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DIVISION OF PLANT PATHOLOGY AND PHYSIOLOGY

Cotton Root-Rot and Its Control

AGRICULTURAL AND MECHANICAL COLLEGE OF TEXAS

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Root-rot occurs in at least 196 counties of Texas and in at least 30 soil series. Root-rot concerns not only those directly engaged in agriculture, but also persons living in cities and towns, since the disease attacks field and truck crops, fruit trees, ornamentals, shrubs, and shade trees.

Root-rot is caused by a fungus, *Phymatotrichum omnivorum*, which attacks the roots of susceptible plants and causes them to decay. The vegetative strands of the fungus are found on the diseased roots, and the spore-mat stage is formed on the surface of the soil above the affected roots. Resting bodies, or sclerotia, are formed in the soil near the diseased roots, and aid in the survival of the fungus.

Root-rot spreads from plant to plant chiefly along the roots rather than by independent growth for long distances through the soil. The root-rot fungus overwinters in an active, vegetative condition on the living though infected roots of susceptible crops, and continues to spread along these roots during winter even after the tops of the plants have been killed by frost. In a dormant condition, the fungus overwinters as sclerotia. Weeds aid in the overwintering of root-rot, since the fungus may survive on their roots.

Tentative recommendations for control are given. Emphasis is still placed on rotation with non-susceptible crops, together with clean culture, which should be practiced throughout the entire rotation period, both while the crops are growing and during fall, winter, and spring. Since sclerotia may survive in the soil for at least three years, rotations with grain sorghums, corn, wheat, oats, or other non-susceptible crops for three years are recommended.

Various other possible methods for the control of root-rot are still in the experimental stage, including, for instance, attempts to acidify soils, the use of soil disinfectants, fertilizers and manure, deep plowing and subsoiling, and testing and development of resistant varieties.

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COTTON ROOT-ROT AND ITS CONTROL*

By

J. J. TAUBENHAUS AND WALTER N. EZEKIEL

Root-rot is a disease which attacks not only cotton and other field crops such as alfalfa and cowpeas, and vegetable crops such as carrots and sweet potatoes, but also trees such as elms and chinaberries, and ornamental shrubs and flowers such as the privet, rose, and chrysanthemum. In the areas where it is serious, root-rot thus concerns the farmer, the truck grower, the nurseryman, the home gardener, and even those living in towns and cities who are interested in the beautification of home grounds or city streets and parks.

The fact that root-rot is caused by a fungus, *Phymatotrichum omnivorum* (Shear) Duggar, which attacks the roots of a number of plants, was first recognized by Pammel in 1888 (10).† The disease has since been studied by workers of the Texas Agricultural Experiment Station and of the United States Department of Agriculture, and considerable information about the disease has been acquired in this way. It is the object of this Bulletin to summarize this information, which has been published in various technical journals, in order to meet the frequent requests for such a summary, and to present a tentative outline of control methods which can now be recommended for use against root-rot.

To be effective, control methods must be based upon thorough knowledge of such facts about root-rot as the life history of the fungus which causes the disease and the conditions under which it persists. Further information of this nature is the object of studies now under way both in the laboratory and in the field. It is hoped that these studies will lead to improved methods of control, which will then be presented in later bulletins.

ECONOMIC IMPORTANCE OF ROOT-ROT

Root-rot is one of the most destructive plant diseases known. Annual losses from root-rot to the cotton crop of Texas are estimated at 10 to 15 per cent. This direct reduction in yield results from the early death of large numbers of plants, which thus produce few or no bolls. Even on infected plants which mature some bolls, the lint may be of a quality inferior to that of lint from normal plants and hence

*Root-rot investigations in Texas since 1928 have been carried on under a cooperative agreement between the Texas Agricultural Experiment Station and the Bureau of Chemistry and Soils and the Bureau of Plant Industry of the United States Department of Agriculture, and reports of investigations by these cooperating agencies will appear later.

†Reference is made by number to Literature Cited, p. 39.

may lower the value of the entire crop (25). Further loss may arise from the difficulty of harvesting cotton from plants killed by root-rot, since the cotton is hard to pull from the hardened, undersized, and often only partly-opened bolls of such plants. This has resulted in some instances in the abandonment of the crop in some fields with many dead plants. To the losses to cotton must be added damage to legumes, which are so severely injured as to interfere with their use in systems of rotation in places where the disease occurs. Including the damage to the many other kinds of plants on which root-rot occurs, the average aggregate annual loss from the disease in Texas is estimated as around $100,000,000.

DISTRIBUTION OF ROOT-ROT

Root-rot has been found in 196 counties in Texas as shown in the map (Fig. 1). This map indicates the distribution and relative preva-

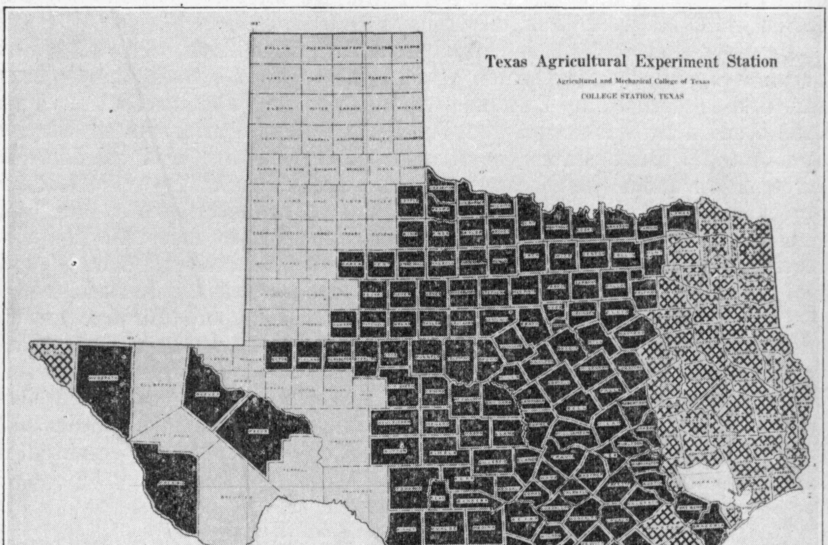

Fig. 1. Known distribution of root-rot in Texas. Black areas indicate counties where root-rot is more prevalent and causes considerable damage; shaded areas, counties where root-rot is known to be present but is less prevalent; white areas, counties where root-rot has not been found or where no record is available.

lence of the disease by counties only, and it should not be thought that root-rot occurs uniformly throughout each county. In regions where the disease is very prevalent, as in Central, Northwest, and South Texas and in part of West Texas, there are limited areas, chiefly of sandy soils, where the disease occurs less frequently than on plants growing in the prevailing dark calcareous soils. In Eastern Texas, root-rot occurs in soils which occupy comparatively small areas, but is rare in the prevailing sandy soils.

It is probable that root-rot may later be found in counties where it is not yet known to occur. So far as is known, root-rot is not an introduced disease, but originated in Southwest United States or in Mexico. It is common now on native plants even in virgin land in typical semi-arid regions, in the prairies, in sub-humid regions, and in the humid regions along the Gulf. The disease exists unsuspected on the roots of native plants in virgin soil, and is then discovered when the land is cleared and susceptible crops are grown.

Root-rot occurs not only in Texas but also in parts of Arizona, Oklahoma, New Mexico, Southern California, Arkansas, and Mexico. In Arizona and New Mexico the disease causes losses to crops grown in the irrigated regions. In Arkansas, root-rot has been found in only one county, and in Southern California, it has been found in a few locations. The actual distribution of root-rot in Mexico is largely unknown, but it has been reported from the Laguna District and in Lower California.

HOST PLANTS

Damage from root-rot is most conspicuous when it attacks important cultivated crops such as cotton or alfalfa, or large trees and shrubs such as peaches, figs, elms, and rose bushes. However, it is unfortunately not limited to such a relatively small number of plants. About 550 kinds of plants are now known to be susceptible to the disease. A few of the plants that are frequently attacked by root-rot are listed in Table 1, and a more detailed list of most of the plants which have been studied for resistance or susceptibility to root-rot may be found in Texas Station Bulletin 393.

Some plants are not attacked by root-rot. Among these may be mentioned all members of the grass family, which includes the grain crops such as corn, sorghum, wheat, oats, rice, etc. Most of the plants of the melon, onion, lily, mint, and asparagus families also appear to be highly resistant to the disease. The live-oak, hackberry, and sycamore trees are resistant after the seedling stage. Cabbage appears resistant to root-rot; and many other truck crops such as spinach, carrots, beets, and lettuce are susceptible to root-rot but usually escape infection when grown as fall, winter, or spring crops.

Root-rot attacks many non-cultivated plants, including the native weeds found in virgin lands, such as the common tievine (*Ipomoea trifida*), the ground cherry (*Physalis mollis*), the horsenettle (*Solanum carolinense*), and also many introduced weeds which grow in cultivated fields and along road-sides and fence-rows. The survival of root-rot on these weeds from one year to another makes it difficult to control root-rot by rotation, unless, as will be discussed later, care is taken to destroy these weeds.

Table 1.—Some of the plants that are commonly attacked by root-rot.

Field and vegetable crops	Fruits	Trees and ornamentals	Non-cultivated plants (weeds)
Alfalfa	Apple	Chinaberry	Cockleburs
Beans	Apricot	Dahlia	Crotons
Beets	Blackberry	Elms	Four-o'clock, wild
Carrot	Fig	Lilac	Ground-cherries
Clovers	Grapes	Locust	Goldenrods
Cotton	Jujube	Maples	Mallows
Cowpea	Peach	Mulberries	Morning-glories
Okra	Pear	Pecan	Pigweeds
Soybean	Persimmon	Poplars	Ragweeds
Sweet clovers	Plum	Privet	Sunflowers
Sweet potato	Quince	Rose	Thistles
Tomato	Raspberry	Spruces	Vetches, wild

DESCRIPTION OF THE DISEASE

The first symptom of root-rot to be seen above ground is a slight yellow to yellowish-bronze discoloration of the leaves of affected plants. Soon after, the upper leaves of the plant may droop and wilt, while the lower leaves remain turgid. This is particularly noticeable early in the morning. This is followed by sudden wilting and drooping of all the foliage of the affected plant (Fig 2). It is by this sudden wilting of the foliage that the presence of the disease is usually first recognized. With plants such as cotton or alfalfa, the foliage may wilt completely within ten to twelve hours after the first slight wilting. Some plants may revive at night to wilt permanently the following day. Leaves of wilted cotton plants feel warmer to the touch than do the leaves of undiseased plants; and preliminary measurements (4) show that the temperature of affected leaves may be 2° to 5° F. higher than that of otherwise similar leaves on nearby normal plants. With shrubs and trees, the leaves yellow and shed prematurely, while the plants may survive for a number of seasons before they finally wilt and die. Not infrequently, however, trees and shrubs die quite rapidly after infection.

