in 1929 and again in March, 1932, to upper 3 to 4 inches of soil only.

ditions on overwintering and final survival of root rot. Occurrence of root rot was favored in some seasons by watering. Root-rot notes were taken at the end of each season, usually late in October or in November. At this time, the roots of each third plant along the row were pulled and examined. Roots of the intermediate plants were left in place in the ground over winter to facilitate natural survival of the root-rot fungus.

Percentages of plants actually killed by root rot were usually not markedly different from the total percentages attacked, which included also those with infected roots but no aboveground symptoms. For this reason, only the total percentages of the plants with root rot have been tabulated in the present discussion of these results (Tables 7, 8, and 9).

Soil auger borings were made periodically in the boxes, and the pH determined for each layer in each box. These extensive data cannot all be summarized in this Bulletin; but averages of the pH values for the 0-2 ft. samples are given in Tables 7, 8, and 9. These averages are representative of the soil acidity for many of the boxes, in which the soil remained at the same acidity to the entire depth of the containers. However, in certain boxes the surface soil became more alkaline than deeper layers, or the subsoil below 2 feet deep remained different from the upper layers. Some of these exceptional cases will be discussed in consideration of the results.

Effect of lime: Addition of lime made the soil more favorable for root rot (Table 7). A pH of 7.4 to 8.0 was obtained in all the soils from lime additions. There was little difference in the results between the 1% and the 5% additions. Even at the lower rate, the soils became alkaline and highly suited for the incidence and continued survival of root rot.

Effect of sulphuric acid: The additions of sulphuric acid were effective in eradicating root rot in the Tabor soil. The disease disappeared from the check boxes of this series only after twice overwintering successfully. Sufficient acid to change the soil to approximately pH 5.2-5.5 (boxes 15 and 16), however, eradicated root rot by the end of the first year following inoculation; that is, root rot overwintered once but not a second time. Greater acidification, changing the soil to around pH 5.0 (boxes 17 and 18) prevented root rot from spreading at all from the plants inoculated during the first two years of the experiment, or from surviving afterward by overwintering.

In the Susquehanna and Kirvin series, the acid did not eradicate root rot, which survived in all the boxes until the end of the experiment. Results in the Lufkin series were obscured by the fact that root rot failed to overwinter either in the check box 63, or in the acid boxes, 53 and 54.

Effect of manure: King and Loomis (9, 10, 11) in Arizona have found that continued application of organic manures to cotton grown under irrigation greatly reduced the extent of infection from root rot and delayed the appearance of the disease. Root rot returned again when they discontinued the annual application of manure.

Fresh stable manure was applied to two boxes of the Tabor soil, at 20 tons per acre, in 1929 and again in 1932; and the Kirvin soil, which was more favorable to the disease, was treated with manure at 40 tons per acre in 1929 and 1932 (Table 8). In neither soil material did the treatment eradicate root rot, which instead persisted in all four boxes until the end of the experiment. In fact, since root rot failed to appear in check boxes 1 and 2 of the Tabor series in 1933, during a season favorable for the disease, while it was present in the manured boxes, it might even appear that manure aided in the survival of root rot in this case rather than militating against it. These results resemble those of King and Loomis in that no root rot appeared in the manured boxes in 1932, following the reapplication of manure, while it came back again in 1933. However, the season of 1932 was apparently highly unfavorable for root rot in most of the containers of this experiment, so that this temporary disappearance of the disease from the manured boxes cannot definitely be ascribed to the treatments.

Effect of fertilizer: Four boxes of the experiment were used with additions of 4-8-4 fertilizers spaded into the surface soil in 1929 and again in 1932 at the rate of 1 ton per acre each time. These fertilizers were made up with superphosphate, muriate of potash, and nitrogen; sources of nitrogen were nitrate of soda in the Tabor soil series, and cottonseed meal in the Kirvin soil series. In the Tabor soil, root rot spread throughout the fertilized boxes, just as in the checks, and overwintered successfully for one year after inoculations were discontinued, but failed to reappear in the two following seasons. Meanwhile, root rot disappeared also in the check boxes in the second year, though not in the first. In the Kirvin soil, root rot spread throughout the fertilized boxes, 37 and 38, as well as through the check boxes, and overwintered successfully until the end of the experiment despite the total of 2 tons of fertilizer per acre used in these boxes.

These results indicate no apparent effect from the fertilizers on the prevalence or overwintering of root rot. They agree in this respect with other experiments (16), in which fertilizer salts added in very large amounts to soil materials in large earthenware cylinders did not affect incidence or overwintering of root rot, although additions of equal weights of sodium chloride caused definite reduction in infection and in death of plants. Plot experiments on Blackland prairie soils, summarized recently by Jordan, Dawson, Skinner, and Hunter (8), led them to the conclusion that continued fertilizer additions have increased yields and caused definite though slight reductions in the proportions of cotton plants killed by root rot.

Effect of rarer plant nutrients: One of the suggestions to explain the continued prevalence of Phymatotrichum root rot in cultivated soils of the Southwest has been the possible lack in the soils of some material essential to plant growth, with the assumption that this lack either makes plants susceptible to the disease or directly aids the survival of the fungus. Such an hypothesis would seem quite improbable from the wide range of soil and climatic conditions obtaining through the thousands of square miles over which the root-rot fungus is destructive. It was nevertheless considered advisable to add to this experiment a set of boxes into which were incorporated a variety of chemicals, most of which are known to be essential to plant growth, in low concentrations. These materials are not usually included in fertilizer mixtures since they are generally present in most soils and only small amounts are needed by plants.

The additions made (in boxes 49 and 50) were calculated to supply the following weights of the materials per acre of surface: manganese sulphate 50 pounds, potassium iodide 5 pounds, iron sulphate 50 pounds, nickel sulphate 5 pounds, copper sulphate 10 pounds, and borax 2 pounds. These additions were repeated at the same rates in 1932. The results showed no effect on the incidence or prevalence of root rot, which spread rapidly in these boxes and survived until the end of the experiment. Prevalence and destructiveness of root rot are therefore probably not associated with lack of any of the various ions added to these boxes.

Effect of sodium carbonate: Additions of sodium carbonate (Table 8) were made to adjust soils slightly toward alkalinity without at the same time adding calcium. These additions of 0.1% to Tabor and to Susquehanna soil materials changed the average pH for the entire depth into ranges (pH 6.4 to 7.4) definitely suitable for Phymatotrichum root rot.

With the Tabor soil (boxes 11 and 12) the treatment prevented any spread of root rot from the plants inoculated in 1929, prevented development of symptoms even on the inoculated plants in 1930, and prevented any appearance of root rot thereafter from overwintering. However, the sodium carbonate accumulated in the surface soil layer enough to darken it visibly, to impede growth of the cotton plants, and to produce a reaction of around pH 7.8 to 8.3 in the upper ten inches of soil as compared with around pH 6.3 to 6.5 in the lower layers. Sodium carbonate here was specifically inhibitory to Phymatotrichum root rot, since lime additions that produced the same pH were favorable for the disease. Apparently development or survival of root rot is impeded by somewhat lower concentrations of sodium carbonate than can be withstood by the cotton plant, since cotton was grown successfully each year in boxes 11 and 12.

With the Susquehanna soil (boxes 25 and 26) the sodium carbonate changed the surface soil layers to around pH 7.0-7.4, while the deeper soil remained at around pH 6.0 to 6.6. The growth of plants in these boxes was not interfered with by the treatment, nor was the development of root rot, which exceeded that in the checks. The disease survived until the end of the experiment, and caused losses every year, although root rot disappeared from the check boxes after 1931. It is difficult to explain why sodium carbonate controlled root rot in the Tabor soil but not in the Susquehanna, except that the same soil conditions that held the sodium carbonate dispersed throughout the soil and prevented accumulation of it in the surface layer may have prevented it from acting on the root-rot fungus.

It may be noted that these results agree with field observations which indicate that the cotton plant is more tolerant of "alkali" soils than is the root-rot fungus.

