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The Control of Cotton Root Rot in the Blackland Region of Texas

AGRICULTURAL AND MECHANICAL COLLEGE OF TEXAS

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Marked and consistent reduction in the severity of cotton root rot in fields with established infestations has resulted from rotations with non-susceptible crops in which cotton was grown only one-fourth of the time. Outstanding increases in cotton yields also resulted from these rotations. A non-susceptible crop period of at least two years is required before the severity of the disease is reduced; simple alternations of susceptible and non-susceptible crops are of little value in reducing root rot. The control of susceptible weeds is a prerequisite to the reduction of root rot severity by crop rotation.

Previously uninfested parts of a field may be protected from further invasion of root rot by barriers of closely planted sorghum, a vigorous-growing, non-susceptible crop.

The severity of cotton root rot in established locations has also been reduced under certain conditions by the use of organic manures, clean fallow, deep tillage, and the application of soil amendments.

The severe losses to cotton stands that occur during the summer throughout the Blackland region of Texas, are caused by the fungus Phymatotrichum omnivorum (Shear) Duggar. This fungus also attacks and causes the decay of the roots of a great many other plants, both cultivated crops and weeds. It does not, however, attack any of the cultivated or wild grasses.

Three stages in the life history of the fungus are known: (1) the actively growing strand or vegetative stage, (2) the resting or sclerotial stage, and (3) the spore stage. The strand growth of root rot is the destructive stage and it serves to spread and perpetuate the fungus. Sclerotia are formed in the strands of the fungus and serve to perpetuate the disease over long periods, even in the absence of susceptible plants. So far as is known, root-rot spores neither spread nor perpetuate the fungus.

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THE CONTROL OF COTTON ROOT ROT IN THE BLACKLAND REGION OF TEXAS

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The cotton root-rot disease caused by the fungus *Phymatotrichum omnivorum* (Shear) Duggar attacks the roots of a large number of both wild and cultivated plants and is very destructive to cotton in some years (47, 52, 61, 66, 67, 69). Ezekiel and Taubenhaus estimated that in 1928, a typical season, the Texas cotton crop was reduced 440,000 bales by this disease (12). The large acreage of cotton concentrated on the fertile, highly calcareous soils of the Blackland region of Texas furnishes very favorable conditions for the development and spread of root rot, and frequently the annual loss in this region is more than half that of the entire State (1, 12, 16). On the Blackland farms where this disease has become established and on which cotton is frequently grown on the same land year after year, root rot is a constant hazard to cotton production.

Information concerning the control of root rot is of particular importance to the farmers of the Blackland region, and it is the purpose of this publication to discuss the available information that may be useful in the practical control of root rot in this region. Much of this information will also be useful to farmers in other parts of Texas where this disease is prevalent.

In selecting the information that may be used, it is desired to consider the investigations conducted in other sections and other states as well as those conducted in the Blacklands. Cotton root rot is also serious in certain parts of Arizona, New Mexico, and Oklahoma, and is known to occur in Arkansas, California, Utah, Nevada, and Mexico (9, 12, 19, 24, 26, 59, 63, 65, 69, 72). Extensive studies of the root-rot disease have been made, particularly in Texas and Arizona. In Texas the current investigations are being conducted primarily by the Texas Agricultural Experiment Station, the University of Texas, and the United States Department of Agriculture. The work in Arizona is carried on principally by the United States Department of Agriculture and the University of Arizona.

Studies in recent years have greatly extended the knowledge of the life history of the root-rot fungus, its means of spread and perpetuation in the field, and its behavior under a wide variety of environmental conditions. Based on the available information of the disease, numerous methods of control have been tried. Preparatory to discussing these methods of control as applied to the Blacklands, certain fundamental information about the disease and its method of spread and perpetuation is pointed out.

METHODS OF SPREAD AND PERPETUATION OF THE COTTON ROOT-ROT FUNGUS

To appreciate fully the nature of the root-rot hazard and to understand the principles of some of the more practical means of controlling this disease, one must know the methods of spread and perpetuation of the root-rot fungus.

Some classes of plants are attacked by the root-rot fungus, while others are not. Those plants on which root rot flourishes and from which it obtains nourishment are referred to as susceptible plants. Those on which the disease will not grow are called non-susceptible plants. Several previous publications have classified a large number of plants, both wild and cultivated, some as to their immunity and others as to their degree of susceptibility to the disease (2, 3, 4, 41, 61, 66, 67, 69). As has already been indicated, cotton is highly susceptible to the disease and is the most generally grown susceptible plant in the Blacklands. In these cotton fields, a large number of fleshy tap-rooted weeds often persist that are susceptible to the disease. Many of the legumes are also susceptible. Grass plants, both wild and cultivated, are immune to the disease. Some of the non-susceptible crops commonly grown in the Blacklands are corn, sorghum, oats, and wheat. These crops do not furnish nourishment for the root-rot fungus and under proper management may be used to control the disease, while the planting of susceptible crops encourages its spread and perpetuation.

Stages in the Life History of the Fungus

In the usual cotton field in the Blacklands, large numbers of cotton plants may be seen dying from root rot during the summer months. By selecting a freshly wilted cotton plant and pulling it up, one may find the root-rot fungus on the tap root. The fungus may be seen with the naked eye as a loosely attached, whitish to buff colored, string-like growth clinging to the root (14, 36, 39, 54, 60, 63, 65, 72). This is the actively growing and destructive stage of the fungus. It is referred to as the strand growth or vegetative stage of the fungus, as distinguished from the other stages of the disease. As the freshly wilted cotton plant is pulled up, the major portion of the root system of the plant, together with the bulk of the strand growth of the fungus, is left in the ground. In addition, a second stage of the fungus, known as the sclerotial stage, is also left in the ground (8, 22, 23, 29, 31, 32, 35, 37, 38, 39, 68).

The sclerotial stage is the resting or dormant stage and is not destructive until it germinates and produces new fungus strands. The individual units of the sclerotial stage of the fungus are the sclerotia, which are specialized sections of the fungus strands usually formed as swellings. These swellings vary from approximately the size of a mustard seed to that of a wheat kernel and are of various shapes. After the death of the cotton roots and the vegetative strands of the fungus, these sclerotia remain in the soil in a dormant but viable condition for long periods. These root-rot sclerotia are such a small part of the soil mass and are so near the color of other organic material in the soil that the ordinary observer is not likely to find them. They are usually available for inspection only after they are located by an experienced observer.

There is also a third stage of the root-rot fungus known as the spore stage (5, 20, 23, 29, 34, 39, 63, 65, 72). This stage is found on exposed surfaces of the soil. In the summer it may be seen occasionally during damp, cloudy weather as whitish to buff colored mats on the soil surface. While it has been demonstrated that these spore mats are developed by the extension of the root-rot fungus strands, this stage apparently is non-functional and the part it plays in the spread or perpetuation of the root-rot disease is not known.

The vegetative and the sclerotial stages of the root-rot fungus are functional. The vegetative stage has the ability to grow and elongate and is responsible for the spread of the disease except in rare instances. This stage may also perpetuate the disease. The sclerotial stage functions only to perpetuate the disease, except when moved artificially by man or by abnormal natural agents.

The Behavior and Functions of the Vegetative Strands

The vegetative and sclerotial stages of the root-rot fungus are closely interrelated and, as is indicated by the foregoing description, one is produced by the other. However, the behavior and functions of these stages of the fungus can be more easily understood by considering them separately. The vegetative stage will be considered first.