Wilting of plants caused by root-rot is always preceded by decay of the roots. There are other conditions which may make plants wilt, but without causing immediate decay of the roots. Thus the Fusarium wilt of cotton does not cause marked deterioration of the roots; neither drought nor root strangulation (24) is accompanied by decay; nor does alkali produce a rotted condition. Presence of root-rot is certain when parts of the roots are decayed by the time the plant wilts, and when the characteristic strands of the fungus which causes the disease are found on these decayed roots.

The progress of root-rot on cotton plants is similar to that on other herbaceous plants. With trees, the symptoms are similar except that affected trees do not succumb so rapidly to the disease, probably on account of the more extensive root systems. Typical root-rot on cotton plants may be described from some inoculated plants grown in experimental containers (5). Within a week after the inoculation, the taproots were covered often for distances of more than six inches with the characteristic fungus strands, which were mostly whitish but in places were already assuming the characteristic yellowish-buff color. At this time, the plants showed no signs of the disease above ground. Five days later (12 days after the inoculation) some of the plants began to wilt. Sharply depressed, dark-brown lesions were found by this time on the roots even of plants that had not yet wilted. These lesions enlarged and merged, frequently involving most of the surface of the taproots and girdling them before the plants wilted, apparently from lack

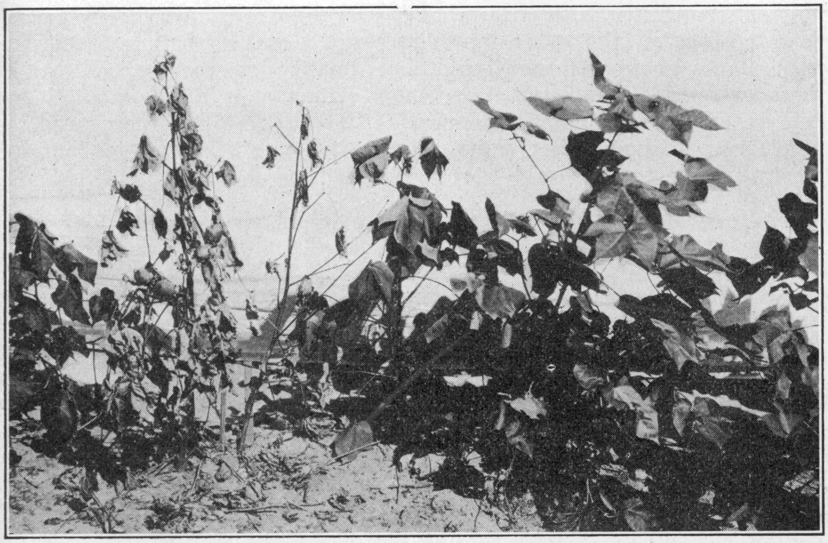

Fig. 2. Cotton plants with Phymatotrichum root-rot, showing dead, recently wilted, and healthy plants.

of water. By the end of three weeks, most of the inoculated plants had succumbed.

In the rotting of the roots, the outer tissues decay and soften before there is much injury to the central woody cylinder. Gradually, the disease involves more and more of the root system, which decays and is reduced finally to a soft, friable condition. With cotton roots, there is a very characteristic reddish-brown discoloration of the inner tissues of the roots, beyond the rotted area. This discoloration extends into both the infected tissues below and the sound tissue above, and reddened streaks extend inside the stem even to an inch or so above the surface of the ground.

The decay is confined to the particular portions of the roots invaded, the uninvaded areas remaining alive for months or years (depending on the host plants) after part of the root and the top of the plant have been killed. Thus after the top of a plant has wilted and died and the tap-root has rotted and disintegrated in the soil, there may remain, at the periphery and below the area of infection, numerous parts of roots, still alive and still harboring the root-rot fungus. However, the disease may eventually extend to the ends of the roots. The fungus followed the roots of 2-year-old alfalfa plants and of jujube trees to a depth of eight feet (18).

Infected plants do not always succumb, however. Some plants recover by sending out new lateral roots above the infected part of the tap-root, and these plants may survive for a short time only, or persist for some months, or occasionally recover completely. This has been noticed frequently with alfalfa and sweet clover following irrigation. With cotton, on the other hand, recovery seems to be more common with plants grown without irrigation, during dry weather. Either of these extreme soil-moisture conditions evidently is unfavorable to the fungus. With resistant plants such as the Turk's-cap Hibiscus and the pomegranate, the young plants become infected with root-rot but are generally able to develop new root systems and recover completely.

THE CAUSE OF ROOT-ROT

Root-rot is caused by a fungus, technically known as *Phymatotrichum omnivorum* (Shear) Duggar, which may be readily seen even with the naked eye on the roots of plants that are affected by the disease. This fungus is invariably present on the roots of plants with root-rot. The fungus has been repeatedly isolated in pure cultures from naturally infected plants from the field. Pure cultures of the fungus and sclerotia produced in pure cultures (25, 7, 20) have been used to inoculate normal plants, and the inoculated plants succumbed to root-rot while uninoculated, check plants kept under the same conditions remained normal. The fungus has been reisolated from the inoculated plants, and proved to be identical with the original cultures and with the organism as found on naturally infected roots in the field. This chain of evidence, very briefly summarized here, constitutes the scientific proof that the fungus, *P. omnivorum,* is actually the cause of root-rot.

In addition to the inoculations from pure cultures, literally thousands of plants have been artificially inoculated with root-rot by a method that has been developed for field work on a large scale (16). The tap-root or lateral roots of a freshly infected plant are inserted in the ground, close to the roots of a healthy plant, and water is then applied copiously. High percentages of infection have been secured in inoculations of various plants with diseased cotton and alfalfa roots, and reciprocal inoculations have been equally successful. These results of cross-inoculations, some of which are summarized in Table 2, indicate that the same fungus causes root-rot on many different kinds of plants.

Table 2.—Cross-inoculations of various plants in the field, using naturally-infected roots as inoculum; College Station, Texas, 1927.

Kind of root inoculum used	Plants inoculated		Per cent of plants with root-rot
	Kind	Number	
Cotton	Cotton	2714	81
Cotton	Fig	25	100
Cotton	Guar	260	83
Cotton	Jujube	25	72
Cotton	Mulberry	15	100
Cotton	Pomegranate	870	4
Cotton	Rose	27	70
Alfalfa	Cotton	140	27
Fig	Cotton	250	92
Grape	Cotton	114	78
Jujube	Cotton	160	100
Olive	Cotton	23	74
Peach	Cotton	111	91
Mulberry	Fig	25	100

LIFE HISTORY OF THE ROOT-ROT FUNGUS

An important part of the study of any plant disease is to find all the various stages of the organism which causes the disease. It is necessary to know by what means the organism reproduces itself, and how it survives dry weather, the cold of winter, or other unfavorable conditions. The final aim of such study is to find some way to check the growth of the fungus during some particularly vulnerable period of its life cycle, thus causing it finally to die out. Detailed studies have been made on the life history of the root-rot fungus, and should be continued until sufficient information has been accumulated to furnish an adequate basis for the development of control methods.

Stages of the root-rot fungus

At least three stages of the fungus are already known: the vegetative stage, which attacks the roots of plants; the resting, or sclerotial stage, by which the fungus can survive conditions unfavorable to the vegetative stage; and the spore-mat stage, whose function is yet unknown.

The vegetative or Ozonium stage. The vegetative stage of the root-rot fungus consists of the strands which grow on the roots of infected plants, and which spread also to some extent into the soil near the diseased roots. It is this stage of the fungus which causes the damage to plants. The vegetative stage is involved also in the spread and overwintering of the fungus, as will be discussed below.

The vegetative strands are white when they first grow over the roots, but by the time the plant has wilted, the strands have usually turned to a yellowish-buff color. They consist of parallel hyphae or fungus threads, which anastomose frequently. The individual hyphae resemble those of Rhizoctonia in the mode of branching and septation. Surrounding the strands is a characteristic fine fuzzy coating, which consists of short upright hyphae, with acicular or needle-like tips arising from the typically cruciform branching (Fig. 3, *a*).

The resting or sclerotial stage. The resting stage of the root-rot fungus consists of small, dark, firm, rounded bodies, known as sclerotia, usually smaller than radish seed, which are produced as enlargements of the vegetative strands in the soil near infected roots. Sclerotia have been found most abundantly at depths of eight to twenty-four inches in the soil. They may be formed either singly, in chains, or in clusters (Fig. 4, *c*). The individual sclerotia are spindle-shaped to spheroid, with a dark buff outer layer and a lighter-colored interior of pseudoparenchymatous tissue. The developing sclerotia are first creamy-white and covered with the typical fuzzy growth of acicular branches. As they mature, the outside darkens to buff and then finally to a deep brown, and the fuzzy growth gradually disappears.

Normal cotton plants have been inoculated with sclerotia produced under natural conditions and with a pure culture isolated from a sclerotium and both series of plants succumbed to root-rot, thus proving experimentally that the growth from sclerotia is able to infect cotton plants and to produce typical root-rot. Field observations discussed below indicate further that the sclerotia are an important means of overwintering.

In addition to the typical sclerotia, some specialized strands, which have been found in the field, appear to function much like the sclerotia (1). These dark, usually smooth, strand-sclerotia have been found in locations where they apparently had overwintered and acted as centers of infection for the 1929 crop. These strand-sclerotia differ from the typical vegetative strands in that the fuzzy growth of acicular branchings disappears as the dormant strands become older. B. F. Dana has reported inoculation of cotton plants with overwintered strand-sclerotia (1), which may apparently be considered similar to ordinary sclerotia except that they are formed under some conditions that inhibit development into the rounded shapes typical of sclerotia.

The widespread and frequent occurrence of sclerotia in the field has been proved by extensive excavations. Sclerotia were found in Bell, Brazos, Fort Bend, Hidalgo, Jim Wells, Milam, Nueces, Refugio, San Patricio, Washington, Wharton, Wichita, and Williamson counties; and in the following soils: Brennan fine sandy loam, Crockett clay loam, Crockett clay, Duval fine sandy loam, Lake Charles clay, Lufkin fine sandy loam, Miller clay, Orelia clay loam, Orelia fine sandy loam, Trinity clay, Victoria clay, Victoria clay loam, Wilson clay loam, and Yahola clay loam. Sclerotia have been found in fields of infected garden beets, carrots, sugar beets, okra, and sweet potatoes, as well as of cotton.