Effect of gypsum: Gypsum (calcium sulphate) was used to add calcium without making the soil alkaline. It was of particular interest in comparison with lime additions, which increase both the pH and the calcium content. Additions of gypsum amounting to 1% of the dry weight of the Tabor and Susquehanna soil materials made these soils highly acid (Tables 10 and 11), and did not reduce the incidence or overwintering of root rot. With the Tabor soil (Table 8, boxes 13 and 14), root rot was approximately as prevalent as in the untreated checks. In the Susquehanna soil, root rot was prevalent every year in the gypsum-treated boxes (27 and 28), although it failed to become well established in the checks. Since all treatments in the Susquehanna series appeared to improve this soil for root rot, the results with gypsum here were of less importance than if this soil had not seemed so readily transposed to a favorable substratum. Nevertheless, root rot overwintered successfully for three years and produced heavy percentages of infection in these boxes which contained large additions of calcium sulphate.

Depth of acid layer of soil as affecting development of root rot: Many of the soils of Texas have developed from calcareous materials. Those in which the surface is acid are in some cases over calcareous subsoils. It was desired to find how deep a layer of acid soil would be necessary to prevent root rot from surviving in calcareous soil below. A series of boxes of Lufkin fine sandy loam soil, as outlined in Table 9, was set up with lower alkaline layers to which 1% of limestone had been added. Samples made periodically showed these lower layers to have reactions usually between pH 7.3 and 8.0. The upper layers were acidified with sulphuric acid to pH 5.5 to 6.2.

In 1929 and 1930, each box was inoculated. Root rot was abundant in the boxes that were alkaline to the entire depth (boxes 51 and 52). In the other boxes, however, it was generally confined to the inoculated plants. In 1931, root rot recurred only in the soil alkaline to the entire depth and in the boxes with six inches of acid soil, and in the next year, only in the boxes with alkaline soil to the entire depth.

These results would suggest that even a six-inch layer of acid surface soil is sufficient to cause final eradication of root rot, while a twelve-inch layer may cause immediate disappearance of the disease. It must be considered, however, that under the conditions of the experiment the disease may not have become well established in the deeper alkaline layers of this soil, and that therefore the experimental conditions here may not have been comparable to field conditions in which root rot might have been indigenous for many years. For the same reason, these results can scarcely be interpreted as proving that root rot could be eliminated from infested areas by some treatment that would make the upper six to twelve inches of the soil unfavorable for the root-rot fungus.

Root rot as influenced by changes in soil acidity: The experiment summarized in Tables 7, 8, and 9 has furnished information on the suitability

Table 9. Incidence and persistence of Phymatotrichum root rot in boxes of Lufkin fine sandy loam soil material, with upper layers adjusted to acidity by addition of sulphuric acid to estimated pH 5.0, and lower layers adjusted to alkalinity by addition of 1 per cent limestone.

Depth of acid and alkaline soil layers		Box No.	pH of soil of the acid layers				Percentages of plants attacked by root rot			
Acid layer	Alkaline layer		1929	1930	1931	1932	1929	1930	1931	1932
inches	inches									
.....	0–36	51	...	...	...	...	46	68	4	3
		52	...	...	...	...	26	33	17	11
0–6	6–36	55	5.7	6.8	5.3	6.3	5	4	12	0
		56	5.6	6.9	6.2	6.5	19	7	20	0
0–12	12–36	57	5.6	5.9	5.5	5.7	0	8	0	0
		58	5.6	6.5	5.8	6.1	11	4	0	0
0–18	18–36	59	5.5	6.2	5.1	5.6	33	5	0	0
		60	5.6	6.0	5.5	5.8	6	6	0	0
0–24	24–36	61	5.5	5.8	5.3	5.6	11	4	0	0
		62	5.4	5.7	5.4	5.5	0	8	0	0
0–36	.....	53	5.5	5.6	6.0	5.5	13	2	0	0
		54	5.2	5.6	5.6	5.4	0	2	0	0

to root rot, under somewhat controlled conditions, of four different soil types following treatments with lime, sulphuric acid, gypsum, sodium carbonate, manure, and fertilizer. These results were discussed above chiefly with regard to the effect of the materials as such on the incidence or overwintering of root rot. In general, soils that became more acid were less suited to root rot, and soils that became more alkaline were more suited for the disease. Additions of lime have invariably made the soil definitely alkaline and definitely favorable for root rot. Similarly, in the manured and fertilized soils, differences in the amount of root rot may well have been due to chance, and the soil acidity was apparently not of importance. With the boxes to which gypsum was added, however, rather definite acidification of the soil was not followed by reduction in the incidence or overwintering of root rot. These exceptional cases are examined more fully below. The complete data on hydrogen-ion concentrations of samples from the gypsum boxes are given in Tables 10 and 11, along with similar data for the untreated soil and sulphuric-acid treated soil of the Tabor and Susquehanna series.

It should be noted first, from Table 10, that the deeper layers of soil in both of the gypsum-treated boxes became very acid. These deeper layers would not explain the difference in the survival of root rot in these boxes. It diminished slowly in box 13, to disappear in 1933, while it survived in the other box, 14. Changes in the 0-10 inch soil layer, on the other hand, correlate with this course of events. In box 14, this surface layer did not become more acid than pH 5.7, and by the end of 1931 had changed back toward neutrality; but in box 13, the acidity in this layer became more intense than pH 5.5, going at the end of 1931 to pH 5.1. A similar relation appears in the boxes of this series

Table 10. Detailed soil reaction data for a few boxes of the Tabor fine sandy loam series, showing pH determinations on samples taken at the various dates indicated.

Soil treatments	Box No.	Date of taking samples	pH of soil samples from following depths, inches:				
			0-10	10-18	18-25	25-32	32-36
Checks, untreated.........	1	Oct. 6, 1929	6.1	5.0	5.9	7.3	7.5
		Feb. 27, 1930	6.2	5.6	5.8	6.0	7.2
		Mar. 19, 1931	6.1	5.6	5.3	5.7	6.5
		Dec. 4, 1931	7.9	4.9	5.3	6.1	7.6
		Nov. 18, 1932	6.8	5.4	5.4	6.6	6.9
		Jan. 9, 1934	6.9	5.3	5.5	5.7	7.5
	2	Oct. 6, 1929	6.9	5.8	5.9	6.0	7.5
		Feb. 27, 1930	6.2	5.6	5.7	5.9	7.2
		Mar. 19, 1931	6.9	5.4	5.1	5.4	6.4
		Dec. 4, 1931	7.2	5.7	5.5	5.6	7.5
		Nov. 18, 1932	6.9	5.6	5.4	5.5	7.1
		Jan. 9, 1934	7.2	5.7	5.4	5.5	6.3
Gypsum, 1%.............	13	Oct. 6, 1929	6.0	4.4	4.7	4.9	6.3
		Oct. 26, 1929	6.1	4.3	4.5	5.6	5.9
		Nov. 27, 1929	5.9	4.2	4.5	4.6	5.7
		do	5.8	4.2	4.4	4.8	5.6
		Feb. 27, 1930	5.9	4.3	4.4	5.5	5.6
		Mar. 19, 1931	5.7	4.6	4.5	5.1	5.5
		Dec. 4, 1931	5.1	4.5	4.2	4.1	5.6
		Nov. 18, 1932	6.2	4.3	4.3	4.7	5.6
		Jan. 9, 1934	6.5	5.5	5.0	5.2	5.3
	14	Oct. 6, 1929	6.1	4.4	4.5	4.7	6.1
		Oct. 26, 1929	5.9	4.4	4.6	4.6	6.3
		Feb. 27, 1930	6.1	4.3	4.5	4.7	5.6
		Mar. 19, 1931	5.7	4.6	4.5	5.1	5.3
		Dec. 4, 1931	6.4	4.2	4.2	4.6	5.4
		Nov. 18, 1932	7.1	4.5	4.6	5.0	5.7
		Jan. 9, 1934	7.0	4.8	4.7	5.0	5.3
Acid, to estimated pH 5.5.	15	Oct. 6, 1929	5.9	5.6	5.3	5.5	5.6
		Oct. 26, 1929	5.8	4.8	4.7	4.9	5.0
		Nov. 27, 1929	5.6	4.7	4.7	4.7	5.4
		do	6.0	4.8	4.6	4.7	5.3
		Feb. 27, 1930	5.6	4.9	4.9	5.5	5.7
		Mar. 19, 1931	5.2	5.0	5.1	5.0	5.0
		Dec. 4, 1931	5.6	4.8	4.8	4.8	5.0
		Nov. 18, 1932	5.8	5.1	4.9	4.8	5.5
		Jan. 9, 1934	6.3	5.2	5.1	5.3	5.2
	16	Oct. 6, 1929	5.9	5.4	5.4	5.4	5.4
		Oct. 26, 1929	5.6	5.0	5.1	5.1	5.1
		Nov. 27, 1929	5.8	4.8	4.7	4.7	5.3
		do	5.7	4.7	4.7	4.7	5.3
		Feb. 27, 1930	5.8	5.4	5.4	5.6	5.7
		Mar. 19, 1931	5.4	5.1	5.0	5.3	5.4
		Dec. 4, 1931	5.2	5.1	5.0	5.0	5.5
		Nov. 18, 1932	6.2	5.2	5.3	5.2	5.2
		Jan. 9, 1934	5.6	5.3	5.1	5.2	5.7
Acid, to estimated pH 4.5.	17	Oct. 6, 1929	5.2	5.4	5.0	5.1	5.4
		Oct. 26, 1929	4.6	4.5	4.5	4.6	4.7
		Nov. 27, 1929	5.4	4.6	4.6	4.8	5.4
		do	5.4	4.6	4.7	4.6	5.2
		Feb. 27, 1930	5.4	4.9	4.8	4.9	5.2
		Mar. 19, 1931	5.2	5.0	4.8	4.8	4.8
		Dec. 4, 1931	5.4	4.8	4.8	4.8	5.1
		Nov. 18, 1932	5.9	5.1	4.9	5.4	5.4
		Jan. 9, 1934	6.0	5.5	5.2	5.3	5.5
	18	Oct. 6, 1929	6.2	5.3	5.3	5.2	5.4
		Oct. 26, 1929	4.8	4.8	4.7	4.8	5.0