When cotton is planted on land previously infested with root-rot, the fungus is furnished an extremely favorable distribution of susceptible plants upon which to thrive. In the cotton fields with full stands, the fungus is provided a new food source in the form of root systems of individual cotton plants every eight to twelve inches in every row. These roots are not only distributed to considerable depth in the soil but are thoroughly interspersed with the roots of their neighboring plants. There is, then, contact or very close proximity of the roots of neighboring cotton plants. As the vegetative strands attack and spread over the root system of one plant, they soon grow on the healthy roots of the neighboring plant. By the time the disease has killed one plant in an area, or soon thereafter, the neighboring plants become infected. The new strand growth is the actively feeding portion of the fungus, and the older parts of the strands, left back on the diseased and dying portion of the cotton roots, gradually exhaust the available food and die with the root to which they are attached. This stage of the fungus is maintained by its ability to spread and invade the live roots of the remaining susceptible plants. By the continued spread of the fungus from the live roots of one cotton plant to those of another, the fungus can continue to live as long as there are healthy, susceptible, and neighboring plants.

This spread of the vegetative strands does not cease with the coming of winter nor is it halted by the destruction of the root crowns of the cotton plants by the usual fall plowing. Numerous excavations during the winter and spring months have demonstrated the presence of live cotton roots in the soil from the previous year's crop (47, 64). Where cotton is grown year after year the root-rot fungus may perpetuate itself indefinitely simply by the spread of the vegetative stage on the live roots of cotton.

If cotton, however, were the only susceptible plant growing in the field, the omission of cotton growing for a single year would, except in rare instances, eliminate the vegetative stage as a means of perpetuating the disease, for cotton roots have never been found to remain alive as long as twelve months without stalk growth. But, as previously mentioned, root rot thrives on many fleshy tap-rooted weeds that persist in cotton fields. The perennial weeds of this type especially aid in the maintenance of the disease by the spread of vegetative strands. The common tie vine, *Ipomea trifida,* may be used to illustrate the behavior of the fungus on this type of weed.

Tie vines are somewhat resistant to the disease and have the ability to put out new roots readily. By these means the infected tie vines often remain alive for many years. These persistent perennial weeds harbor the active strands of the fungus year after year and may be a constant source of re-infection to cultivated crops, although cotton growing may be interrupted for several years. In any field where the stand of susceptible perennial weeds is close, they must be controlled or eradicated before root rot is likely to be controlled.

In rare instances, the vegetative stage of the fungus has also been reported to survive for extended periods on dead and partially decomposed plant tissue, even in the absence of any live roots of susceptible plants (29, 35, 43, 44). This behavior, however, does not appear to occur frequently enough to affect control practices materially.

The Function of Sclerotia

Although the presence of live roots of susceptible plants aids in the survival of the root-rot fungus, perpetuation of this disease is not dependent upon the continuity of live roots of susceptible plants. As the fungus grows over the roots of a cotton plant or any other susceptible plant, it produces resting bodies known as sclerotia. These sclerotia remain in the soil, temporarily dormant, after the fungus strands that produced them and the roots of the susceptible plants are dead. In later seasons, when conditions are favorable, these sclerotia may germinate and start new infections if the live roots of a susceptible plant happen to be near. New fungus strands are developed and the vegetative stage of the fungus again starts its spread. By means of sclerotia, root rot may survive many years of non-susceptible crops, even in fields where no weeds exist. These sclerotia have been found in the soil as deep as the roots of susceptible plants grow. In cotton fields in the Blackland region, sclerotia have been found abundant from 3 to 36 inches deep in the soil and most abundant from 12 to 24 inches (2, 35, 53). At such depths it is usually impractical to affect them by tillage or chemical treatments. With each crop of cotton or other susceptible crop, a new lot of sclerotia may be produced, so that growing cotton year after year permits the accumulation of an enormous number of viable sclerotia. The presence of a close stand of perennial weeds on the land further complicates the root-rot problem, since the weeds often survive in non-susceptible crops and insure the perpetuation of the disease both by actively growing vegetative strands and also by the production of repeated lots of sclerotia. Complete information on the various factors affecting the length of time sclerotia remain viable has not yet been developed, but a working knowledge upon which to project control recommendations is available.

While individual colonies of sclerotia have been known to remain viable for rather long periods, most of the sclerotia under field conditions apparently are dead by the end of the third year of a non-susceptible plant period (53). On the other hand, it is known that the number of viable sclerotia that can survive one year of non-susceptible plants is very great and that there is a high carry-over of root rot in the following cotton crop.

This information of the spread and the perpetuation of the root-rot disease is the basis of effective means of preventing the further spread and of controlling the disease.

PREVENTING THE FURTHER SPREAD OF COTTON ROOT ROT

Although root rot is generally distributed over most of the farms of the Blackland region, there are still a number of farms in the region on which the disease is restricted to certain portions of the field. On some of these farms, the further spread of the disease may be inhibited by unfavorable natural conditions. However, on many other farms, root rot is still in the process of invading previously disease-free areas. Simple and effective means of preventing the further spread of cotton root rot into previously uninfested portions of a field may be used to great practical value on the farms now being invaded.

In one of the early root-rot experiments at Greenville, Texas, McNamara and Hooton used barriers to prevent the spread of root rot from infested parts of a field into previously uninfested parts (34). The Greenville experiment provided a double walled plank barrier with a 4-inch air space between the walls placed at sufficient depth to intercept all the roots of cotton plants between the infested and uninfested parts of the field and thereby prevented the further spread of the disease (63, 65, 72). Since that time, Taubenhaus and Ezekiel have accomplished the same results with strips of sorghum, and they and other workers have tested numerous types of barriers designed to prevent the spread of root rot (2, 9, 10, 21, 28, 29, 31). Effective barriers provide a positive gap between the roots of the susceptible plants in the two parts of the field. They take advantage of the information cited earlier that the root-rot disease spreads from one location to another along the live roots of susceptible plants.

Barriers of closely-planted, vigorously-growing, non-susceptible crops such as the sorghums are the most practical of the effective barriers. The sorghum barriers prevent the contact or close proximity of the live roots of susceptible plants in the infested and the previously uninfested portions of a field and are effective as long as they are placed well in advance of the spreading infestation, are sufficiently wide, are planted to a close stand, and are free of susceptible weeds. Sorghum barriers are applicable to any farm on which the root rot is at present restricted to a definite portion of the farm and is in the process of spreading to the rest of the farm. Root rot has never been known to cross a properly placed and properly maintained sorghum barrier under dry land conditions and the present knowledge of this disease indicates that root rot is not likely to cross such a barrier except under very unusual conditions.

The vigorous-growing, non-susceptible crops such as the sorghums make effective root-rot barriers because they successfully compete with cotton for the exclusive possession of the soil below the non-susceptible crop during the time cotton in the adjacent area is making its growth. Only the invasion of roots of susceptible shrubs and trees which may go below the sorghum roots is likely to endanger the effectiveness of a sorghum barrier. Such crops as corn and oats, although non-susceptible, permit the invasion of cotton roots from the adjacent cotton plants and can not be expected to make effective root-rot barriers (47).

If the farmer wishes to restrict the root-rot disease to the minimum area, the sorghum barrier should be planted parallel to the boundary of the root-rot infestation. The location of the sorghum barrier should be determined and marked in the fall of the year prior to planting the sorghum in the spring. If the location of the barrier is delayed until spring, there will be no visible evidence of the boundary between the root-rot infested and the disease-free parts of the field. It is also advisable to mark the barrier at least 12 feet in advance of the observed boundary to allow for any additional spread that the disease may have made that is not evident above ground. Also some additional spread frequently takes place during the winter months on the live cotton roots below the plow depth. While a barrier of one or two rows of sorghum may be effective if properly placed and maintained, under practical field conditions the sorghum barrier should be at least 30 feet wide. Either broadcast or row sorghum may be used. A simple procedure for small root rot spots, would be to plant the infested area to sorghum and extend the planting fully 30 feet beyond the limits of the infestation. Once the sorghum barrier is established, its location from year to year may be easily identified by some simple method such as back furrows.