True sclerotia were described in 1928 (8) and sclerotia were found in the field for the first time during the summer of 1929 (9, 1, 20). King and Loomis (8) were able to develop sclerotia in cultures of the root-rot fungus on sterilized sand and old cotton stems, and Dana (1) as well as the writers (20) found that the growth from freshly infected

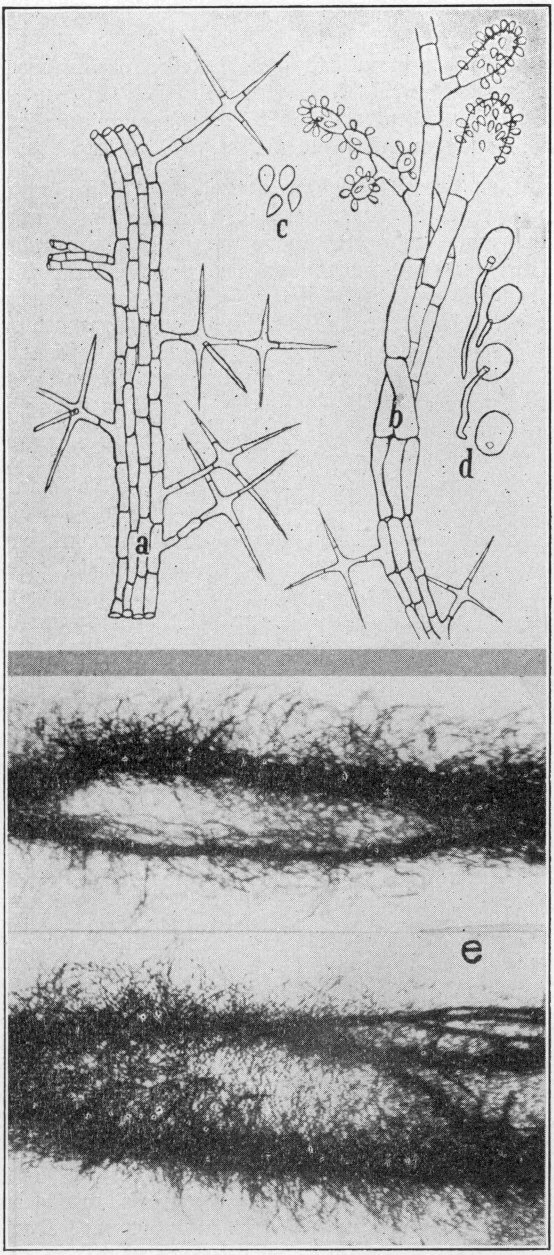

Fig. 3. *Phymatotrichum omnivorum,* the fungus which causes root-rot. *a,* an individual vegetative strand with the accompanying typical acicular branches; *b,* morphologic connection of conidia-bearing cells of Phymatotrichum above ground with the underground vegetative strands beneath, as observed under the microscope; *c,* individual conidia; *d,* germinating conidia; and *e,* photo-micrograph of typical strands as found on roots of diseased plants. (All much enlarged.)

carrots and cotton roots in moist, unsterilized soil produced large numbers of sclerotia. Sclerotia were also produced in the laboratory at College Station in pure cultures of *P. omnivorum* on sterilized cotton stems and in cultures on synthetic media.

The spore-mat or Phymatotrichum stage. The spore-mat, or asexual, conidiospore stage is the only part of the life cycle of the root-rot fungus that is known to occur above ground. Spore-mats are found occasionally during warm, moist weather, usually near infected plants or where plants have previously died from root-rot. The spore-mat appears first as a small, whitish, flat but fluffy fungus growth on the surface of the ground. It increases rapidly to an elevated, flattened, cushion-like mass two to eighteen inches in diameter and usually less than one-fourth inch in thickness (Fig. 4, *a* and *b*). The entire exposed portion of the spore-mat turns eventually into a mass of extremely minute, buff-colored spores, which gradually blow away. The conidiospores themselves are hyaline, globose to ovoid, and 4.5 to 7 microns in diameter (Fig. 3, *b* to *d*).

Careful microscopic study has shown continuity of hyphal growth from the underground strands, with their characteristic acicular branchings, to the conidia-bearing mycelium of spore-mats above ground (Fig. 3, *b*); and the Phymatotrichum stage has been found in pure culture (25). There can therefore be no doubt that the vegetative Ozonium stage and the Phymatotrichum conidial stage are stages in the life cycle of the same fungus.

Only low percentages of germination have been secured with the spores, and the germ-tubes produced from such spores soon disintegrated. Inoculations of plants with these spores so far have also proved unsuccessful; it is therefore not yet known whether they can play a part in the spread or overwintering of root-rot.

Spore-mats have been found on some but not all soils in which root-rot is prevalent. Spore-mats have been observed on Bell clay, Crawford clay, Houston black clay, Lake Charles clay, Miller clay, Orelia clay loam, Trinity clay, Victoria clay loam, Wilson clay, and Yahola clay loam soils. On the other hand, they have rarely been found on Lufkin fine sandy loam, and none have yet been found on any of the Crockett soils.

A possible perfect stage. Most fungi have a perfect, or sexual, spore stage in addition to asexual, imperfect stages. A fungus growth known as Hydnum has been found near plants with root-rot, and has been suspected of being the sexual spore stage of the root-rot fungus (14). The writers have isolated cultures from the tissues of a Hydnum found on cotton plants killed by root-rot. There was no resemblance between these diploid cultures and cultures of *P. omnivorum*. During the summer and fall of 1930, Hydnum fructifications were produced profusely along the sides of holes dug near cotton plants growing in an experimental field at College Station. But the Hydnum appeared not only in that part of the field in which root-rot was prevalent, but also in holes sunk 57 feet beyond this area, in a portion of the field in which cotton plants had not been attacked by root-rot for at least five years. Cotton plants were inoculated with masses of mature spines containing many basidiospores, but none became infected, while parallel inoculations with infected roots and with sclerotia caused rapid development of root-rot. This Hydnum is therefore probably not a stage of the root-rot fungus. Certain other fruiting stages are suspected of being the perfect stage of the root-rot fungus and are now being investigated.

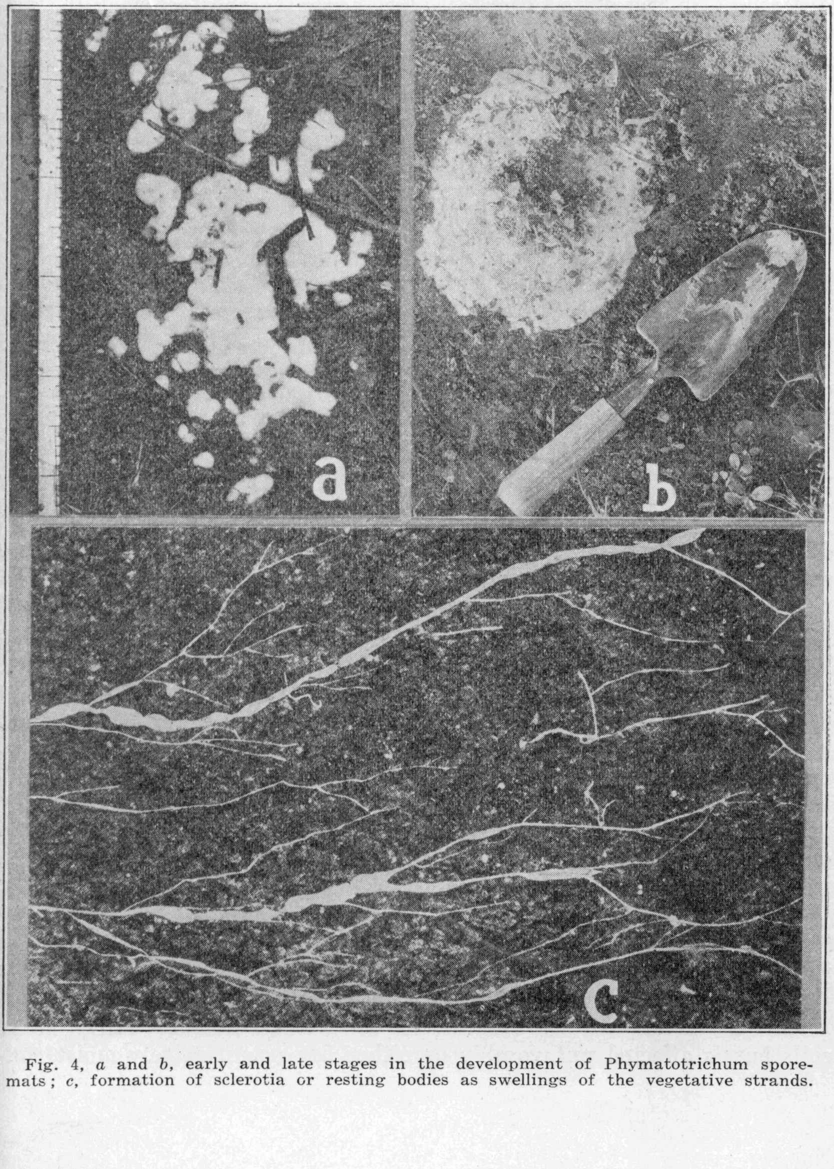

Fig. 4, *a* and *b*, early and late stages in the development of Phymatotrichum spore-mats; *c*, formation of sclerotia or resting bodies as swellings of the vegetative strands.

Soil and Weather Conditions Affecting Root-rot

While root-rot occurs extensively throughout Texas, there are certain sections in which it has as yet been less destructive than it is elsewhere. For instance, in East Texas root-rot has been less prevalent than in the blackland regions of Central and South Texas. It is of importance to know whether such differences in the distribution of the disease are due to permanent differences in the soil or climate of the various regions, and are therefore likely to continue, or whether the differences in the distribution are due merely to the fact that the disease has not yet been introduced. Furthermore, even where it is prevalent root-rot does not cause the same amount of loss every year (15). Studies have been initiated to determine the probable cause of differences in the distribution of root-rot, and also of differences in destructiveness in the same region during various periods. Such studies are of further importance because the discovery of natural conditions which keep the disease in check may furnish clues to the development of effective methods of control.

Soils. It was formerly considered that root-rot was confined to the black waxy soils, particularly the Houston clay soils, in which it is so destructive. The disease has now been found in some soils in nearly every section of Texas, as shown in Fig. 1. Root-rot attacks plants growing in clay, loamy, and sandy soils. The disease has been found in soils of various textural classes in the following important soil series: Abilene, Bastrop, Bell, Brennan, Catalpa, Crawford, Crockett, Denton, Duval, Guadalupe, Hidalgo, Houston, Johnston, Kirvin, Lake Charles, Laredo, Lufkin, Milam, Miller, Norfolk, Orelia, San Saba, Susquehanna, Tabor, Trinity, Victoria, Webb, Willacy, and Yahola. Considerable differences in the destructiveness of root-rot have been found to be associated with differences in the soil reaction, that is, the acidity or alkalinity of the soil, as will be discussed below. Some work now in progress is planned to ascertain to what extent the prevalence of root-rot may be influenced by differences in soil texture or other characteristics in addition to the reaction.