Table 10. Detailed soil reaction data for a few boxes of the Tabor fine sandy loam series, showing pH determinations on samples taken at the various dates indicated.—(Continued)

Soil treatments	Box No.	Date of taking samples	pH of soil samples from following depths, inches:				
			0-10	10-18	18-25	25-32	32-36
		Nov. 27, 1929	5.5	4.6	4.7	4.8	5.2
		do	5.3	4.4	4.4	4.6	4.7
		Feb. 27, 1930	5.6	4.7	4.7	4.7	4.9
		Mar. 19, 1931	5.3	4.9	4.7	4.5	4.6
		Dec. 4, 1931	5.5	5.0	5.1	5.7	5.4
		Nov. 18, 1932	5.7	5.1	5.3	5.9	5.9
		Jan. 9, 1934	6.1	5.3	5.3	5.3	5.5

to which sulphuric acid was added. Root rot was never able to become established in boxes 17 and 18, only the inoculated plants being killed; but in boxes 15 and 16, root rot spread well in 1929 and 1930, overwintered to cause some loss in 1931, and then disappeared. In all four of these boxes, the deeper soil layers were generally more acid than pH 5.5, and frequently beyond 5.0. However, the reaction of the surface layer of soil in boxes 17 and 18 was usually more acid than pH 5.5 during the entire period of the experiment, while in boxes 15 and 16 the reaction did not pass this point until 1931, after which time root rot disappeared from these boxes. Root rot disappeared from boxes 15 and 16, in which the deeper soil layers became much less acid than in box 14, from which it was not eradicated. However, the surface soil of boxes 15 and 16 became more acid than that of box 14.

The results of the Susquehanna soil series can be interpreted similarly from the hydrogen-ion concentration data given in Table 11. Root rot was not controlled here despite the definite acidification of the lower layers of the soil by acid (boxes 31 and 32) and by gypsum (boxes 27 and 28). But in none of these boxes did the uppermost soil layer become as acid as pH 5.5, and the next layer, 3½-10 inches deep, passed this point in the acid boxes but not in the gypsum boxes, in which root rot was much the more destructive.

This line of reasoning indicates a tentative conclusion that, under the conditions of this experiment, acidification of the surface soil to at least pH 5.5 was necessary to produce rapid changes in the prevalence of root rot. More extreme acidification of the deeper soil, with the surface layer left near neutrality, was not sufficient to eradicate the disease. As shown above (Table 9), under the reverse conditions, with an acid surface layer and a calcareous, alkaline subsoil, root rot was apparently controlled by the presence of a six to twelve-inch acid surface layer of soil. These results agree in showing the apparent crucial importance of the surface soil layer in determining the effectiveness of soil acidity in limiting development and overwintering of root rot.

While these results thus agree with earlier work in showing a correlation between the pH of the soil and the prevalence of root rot, they do not furnish any definite information on the particular factors effective in causing the correlation. The data above do not furnish conclusive evidence that the determining factor in the instances cited was the

Table 11. Detailed soil reaction data for a few boxes of the Susquehanna fine sandy loam series, showing pH determinations on samples taken at the various dates indicated.

Soil treatments	Box No.	Date of taking samples	pH of soil samples from following depths, inches: 0-3½	3½-10	10-16	16-26	26-36
Checks, untreated.........	19	Oct. 6, 1929	6.9	6.4	6.0	5.7	5.7
		Feb. 27, 1930	6.7	6.5	5.8	5.8	6.2
		Mar. 19, 1931	6.2	6.5	4.6	5.5	5.4
		Dec. 4, 1931	6.7	6.6	5.2	5.3	5.3
		Nov. 18, 1932	6.4	6.6	5.1	5.1	5.6
		Jan. 9, 1934	7.0	6.9	5.6	5.5	5.7
	20	Oct. 6, 1929	6.9	6.8	5.9	5.6	5.7
		Nov. 27, 1929	6.7	6.0	5.4	5.6	5.5
		do	6.9	6.1	5.5	5.4	5.5
		Feb. 27, 1930	6.9	6.6	5.7	5.7	6.1
		Mar. 19, 1931	6.7	6.1	5.6	5.3	5.3
		Dec. 4, 1931	6.6	6.4	5.4	5.4	5.4
		Nov. 18, 1932	6.1	6.1	5.3	5.1	5.1
		Jan. 9, 1934	7.1	7.0	5.6	5.7	5.5
Gypsum, 1%............	27	Oct. 6, 1929	6.9	6.4	4.7	4.6	4.9
		Oct. 26, 1929	6.8	6.3	4.6	4.5	4.5
		Feb. 27, 1930	6.6	6.3	4.6	4.6	4.6
		Mar. 19, 1931	6.3	5.9	5.0	4.5	4.4
		Dec. 4, 1931	6.2	6.5	4.7	4.4	4.6
		Nov. 18, 1932	6.4	6.3	4.8	4.6	5.1
		Jan. 9, 1934	7.3	7.1	5.1	4.5	5.2
	28	Oct. 6, 1929	6.8	6.2	4.4	4.4	4.8
		Oct. 26, 1929	6.8	6.1	4.4	4.6	4.7
		Feb. 27, 1930	6.7	6.3	4.5	4.7	4.8
		Mar. 19, 1931	6.5	6.4	4.9	4.3	4.5
		Dec. 4, 1931	6.8	6.2	4.4	4.2	4.5
		Nov. 18, 1932	6.5	6.3	4.7	4.3	4.5
		Jan. 9, 1934	7.1	6.5	5.6	4.4	4.6
Acid, to estimated pH 4.5.	31	Oct. 6, 1929	6.0	6.0	4.6	4.6	4.8
		Oct. 26, 1929	5.7	4.9	4.4	4.5	4.6
		Nov. 27, 1929	6.4	5.8	4.6	4.4	4.5
		do	6.0	5.5	4.5	4.4	4.5
		Feb. 27, 1930	5.6	5.7	4.5	4.5	4.7
		Mar. 19, 1931	5.7	5.2	4.8	4.5	4.6
		Dec. 4, 1931	6.2	5.1	4.5	4.4	4.6
		Nov. 18, 1932	6.0	6.2	4.8	4.7	5.2
		Jan. 9, 1934	6.5	6.2	4.8	4.8	4.9
	32	Oct. 6, 1929	5.7	6.3	4.7	4.6	5.1
		Oct. 26, 1929	5.8	5.5	4.4	4.4	4.6
		Nov. 27, 1929	5.9	5.6	4.7	4.4	4.6
		do	5.9	5.6	4.3	4.2	4.5
		Feb. 27, 1930	5.7	5.5	4.6	4.5	4.8
		Mar. 19, 1931	6.0	5.9	5.0	4.7	4.8
		Dec. 4, 1931	5.6	5.3	4.5	4.6	4.9
		Nov. 18, 1932	5.6	5.8	4.9	5.0	5.1
		Jan. 9, 1934	6.8	6.3	5.0	4.8	5.4

hydrogen-ion concentration alone. But it is obvious that continued prevalence of root rot in this experiment was associated more closely with the final pH of the soils than with original differences in the soil types.