Sorghum barriers require a minimum cost to establish, but they are effective for only one season at a time and have to be planted on the same location year after year as long as protection is desired. Sorghum yields may decrease slightly from the continuous planting of this crop, but the early destruction of the sorghum stubble and the occasional sacrifice of a crop for green manuring will help to maintain the productiveness of the sorghum.

Root rot neither follows field lines nor terrace lines and to only a minor extent row direction, and the use of a sorghum barrier may require an artificial subdivision of a field, interfering somewhat with cultural practices. If a farmer objects to this artificial subdivision of a field by the irregular shape of root-rot infested areas, there is always an opportunity to square up the root-rot infested field by placing the sorghum barrier immediately ahead of the most advanced point of infestation and parallel to property or terrace lines. Such a procedure, while it permits the uninfested parts of the field behind the barrier to become infested, will establish a definite line beyond which root rot can not spread.

ROTATION AS A METHOD OF CONTROLLING COTTON ROOT ROT

Numerous methods of controlling cotton root rot in established locations have been tested by the several agencies studying this disease. While none of the methods developed thus far have eradicated the disease, several of them have materially reduced its severity. The most practical method of controlling cotton root rot on most of the farms in the Blackland region of Texas, at present, is by the proper rotation of non-susceptible crops with cotton. In this publication, the phrase "control of cotton root rot" as applied to established infestations means the reduction of stand losses of the susceptible crop caused by root rot on the treated areas compared with the stand losses occurring on the untreated areas. It does not mean the elimination of stand losses of the susceptible crop caused by this disease.

Early Observations of Rotations

The value of certain types of crop rotations as a practical means of controlling cotton root rot has been known for a long time and has been demonstrated both by formal experiments and by the experience of many farmers. Dr. L. H. Pammel, the first plant disease specialist of the Texas Agricultural Experiment Station, was one of the first scientists to point out the value and the requirements of crop rotations in controlling this disease (41, 42). Since Pammel's time, crop rotation experiments under root-rot conditions have been conducted at San Antonio, Texas, by the United States Department of Agriculture and on two separate locations at Temple, Texas, by the Texas Agricultural Experiment Station (45, 46, 50, 55, 56, 57). The accumulated information has indicated certain rather definite requirements of a rotation to control cotton root rot.

As Pammel began his studies on cotton root rot in 1888, he found that many of the cotton planters had already gained considerable experience with this disease and that several of the more observant farmers already knew enough about root rot to control it. Pammel states in Texas Station Bulletin No. 4, written in 1888 (41), that

"In north Texas, where small grains are a certain crop, rotation is often resorted to to prevent the 'dying of cotton'. As an illustration: Four years ago considerable cotton was killed by Root Rot in a field of Mr. Ormsby Scott, near Melissa. Since that time the field has been planted in corn, oats and wheat, and the present year in cotton. On the first of September very little dead cotton was found in that field. Similar cases have been found at Plano, San Marcos and Independence.

"Mr. H. R. von Bieberstein recommends for South Texas a three-year rotation, using oats, corn and millet.

"That a simple alternation of crops is not sufficient is well illustrated in the following cases: At Independence, Captain Tom Clay pointed out a number of fields to me which had been in corn the year before, yet cotton was dying quite severely.

"I think from a practical point of view a proper rotation of crops is the best way to destroy the fungus.

"In rotation care must be taken not to follow cotton by plants which are subject to Root Rot . . . . So far as is known the fibrous rooted plants, such as corn, oats and wheat, are exempt from the disease, and where practicable should follow cotton.

"Certain weeds are also subject to the disease, hence fields ought to be kept rigidly clean . . . . It will be of little use to rotate, if weeds which harbor the fungus are allowed to grow in the field."

Thus almost fifty years ago, Pammel pointed out the most effective factors in the successful utilization of crop rotations to control cotton root rot. And crop rotations as recommended by Pammel have been employed to good advantage throughout the years by many of the careful farmers who have known the value of desirable rotations in controlling this disease.

Early Rotation Experiments in Root-Rot Infested Areas

In summarizing the results of the crop rotations conducted at the United States Field Station at San Antonio, Ratliffe reported in 1934 that "In these experiments 2-year rotations of cotton with non-susceptible crops have proved of very little value in the control of root rot, 3-year rotations appear to have been slightly more effective, while in 4-year rotations, the disease has been effectively checked though not eliminated" (45). The yields of crops in the San Antonio test were reported by Ratliffe and Atkins (46) in 1931, and they conclude that "Cotton yields were generally higher in rotation than under continuous cropping."

The results of rotations at Temple conducted on the old Experiment Station farm during the period 1914-24 were reported by Reynolds and Killough (50). They stated: "It will be observed that the rotated cotton in every case did not have as much root rot as did the cotton grown continuously on the same land. In fact, rotation of crops practically controlled, although it did not eradicate the disease." Reynolds and Killough also reported much higher yields of cotton on the rotated than on the non-rotated areas.

The yields of the non-susceptible crops used in the San Antonio and Temple tests were affected in varying degrees by the rotation used (46, 50). Ratliffe and Atkins reported that in the San Antonio test the highest yields of corn were from rotations in which early seed bed preparation for corn was permitted. Milo yields were highest in 4-year rotations, although the yields in 3-year rotations were nearly as high. Yields of broadcast sorghums were increased by rotation. Oat production was seriously handicapped by the lack of varieties resistant to leaf rust and stem rust; however, yields of oats were practically as high under continuous cropping as when grown in rotations. Reynolds and Killough reporting on the rotation test at Temple prior to 1928 indicate that the yields of corn were increased considerably by rotations and were highest when corn was preceded by a leguminous crop. The yield of wheat was increased by rotations but oats benefited very little by rotation. In this early Temple test no comparisons of rotated and non-rotated sorghums were available.

ROTATION STUDIES AT TEMPLE

The rotations begun at Temple in 1914 were abandoned in the winter of 1927 when Substation No. 5 was relocated. This change in location was made primarily to provide additional areas of severely infested land for the purpose of studying and developing methods of controlling the root-rot disease. In 1928 experiments were instituted at the new station to study further the effects of cropping systems on the yield of crops and the control of cotton root rot. These systems, with minor exceptions, have been followed continuously.

Rogers has recently reported the results obtained on a part of the areas included in these cropping systems. He states that "Four-year rotations of cotton with non-susceptible crops—corn, sorghum, and small grain (oats and wheat)—showed consistent reduction in root rot" (53).

In the present publication, a more complete report of the cropping systems studied at Temple from 1928 through 1936 is given. The root rot data used in this analysis were collected by B. F. Dana and Dr. C. H. Rogers. The yield data were collected by H. E. Dunlavy. These experiments are being continued and further progress reports on the results secured are to be made in the future.

The cropping systems used on the current experiments at Temple include continuously cropped areas of cotton, corn, sorghum, and oats.

In contrast to this continuous cropping are the rotation studies involving the use of cotton twice in three years, once in two years, once in three years, and once in four years. In the years that the rotated areas are not planted to cotton, the land is planted to crops immune or highly resistant to root rot, except in a few cases where the land is fallowed.

All systems of cropping are conducted in duplicate and areas representing the various cropping treatments are planted to cotton each year. The fields used for these studies are relatively free of perennial weeds and the previous history of the root rot on the areas studied indicates that the initial infestations were severe and generally distributed. The individual cropping systems in which cotton is planted and for which records are complete are given in Table 1.