Temperature relations. The development of root-rot has been found to be favored by summer temperatures (15). During the growing season for cotton, the temperature is favorable for the disease. The lowered soil and air temperatures of fall cause an abrupt decrease in wilting of plants from root-rot. Even those plants that are already badly injured by root-rot usually do not wilt during fall or winter, but the disease continues to advance along the roots, spreading, even after frost, to plants previously uninfected. Fig. 5 illustrates graphically the spread that occurred during late fall, winter, and early spring in two cotton fields in Brazos County (20). Spread during winter is probably general, the extent of winter spread being determined in any locality by the soil and weather conditions.

Moisture relations. In general, root-rot is favored by fairly moist soils but is affected unfavorably by either dry or excessively moist con-

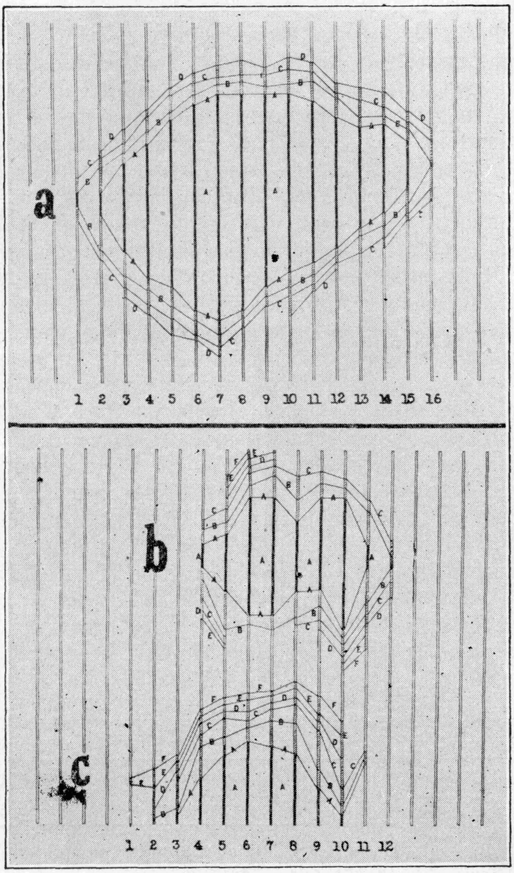

Fig. 5. Spread of root-rot along cotton roots during winter; *a,* in field with a single large root-rot spot; *b* and *c,* in another field with two root-rot spots. Solid lines and areas included by line A indicate limits of infection on the roots on September 30, 1927; spread along roots during winter to B, by October 27; to C, by November 30; to D, by December 20; to E, by January 22; and to F, by February 20.

ditions. Observations on the progress of root-rot in the field (15) indicate that moist soil favors the spread of the disease and that soil moisture is the usual limiting factor during the growing season when the temperature conditions are favorable. Root-rot appears to be checked during droughty periods. Thus, during both 1929 and 1930, there were losses from root-rot early in the season following rainy weather, but after the droughts which began in June of both years there was little further spread and relatively low losses from the disease occurred during these seasons.

One of the most interesting facts in the local distribution of root-rot is that in Texas the disease rarely occurs on crops growing in creek or river bottom lands that are subject to periodic overflows. Soils in such places are not unsuitable for root-rot, since cotton plants growing in a typical creek bottom were successfully inoculated and root-rot reappeared on the following crop (22). It therefore seems possible that conditions of excessive soil moisture during or following periods of inundation are responsible for the absence of the disease in these places.

An experiment (22) has been carried out to determine the effect of flooding on the vegetative stage of the fungus, as it occurs on cotton roots. Naturally-infected cotton roots were stored in crocks of saturated soil, and others in crocks of air which was kept moist by a layer of soil below the roots and a loose cover above. Periodically, the virulence of the fungus on the roots was tested by taking 16 roots of each of the series as designated in Table 3, and inoculating 10 to 12 normal cotton plants. The results showed that vegetative strands on infected cotton roots were no longer virulent after the roots had been stored in flooded soil for only a few days, while at the same temperature the fungus was still virulent for at least two weeks on the roots that were stored in moist air. In field experiments (22) carried on at Iowa Park, however, root-rot was not controlled by flooding the surface of the land even for 120 days. This failure to obtain control by flooding is probably to be ascribed both to the lack of as complete saturation of the soil in the field as was obtained in the laboratory experiment, and to the possible presence of sclerotia, which have been shown (3) to withstand long periods of immersion.

Table 3.—Virulence of the root-rot fungus on tap-roots of naturally-infected cotton plants as affected by storage in flooded soil, in moist air, and at low temperatures.

Date	Time interval since experiment started	Tests of virulence by inoculations on normal cotton plants; successful inoculations indicated by "+" and lack of infection by "—."			
		Roots stored in flooded soil, at 67°-80° F.	Roots stored in moist air, at 67°-80° F.	Roots stored in moist air, at 34°-36° F.	Checks. Roots collected in the field at each date of testing
1929					
Sept. 11	0 (initial)	+	+	+	+
Sept. 12	1 day	+	+	+	....
Sept. 14	3 days	—	+	+	+
Sept. 18	1 week	—	+	+	+
Sept. 25	2 weeks	—	+	—	+
Oct. 2	3 weeks	—	—	+	+
Oct. 9	4 weeks	—	—	—	—
Oct. 23	6 weeks	—	—	—	+
Nov. 6	8 weeks	—	—	—	—

Soil reaction. The occurrence and destructiveness of root-rot are influenced directly by the reaction of the soil or by some other factor associated with the soil reaction. Alkaline soils favor the disease, whether the alkalinity is a natural characteristic of the soil or is produced by additions to the soil, and whether the soil is in its original location or is transported to some experimental container. Similarly, acidity of soils tends to inhibit the incidence, destructiveness, and overwintering of root-rot whether the acidity is natural or artificial.

As was mentioned above, root-rot is markedly more destructive in the blackland regions of Texas, where the soils are mostly alkaline in reaction, than in Eastern Texas where many of the soils are somewhat acid. Thus in a field survey of sixteen counties (21), root-rot was found in 34 per cent of the fields with acid soils of pH 5.5 to 6.4, in 60 per cent of the fields with soils of pH 6.5 to 7.4, and in 71 per cent of fields with definitely alkaline soils of pH 7.5 and above. Extensive experiments have since been carried out, first, to find whether the correlation observed was with the soil reaction rather than with regional or climatic conditions, and second, to find the degree of acidity that might be necessary to check the spread of root-rot.

Evidence that the occurrence of root-rot is controlled by differences in soil reaction was furnished by an experiment started in 1928. Soil material of seven different types was placed in large wooden boxes at College Station. Cotton was planted in a row down the middle of each box, and root-rot introduced by repeated artificial inoculation in 1928 at only one end of the row in each box. There was no additional artificial inoculation during 1929 and 1930. As may be noted in Table 4, the results were in accord with the reaction of the various soils. Root-rot spread during 1928 to greater distances in the more alkaline soils, that is, in those with the higher pH values. No spread occurred in the most acid soils. Only one of the inoculated plants died in the soil with a pH of 5.5 and not one plant in the Tabor soil with pH 5.8 (Fig. 6). The disease overwintered successfully and reappeared in 1929 in every container in which there had been any infection the previous year. Root-rot appeared again in 1930, and again caused greater losses in the more alkaline soils than in the acid soils.

Table 4.—Inoculation experiment with rows of cotton in containers filled with soils of different reactions.

Soil type	pH of soil (0-2 feet deep)	Spread of root-rot along rows during 1928, feet	Percentage of plants infected		
			1928	1929	1930
Susquehanna fine sandy loam, shallow phase	5.5	0	2	8	0
Tabor fine sandy loam, shallow phase	5.8	0	0	0	0
Och'ockonee clay loam	6.3	4	27	59	20
Tabor fine sandy loam	6.7	4	29	34	0
Kirvin fine sandy loam	7.1	5½	30	80	44
Caddo fine sandy loam	7.6	7½	53	82	31
Houston black clay	7.7	7½	74	100	93

A number of other experiments (5) have been carried out, in some cases with soils varying naturally in their reaction and in other cases with soils in which the reaction was adjusted artificially by the addition of various materials. Cotton plants were grown in these soils and inoculated with root-rot. In every experiment, the percentage of infection and the percentage of plants killed by root-rot were higher in the neutral or alkaline soils than was the case in the acid soils. The average interval between the inoculation and the wilting of plants was slightly longer in the acid soils; and root-rot spread a shorter distance as well as more slowly in the acid soils than in neutral or alkaline soils. There was a marked diminution of root-rot at about pH 6.0, and no root-rot appeared in containers with the soil as acid as pH 5.0.

Sulphur applied to the soil is oxidized by bacteria to sulphuric acid, and if a sufficient quantity is applied, will make the soil acid. Pre-

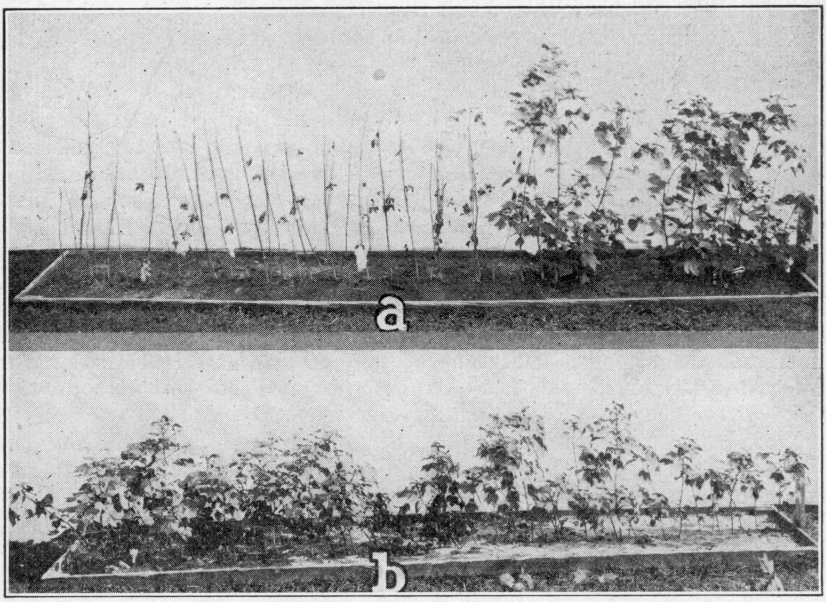

Fig. 6. Effect of differences in soil reaction on spread of root-rot along rows of cotton plants inoculated repeatedly at the left end; *a*, in box of Houston black clay, pH 7.7, in which root-rot had spread more than half way down the row by November 15, 1928; *b*, in box of Tabor fine sandy loam, pH 5.8, no root-rot.

liminary tests with sulphur for the control of root-rot have been carried out in containers and in field plats. In both series, the sulphur was mixed only with the surface soil and acidified only the surface layer. Root-rot was reduced but not eliminated even with surface soils as acid as pH 3.4, when this acidity extended only to depths of three to six inches. Acid injury of the cotton roots occurred in surface soils acidified to pH 2.0 to 4.0, even though the subsurface was still neutral or alkaline. These results indicate that while use of sulphur for the acidification of soils may be a possible method of control in soils low in lime, it is necessary to devise means for mixing the sulphur uniformly with the soil to a depth of perhaps one foot, and to avoid applying excessive amounts, which may cause injury to crops.