Lufkin Fine Sandy Loam Soil Acidified at Various Depths and with Inoculum at Various Depths.

This experiment was set up in the spring of 1929, with some of the Lufkin fine sandy loam soil material, as used in the preceding experiment, in a series of 16 smaller wood boxes, 2 feet in each dimension. This soil was adjusted either to alkalinity by addition of 1% of ground limestone, or to acidity by addition of sulphuric acid calculated to change the soil to pH 5.0. As indicated in Table 12, in four of the boxes the soil was made alkaline to the entire depth of two feet; in another four boxes,

Table 12. Incidence and persistence of Phymatotrichum root rot in Lufkin fine sandy loam soil material adjusted as indicated.

Soil reaction	Box No.	Location of inoculum	Percentage of cotton plants succumbing to root rot	
			1929	1930
All alkaline (pH 7.2-8.0)	1	In upper foot of soil	100	67
	2	do	67	0
	3	In lower foot of soil	0	0
	4	do	100	100
All acid (pH 4.9-5.5)	5	In upper foot of soil	0	0
	6	do	0	0
	7	In lower foot of soil	0	0
	8	do	0	0
Upper foot acid, lower foot alkaline	9	In upper foot of soil	17	0
	10	do	17	0
	11	In lower foot of soil	0	0
	12	do	0	0
Upper foot alkaline, lower foot acid	13	In upper foot of soil	83	0
	14	do	100	100
	15	In lower foot of soil	0	0
	16	do	0	0

the soil was made acid to two feet deep; in four more, the upper foot of soil was made acid and the lower foot alkaline; and in the final four, the upper foot was made alkaline and the lower foot acid. The upper foot of soil in each box was a brownish-gray fine sand and the subsoil was a stiff gray clay.

Cotton was planted in these boxes in 1929 and 1930. In 1929 the plants were thinned to 6 plants per box, and in 1930 to 8-20 plants per box. In 1929, two plants in each box were inoculated heavily with root rot. The inoculum consisted of the roots of freshly-wilted cotton plants, trimmed down to exactly eight inches in length. Four roots were used for each plant to be inoculated. In two of each set of boxes, the inoculum was placed in the upper foot of soil by inserting it in holes bored to a depth of 10 inches with a soil auger; in the other two boxes, it was placed in the lower foot of the soil in holes bored to 22 inches.

The results obtained are shown in Table 12. It will be noted that when the boxes were first inoculated root rot killed most of the plants in the alkaline soil (boxes 1-4), but none of those in the acid soil (boxes 5-8). In boxes with the upper soil acid and the lower soil alkaline, root rot killed only two of the plants in the boxes in which the inoculum was placed in the acid surface soil (boxes 9 and 10), and did not appear in boxes 11 and 12 in which the inoculum was placed in the lower alkaline soil layers. In the boxes with alkaline surface soil and acid subsoil, root rot again appeared only in the boxes inoculated in the upper soil layer, and killed most of the plants in boxes 13 and 14.

The final column shows the prevalence of root rot after wintering over in these boxes. The disease did not appear in 1930 in the boxes with the soil acid throughout or in the boxes with acid soil in the surface layer. It reappeared only in boxes 1 and 4, with the soil alkaline throughout, and in box 14, in which the upper foot was alkaline and the lower foot was acid.

In this experiment, the hydrogen-ion concentration of the upper layer of soil was apparently of importance in limiting the development of root rot, while the pH of the deeper soil layer did not appear to affect the results under these conditions. Thus, root rot was introduced in 1929 on plants with the deeper roots in definitely alkaline soil (boxes 9 and 10), yet the disease did not become established there to reappear in 1930. Meanwhile, the disease had killed most of the plants in boxes 13 and 14, with the upper alkaline soil underlain by acid subsoil, and overwintered successfully in one of these boxes.

EXPERIMENTS WITH SOIL ACIDIFICATION AS A POSSIBLE MEANS OF CONTROL

The various experiments summarized above demonstrate that prevalence and destructiveness of root rot is closely correlated with the acidity or alkalinity of the soil. Acid soils are always less favorable for root rot, while alkaline soils are more favorable. It has therefore appeared possible that root rot might be controlled by acidification of the soil. Soil acidification has been attempted in a number of experiments by the application of sulphur, which is eventually oxidized in soils to sulphuric acid.

In an experiment at the Temple, Texas, substation, yearly additions of 10,000 pounds per acre of sulphur were disked into the surface soil in plats of Bell clay (a calcareous soil) from 1920 to 1926. The soil did not become acid nor was there any apparent change in prevalence of root rot (12, 18). This indicated that acidification would probably not be a useful means of control in highly calcareous soils.

In the fall of 1927, sulphur was applied (by H. E. Rea) in empirical amounts in a series of field tests with soils that are not highly calcareous. The large amounts of sulphur used acidified the surface sufficiently to injure crops in 1928 and 1929 (15), while root rot persisted in the sub-surface soil (which remained alkaline) and attacked the deeper roots of the plants. These tests showed that soils not highly calcareous could be acidified, but that care would be needed to obviate crop injury from excessive acidity. The three experiments summarized below were tests of the effect of sulphur in possible control of root rot under somewhat controlled conditions.

Preliminary Test of Plain and Oxidized Sulphurs in Small Containers

In connection with the possibility of using sulphur for soil acidification for possible control of root rot, the question was considered whether it would be desirable to use for such purpose sulphur to which had been added materials to hasten the oxidation in the soil to form sulphuric acid. An experiment was set up in which eight different commercial sulphur preparations were tested, each at three rates of application, in small metal containers. On June 12, 1928, these sulphurs were incorporated at rates of 5,000, 10,000, and 15,000 pounds per acre into the surface one or two inches of soil of the Crockett clay loam surface soil material used, and were still present in large lumps at these depths at the end of the season. The acidity that developed was apparently largely localized during the period of this experiment to the upper soil in which the sulphur was placed. The lower roots of some of the plants were attacked by root rot, while parts of the tap-roots, in the acid surface soil, showed acid injury.

Cotton was planted, thinned to about four plants per container, and inoculated with root rot. At the end of the season, all the plants were pulled and the roots examined. It was found that many plants had been killed by acid injury, as shown by the characteristic enlarged cracked regions and the absence of Phymatotrichum strands. Plants with acid injury were more abundant in the series with higher rates of application of sulphur than in series with 5,000 pounds per acre, and were more abundant in series in which the soil actually became highly acid than in less acid soil.

Root rot, on the contrary, was much less destructive in the acid soils. While some of the plants in the soils treated with sulphur developed traces of root rot, usually only on the tips of the roots, the disease killed only three per cent of the plants in the series receiving 5,000 pounds of sulphur per acre, one per cent in the 10,000-pound series, and none in the 15,000 pound series (Table 13). Meanwhile, forty per cent of the check plants had been killed by root rot.