In conducting these experiments on cropping systems, the cultural methods—including time and method of plowing the land; time, method, and rate of seeding; time and method of cultivation; the variety of crops planted; and insect control practices—have been alike on both rotated and non-rotated areas so far as seasonal conditions permitted. However, the

Table 1.—Average percentage of cotton root rot at end of season for cropping systems at Temple, 1928-36

Cropping system	Previous crop	Pre-rotation period				Effective rotation period						
		1928	1929	1930	Average	1931	1932	1933	1934	1935	1936	Average
Continuous cotton	cotton	99	57	29	62	25	39	97	57	96	90	67
Cotton twice in 3 years:												
Cotton, cotton, oats	cotton	95	58	56	70	22	92	100	40	97	93	74
Cotton, cotton, oats	oats	77	25	6	36	34	68	88	64	95	78	71
Cotton, cotton, fallow	cotton	96	63	59	73	35	74	81	58	96	60	67
Cotton, cotton, fallow	fallow	84	31	29	48	36	57	81	55	75	72	63
Average	.....	.....	.....	.....	57	.....	.....	.....	.....	.....	.....	69
Cotton once in 2 years:												
Cotton, corn	corn	91	22	34	49	36	63	87	59	70	70	64
Cotton, oats	oats	100	52	12	55	42	38	68	46	90	65	58
Cotton, sorghum	sorghum	96	51	60	69	60	86	91	57	86	65	74
Cotton, guar	guar	93	19	54	55	27	65	84	35	75	52	56
Average	.....	.....	.....	.....	57	.....	.....	.....	.....	.....	.....	63
Cotton once in 3 years:												
Cotton, corn, oats	oats	86	47	5	46	3	20	50	16	48	82	36
Cotton, sorghum, oats	oats	95	53	23	57	13	51	66	35	86	88	56
Average	.....	.....	.....	.....	52	.....	.....	.....	.....	.....	.....	46
Cotton once in 4 years:												
Cotton, corn, sorghum, oats	oats	96	54	18	56	8	14	62	12	32	23	25

various soil areas used for different crop treatments in this study varied as to productiveness and as to the prevalence of root rot.

At the beginning of these experiments two continuously cropped areas were provided, one on Houston clay soil and the other on deep Houston black clay soil. These areas were located on opposite sides of the farm and varied widely in productiveness. This difference in productiveness was associated with differences in soil type and land slope. Most of the rotated areas were located on soils with varying degrees of similarity to the check areas and the yields of the individual areas under rotation have tended to parallel most closely the yields of the continuously cropped areas to which they were most similar in soil type and land slope. The yields observed in this experiment were influenced by (a) original differences in soil fertility and the prevalence of root rot and (b) the cropping systems used. In this report the results secured on the more productive continuously cropped area located on deep Houston black clay have been used as the basis of comparing the results secured on other areas. To eliminate as far as possible the effect of original variations, the observed yields on each rotated area were adjusted by ratios obtained by dividing the average yields in the pre-rotation period, 1928 to 1930, by the corresponding figure for the continuously cropped area. The averages for the rotation period 1931 to 1936 were divided by their respective ratios to obtain the "adjusted averages," which represent approximately the effect of the cropping system itself on the results. Similar adjustments were also made for root rot percentages in cases where comparisons were made between areas that originally varied widely as to the prevalence of root rot.

The results secured from the various cropping systems are presented under the two classes of crops grown: (a) cotton, which is susceptible to root rot, and (b) the feed crops—corn, sorghum, and oats—which are immune to the disease. In discussing the information secured on cotton, attention is given first to the losses of cotton stands caused by root rot in the various cropping systems. The relationship of the frequency with which cotton was planted in each cropping system to the cotton yields secured and the root-rot losses sustained are then discussed. Attention is also given to the influence on the yield of cotton of the crop practices immediately preceding cotton in the rotation. The discussion on the non-susceptible crops gives consideration to the effect of the frequency with which each crop is grown in the rotation on the yield of that crop. Some information is also presented on the effect of the preceding crop practice on the yield of oats.

Results Secured with Cotton

Root-rot losses to cotton stands. The percentages of loss to cotton stands caused by root rot in the various cropping systems are presented in Table 1. In this table the information on the percentages of root rot are grouped under five types of cropping system, as follows: (a) continuous cotton, or cotton every year, (b) cotton twice in three years, or

2/3 of the time, (c) cotton once in two years, or 1/2 of the time, (d) cotton once in three years, or 1/3 of the time, and (e) cotton once in four years, or 1/4 of the time. As may be learned from the column headed "Cropping Systems" in Table 1, corn, sorghum, oats, guar, or fallow was used in the years cotton was not grown. Corn, sorghum, and oats are immune to the root-rot disease, and guar is highly resistant. There was never a very wide variety or a close stand of root-rot susceptible weeds on the area used in the experiment. Also the cultural practices used were such as to control weeds on the areas used in the rotations, and during the year fallow was practiced, the land was plowed at regular intervals to destroy all plant growth.

By 1931 all of the rotations had completed their first cycle and were all fully effective during the same year for the first time. By the end of 1936, these rotations had been effective for six years, so that the average root-rot percentages for the period, 1931 through 1936, show the effect of each rotation on the control of the cotton root-rot disease. During this period an average of 67 per cent of the cotton plants on the continuous cotton area were killed by root rot, as shown in Table 1, while on the areas planted to cotton 2/3, 1/2, 1/3, and 1/4 of the time, the average root-rot percentages were 69, 63, 46, 25, respectively. These percentages show that the severity of root rot was not reduced until cotton was withheld from the land for at least two years; and after that the reduction was greater the less frequently cotton was grown. In the 4-year rotation of cotton, corn, sorghum, and oats where cotton was planted only 1/4 of the time, marked control of the disease was secured. Also an inspection of the annual average percentages of root rot on the continuous cotton and the 4-year rotations given in Table 1 shows that the control obtained by planting cotton 1/4 of the time was consistent from year to year. From this table it may be seen that the stand losses from root rot on the continuous cotton area during 1931, 1932, 1933, 1934, 1935, and 1936, respectively, were 17, 25, 35, 45, 64, and 67 percent higher than on the 4-year rotation.

Effect of frequency of cotton in rotation on the yield of cotton. The most frequent use of cotton was on the continuous cotton area, where cotton was grown every year. The next most frequent use of cotton was in the 3-year rotations in which cotton was planted 2/3 of the time. In other types of rotations, cotton was grown 1/2, 1/3, and 1/4 of the time. The cotton yields for each of the cropping systems and the average yields for each type of cropping system are given in Table 2 for the effective rotation periods. From this table it may be seen that cotton yielded at the average rate of 237, 258, 272, 300, and 324 pounds of lint per acre, respectively, in the cropping systems in which cotton was planted all, 2/3, 1/2, 1/3 and 1/4 of the time. From these yields it is seen that, when compared with continuous cotton, the rotations used in this experiment progressively increased the yield of cotton the less frequently this crop was grown.

It is also evident that the most outstanding increases in the yield of cotton were secured in the rotations in which cotton was used only 1/3 and 1/4 of the time and in which the severity of root rot was reduced. Both the greatest increase in yield and the greatest reduction in severity of root rot were secured in the rotation using cotton only 1/4 of the time.