Experimental Studies on Avenues of Spread

Knowledge of how root-rot spreads from plant to plant and from field to field is important in understanding the general behavior of the disease. So far as we know, the root-rot fungus spreads only by the slow growth of its vegetative strands. It has already been suggested (25) that spread occurs as these strands grow along the roots of the infected plant to some point where the roots come near or in contact with those of adjoining plants. It has also been suggested (11) that root-rot might spread also independently of the roots. the fungus strands launching out and advancing in the soil in all directions without regard to the distribution of roots. Some studies on this question of the avenue of spread from infected roots will be summarized below.

Inoculation with soil from root-rot spots. A number of experiments were based on the hypothesis that if the fungus advances into the soil independently of roots, the soil in the active zones of root-rot spots, that is, at the edges of the spots, should contain the advancing hyphae and might thus be infective when used as inoculum. Inoculations were made with cubes of soil taken from next to recently wilted plants in the active zones of root-rot spots in cotton fields near College Station. Although 2,367 healthy cotton plants were inoculated at different times with such cubes of soil, none developed root-rot; while of the 225 plants that were inoculated with infected roots, 180 were attacked by the disease (18).

Experiments with soil from which roots were removed by sifting. To test further whether the soil carries the fungus even when free of roots, three different soils were secured, in each case from active zones of root-rot spots, and transported to College Station. Half of the soil of each type was sifted to remove all roots which did not pass through the one-fourth-inch mesh sieve, and the other half used as secured (18). The soil was placed in long containers, and a row of cotton was planted

Table 5.—The effect of sifting soil to remove roots on the subsequent appearance of root-rot on cotton plants grown in the soil.

Soil	Original treatment, fall of 1927	1928 results		1929 results		1930 results	
		Number of centersof root-rot	Percentage of plants infected	Number of centersof root-rot	Percentage of plants infected	Number of centersof root-rot	Percentage of plants infected
Lufkin fine sandy loam	Sifted	0	0	0	0	0	0
	Unsifted	2	84	4	76	2	87
Wilson clay loam	Sifted	0	0	0	0	0	0
	Unsifted	2	52	2	6	1	3
Crockett clay loam	Sifted	0	0	0	0	0	0
	Unsifted	2	81	6	100	2	3

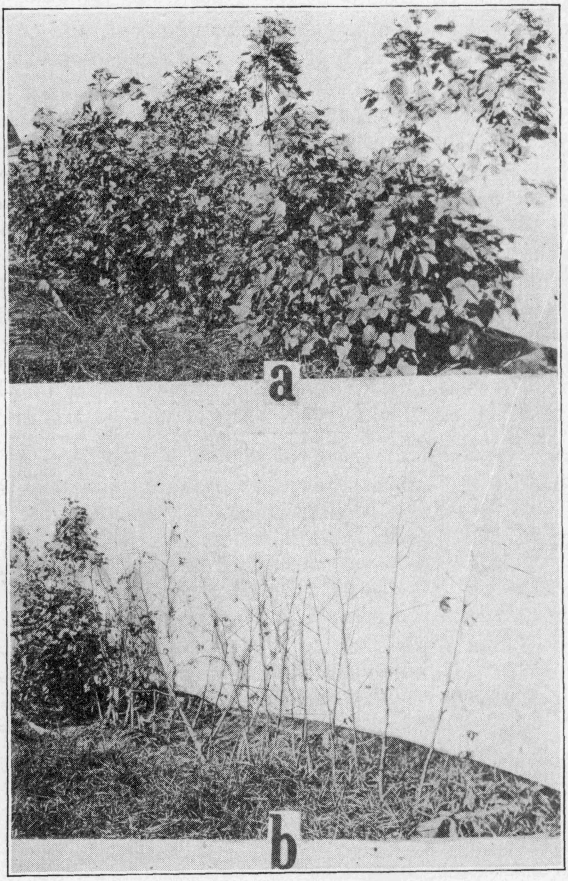

Fig. 7. Rows of cotton grown in 1928 in containers filled with Lufkin fine sandy loam originally taken from active root-rot zones. *a*, sifted soil, no root-rot appeared; *b*, unsifted soil, 83 per cent root-rot.

down the middle of each container in 1928, in 1929, and in 1930. As shown in Table 5, root-rot appeared in each container of unsifted soil, but did not appear in the sifted soil even after two years (Fig. 7).

Sifting of the soil does not render it unsuitable for later reintroduction of the disease. Crockett clay loam soil was sifted, placed in small boxes in some of which infected roots were also included, and cotton was planted. Root-rot attacked the plants in the sifted soil to which root inoculum had been added, but none appeared in the check boxes of sifted soil without root inoculum. It therefore appears that the absence of root-rot in sifted soil was probably due to the elimination of the infected roots, rather than to possible physical changes in the soil as a result of the sifting.

Field excavations around infected plants. If the root-rot fungus spreads in the soil independently of roots, it should be possible to detect this spread by careful dissection and examination of the soil around isolated infected plants, since the fungus strands can be readily seen, even in soil, by careful examination with the naked eye or with the hand lens (18). In 1929, 117 infected cotton plants were carefully excavated. No evidence was found of infection resulting from spread through the soil independently of roots while in every excavation the fungus was found traveling along the lateral roots and along even the finest rootlets, and spreading from plant to plant apparently as the result of complete or proximate root contact. Near the centers of well advanced root-rot spots, isolated strands were found occasionally which appeared to be advancing in the soil independently of roots. These strands were frequently following openings made by insects or earthworms, or were clinging to remnants of rootlets that had almost completely decayed.

Laboratory studies on growth of the fungus through soil. Further information on the possibility of growth of the root-rot fungus through the soil has been obtained from studies on the growth of the fungus in soils in glass containers in the laboratory (8, 18, 1). The fungus strands grew to a considerable distance over the surface soil and to greater distances, often 2 to 3 feet, between the soil and the glass walls of the containers. It was found (18) that growth was confined almost exclusively to those surfaces, and that the soil itself was penetrated by the strand growth only at a few points and only to a distance of about half an inch. In later experiments, it has been possible to obtain strand growth for a distance of at least four inches through the loose soil from inoculum placed in the middle of containers.

These studies thus show that at least in the laboratory, the fungus can extend into the loose soil, independently of roots. We have as yet little information as to just how extensively such spread of strands in the soil may occur in the field, and no direct evidence that spread of root-rot from plant to plant occurs as a result of such spread for any considerable distance independently of roots. It has been proved that root-rot can spread from infected roots to adjacent normal roots; whether it spreads also by very extensive growth of the fungus through the soil independently of roots is still under investigation.

Possible spread by spores. At least one spore stage (the spore-mat or Phymatotrichum stage) is known to be a part of the life cycle of the root-rot fungus, but there is as yet no evidence that spores are concerned in the spread of the disease. As previously stated, no successful inoculations have yet been obtained with the spores. There is negative evidence in the fact that no cases have been found in which root-rot had arisen sporadically at distances from previously infected plants and in the absence of apparent sources of infection, as might occur were the disease spread by spores blown by the wind or borne by water. In alfalfa fields, spore-mats have been observed in irrigation ditches, and spores from these mats have been spread by the irrigation water throughout the fields. No scattered infections resulting from these spores have been observed, further spread of root-rot remaining confined to that from the original centers observed earlier in the season.

Overwintering on Infected Roots of Cultivated Plants

In the study of overwintering, we are concerned with finding in what ways the fungus survives the unfavorable conditions of winter. The final aim of such studies is, of course, to find how to prevent this survival of the fungus, and in this way to develop methods that can be used to control the root-rot disease. The fungus is now known to survive in the vegetative condition on the roots of crop plants and of weeds, and as resting bodies in the soil.

While the tops of cotton plants always succumb to the first killing frost in the fall, the roots of such plants are not killed by the frost, and many survive the entire winter (20). The root-rot fungus overwinters on these roots, apparently by spreading gradually during fall, winter, and spring, and infecting the parts of the roots that were still unattacked at the time of frost. The results presented below are evidence that the vegetative stage of the root-rot fungus remains viable, on infected roots in the ground, only so long as such roots remain undecayed and apparently only in the vicinity of the undecayed tissue.

Occurrence of root-rot on overwintered roots. Overwintered cotton roots frequently are infected with root-rot. In Table 6, observations are presented on the occurrence of root-rot on the overwintered roots of plants near root-rot spots. Root-rot lives over similarly on the roots of trees and shrubs, as well as of herbaceous plants such as okra, peppers, sweet potatoes, and eggplants.

Viability of P. omnivorum on overwintered roots. Cultures were made in attempts to isolate the root-rot fungus from infected material collected at different times of the year. The organism was readily isolated from cotton roots collected during the fall, winter, and spring months, though it will be noted (Table 7) that the percentage of pure cultures obtained diminished as the age of the material in the fields increased. The fungus was readily isolated from infected living roots, but not from roots which were infected but decayed, which agrees with other evidence (20) in indicating that *P. omnivorum* survives in an active condition in the partially decayed portions of roots that are attacked by root-rot rather than in the completely decayed portions of the same roots.

Inoculation of normal plants with overwintered, infected cotton roots. Overwintered infected cotton roots from Weslaco were used on March 13, 1929, to inoculate cotton plants growing in two large metal containers in the greenhouse. All plants in one container died from root-rot, and the roots of plants in the other container were found to be infected. None of the plants in many check containers became infected.

Table 6.—Presence of root-rot on overwintered cotton roots, as shown by field examinations of the still living roots of cotton plants pulled from slightly beyond the edges of root-rot spots.

Date	Location	Number of plants examined	Per cent of plants with infected roots
Sept., 1926	College Station	46	12
Sept., 1926	Bryan	200	9
Sept., 1926	Benchley	79	30
Sept., 1926	Temple	300	28
Oct., 1926	College Station	160	21
Oct., 1926	Bryan	90	19
Oct., 1926	Benchley	150	17
Oct., 1926	Temple	300	24
Nov., 1926	College Station	25	16
Nov., 1926	Bryan	100	19
Nov., 1926	Benchley	100	21
Dec., 1926	College Station	100	14
Dec., 1926	Temple	300	17
Jan., 1927	College Station	100	9
Jan., 1927	Benchley	400	13
Jan., 1927	Temple	500	17
Feb., 1927	College Station	90	7
Feb., 1927	Temple	300	11
Mar., 1927	Bryan	150	9
Mar., 1927	Benchley	200	11
Mar., 1927	Temple	500	12
April, 1927	Bryan	100	6
April, 1927	Temple	200	9
May, 1927	Bryan	60	5
May, 1927	Temple	300	7

Table 7.—Attempted isolations of the root-rot fungus from living though partially decayed cotton roots, and from entirely decayed, infected roots.