In this experiment, more intense acidities were developed in the soil to which the sulphur containing oxidizing materials had been added, than in the soils with sulphur alone. There was correspondingly greater sulphur injury on plants in these series than on plants in the plain sulphur series. Root rot occurred on plants in the series treated with commercial flour of sulphur or with mixtures containing sublimed flowers of sulphur, to a greater extent than in series treated with velvet flowers of sulphur or with mixtures containing the adhesive ground

Table 13. Root rot and acid injury of cotton plants grown in small containers of Crockett clay loam surface soil material treated with plain and oxidizing sulphurs; 4 containers per series except 12 used for checks; 4 plants per container.

Material	Rate, lbs, per acre	pH	Percentages of plants: with root rot	killed by root rot	with sulphur injury	killed by sulphur injury
Velvet flowers of sulphur	5,000	3.8-5.7	0	0	0	0
	10,000	2.7-3.1	0	0	13	0
	15,000	2.9-3.9	0	0	20	0
Commercial flour of sulphur	5,000	3.8-4.2	41	0	23	0
	10,000	2.8-2.9	25	0	19	0
	15,000	3.9-4.0	37	0	44	0
Sublimed flowers of sulphur plus $KMnO_4$ as oxidizing agent	5,000	3.6-3.8	50	0	93	7
	10,000	2.3-3.1	6	0	38	13
	15,000	2.6-2.8	0	0	57	44
Adhesive ground sulphur plus $KMnO_4$ as oxidizing agent	5,000	2.3-4.1	0	0	0	0
	10,000	2.4-3.0	7	0	28	7
	15,000	2.5-2.6	0	0	73	13
Sublimed flowers of sulphur plus catalytic oxidizing agent	5,000	3.1-3.3	28	14	14	7
	10,000	2.6-3.0	0	0	29	0
	15,000	2.8-3.3	0	0	35	14
Adhesive ground sulphur plus catalytic oxidizing agent	5,000	3.0-3.5	0	0	14	7
	10,000	2.2-2.9	0	0	92	0
	15,000	2.1-2.6	0	0	100	43
Sublimed flowers of sulphur plus $KMnO_4$ and catalytic oxidizing agent	5,000	3.9-4.1	14	7	0	0
	10,000	2.5-2.8	7	7	0	0
	15,000	2.1-3.3	0	0	23	0
Adhesive ground sulphur plus $KMnO_4$ and catalytic oxidizing agent	5,000	2.5-3.7	0	0	14	0
	10,000	2.6-3.0	0	0	27	0
	15,000	2.1-2.9	0	0	34	7
None, checks	.....	5.2-6.0	62	40	0	0

sulphur. The difference was not accompanied by a difference in the final pH in these series, but may have been due to differences in speed of initial acidification. Mortality from root rot was negligible in all the treated series.

These results confirmed the general conclusion that sufficiently acid soils will prevent successful attack of plants by Phymatotrichum root rot, even when the disease is introduced by artificial inoculation. The rates of materials used here were excessive and caused injuries to the plants in the first year, with total failure to secure a stand in the following year; hence these results did not point toward practical application of sulphur for control of the disease.

Sulphur Applied at Various Depths in Small Plats

This experiment was planned to determine whether sulphur mixed to various depths with the soil would be able to exclude root rot. The location used for the experiment was a plat, originally of Lufkin fine sandy loam soil, that had been used for years as a garden and in which root rot had not appeared. The soil was quite favorable for root rot, as shown by the pH of 6.8 to 7.6, and by successful inoculations in nearby plats as well as in the plats of this experiment. For the treatments, nine small plats each ten feet long and six and one-half feet wide were used, and an adjoining larger area was used for a check plat (Table 14). Finely-ground sulphur was worked in to depths of 4 inches

Table 14. Sulphur applied to various depths in small plats of Lufkin fine sandy loam soil.

Plat No.	Depths of soil layers in which sulphur applied	Factor by which estimated sulphur rate multiplied *	Rates of actual sulphur application, in soil layers specified †, pounds per acre
	inches		
1	0–4	1⅓	2,400
2	0–6	1⅓	2,934
	6–12		1,866
3	0–6	1⅓	2,134
	6–12		1,866
	12–24		3,732
4	0–4	2	2,400
5	0–6	2	2,400
	6–12		2,800
6	0–6	2	3,600
	6–12		2,800
	12–24		5,600
7	0–4	3	4,800
8	0–6	3	1,200
	6–12		4,200
9	0–6	3	1,200
	6–12		4,200
	12–24		8,400
10	.....	...	0

*Estimated rates determined by laboratory tests of samples from the various soil layers in each plat, to find amounts of sulphur needed to reach pH 5.0, were then multiplied by the factors given to obtain the rates of application.

†Total applications per plat were sums of those specified for the various soil layers.

in three of the plats, to 12 inches in three plats, and to 24 inches in the remaining three treated plats. Each of the three plats treated to a similar depth was treated at a different rate. The rates were calculated from laboratory tests, by the method of Fraps and Carlyle (7), on samples of soil from the layers of each plat, to determine the amounts of sulphur required to convert the soils to around pH 4.5 if all the sulphur were oxidized immediately. Since all the sulphur would not be oxidized at any one time, it was assumed that the maximum acidity to be expected from such an addition would be around pH 5.0. To provide suitable variations in the treatments, the rates arrived at from these determinations were then arbitrarily multiplied by factors of either 1⅓, 2, or 3. Thus plat 1 was treated to a depth of 4 inches with 1⅓ times the amount of sulphur estimated necessary to produce pH 5.0; and so on.

These applications were made by digging away the soil to the required depth in the various plats, and then mixing in the sulphur with the proper soil layer as it was replaced. The sulphur was thus mixed much more thoroughly with the soil than could be done under field conditions, the object of the experiment being to find whether under such optimum conditions of application the materials applied would be able to exclude root rot from these plats. The sulphur applications were completed in April, 1930.

Table 15. Changes in soil acidity produced by addition of sulphur to plats of Lufkin fine sandy loam soil.

Plat No.	Total amounts of sulphur, as lb. per acre, and depths to which applied		Date of soil samples	Mean pH of soil samples, on the dates specified, from the following depths:					
	Pounds	Inches		0-6 inches	6-12 inches	12-18 inches	18-24 inches	24-30 inches	30-36 inches
1	2,400	0-4	Feb. 20, 1931	5.8	6.3	6.5	7.1	7.3	7.8
			Apr. 11, 1932	6.9	6.6	6.6	6.8	7.2	7.6
			Nov. 30, 1932	7.2	6.7	6.6	7.0	7.1	7.4
2	4,800	0-12	Feb. 20, 1931	5.7	5.9	6.3	7.4	7.6	7.9
			Apr. 11, 1932	6.3	5.4	5.7	6.4	7.0	7.4
			Nov. 30, 1932	5.6	5.5	5.4	6.6	6.8	7.4
3	7,732	0-24	Feb. 20, 1931	5.5	4.8	4.7	5.3	7.0	7.6
			Apr. 11, 1932	6.3	5.8	5.5	5.6	6.0	7.1
			Nov. 30, 1932	5.9	4.9	5.0	5.1	5.8	7.0
4	2,400	0-4	Feb. 20, 1931	4.5	4.9	5.7	6.6	7.3	7.8
			Apr. 11, 1932	6.7	6.2	5.8	6.3	6.8	6.6
			Nov. 30, 1932	6.1	5.7	5.7	5.9	6.7	7.1
5	5,200	0-12	Feb. 20, 1931	5.2	4.6	5.1	5.8	6.9	7.5
			Apr. 11, 1932	6.2	4.3	5.5	6.2	6.7	7.0
			Nov. 30, 1932	6.6	5.4	5.3	5.8	6.6	7.0
6	12,000	0-24	Feb. 20, 1931	4.0	3.8	4.0	4.4	4.8	6.8
			Apr. 11, 1932	5.4	4.5	4.3	4.2	5.2	6.3
			Nov. 30, 1932	5.0	4.5	4.4	4.5	4.5	5.5
7	4,800	0-4	Feb. 20, 1931	3.9	4.2	5.7	5.5	6.7	6.6
			Apr. 11, 1932	4.8	4.8	5.6	5.8	6.2	7.0
			Nov. 30, 1932	5.3	4.9	5.5	5.7	6.2	6.9
8	5,400	0-12	Feb. 20, 1931	5.5	3.4	4.8	6.1	6.8	7.2
			Apr. 11, 1932	5.6	4.8	5.6	5.9	6.7	7.0
			Nov. 30, 1932	6.8	4.5	4.5	5.0	5.9	6.5
9	13,800	0-24	Feb. 20, 1931	6.0	4.2	3.8	4.1	5.7	7.0
			Apr. 11, 1932	6.4	4.6	4.5	4.5	5.2	6.1
			Nov. 30, 1932	6.9	4.8	4.5	4.2	4.5	5.9
10	None, check...........		Feb. 20, 1931	8.3	8.1	8.1	8.0	8.0	8.1
			Apr. 11, 1932	8.4	8.4	8.1	7.8	7.8	7.8
			Nov. 30, 1932	8.6	8.7	8.3	8.1	7.9	7.9