Table 2.—Average yield in pounds of lint cotton per acre for cropping systems at Temple, 1931-36

Cropping systems	Previous crop	1931	1932	1933	1934	1935	1936	Average	Adjusted average yield 1931–36
Continuous cotton	cotton	293	320	249	264	150	148	237	237
Cotton twice in 3 years:									
Cotton, cotton, oats	cotton	283	168	223	182	35	102	166	210
Cotton, cotton, oats	oats	310	263	259	193	140	279	241	298
Cotton, cotton, fallow	cotton	337	245	230	245	104	279	240	267
Cotton, cotton, fallow	fallow	341	157	352	211	175	210	241	256
Average								222	258
Cotton once in 2 years:									
Cotton, corn	corn	327	219	335	297	160	350	281	302
Cotton, oats	oats	189	262	286	222	132	220	218	260
Cotton, sorghum	sorghum	133	179	302	256	108	211	198	230
Cotton, guar	guar	292	269	327	288	203	333	285	294
Average								246	272
Cotton once in 3 years:									
Cotton, corn, oats	oats	288	200	294	188	256	240	244	294
Cotton, sorghum, oats	oats	368	275	358	251	216	216	281	305
Average								262	300
Cotton once in 4 years:									
Cotton, corn, sorghum, oats	oats	313	260	370	240	222	306	285	324

However, small increases in yield were also secured in the rotation in which cotton was used as frequently as 2/3 and 1/2 of the time. This suggests that factors other than the control of root rot also contributed to the increased yields obtained on the rotated areas. The influences of the crop practices immediately preceding cotton were factors affecting the yield.

Effect of preceding crop practices on the yield of cotton. The effects of the crop practices immediately preceding cotton are indicated by the results secured from the 2-year rotations in which cotton followed corn, oats, sorghum and guar in different rotations. The average adjusted yields of cotton following these crops compared with the average of continuous cotton are taken from Table 2 and reproduced in Table 3 together with the corresponding adjusted root-rot percentages. Adjusted averages and root-rot percentages are used so as to eliminate as far as possible the original differences in soil fertility and the prevalence of root rot between these areas and thereby clarify the influence of preceding crop practices.

As previously pointed out, in the rotations in which cotton was planted as frequently as once every two years, root rot was not consistently reduced. However, the yield of cotton in these rotations was affected by the preceding crop practices. The yield of cotton following corn during the 1931-36 period was higher than the yield of continuous cotton. Cotton following corn yielded 302 pounds of lint per acre compared with 237 for continuous cotton. The increased yield of cotton following corn compared with continuous cotton in these experiments was probably caused by several factors. For one thing, the corn plant is of determinate growth and probably takes little or no plant nutrient from the soil after it matures late in the summer, while cotton often continues to make some growth until frost. Also, as the corn matured, weeds and grass frequently made considerable growth which, in these experiments, was turned under as green manure. Another factor that tended to increase cotton yields in this 2-year rotation was the early preparation of the land for cotton. Where cotton followed corn, fall plowing was accomplished from one to two months earlier than was practical where cotton followed cotton. These conditions all tended to increase the plant nutrients and soil moisture available for starting the cotton crop following corn.

Table 3.—Adjusted average cotton yields and root-rot percentages for continuous cotton and cotton in 2-year rotations preceded by corn, oats, sorghum, and guar, respectively, 1931-36

Preceding crop	Adjusted pounds of lint per acre	Adjusted Average root-rot percentages
Continuous cotton	237	67
Corn	302	81
Oats	260	65
Sorghum	230	67
Guar	294	63

Similar opportunities to increase the yield of the following cotton crop existed on the oat stubble land. Apparently these opportunities were only partially realized in these experiments, since cotton following oats gave a yield intermediate between the yield of cotton following corn and continuous cotton. The yield of cotton following oats was 260 pounds of lint per acre as compared with 302 following corn and 237 for continuous cotton. After the oats were harvested, clean fallow was maintained throughout the summer with the expectation of eradicating weeds, some of which are carriers of root rot. This emphasis on clean fallow precluded the production of a natural green manure crop and probably accounts for the relatively lower yields of cotton following oats compared with cotton following corn.

Cotton yields following sorghums in the Temple experiments were more satisfactory than are ordinarily obtained by Blackland farmers. In this experiment, cotton following sorghum yielded 230 pounds of lint per acre as compared with 237 pounds for continuous cotton. These yields are not significantly different and it may be said that cotton following sorghum yielded as well as continuous cotton. The difference in handling the sorghum stubble in these experiments compared with the usual procedure followed by the farmers may account in part for the results secured. In these tests the sorghum stubble was destroyed by plowing as soon after harvesting the first crop as was practical. This was ordinarily accomplished prior to September 1. This early preparation of the sorghum stubble land provided a rather long period for the decomposition of the stubble material prior to planting the following cotton crop. Ordinarily farmers are late in plowing their stubble land and quite frequently they harvest a second cutting of sorghum. As a result of this practice, the sorghum stubble often stands until frost without being turned under. Cotton planted on sorghum land handled in this manner usually yields less than continuous cotton, no doubt partially due to the depletion of available soil moisture and nitrogen at cotton planting time.

From the results presented in Table 3, it may be seen that cotton following guar yielded 294 pounds of lint per acre as compared with 302 pounds following corn and 237 pounds from continuous cotton. While the yield of cotton following guar was much higher than the yield of continuous cotton, it is surprising that the yield was not also higher than for cotton following corn. It is normally expected that the yield of cotton following a legume, such as guar, will exceed that of cotton following a non-leguminous crop, such as corn. However, repeated examination during the summers of 1935 and 1936 showed the roots of guar to be practically devoid of nodules, so that these crops most likely obtained very little nitrogen from the air and therefore added little or no nitrogen to the soil from this source. Also in most years the guar was harvested and removed from the land and only a limited amount of the crop residues plowed under. Under different crop management where inoculation of the legume is provided and the entire crop turned under as green manure, higher yields of cotton following a legume might be expected.

Results Secured with Non-Susceptible Crops

The records from these tests furnish information for corn, sorghum, and oats as to the effect of frequency with which each crop was included in the rotation on the yield of the individual crop. In the case of oats, records are also available on the effect of the preceding crop practices. Yield records on guar are incomplete and for this reason were not used in this analysis. The 1931-36 average yields of corn, sorghum, and oats adjusted to eliminate original variation are given in Table 4 for the various cropping systems.

Effect of cropping systems on the yield of corn. From the records presented in Table 4, it may be seen that corn grown in rotation with other crops during the period 1931-36 yielded an average of 29 bushels of shelled corn per acre, while corn grown continuously on the same land produced only 22.7 bushels. This is a difference of 6.3 bushels, or 28 per cent, in favor of rotation. It is evident that the frequency with which corn was grown in the rotation had little or no effect on the yield of corn.

Corn grown every other year yielded just as much as corn grown only every fourth year.

Table 4.—Effect of frequency of use in the rotation on the yield per acre of corn, sorghum, and oats, 1931-36

Time in each crop	Corn shelled, bushels	Sorghum		Oats, bushels
		Grain, bu.	Forage, tons	
Continuous	22.7	24.2	2.82	32.1
One-half	29.1	31.2	3.95	32.5
One-third	28.9	26.7	3.93	31.1
One-fourth	29.1	33.6	4.58	incomplete record
Rotation average	29.0	30.5	4.15	31.8

Effect of cropping systems on the yield of sorghum. Sorghum under rotation gave somewhat higher yields than continuous sorghum. Darso was the sorghum variety grown in these tests from 1931 through 1936. As shown in Table 4 darso grown in rotation with other crops produced 6.3 bushels of grain and 1.3 tons of cured forage more per acre than when grown continuously on the same land. Part of these differences in the yield of sorghum were probably due to the sorghum disease, *Phthium arrhenomanes.* This disease was prevalent on the continuously cropped and rotated areas in 1937, and the comparatively low yields recorded for the continuously cropped area in 1935 and 1936 may have been due in part to this disease. There appeared to be only a slight tendency for the grain yields to increase the less frequently darso was grown. There was, however, an increase in the yield of forage from darso grown only once every four years compared with darso grown every other year. Darso grown only once every four years produced 4.58 tons of forage per acre as compared with 3.95 tons when grown every other year.