Source of material	Date of collection and culturing	Results with infected living roots		Results with infected decayed roots	
		Number of tubes	Per cent of tubes yielding pure cultures of *P. omnivorum*	Number of tubes	Per cent of tubes yielding pure cultures of *P. omnivorum*
Zemanek farm, Benchley, Texas.	Aug. 16, 1926	90	12	45	0
	Sept. 22, 1926	111	7	316	0
	Oct. 18, 1926	390	6	316	0
	Dec. 14, 1926	518	4	260	0
	Jan. 16, 1927	400	2	100	0
Williams farm, Benchley, Texas.	Aug. 18, 1926	210	11	210	0
	Sept. 24, 1926	464	6	209	0
	Oct. 20, 1926	416	5	210	0
	Dec. 20, 1926	414	3	270	0
	Jan. 18, 1927	200	2	87	0
	Mar. 20, 1927	119	1	52	0
	Feb. 23, 1928	523	2	189	0
	Mar. 22, 1928	427	1	136	0

Infected but still living cotton roots were secured on July 2, 1930, from a field in Brazos County in which they had survived since 1929.

These overwintered cotton roots were then used to inoculate normal okra plants. Two of the pieces of 1929 root inoculum were used for each okra plant. By July 18, the eight inoculated plants had wilted, while the checks remained normal.

These inoculation experiments complete the chain of evidence which indicates that *P. omnivorum* survives the winter in an actively growing condition on infected but only partially decayed roots of cultivated plants. Large numbers of infected but undecayed roots remaining in the ground over winter are important sources of early infections of the new crop.

Overwintering on Infected Roots of Weeds

Root-rot originates in fields from infected native plants, and is carried along in the fields not only on native weeds but on others that may be introduced. The disease persists on the roots of weeds such as the common tievine, the ground-cherry, the horsenettle, and others of the many species of non-cultivated plants known to be susceptible to root-rot (17).

Infected native plants serve as points of infection in newly-cleared fields. Infection of cotton plants in newly-cleared land in parts of West and South Texas has been traced to the roots of infected native plants, such as the mesquite, which had persisted in the cleared land (17). It is not uncommon to find roots of various perennials, particularly shrubs and trees, persisting in cleared land which has been cropped for years. The roots of such plants may continue to sprout year after year, in spite of attempts to destroy them with the plow. This is the case (20) with oaks, pecans, and native species of walnuts, all of which are susceptible to root-rot.

Winter annual weeds. On account of the mild winter climate of most parts of Texas, a large number of winter annual weeds occur abundantly. These weeds start to grow late in fall, remain alive all winter, continue their development the following spring, and then usually mature and die during the early part of the summer. Studies have been made by Wolff and Dana (26) at Substation No. 5, to determine the possible importance of winter annuals in the overwintering of root-rot. They found that during March and April less than 1 per cent of the annual plants examined had infected roots, while over 10 per cent of the perennial weeds showed infection. During May, much higher percentages of infection were found on the roots of the annual plants, many of which had begun to die by this time. In addition to overwintering on the roots of winter annuals, they may assume further importance in the root-rot problem by their increase of overwintered infection, during late spring and early summer, in time to cause heavy early infection of the crops that are planted. For instance, overwintered, infected cotton roots may transmit root-rot to winter annual weeds, which in turn may transmit the disease to the new cotton crop.

Weeds in cultivated fields. There are some weeds in nearly all cultivated fields. Weeds may aid in the overwintering of the disease in fields of crops susceptible to root-rot, but may be of even more importance in the overwintering of root-rot in fields devoted to cereal or grain crops for the purpose of controlling root-rot. In such fields, rootroot may overwinter on the roots of the susceptible weeds and thus be carried over to susceptible crops planted in following years, in this way defeating the purpose of the rotation.

Weeds in stubble land. In stubble land left fallow, root-rot may increase through the increase of perennial weeds and the spread of root-rot on these weeds. Thus in an oat stubble field in Robertson County in 1928, it was found (20) that the cotton roots of the 1927 cotton crop had mostly died by September 1, 1928. By this time, however, the field was completely covered with weeds, and root-rot was found on the roots of fourteen species of these weeds, as listed in Table 8. It is evident that while oats or wheat may be valuable in a rotation, weeds in the stubble land must be kept down if root-rot is to be controlled.

Table 8.—Weeds with root-rot, found September 1, 1928, in stubble of 1928 oat field which had been in continuous cotton from 1919 to 1927.

Weeds	Percentage of plants with root-rot
Sesban macrocarpa	40
Xanthium sp.	21
Croton monanthogynus	17
Sida spinosa	14
Euphorbia humistrata	12
Croton capitatus	7
Aster exilis	7
Eupatorium serotinum	6
Iva ciliata	4
Leptilon canadense	4
Heterotheca subaxillaris	3
Amphiachyris dracunculoides	3
Jacquemontia tamnifolia	2
Ambrosia psilostachya	2

Weeds in fence-rows and waste lands. Root-rot occurs commonly on the roots of susceptible weeds that are allowed to grow along the fence-rows, in ditches, and in other waste land near fields in which the disease occurs. These weeds thus maintain a continuous reservoir of infection, from which the disease may spread year after year. With the adoption of adequate rotation or other methods of control, to reduce the amount of root-rot in the cultivated portions of farms, care will be necessary to destroy weed carriers of root-rot on these adjacent uncultivated areas.

Sclerotia as Means of Overwintering

The resting bodies of the fungus, or sclerotia, have been found to play an important part in the overwintering of root-rot. Early in the spring of 1929, numerous excavations were made to find the source of early infections in cotton fields. In some of the fields the excavations showed that the fields were free from most, if not all, of the roots of root-rot carriers. However, large numbers of sclerotia were found near the infected plants. The same spring, excavations were made at the Temple Substation (1) and sclerotia were found under infected cotton plants which grew on land which had been kept in clean fallow during 1928. Sclerotia have since been found in infected fields in various parts of Texas where root-rot occurs. These observations agree with those of other workers (9, 3) and indicate that the sclerotial stage is probably of considerable importance in the overwintering of root-rot.

Germination of sclerotia. Sclerotia of *P. omnivorum* germinate readily in moist soil, on moist filter paper, or on agar. The resultant growth is typical of the root-rot fungus. Sclerotia which fail to germinate have been found to be parasitized by various organisms, which may also be concerned in the eventual disappearance of the sclerotia in the field. By removing the growth from the sclerotia and placing them again on moist filter paper, it has been found (20) that the same sclerotia may germinate repeatedly, in some cases for at least five times.

Inoculation of normal cotton plants with sclerotia. Fresh sclerotia from a carrot field were placed in contact with the roots of cotton plants, secured from a field free from root-rot, in jars filled with moist Houston black clay soil. Pure-culture inoculum was used in other jars, and two jars were left as checks without inoculum. As summarized in Table 9, infection of the roots occurred in every jar where sclerotia were used as inoculum, and in those in which pure cultures were used; while the uninoculated plants remained healthy (20). This and more recent inoculation experiments, as well as experiments carried out independ-

Table 9.—Inoculation of normal cotton plants with sclerotia of *P. omnivorum.*

Inoculum	Number of jars, with two plants per jar	Results after two months	
		Number of new sclerotia produced in the jars	Per cent of plants with root-rot
50 sclerotia per jar	6	717	100
Pure culture grown on sterilized cotton stems	2	165	100
None (check)	2	0	0

ently by other workers (3), have proved that growth from sclerotia of *P. omnivorum* can infect normal cotton plants. Since sclerotia occur commonly in the field, it is apparent that the sclerotia play an important role in the overwintering of the root-rot fungus.

Seasonal production of sclerotia. The early excavations for sclerotia were in fields previously devoted for years to susceptible crops, and there was no way to determine when the sclerotia had been produced. In the laboratory, sclerotia were produced in soil chambers from naturally-infected cotton roots taken in from the field at monthly intervals throughout the year. This indicates that production of sclerotia is probably not dependent on seasonal differences in the fungus growth on infected roots.

In the spring of 1930, okra was planted in a plat used by one of the writers (Taubenhaus) as a home garden for the previous nine years, and thus definitely known to be free from root-rot, which has also never been observed in the surrounding home gardens and grounds. The okra plants were inoculated on July 2 with fresh infected root inoculum of 1930 cotton roots and succumbed rapidly to typical root-rot. On August 10, excavations were made and a large number of mature sclerotia were found under the wilting and dead plants. It is

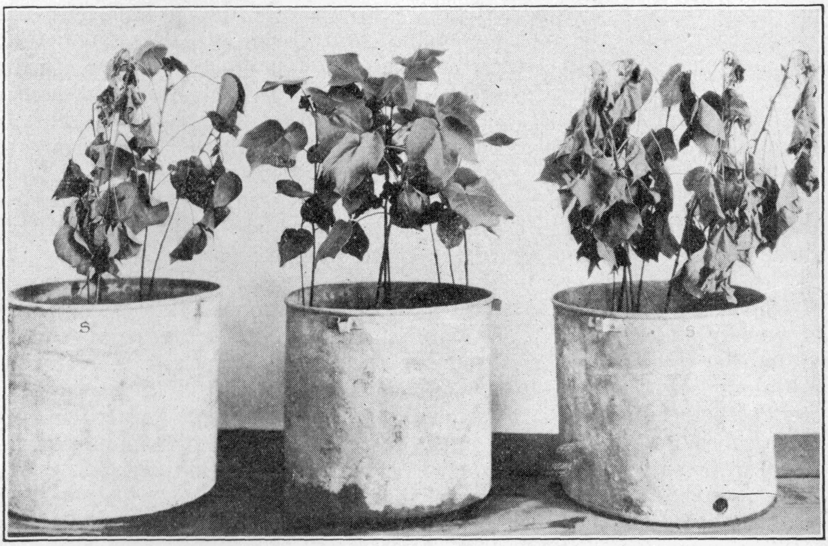

Fig. 8. Right and left, cotton plants inoculated August 10 with sclerotia produced in the field between July 2 and the date of inoculation; center can, check, uninoculated plants. Photographed August 30.

evident that these sclerotia were formed between July 2 and August 10. These sclerotia germinated readily, and caused infection of inoculated cotton plants (Fig. 8). Sclerotia may therefore be produced early in the summer, coincident with the death of plants infected early in the season, and these sclerotia are sufficiently mature to cause new infections of other plants during the same season.