Cotton was grown in the plats in 1930, 1931, and 1932, and irrigated at about 10-day intervals. Root rot was introduced by artificial inoculation (13), in the center of each plat, in 1930 and 1931. The plants inoculated were marked by stakes, and notes taken to indicate possible spread as well as the final percentages of plants with root rot. At the end of the season, notes were taken on aboveground symptoms of root rot, and in addition the root of at least one plant in each three was pulled and possible underground infection noted.

In 1930, root rot attacked only plants around the points of inoculation in the treated plats. During 1931, root rot killed many plants along the outer rows of the treated plats (Fig. 1). These plants probably became infected by the disease spreading along roots found extending entirely outside of the treated plats into infested areas. It is to be noted that soil samples taken (in April, 1932) outside of several treated plats showed that the sulphur applied within these plats had caused only insignificant changes in the pH at distances as close as 3 inches outside of the plats. During the same 2-year period since the sulphur had been applied, the soil in these plats had become definitely acid to 30 inches deep from sulphur applied to a depth of only 4 inches (Table 15). This is in line with the general conclusion that horizontal movement of soil solutes is much less than vertical movement.

While root rot had become established only at occasional points in the treated plats, it had spread rapidly in the untreated check plats, and in 1931 and 1932 attacked most of the plants.

In the treated plats, root rot became of importance only in 1932. In that year it spread in from the edges, as well as from the few points toward the center of some of the plats in which it had become established, and attacked most of the plants in plats 1, 2, 5, 7, 8, and 9

Table 16. Incidence of Phymatotrichum root rot in Lufkin fine sandy loam plats into which sulphur applied at various rates and to various depths.

Plat No.	Total amounts of sulphur, as lb. per acre, and depths to which applied		1930 results			1931 results			1932 results		
	Pounds	Inches	No. of plants	Per cent of plants— With root rot	Per cent of plants— Killed	No. of plants	Per cent of plants— With root rot	Per cent of plants— Killed	No. of plants	Per cent of plants— With root rot	Per cent of plants— Killed
1	2,400	0–4	134	1	0	129	22*	21	154	82	77
2	4,800	0–12	84	1	1	135	21*	18	146	64	62
3	7,732	0–24	98	3	0	146	19*	8	145	36	35
4	2,400	0–4	74	0	0	119	9	7	171	11	10
5	5,200	0–12	108	0	0	123	1	0	167	58	53
6	12,000	0–24	73	0	0	159	0	0	165	5	4
7	4,800	0–4	75	1	0	111	7*	5	135	53	47
8	5,400	0–12	133	6	6	144	34*	32	138	85	80
9	13,800	0–24	115	2	0	134	8*	7	125	80	68
10	None, check........		130	27	18	297	92	72	265	85	77

*Some or all of plants with root rot at edge of treated plat, adjoining untreated plat in which root rot prevalent.

(Table 16). Distribution of the disease was limited to certain portions only of plats 2, 3, 4, 5, and 7 (Fig. 1), and accordingly soil samples were taken from the plats at locations selected in such a way as to find

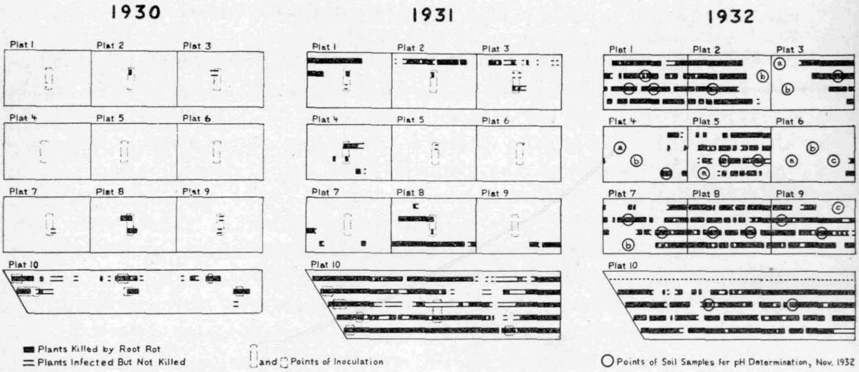

Fig. 1. Diagram of arrangement of plats in which sulphur was applied at different rates and to different depths. Locations of plants with root rot are indicated by areas blocked off, the remaining unmarked portions of rows indicating normal plants. Points from which soil samples were taken November, 1932, lettered from left to right in each plat.

whether this distribution of root rot was correlated with differences in pH within these plats. The points at which samples were taken are designated in Figure 1, along with the distribution of root rot, and the pH values of the samples are given in detail in Table 17.

These samples showed a surprisingly close relation between the distribution of root rot in 1932 and the pH. In five of the six plats in which samples could be taken from root-rot and root-rot-free areas, the more acid samples came from the root-rot-free zones. The one exception was plat 9, in which the root-rot-free zone as well as the root-rot zone proved to have a surface pH suitable for the disease. It is obvious that root rot need not necessarily have occurred everywhere that the soil was favorable.

In the plats in which the comparison can be made, average values for nine samples from root-rot areas, beginning with the upper soil layer, were the following: pH 6.4, 5.5, 5.4, 5.6, 6.1, and 7.0. Corresponding averages for 8 samples from root-rot-free areas in these plats were these: pH 5.75, 5.0, 5.0, 5.4, 5.9, and 6.7. There were thus differences at all depths, exceeding 0.5 pH in the upper foot, and amounting to only 0.2 to 0.3 pH in the lower foot and a half. This comparison would suggest that the acidity of any or all of the soil layers might have been of significance in determining the distribution of root rot in these plats.

For somewhat more precise comparison, it may be noted that despite large applications of sulphur in these plats, and the intense acidities still present in the lower soil layers, root rot spread widely in 1932 in

Table 17. Hydrogen-ion concentration of soil in individual points in plats from samples taken November 20, 1932. (Letters designating points of sampling are the same as those used in Figure 1; italics indicate samples from root-rot-free areas.)