Effect of cropping systems on the yield of oats. The average yield of oats in rotation, as shown in Table 4, was 31.8 bushels per acre as compared with 32.1 for continuous oats. From these records, it is apparent that there was no significant difference in the yield of oats on the rotated and non-rotated areas and that the frequency with which oats was used did not affect the yields.

Effect of the preceding crop practices on the yield of oats. The preceding crop practices, however, did affect the yield of oats, as shown in Table 5.

The influence of the previous crop on the yield of oats in these tests was closely associated with the condition of the seed bed at the time of sowing oats, except in the case where sorghum was the previous crop. The highest yields of oats were obtained by sowing on cotton stalk land which furnished a clean, firm seed bed. Oats following oats were sown on a moderately loose seed bed, while oats following corn were sown on a very loose seed bed. To prepare corn land for fall seeding of oats, it was necessary to plow the land at least 3 1/2 to 4 inches deep to turn under the vegetative litter present on the corn land. Both the plowing operations and also the vegetation plowed under resulted in a loose seed bed. The decomposition of the vegetative litter probably also deprived the growing oat crop of considerable nitrogen during the early growth of the crop. Sorghum probably leaves the soil temporarily depleted in both soil moisture and available nitrogen. The interval between the sorghum and oat crop was usually too short to permit the normal activities of soil organisms and weather to correct this condition. The detrimental effects of the sorghum on the following oat crop were most evident in seasons when seed bed preparation for oats was either delayed or omitted. The difficulty of following oats after sorghum was largely responsible for the failure to secure complete records for oats in the 4-year rotation in Table 4.

Table 5.—Effect of preceding crop practices on the yield of oats, 1931-36

Preceding crop	Acre yield, bushels of grain
Cotton	34.2
Oats	32.1
Corn	30.0
Sorghum	27.3

Conclusions from Current Rotations at Temple

Although cotton root rot was not eradicated, its severity was reduced in those rotations providing at least a two-year non-susceptible crop period between cotton crops under the conditions of a scattered stand of weeds that carry root rot. Marked and consistent reduction in severity of the disease was obtained in rotations using cotton only 1/4 of the time.

All the rotations used increased the yield of cotton whether they reduced the severity of root rot or not. Cotton yields were progressively increased the less frequently cotton was grown in the rotation and the major increases in cotton yields were closely associated with the degree to which root rot infestation was reduced. Outstanding increases in yield of rotated cotton over that of continuous cotton were secured in rotations in which cotton was grown only 1/4 of the time.

Factors other than the reduction of cotton root rot contributed to increases in cotton yields secured by rotation. The other factors contributing to increased cotton yields in these rotations apparently were associated with the management of the crop immediately preceding cotton. In these experiments, cotton yields were increased most when preceded by corn, guar, and oats, in the order named. Under the crop management used in these experiments, sorghum did not decrease the yield of cotton when it preceded cotton.

Rotation with other crops increased the yield of corn and sorghum when compared with continuous growing of these crops. However, non-rotated oats made yields just as high as did rotated oats.

The frequency with which corn and sorghum were grown in the rotation had very little effect on their yields.

The preceding crop practices affected the yield of oats and the highest yields were obtained when the preceding crop provided a clean, firm seed bed for oats. Oats preceded by cotton produced the highest yields, while oats preceded by sorghum made the lowest yield.

Practical Uses of Rotations

From a review of the rotation experiments conducted in the Blacklands prior to 1928 and from an analysis of the current experiments at Temple, it is evident that the factors essential to the control of root rot by crop rotation originally recommended by the Experiment Station have been confirmed and redemonstrated. These recommendations, in brief, were: (a) eradicate root-rot susceptible weeds, (b) follow cotton by three years of non-suscepible crops for effective root-rot control and marked increases in cotton yields. These recommendations have stood the test of time and are now, nearly fifty years after they were first made, the most practical means of controlling root rot under field conditions in the Blacklands.

Eradication of susceptible weeds. The eradication of susceptible weeds is a prerequisite to the control of cotton root rot by crop rotations. Certain perennial weeds may persist on the land whether the crops are rotated or not, and the rotation of crops may have only an indirect influence upon their eradication by using crops such as sorghum that tend to smother the weeds or by making the land available for cultural operations at unusual times of the year. Continuous cotton land is never available for summer plowing; so certain types of weeds become prevalent, while summer or early fall plowing to destroy these weeds may be accomplished following the harvest of almost any of the non-susceptible crops (47). The management of the individual kinds of crops grown, and not the rotation used, largely determines the extent to which susceptible weeds may be controlled. Thorough and sustained cultivation is the most effective means of eradicating weeds. Where sheep are available, they may often be used to considerable advantage in controlling weeds.

Flexible uses of non-susceptible crops. In addition to eradicating root-rot susceptible weeds from his field, the farmer also has to meet the requirements of rotations designed to control root rot. The rotation used by any individual Blackland farmer is naturally influenced by the restricted number of non-susceptible crops he grows.

Varieties of corn and sorghum adapted to almost any conditions found in the Blackland region are available and corn particularly is extensively grown. Many excellent varieties of sorghum are available but some of them are of more recent distribution and the value of sorghum is not fully appreciated by many farmers of the region. Grain sorghums are grown most extensively on those Blackland farms and in the sections where corn is likely to suffer from droughts. The varieties of wheat and oats now in use by Blackland farmers are susceptible to leaf and stem rust and are extensively planted only in those sections and on those soils of the region where serious damage from rust is less likely to occur.

Individual farmers throughout the Blacklands have not only eradicated susceptible weeds on their land, but also have grown sufficient acreages and kinds of non-susceptible crops to permit the extensive use of rotations in which cotton is grown as infrequently as 1/4 of the time. Where such practices have been followed over long periods, root-rot infestations are of minor importance and cotton yields are comparatively high. But most Blackland farmers, although they rotate their crops, do not provide intervals of sufficient duration between cotton crops to effect root-rot control. In some cases this may have been because the farmer has not understood the principal features of a rotation designed to control root rot or because he has not visualized the elasticity of the non-susceptible crop schedule recommended to him. In the past the word "rotation" when applied to cropping systems has ordinarily meant "equal acreages of different crops grown in a definite sequence or fixed order." In conducting formal crop rotation experiments this definition of the word "rotation" has been used so as to simplify the prosecution and interpretation of the experiments. However, in the following discussion of the application of these results to conditions of Blackland farmers, the word "rotation" is used to mean "the recurrent interruptions of cotton growing or other root-rot susceptible crops on any particular piece of land by one or more years of root-rot immune crops, independent of the kinds, acreages, or sequence of these crops." From the standpoint of root-rot control, the principal feature of a rotation is the number of years between cotton or other susceptible crops on the same piece of land. If material reduction in the prevalence of the disease is to be expected, the land in question should be free of cotton and all other root-rot susceptible plants, both wild and cultivated, for three years.

During the three-year non-susceptible plant period any number, kinds, or acreages of cultivated grasses such as corn, sorghum, oats, wheat, barley, sudan grass, and millet may be planted in any order or combination desired. Also wild grasses may be permitted to grow in these crops without materially affecting the degree of root-rot control. The non-susceptible crop schedule on any particular piece of land may be as elastic as the crop adaptation of the land and the tolerance of the crop to be planted to the crop that preceded it will permit. Within these limitations, which are independent of root-rot control, the farmer may select the kinds and acreages of non-susceptible crops he is to plant on any portion of his farm from year to year and on the basis of the probable market demands, requirements for home consumption, and his facilities for producing each crop. Furthermore, a rotation designed to control root rot may be used on any part of a farm where this disease is particularly destructive without affecting the cropping system on another part of the farm where the disease is less severe or absent altogether. Used in this way a rotation to control root rot on severely infested areas need not upset the balance of cash and feed crops for the entire farm.