Spores as Possible Means of Overwintering

Cotton plants and other susceptible hosts have repeatedly been inoculated with Phymatotrichum spores, but no infection has resulted. It is thus not known whether Phymatotrichum spores can cause infection, and whether they are of any importance in the overwintering of the disease. It is, however, possible that either the Phymatotrichum stage, or some as yet unknown perfect stage, may be involved to some extent in the overwintering and spread of root-rot.

Periodic Variations in Occurrence and Severity of Root-rot as Related to Overwintering

Even within a single locality, in a favorable soil, the apparently "erratic" behavior of root-rot has puzzled scientists as well as laymen. Taubenhaus and Killough (25) have described the frequent cumulative increases in root-rot during a period of years, followed by abrupt decreases in loss in the same field in the next season. Such differences in loss from root-rot during different years may be due to differences in the weather, since root-root spreads less in dry seasons. This explanation will not suffice for the cases, such as those pointed out also by McNamara, Hooton and Porter (3), in which root-rot becomes increasingly prevalent in one field at the same time that it decreases in severity in an adjacent field. Such decreases in severity, which McNamara calls the "breaking up" of a root-rot spot, apparently indicate a definite tendency for loss from root-rot to increase gradually in destructiveness in favorable soils to a maximum, after which the loss may fall off abruptly, only to begin again the gradual increase.

The further evidence in this Bulletin as to infected roots as means of overwintering tends to confirm the explanation of this phenomenon previously advanced (25). As pointed out above, the fungus appears to overwinter in a vegetative stage most successfully if not solely by advancing along the living roots of susceptible host plants. During the time root-rot is increasing in a given field, larger areas of plants are killed each year, but there is also each year a constantly larger total amount of actively growing mycelium to overwinter on the roots that are not yet entirely decayed. Finally, however, during some year enough plants may be infected so early in the season that by the end of the season a large proportion of all available roots in the field are already decayed, with resultant death of the vegetative strands on these roots. That is, the disease destroys such a large proportion of plants during summer and early fall that relatively few undecayed roots are left on which the fungus can overwinter in a vegetative condition. Therefore, there may be a decided decrease in the number of centers from which the disease can spread the following year, and a corresponding decrease in loss from root-rot.

In such a sequence of events, the relation of sclerotia is problematic. In a field in which the majority of host roots have been killed by root-rot early in the season, followed by death of the Phymatotrichum strands on the roots, it is possible that soil microorganisms increasing on the decaying strands may attack the sclerotia also, thus reducing overwintering from sclerotia along with reduction of overwintering on live roots. The remaining sclerotia may be at times the sole means of survival of root-rot in such a field.

This periodicity in destructiveness of root-rot, in addition to variation due to weather conditions, may explain conflicting results sometimes obtained in field experiments and must be considered in the planning of experimental work. It is not safe to conclude that because root-rot was very abundant in a field in one season it will reappear to a similar extent during the next season. Experiments in which apparent benefit is obtained from a treatment should thus be repeated sufficiently to prove that the results are due to the treatment and not to a natural decrease in loss.

EXPERIMENTS ON METHODS OF CONTROL

In addition to the systematic study of the root-rot disease and of the causal organism, there have also been many attempts made to control root-rot by the application of methods that have been useful against other plant diseases or which have been suggested from studies of the problem. Such experiments have included attempts to eradicate the root-rot fungus from the soil by mechanical treatment such as subsoiling, or to starve it out by rotating with non-susceptible crops. Various materials have been applied in attempts to destroy the organism in the soil. Applications of fertilizer and manure have been tried both on the theory that susceptibility to root-rot might be caused by lack of proper nutrition of the host plants and for the purpose of increasing yields even without controlling the disease. Attempts have also been made to find or develop varieties of plants resistant to root-rot.

Soil disinfectants. Several attempts to control root-rot by the application of chemicals such as formaldehyde and organic mercury compounds have been reported (25, 6, 3). These tests with disinfectants are still in the experimental stage, although some promising results have been obtained by various workers. The chief difficulty in the use of soil disinfectants against root-rot is that the materials must penetrate the soil to a considerable depth to come in contact with the fungus and thus control root-rot.

Extensive tests of the relative effectiveness of various organic mercury compounds, standard fungicides, and other chemicals are now under way both in the laboratory (18) and in plats. These tests will indicate which of the materials are worthy of further trials. It is not expected that cost of the chemicals will be low enough to warrant their use over entire fields. Certain chemicals may, however, prove useful in the control of root-rot on valuable shade and nursery trees; in the eradication of isolated spots in fields; and perhaps in use in barriers to prevent spread of the disease. It is too soon as yet to recommend any soil-disinfecting material for use against root-rot.

Fertilizer and manure experiments. In experiments in which fertilizers were applied to Norfolk fine sandy loam soil in small containers, little difference was found either in the incidence of root-rot following the inoculation or in the amount of overwintering except in a single series. In this series, root-rot appeared to be practically eliminated by application of 10,000 pounds per acre of a 4-8-4 fertilizer. In 1929, manure was tested in four large wood containers at rates of twenty and forty tons per acre. The smaller application apparently did not affect the spread of root-rot; but in the two boxes which received manure at the rate of forty tons, spread was less than half that in the checks. This reduction was possibly caused by the drying effect of this large addition of organic matter to the soil. It may be noted that King and Loomis (7) have reported that the use of manure produced considerable reduction in root-rot in their experimental plats at Sacaton, Arizona. However, early experiments (25) at Substation No. 5 at Temple, Texas, seemed to indicate that continued application of manure had little effect on the occurrence of root-rot in the field plats. Further work is necessary to determine whether manure or fertilizers will be of practical value in the control of root-rot.

Deep plowing and subsoiling experiments. Deep plowing was advocated against root-rot by earlier workers, but trials (25) at Substation No. 5 indicated that deep plowing was of little value. However, in these early plowing experiments the plows penetrated only ten inches. More recently, subsoiling has been tried for the control of root-rot. During the season of 1929 sufficiently promising results were obtained to warrant further tests of subsoiling (3), and such tests are under way at the Temple Substation.

Rotation and clean cultural practices. Rotation has been advocated against root-rot since first knowledge of the disease, and remains the best method of attack known. Rotations for the control of root-rot are of little practical value unless care is taken to prevent growth and overwintering of susceptible weeds. Overwintering of the disease on weeds is probably the explanation of many of the failures to obtain even a small measure of control by rotation in early experiments by various investigators. In more recent experiments, the loss from root-rot was reduced from 39.7 per cent to 4.8 per cent by four-year rotations (13). The failure to obtain complete control by shorter rotations is to be attributed partly to survival of root-rot on the surviving roots of susceptible weeds and perhaps mostly to the survival of sclerotia which can survive in the ground for at least two years and probably longer. Final recommendations on rotation await more complete knowledge of the longevity of sclerotia in the soil.

Sorghum barriers. One of the problems in the control of root-rot has been to prevent its reintroduction by spread of the fungus from infested areas into adjoining plats that had been freed of the disease. Four to twelve rows of grain sorghums, kept free of weeds, have been found valuable as barriers to separate such plats or fields, and appear to prevent the spread of root-rot. In excavations at San Antonio and in North Texas, it was found that cotton roots did not spread beneath adjoining rows of sorghum plants, so that the sorghum separated the roots of neighboring cotton plats and thus prevented spread of root-rot. Further tests of sorghum and other crop barriers are in progress.

Chemical barriers. Promising results have been obtained in the use of trenches of soil mixed with various chemicals as barriers against spread of root-rot. In experiments at College Station, some barriers, consisting of soil mixed with 2.4 per cent of sulphur, three inches wide and four feet deep, are now being tested. Root-rot has not yet spread from cotton plants on one side to other cotton plants growing on the other side of the barriers, only six inches away.

Resistant varieties. At Substation No. 5, a large number of varieties of cotton and selections of individual strains have been tested during the last three years for possible resistance to root-rot. Most of these have been eliminated as susceptible, except a few which are still under test.

In extensive tests carried on at the Weslaco Substation on varieties of grapes and citrus (3), the Champenel, Mustang, and Black Spanish grapes appear resistant, and *Vitis champini* offers promise as a root stock. The sour orange appears to be a highly resistant citrus root stock, while the Cleopatra and *Citrus trifoliata* root stocks are very susceptible.

Many other plants are being studied at College Station, Temple, and Weslaco in the hope of finding or selecting fruit trees, truck crops, and ornamentals resistant to root-rot. In these studies the roots of each individual plant are artificially inoculated with root-rot, so that plants which survive after repeated inoculations over a period of several years may safely be considered valuable for root-rot areas. So far, the pomegranate and yaupon offer promise as resistant ornamental shrubs. Of two species of hackberries tested, the *Celtis mississippiensis* has shown considerable resistance, as is true of the live-oak. These trees, as well as the sycamore and the mesquite, are commonly found surviving in root-rot areas. The Turk's-cap, *Malvaviscus conzattii*, an ornamental plant grown extensively in the lower Rio Grande Valley, has also proved resistant. The seedlings of these resistant plants occasionally succumb to root-rot, although plants more than two to five years old are rarely killed by the disease.

TENTATIVE RECOMMENDATIONS FOR CONTROL OF ROOT-ROT

The experimental results and observations presented in this Bulletin show the complexity of the root-rot problem and the consequent difficulty of control. Although our knowledge of the disease is still incomplete, enough information is now available to justify the following recommendations, which if followed may help to minimize losses even though root-rot is not entirely eradicated. However, these recommendations are tentative and may need to be modified as further information is obtained.

The main method of control to be recommended now against root-rot is rotation with non-susceptible crops, especially grain sorghums and small grains, combined with clean culture sufficient to destroy weed carriers of root-rot. At least three years of such a non-susceptible crop is recommended between successive crops of cotton, for instance. Longer periods of rotation may later be found necessary for complete eradication of the disease, since the time that the sclerotial stage of the root-rot fungus may persist in the soil and the time that it may take to eradicate perennial weed carriers is not yet known.

Before planting long-lived crops such as alfalfa or fruit trees on newly-cleared land, a preliminary "indicator crop" should be grown to find if root-rot is present. Immediately after clearing the land, a crop such as cotton may be planted to afford an opportunity for the disease to show up. Careful observation of the entire field should be maintained until the end of the season, to locate any possible centers of infection. In case no root-rot appears, the area may tentatively be considered free from the disease. If even a small amount of root-rot shows up, it should be eradicated by proper rotation, instead of planting again a susceptible crop, which would increase the disease. Grain sorghums should be grown for at least three years, planted in rows so that weeds can be kept down. After the crop is harvested, the sprouting stumps of shrubs or trees should be grubbed out, as the roots of these may be deep-seated carriers of root-rot. After the land has been freed of root-rot, a permanent grain-sorghum barrier may be established entirely around the area, particularly if root-rot is prevalent in adjoining fields. The sorghum barrier should be at least four to six rows wide, and where a considerable area of land is to be protected, a wider barrier may be advisable. Sorghum barriers would also aid in preventing spread of the disease from infected newly-cleared lands into adjoining areas that are free from the disease.