Plat No.	Point of sampling	pH of soil from following depths: 0-6 inches	6-12 inches	12-18 inches	18-24 inches	24-30 inches	30-36 inches
1	a	6.8	6.8	6.9	7.1	7.2	7.4
	b	7.2	5.8	6.4	6.9	6.9	7.4
	c	7.5	7.5	6.6	7.0	7.2	7.5
2	a	5.7	6.2	5.8	7.0	7.5	7.9
	b	*5.4*	*4.8*	*4.9*	*6.1*	*6.1*	*6.8*
3	*a*	*5.3*	*4.7*	*4.5*	*4.9*	*5.6*	*6.9*
	b	*5.8*	*5.1*	*4.9*	*5.3*	*5.8*	*7.2*
	c	6.5	5.8	5.7	5.1	5.9	6.8
4	*a*	*5.3*	*5.0*	*5.5*	*5.8*	*7.1*	*7.1*
	b	*6.2*	*5.4*	*5.5*	*5.7*	*6.0*	*6.7*
	c	6.7	6.7	6.2	6.2	6.9	7.4
5	*a*	*5.9*	*5.2*	*5.3*	*5.9*	*6.8*	*6.9*
	b	6.8	6.1	5.4	5.8	6.8	7.2
	c	7.2	4.8	5.2	5.7	6.1	7.0
6	*a*	*4.6*	*4.4*	*4.2*	*4.4*	*4.5*	*5.0*
	b	*5.4*	*4.5*	*4.3*	*4.3*	*4.2*	*5.4*
	c	*5.1*	*4.7*	*4.8*	*4.8*	*4.7*	*6.0*
7	a	5.4	5.1	6.0	5.8	6.4	7.0
	b	*4.9*	*4.3*	*4.8*	*5.3*	*5.9*	*7.0*
	c	5.7	5.3	5.8	5.9	6.3	6.7
8	a	6.8	4.1	4.1	4.8	5.5	6.3
	b	6.7	4.8	4.9	5.2	6.3	6.6
9	a	6.2	5.3	4.8	4.7	4.9	6.0
	b	7.2	4.0	4.0	4.1	4.4	6.8
	c	*7.2*	*5.2*	*4.8*	*3.9*	*4.2*	*5.0*
10	a	8.7	8.7	8.4	8.2	8.0	8.0
	b	8.5	8.6	8.2	7.9	7.8	7.8
Root-rot areas, 14 samples: *							
Range Maximum		7.5	7.5	6.9	7.1	7.5	7.9
Minimum		5.4	4.0	4.0	4.1	4.4	6.0
Mean		6.6	5.6	5.6	5.8	6.3	7.0
Root-rot-free, 11 samples:							
Range Maximum		*7.2*	*5.4*	*5.5*	*6.1*	*7.1*	*7.2*
Minimum		*4.6*	*4.3*	*4.2*	*3.9*	*4.2*	*5.0*
Mean		*5.6*	*4.8*	*4.9*	*5.1*	*5.5*	*6.4*

*Excluding the untreated check area, plat 10.

plats 9, 8, and 5 (excluding the portion of plat 5 around sample 5a). The soil here obviously allowed root rot to spread and kill many of the plants. Comparing the pH with that in plats 4 and 6, which remained free of root rot despite the previous inoculations and the spread during this year, it is to be noted that the values here at 6-12 inches, 12-18 inches, and 18-24 inches averaged almost precisely the same as in corresponding depths in the root-rot area mentioned. But at 0-6 inches, the soil in these root-rot-free plats ranged from pH 4.6 to 6.2, averaging 5.3; while the soil in the root-rot area, overlaying equally acid subsoil, ranged from pH 6.2 to 7.2, averaging 6.65. It seems reasonable to conclude that the crucial difference between these areas that allowed root rot to spread in over plats 8, 9, and 5 was probably the loss of the acidity in the 0-6 inch soil layer.

It is possible that in these plats root rot spread unusually close to the surface, and that such a condition might be true of the rather dense Lufkin soil in which this experiment was located, but might not occur in another soil type. Moreover, artificial irrigation of the plats kept the soil moist during the growing season and presumably thus raised the height in the soil at which spread of root rot could occur. The results of this experiment can therefore be used only with reservations in making any general conclusions.

Under the conditions of this experiment, encroachment of root rot into sulphur-treated plats was not prevented by continued acidity of the deeper soil layers, after the surface soil layer had shifted back toward neutrality. No conclusions can be drawn from this experiment on whether the favorable surface soil layer, overlaying a highly acid subsoil, would have allowed successful overwintering. Also, no information is furnished by this particular experiment as to whether the presence of a thin acid surface layer of soil would have been enough to reduce or eliminate root rot in a field in which the disease was well established and in which the deeper soil remained alkaline. Root rot did not become established during the first year of this experiment in plat 1, in which only the first six inches of soil had become definitely acidified. This would indicate that spread from the inoculated plants was definitely impeded by the acidification of the surface layer of soil in this plat. The open question here is whether root rot would similarly have been impeded had it already been thoroughly established in the favorable soil below, prior to the application of the sulphur.

Sulphur Applied at Small Rates to Surface Soil, in Plats in Which Root Rot was Well Established

This experiment was set up in field plats in which root rot had already become thoroughly established. Sulphur was applied to the surface soil in a small field of Lufkin fine sandy loam soil at College Station. Cotton had been grown in this field and inoculated repeatedly with root rot in 1927 and 1928, so that the disease was quite well established prior to 1929, when the sulphur applications were made.

Commercial flour sulphur (Owl brand) was applied in 1929. It was spread over the surface of three of the plats and spaded into the plowed soil. The rates used were based on tests with samples from each plat to determine the amounts of sulphur needed to change the soil to approximately pH 5.0. Three other plats were treated with lime, applied in 1929, 1930, and again in 1932. These treated plats were each 30 feet long and alternated with untreated check plats each 15 feet long. Cotton was planted each year. It was inoculated artificially with root rot in 1929, but no further inoculations were made in later years. The results of this experiment are considered in detail in a separate paper (2) and will only be summarized here.

Effect of surface applications of sulphur on pH of the soil: Periodic sampling of the soil showed that the greatest effect from the addition of sulphur was obtained in the 0-6 inch layer of soil (Table 18). Within three months, the soil in two of the treated plats became more acid than pH 5. There was later a gradual shift back toward neutrality. The deeper soil layers were not changed so rapidly nor to such a great extent. The deeper soil became gradually more acid over a period of two to three years, the greatest acidity at about two feet deep being reached at the end of this time. Thereafter there was a fairly rapid shift back toward the original reaction.

Table 18. Average hydrogen-ion concentration at different depths in plats treated with sulphur on April 2, 1929. (The first set of samples was taken prior to application of the sulphur.)

Plats	Date of sampling	Interval since sulphur applied, months	Mean pH values for the depths specified				
			0-6 inches	6-12 inches	12-18 inches	18-24 inches	24-36 inches
A	Jan. 21, 1929	..	6.6	6.7	6.3	6.4	6.9
	June 28, 1929	3	4.7	5.9	6.0	6.4	7.1
	March 5, 1930	11	5.3	5.8	6.0	6.2	6.6
	Feb. 18, 1931	23	5.8	5.9	5.9	6.2	6.7
	Dec. 23, 1931	33	5.5	5.7	5.7	5.7	6.0
	Oct. 26, 1932	43	5.7	5.7	5.9	6.1	6.0
	Jan. 8, 1934	57	6.3	6.2	6.3	6.5	6.6
E	Jan. 21, 1929	..	5.9	5.9	6.1	6.4	6.8
	June 28, 1929	3	4.6	5.8	6.3	6.7	7.0
	March 5, 1930	11	4.7	5.6	6.0	6.1	6.6
	Feb. 18, 1931	23	5.5	6.0	5.9	5.9	6.5
	Dec. 23, 1931	33	5.5	5.7	5.8	5.9	6.0
	Oct. 26, 1932	43	5.4	5.5	5.8	6.0	6.3
	Jan. 8, 1934	57	5.8	6.0	6.2	6.4	6.7
I	Jan. 21, 1929	..	6.0	6.5	6.9	7.1	7.2
	June 28, 1929	3	5.8	6.3	6.6	6.7	6.8
	March 5, 1930	11	5.3	6.2	6.5	6.6	7.0
	Feb. 18, 1931	23	6.4	6.7	6.8	6.9	7.3
	Dec. 23, 1931	33	6.0	6.1	6.4	6.7	6.9
	Oct. 26, 1932	43	5.5	5.6	5.9	6.2	6.6
	Jan. 8, 1934	57	6.0	6.1	6.5	6.7	6.9

Effect of the applications on development and overwintering of root rot: As may be noted in Table 19, root rot diminished only slightly in the sulphur plats in the summer following the sulphur applications, despite the acidity obtained in the surface soil during that season. This was presumably because every plant was inoculated with root rot this year. The disease increased in the check plats and in the limed plats, instead of decreasing. In 1930 and 1931, root rot decreased in abundance in the check plats, with unfavorable weather conditions, and decreased even more in the sulphur plats. In fact, the disease seemed about to disappear from the sulphur plats in 1931. The following years, however, were more favorable for root rot, and the disease

Table 19. Summary of effect of sulphur and lime applications on the occurrence of *Phymatotrichum* root rot on cotton plants. (1928 figures are for occurrence prior to distribution of sulphur and lime.)