Use of a single non-susceptible crop. Many Blackland farmers grow only two major crops, cotton and corn. If corn is the only root-rot immune crop grown, only a simple alternation of crops is feasible. Such a rotation seldom, if ever, reduces the severity of root rot, even though weeds are absent. Very frequently this is because too many viable sclerotia survive a single year of non-susceptible plants. A two-crop farmer, if one of the crops is highly susceptible to root rot, usually has very little opportunity to follow the kind of rotation that is necessary for the control of the disease. This is particularly true if the non-susceptitble crop is corn or sorghum, since neither of these crops can follow itself without danger of reducing the yield materially (46, 50). However, the farmer who grows only cotton and corn can follow cropping practices that will increase the yield of cotton, although root rot is not controlled. As shown by the results presented in Table 3, the yield of cotton was comparatively high in the 2-year rotation of cotton and corn when liberal amounts of crop residue were plowed under early in the fall following the harvest of corn.

On the two-crop farm where the crops grown are cotton and small grain, the cropping system necessary for the control of root rot may be followed, at least on selected portions of the farm. In a previous section of this report, it has been shown that, although the yield of oats at Temple was higher when oats followed cotton than when oats followed oats, the yield of continuous oats over a nine-year period was almost as high as rotated oats. Similar results with oats have also been secured by other workers (46, 50). Thus a 4-year rotation of cotton with oats in which cotton is planted only 1/4 of the time is practical, since continuous oats may be used for the three years required. Such a cotton-and-oats rotation may be used for selected portions of the farm or for the entire farm, depending upon the proportional acreage of cotton and oats normally grown. Other small grains may be used in a similar manner. If weeds are controlled, such a rotation may be expected to control root rot effectively and to increase materially the yields of cotton with only a slight sacrifice in the yield of small grain.

Use of two non-susceptible crops. On farms where two or more non-susceptible crops are normally grown, the required type of rotation to control root rot can nearly always be used, if not for the entire farm, at least on selected areas. If cotton, corn, and sorghum are the crops grown, for example, it is practical to use a 3-year rotation for as large an area as is planted to the non-susceptible crop with the smallest acreage. In the Blacklands, the smallest acreage on a given farm is at present likely to be sorghum. In this case, a 3-year rotation using cotton only 1/3 of the time can be used on an area the size of the sorghum acreage. Such a procedure may be expected to give moderate protection from root rot losses on the area involved if careful attention is given to eradicating weeds. This practice cannot be expected to control root rot as regularly or as effectively as using cotton only 1/4 of the time. It is, however, superior to the simple alternation of the corn and sorghum with cotton or continuous cotton.

Where small grain and at least one other non-susceptible crop are grown, a rotation using cotton only 1/4 of the time is nearly always feasible. If, for example, the crops grown are cotton, small grain, and corn, a rotation of cotton the first year, small grain the second and third years, and corn the fourth year followed again by cotton should prove effective. Again the acreage involved in the rotation may depend upon the area planted to the non-susceptible crop with the lowest acreage. Also, as indicated previously, the effectiveness of the rotation will be partially or entirely lost if weeds are not eradicated. If weeds are eliminated and cotton is grown only 1/4 of the time, effective control of root rot and marked increase in yield of cotton compared to continuous planting of cotton may be expected.

Rotation of cotton with three or more non-susceptible crops. On farms where a large number of non-susceptible crops, such as corn, sorghum, oats, wheat, sudan grass, millet, and other grass crops are well adapted and are normally planted or may be profitable planted, the matter of following a 4-year rotation using cotton only 1/4 of the time is simplified. In the future many more farmers may be expected to grow high acreages on non-susceptible crops as current results of crops breeding by State and Federal workers specializing on certain of these crops promise to yield even more widely adapted and higher yielding strains on non-susceptible crops than are now available (2). This is especially apt to be the case with small grains as high-yielding, rust-resistant strains are distributed. As the acreage of these non-susceptible crops increases in proportion to the acreage of cotton grown, a greater and greater portion of the farms may be involved in the required rotation. On those farms where the cotton acreage is relatively small and the acreage of the non-susceptible grass crops is relatively large, the maximum benefits of crop rotation in controlling cotton root rot may be obtained. But on those farms where cotton is planted almost exclusively and there is not the will nor the opportunity for the farmer to use increased kinds and acreages of non-susceptible crops, there is very little opportunity to control cotton root rot by crop rotations. On the majority of farms in the Blackland region, with conditions intermediate between these two extremes, crop rotations properly managed may be used to considerable advantage in reducing the severity of root rot.

Possibilities of increased utilization of non-susceptible crops. The cropping systems needed for the most effective control of cotton root rot require the planting of relatively large proportions of the cultivated land on Blackland farms to non-susceptible crops and only moderate acreages to cotton. In the past the average income per acre made from cotton even under serious root-rot infestations has usually been greater than the average income from most non-susceptible crops. Except on certain soils and in certain sections of the Blacklands where conditions are more favorable for the non-susceptible crops than for cotton, these crops have rarely been grown for sale as cash crops but have been grown for consumptive purposes and only the surpluses sold.

In contrast to the usual practice, individual farmers throughout the Blacklands who control sufficient crop acreage to make it feasible to grow a number of crops and who have adequate supplies of stock water have for years diversified their farming activities. These farmers have long grown relatively high acreages of non-susceptible crops and only moderate acreages of cotton. By utilizing their non-susceptible feed crops in the production of salable livestock or livestock products to supplement their income from cotton production, these farmers have made relatively high farm incomes. As a result of their diversified farming, these farmers have sufficient acreages of non-susceptible crops to provide the type of rotations required to control root rot effectively. While the majority of Blackland farmers have not followed this procedure, the success of those who have indicates that many others with similar resources might well do so.

No radical change in farm organization is recommended within a short period. Any change that is to be made should be made gradually and should pay its way as the change is made. Non-susceptible crops should not be planted at the risk of materially lowering farm income, regardless of their usefulness in controlling root rot or in improving soil fertility. Only when such a crop promises to add materially to the net farm income is there sufficient justification for planting it. However, farmers should not attach too much importance to high income per acre. The cost of producing a crop as well as the number of acres a man can tend are also to be considered. One man, for example, can tend rather large acreages of oats without seriously interfering with the normal size of his cotton crop; and oats, although a low income crop, is relatively inexpensive to produce. If sufficient land is available, both cotton and oats can be produced with only moderate additional expense. Often the only income received from oats is from the sale of grain. Yet where this crop is planted in the fall, it may be grazed by salable livestock at least five months of the year, without serious risk of lowering grain yield, and the value of this pasturage may materially increase the per-acre income from oats (58).

In addition to small grains, other non-susceptible crops such as corn, sorghum, and sudan grass may be grown without prohibitive competition with cotton for labor and equipment, and many opportunities to secure increased incomes from these crops are available to farmers who are willing to utilize them. The accessibility of extensive acreages of previously little-used, small-grain pasturage and the ease of providing high-carrying-capacity summer pastures of sudan and other grasses together with the opportunity to produce large quantities of cheap forage from planting increased acreages of sorghum should attract many Blackland cotton farmers to fatten beef cattle as a supplementary enterprise to cotton production. Small dairy enterprises should appeal to others. And in still other instances, farm flocks of sheep may be used.