An alternative procedure might be suggested for newly-cleared land in sections where root-rot is known to be prevalent. It may be more effective in such cases to omit the "indicator" susceptible crop, and instead to plant immediately a non-susceptible crop such as sorghum, and in this way prevent the disease from getting a start.

Control methods as applied to particular crops will be discussed in more detail below.

Control in field crops, particularly cotton. Continuous cropping with cotton tends to maintain root-rot indefinitely and usually to increase losses from the disease; while rotations with non-susceptible crops such as sorghum, small grains, or corn, tend to reduce the amount of root-rot. Short rotations may be of little value in reducing carry-over of root-rot either on roots or as sclerotia. Rotations with resistant crops, without clean culture, may be of equally little value on account of the certainty that root-rot will be carried over and even increased on the many weeds that are susceptible to the disease. The importance of native weeds in the introduction and maintenance of root-rot probably cannot be overemphasized.

Regardless of the kind of non-susceptible, graminaceous crops that are used in the rotations, there should be at least three years between successive crops of cotton. Where oats and wheat are included in the rotation, it is suggested that the cotton roots should be plowed out in the fall before the grain crop is sown. The following spring, when the crop is harvested, the straw should be turned under or fed to cattle and the manure put back on the land. In any case, it is important to plow up the stubble land as soon as possible, and to keep this fallow land free of weeds until fall, when the next crop of wheat or oats is sown. After this crop is harvested, the field should again be plowed to destroy the weeds, and then kept clean of vegetation until the next crop is planted. After this third grain crop is harvested, the field should be kept free of weeds until the cotton crop is planted the next year.

Corn is not susceptible to root-rot and can be used in rotations for the control of root-rot. The poor results sometimes secured were due to the fact that weeds were allowed to develop unchecked after the last cultivation, with the result that the fields became thick with weeds, on the roots of which root-rot was carried over to the following crop. Where corn is grown, it should be spaced sufficiently far apart in the rows to allow for continued clean culture, and the crop should be harvested and removed early enough to permit working of the stubble land, which should be kept free of weeds until the next crop is planted.

Grain sorghums are the most promising crops for rotations to control root-rot, and they are fortunately adapted to the greater part of Texas. The rank growth of tops and roots of sorghum plants helps to keep down weeds, and planting in rows allows for clean culture. In Nueces County and some other regions, the first cutting is harvested and the second cutting turned under to improve the soil. This practice appears desirable from the standpoint of root-rot control. The stubble land should be kept free of weeds until the next crop is planted. As with the small grains, at least three crops should be grown before the land is planted again to cotton.

In portions of South Texas and in the Winter Garden District, cotton is frequently grown in rotation with truck crops such as cabbage, spinach or onions. This rotation aids in the control of root-rot, since these truck crops are removed early in the season, leaving a long period during which the land may be kept free of weeds which carry root-rot. Crops such as onions and melons, which are resistant to root-rot, are particularly suited for such rotations.

Control in orchards. There is relatively little commercial orcharding in Texas. The commercial peach and pear orchards of Texas are confined to sections free from the disease, and the fig industry is limited to regions along the Coast in which root-rot is of little importance. In regions where root-rot is prevalent, home orchards are often destroyed by the disease, especially when the young trees are planted in former cotton fields or when cotton is grown among the trees. In sections where root-rot prevails, the orchard should be planted in an area freed of root-rot by continued planting of sorghum and clean culture as described above in discussing newly-cleared land. Susceptible crops, such as cotton, okra, sweet potatoes, beets, or carrots, should not be planted between the trees.

Citrus trees, particularly when young, are susceptible to injury from root-rot. The trees should not be planted on newly-cleared land nor on land previously cropped to cotton in which root-rot has appeared. Instead, the trees should be planted only after the land has been freed of root-rot as suggested above. Sour-orange root stocks, which have been found in tests at the Weslaco Substation to be resistant, should be used in preference to other stocks. Young orchards should not be intercropped with cotton nor with susceptible truck crops.

Control in nurseries. Detailed suggestions for control of root-rot in nurseries have been given in a recent article (19). If possible, land should be selected that is free of root-rot; otherwise, attempts should first be made to eradicate it by continued cropping with sorghum coupled with clean culture. Adjacent fields as well as the nursery itself should be watched, and any root-rot that appears should be segregated from the remainder of the nursery by a barrier space of twenty-five to fifty feet, or wider if space is available. This barrier should be plowed, kept free from weeds, and planted to sorghum. Living stumps of trees should be dug out. In regions where there is much danger of spread of root-rot into the nursery, a wide sorghum barrier entirely around the nursery may be recommended as a safeguard.

As an aid to limiting spread of root-rot inside the nursery, plantings should be made in blocks, preferably of one species, rather than in long rows; and these blocks may then be separated from each other by barriers of non-susceptible plants. Blocks in which root-rot appears should be freed of vegetation, spaded deeply during the summer, and kept in clean fallow or planted to sorghum for at least three years.

Control in truck crops. Root-rot usually causes little damage to the commercial truck crops even though many of the truck crops are susceptible. This is probably because the growing season is short, and the crops are grown in the fall, winter, or spring, when root-rot spreads more slowly. However, such crops as carrots may be damaged if they are grown year after year on the same land. Truck crops such as eggplants and beans, when grown during the summer, may be severely injured by root-rot. Rotations with sorghum, corn, or non-susceptible truck crops are recommended.

Control in public and home plantings. Heavy losses of ornamental shrubs and shade trees from root-rot occur throughout the cities and towns in the parts of Texas in which the disease is prevalent. The trees or shrubs as they die from root-rot are frequently replaced by the same kinds, even though they may be quite susceptible to root-rot. It is suggested that instead of planting susceptible trees, the resistant live-oaks, sycamores, and species of hackberries should be planted.

Most of the shrubs commonly grown are susceptible to root-rot and succumb quickly. The pomegranate is highly resistant, particularly older plants, and the various blooming varieties may be used singly, in clumps, or in hedges. The native yaupon appears resistant and may be used in hedges. Monocotyledonous plants, such as palms, cannas, variegated canes, bamboos, yuccas, and ornamental grass such as Pampas grass, are all resistant to root-rot and may be grown in root-rot areas. Resistant annuals that can be recommended are zinnias, marigold, geraniums, stocks, cockscombs, snapdragons, and all the liliaceous plants, such as jonquils and lilies. The early flowering annuals such as Calendula, Shasta daisy, and Gaillardia, are usually not attacked even though they are susceptible to the disease when grown later in the season.

On a small scale, for instance, around public buildings or residences, plants may be grown in cement tanks or troughs built in the ground and filled with soil which has been sifted through a one-fourth-inch-mesh sieve to remove all roots of previous vegetation. These roots must not be allowed to get into the tank. In some experiments reported in this Bulletin root-rot did not appear in tanks filled with soil that had previously been sifted. Sizes of tanks to be used will depend on the nature of the plants. The tanks should be at least two feet deep for small plants, and deeper for shrubs, possibly three to six feet. The cement walls and bottom should be well constructed, of sufficient thickness, and reinforced well enough to prevent cracking which might allow entry of roots from the outside and thus cause reinfection. Before the tank is filled, a six-inch layer of gravel should be placed on the bottom for drainage. A fertile soil should be used; and only the surface soil, down to a depth of three to five inches, should be used, as deeper soil is likely to include the sclerotial resting bodies of the fungus. After preparing this root-rot-free container, care should be taken never to re-introduce the disease by planting balled plants from root-rot areas or shrubs that are already infected.

SUMMARY

Root-rot is known to occur in Arizona, Oklahoma, New Mexico, southern California, and Mexico, and in 196 counties in Texas. It causes annual losses estimated at $100,000,000 a year in Texas alone.

Root-rot attacks a large variety of cultivated plants, including field and truck crops, fruit trees, ornamentals, shrubs, and shade trees. The disease occurs also on weeds in cultivated fields and fence-rows and on the native vegetation in uncleared land. Root-rot does not attack monocotyledonous plants, including the grass and grain crops.

Root-rot is characterized by sudden wilting of the foliage, followed by rapid death in the case of tender plants and gradual or delayed death of shrubs and trees. Plants may recover from the first attack only to succumb eventully to further infection. The roots of diseased plants are decayed as a result of the attack of the root-rot fungus.

Root-rot is caused by the fungus, *Phymatotrichum omnivorum* (Shear) Duggar. Successful cross-inoculations between various host plants are reported. The vegetative or Ozonium strands of the fungus occur on diseased roots, and the spore-mat, or Phymatotrichum stage,

is found on the surface of the ground near infected or dead plants. The sclerotial stage occurs in the soil near diseased roots. Sclerotia are small swellings of the strands, and serve as resting bodies to enable the fungus to survive unfavorable conditions.

Root-rot is not only an important disease in the blacklands, but occurs in almost every soil type found in Texas. It has been found in soils of at least thirty soil series. Root-rot occurs more abundantly, spreads more rapidly, and is more destructive in soils that are neutral or somewhat alkaline than in soils that are acid. This relation has been proved to be true by experimental tests as well as by extensive field observations.

Inoculation experiments and field excavations indicate that the fungus spreads from plant to plant chiefly along the roots rather than independently through the soil. In containers in the laboratory, the fungus grows for certain distances through the loose soil; but there is as yet no direct evidence to show how important such growth independently of roots is in the spread of the disease in the field.

The root-rot fungus overwinters in an active condition on the living roots of infected plants, and in a dormant condition as sclerotia. Cotton roots survive the winter even though the tops are killed by frost; the root-rot fungus has been shown to continue spreading on these roots during the winter; and infected, overwintered roots served as inoculum to infect normal plants. The results of numerous experiments indicate that the vegetative strands of the fungus die as the root tissues decay. The roots of perennial weeds in cultivated fields, fencerows, and stubble land may carry the disease over winter; and the disease may also be carried over to a somewhat lesser extent on roots of winter annuals. The sclerotia are additional means of overwintering. They are of special importance in that they may survive after all infected roots have decayed.

Experiments to test various methods for the control of root-rot are in progress. Some of these are soil disinfectants, fertilizers and manure, deep plowing and subsoiling, rotation with non-suceptible crops and clean culture to check overwintering on weeds, barriers to check spread, and the testing and development of resistant varieties.

Tentative recommendations are given for the control of root-rot. Methods are suggested for field crops, particularly cotton, for orchards, nurseries, truck crops, and public and home plantings. The methods recommended are rotation with non-susceptible crops for at least three years, combined with clean culture to destroy weeds. Rows of sorghum are suggested as barriers to prevent the spread of root-rot into fields free of the disease. Resistant plants are recommended for citrus, grapes, and ornamental plantings.

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