Plats	Treatments	Percentages of plants with root rot					
		1928	1929	1930	1931	1932	1933
A	Sulphur *	89	71	57	33	64	67
E	"	95	70	42	18	70	75
I	"	84	98	48	25	63	97
	All sulphur plats	89	80	49	25	66	80
C	Lime †	89	81	79	60	98	92
G	"	99	93	48	85	98	100
K	"	46	89	50	94	92	99
	All lime plats	78	88	59	80	96	97
B	Check	100	94	59	19	93	84
D	"	100	99	90	38	93	81
F	"	93	91	53	13	91	99
H	"	77	88	62	77	99	99
J	"	92	100	44	80	96	100
L	"	0	33	12	71	72	94
	All check plats	77	84	53	50	91	93

*Sulphur was applied on April 2, 1929, at the following rates: for plat A, 17.5 lb. or at 1,500 lb. per acre; for plat E, 11.7 lb. or at 1,000 lb. per acre; and for plat I (which is smaller than plats A or E) 10.75 lb. or at 1,200 lb. per acre.

†Lime was applied at equal rates in plats C, G, and K, as follows: in 1929, hydrated lime at 1 ton per acre; in 1930, ground limestone at 1,000 lbs. per acre; and in 1932, ground limestone at 1,000 lbs. per acre.

increased in all plats, although there was still less root rot in the sulphur-treated plats than in the other plats.

Inasmuch as root rot became destructive again during these later years of the experiment, even though still less destructive in the sulphur plats than in the lime or check plats, this experiment would not justify any conclusions as to the permanent value of small applications of sulphur for the partial control of root rot or for its possible final elimination from treated areas.

DISCUSSION

Experiments summarized in this Bulletin and in previous publications agree in demonstrating that Phymatotrichum root rot is more prevalent and more destructive, in general, in neutral or alkaline soils. The natural distribution of the disease within its range apparently is determined to a great extent by the presence or absence of such favorable soils. Other factors may be of local importance or of seasonal importance. As has been pointed out (1), within a uniform soil the hydrogen-ion concentration ceases to be a limiting factor and the presence or absence of root rot is controlled by other factors.

In the same way, soil materials adjusted experimentally to various hydrogen-ion concentrations were changed with regard to their suitability for the root-rot fungus. Soil previously unfavorable for the development of the disease has been made favorable by addition of lime. Soil previously favorable for the disease has been acidified and has become unfavorable. Continued prevalence of root rot has been shown in these experiments to be associated more closely with the final hydrogen-ion concentration of the various soil materials than with original differences in the soil types.

It is still not known, however, whether the correlation of the presence and destructiveness of the disease with the favorable soil reaction is due necessarily directly to the pH of the soil, or is based instead on some related difference possibly not even produced by the acidity. Some laboratory work has been done on this problem. It was found that in soil chambers, in the absence of the host plant, differences in the growth of the fungus correlated well with the pH of the soil, and did not correlate so well with concentrations of calcium, potassium, phosphate, carbonate, sulphate, or nitrate ions added to the soil (6). While the favorable effect of alkaline substrata may not necessarily be due directly to the hydrogen-ion concentration, it has not yet been accounted for in any other way.

The possibility of changing soils to make them unsuitable for root rot has been considered in several of the experiments in this Bulletin. It was found impracticable to acidify calcareous soils with a fairly high lime content. This excludes most of the areas in which root rot is most destructive, but still leaves for possible consideration extensive regions in which root rot occurs even though the soils are not highly calcareous.

Experiments with such less highly calcareous soils indicated that large applications of sulphur to these soils might cause crop injury, while at the same time root rot was not quickly eradicated from the unchanged deeper soil layers. In later experiments, smaller applications of sulphur were made so that cotton grown here was not damaged. At the same time, the acidity from these surface applications of sulphur gradually penetrated the soil to several feet deep and apparently lowered the losses from root rot.

While root rot was not eradicated in any of the plat experiments, these results and also some with cotton plants grown in the containers have emphasized the special importance of the pH of the surface soil layer in determining the continued prevalence of root rot. Root rot was apparently eradicated in some of the containers by relatively shallow surface layers of acid soil, despite favorable alkaline subsoil below. In the field plats, the disease spread in over very acid subsoil at points where the surface soil remained or became neutral. This has suggested that further experiments with sulphur for the control of root root should be planned to determine the possible value of intermittent, repeated applications of small amounts of sulphur to the surface of non-calcareous soils.

It may be well to point out that soil acidification for the control of root rot is still in the experimental stage, and is not recommended now for practical use even in those non-calcareous soils in which it may later be found of value.

SUMMARY

(1) Cotton plants grown in adjoining containers, filled with soils varying naturally in hydrogen-ion concentration, were inoculated artificially with root rot, caused by the fungus *Phymatotrichum omnivorum* (Shear) Duggar. Original incidence of root rot following the inoculation, rate of spread, and overwintering of the disease, were greater in the more alkaline soils and less in the more acid soils.

(2) Many other experiments were made with cotton plants in containers of soil materials adjusted to different hydrogen-ion concentrations by additions of sulphur, sulphuric acid, calcium sulphate, ammonium sulphate, lime, or sodium carbonate. Root rot was introduced by artificial inoculation. In general, only low percentages of infection or overwintering were obtained in soils more acid than pH 5.0. In slightly acid to neutral soils, of about pH 6.0 to 7.0, high percentages of infection were obtained following inoculation, but the percentages decreased in following years. In alkaline soils of pH 8.0 to 8.5 high percentages of original infection were obtained and the disease killed large numbers of plants for years thereafter.

(3) The acidity of the surface soil seemed of particular importance. In some cases, a six to twelve-inch surface layer of acid soil caused immediate or final disappearance of root rot. Acidification of the surface soil to at least pH 5.5 apparently was necessary to produce rapid decrease in the prevalence of the disease. With the surface layer left neutral or somewhat alkaline, even extreme acidification of the deeper soil did not eradicate root rot.

(4) Additions of manure, fertilizers, or of the rarer plant nutrients (manganese, sulphur, iodine, iron, nickel, copper, and boron) did not reduce incidence or overwintering of root rot. Additions of sodium carbonate made soil alkaline and less favorable for root rot; cotton plants were more tolerant of such artificially-produced "alkali soil" than was the root-rot fungus.

(5) Highly calcareous soils could not be acidified even by repeated heavy applications of sulphur. Sulphur applied in relatively large amounts on less calcareous soils, both in the field and in small containers, acidified the soil but injured the roots. Sulphur applications were made in small amounts without injury to cotton plants.

(6) In some small field plats of Lufkin fine sandy loam soil, sulphur was worked in to various depths and root rot introduced by artificial inoculation. During the first two years of the experiment, root rot attacked only low percentages of plants in the treated plats. After this time, the disease spread rapidly in those portions of the plats where the surface soil layer had shifted back toward neutrality even though the subsoil had remained acid.

(7) In another test, in field plats in which root rot was already thoroughly established, sulphur was applied in small amounts in the surface soil only. The soil gradually became acid to depths of more

than two feet, over a period of two to three years, and shifted back toward neutrality thereafter. Root rot decreased in these plats in the earlier years of this experiment but became destructive again later.

(8) The experiments summarized in this Bulletin have proved that soils that are originally acid, or that are made acid by additions of various chemicals, are less suitable for infection of plants by the root-rot fungus, and less suitable for continued survival of the fungus from year to year, than are soils originally neutral to alkaline or made so by chemical additions. Unsuitability of acid soils to the root-rot fungus is not necessarily due directly to the hydrogen-ion concentration, but is associated more closely with this factor than with original differences in the soil types.

(9) Practical application of soil acidification to the control of root rot is still in the experimental stage. It is impracticable to acidify highly calcareous soils. For non-calcareous soils, further experiments should be performed to determine the value of repeated surface applications of small amounts of sulphur.

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