The benefits of these opportunities can gradually be obtained by most Blackland farmers, and the early steps toward a more profitable farming system *are easy ones if they are chosen intelligently. Any Blackland* farmer who is not already doing so might well start toward a better type of farming with a family garden and a home supply of poultry, pork, beef, and dairy products as a foundation and expand into desirable livestock enterprises to supplement farm income. Only a short way from the farm pantry are other steps such as improved farm pastures and trench silos, steps that may be taken by most farmers. Working from the farmyard to the fields, farmers may soon realize the benefits of non-susceptible feed crops as a basis of enterprises to supplement cotton farming, and only after sufficient acreages of non-susceptible crops are grown will it be practical to control cotton root rot by the required rotation.

METHODS OTHER THAN CROP ROTATIONS FOR CONTROLLING COTTON ROOT ROT

In addition to the use of crop rotations, cotton root rot can be controlled under certain conditions by other methods, most of which are of little practical value except when used in conjunction with crop rotations and are only occasionally of sufficient promise to be considered as independent methods of controlling the disease. Some of the other methods that have been studied are: (a) the use of organic manures, (b) clean fallow, (c) deep tillage, (d) the use of chemical soil amendments including commercial fertilizers, and (e) the selection of root-rot resistant strains within susceptible crops. A discussion of these special methods should serve to clarify the means by which progress in controlling established root-rot infestations may be expected. Of particular interest are the ways some of these specialized methods may be used in conjunction with crop rotations.

The Use of Organic Manures Under Root-Rot Conditions

Under some specialized conditions root rot has been controlled by the use of heavy applications of organic materials. In Arizona, King controlled root rot under irrigated conditions by annual applications of animal manures at rates of 12 to 14 tons per acre (6, 20, 21, 25, 27, 28, 30, 31). He also secured satisfactory results with equivalent amounts of green manure. The extent to which organic manures may be used for root-rot control under other conditions has not been fully studied but under dry land conditions in the Blackland region of Texas the results secured have not been encouraging. Manure treatments for the control of root rot tried by Scofield (55), Taubenhaus and Killough (72), and Ratliffe (45) gave negative or inconclusive results.

Few attempts have been made to control root rot in the Blackland soils by the use of green manures and before green manures are apt to be used for any purpose in this region more satisfactory green manuring practices are needed. In other sections of the United States where green manuring is practiced, legumes are generally used. In the Blacklands, however, few legumes are well adapted. Most of the winter legumes that have been tested make only mediocre and uncertain growth and often interfere with seed bed preparation of the following money crop. The vigorous growing spring and summer legumes available seldom benefit the land sufficiently to justify the use of the land for a season. Also most of these legumes are highly susceptible to root rot and their use on root-rot infested land is of doubtful value as they tend to spread root rot.

Since so many of the legumes are susceptible to root rot and are only mediocre forage plants, consideration has been given to the value of non-leguminous crops for green manure. In this class, sorghums offer considerable possibility, since they are not only immune to root rot but are also heavy forage yielders, even under favorable conditions of rather short duration. Also sorghums frequently offer an opportunity to secure a green manuring crop incidental to the production of a feed or revenue crop. Where this is feasible considerable benefit may be obtained by turning under second growth and catch crops of sorghum. Although such green manuring practices may have some value in reducing root rot, their principal value is to stimulate the yield of plants that escape the disease. For this reason the best results may be expected when sorghums for green manure are used in rotations designed to control root rot.

Root Rot Control by Clean Fallow

Cotton root rot has been controlled by clean fallow of sufficient duration to kill the roots of susceptible crops, to eradicate or materially reduce the stand of susceptible weeds, and to permit a material reduction in the population of viable sclerotia by natural deaths. In most cases studied, at least two years of clean fallow were necessary to secure control. Clean fallow experiments have been conducted under a wide variety of conditions and at a number of locations throughout the Blackland region of Texas, and practically every agency studying the cotton root-rot disease, both in Texas and in other states, has at some time conducted clean fallow experiments designed to control the disease (27, 29, 30, 31, 33, 34, 36, 45, 47, 53, 55, 72). Various experiments have provided clean fallow periods during the winter months, during the summer months, for one year, two years, and more. One of the longest clean fallow periods studied thus far was for eight years. Few of the clean fallow treatments maintained for less than two years were successful. In common with most other methods of controlling root rot, the control resulting from clean fallow of two or more years was fully effective for only one cotton crop immediately after the treatment. The development of root rot in the second and later cotton crops after the fallow is often just as severe as on the continuous cotton areas.

As an illustration of the results secured with clean culture the following cases may be cited: McNamara and Hooton of Greenville report that "One plat that showed more than 90 per cent infection for the 3 years period from 1919 to 1921, inclusive, showed no infection when returned to cotton in 1924 after a 2-year clean fallow" (34).

With reference to the clean fallow experiments at Temple, Rogers states: "Cotton planted in 1935 on Acre E6, after five and one-half years of clean fallow, had an end season root-rot kill of 6.7 per cent. Part of the area planted to cotton continuously for three years after three-year fallow had 98.2 per cent of the cotton killed by root rot in the same year. Both areas planted again to cotton in 1936 had a 92.9 per cent kill on the part having only 6.7 per cent in 1935 and 98 per cent kill on the part having 98.2 per cent dead in 1935" (2).

Clean fallow was not as effective in root-rot control as the use of non-susceptible crops, except in the eradication of perennial weeds which carry the disease. The use of clean fallow for this purpose is probably justified when the treatment does not interrupt crop production. As an independent method of controlling root rot, clean fallows were impractical in almost every situation they were tried, since the treatments required a long non-crop period and gave only temporary control of the disease. The clean fallow method of controlling the disease was very expensive both in terms of sacrificed income from idle land and also in the extra cost of the tillage operations. As the primary benefit of clean fallow is the earlier eradication of perennial weed carriers of the disease, it is probable that many of these weeds can be eradicated at a much lower cost by other cultural practices and the wise management of livestock grazing in conjunction with the rotation of non-susceptible crops with cotton.

Control of Root Rot by Deep Tillage

Deep plowing has long appealed to the popular imagination as a promising method of controlling soil inhabiting diseases and various types of deep tillage have been advocated from time to time as possible methods of controlling cotton root rot. Even before very much fundamental information concerning the root-rot fungus was developed, Shear and Miles recommended deep plowing in conjunction with crop rotations as a method of controlling this disease (56). From deep plowing and subsoiling experiments conducted at Temple from 1917 to 1921, Taubenhaus and Killough concluded that deep plowing was of little value in controlling root rot (72). In 1926 King reported that deep fall plowing was not adapted to conditions in the irrigated sections of Arizona and that deep spring plowing had little or no effect on the severity of root rot (27).

The early deep tillage tests were for the most part concerned with horse drawn implements and involved only moderate depths. Interest in deep tillage as a root-rot control method has continued, and since 1928 there has ben available at several locations throughout the Blackland region of Texas heavy tractor-drawn subsoiling equipment and various commercial and institutional agencies have tested tillage to depths of 14 to 28 inches as a means of controlling root rot. In most of the trials made, root rot was less severe on the subsoiled areas than on the unsubsoiled areas (2, 8, 9, 10). A marked degree of root-rot control was obtained in some years and in the majority of the cases the yield of cotton was also increased. The results secured by Dunlavy (2) at Temple from 1930 to 1933 are presnted in Table 6.

Table 6.—The effect of subsoiling on the control of cotton root rot and the yield of cotton

Treatment	October 1st Percentage of root rot					Average Pounds of lint cotton per acre				
	1930	1931	1932	1933	Average	1930	1931	1932	1933	Average
Untreated	42.6	41.9	63.8	76.0	56.1	167	206	156	320	212
Subsoiled	34.1	25.6	52.7	48.1	40.1	166	262	192	307	232

In the Temple trials root rot was less severe on the subsoiled plats than on the untreated plats each year. During the 1930-33 period root rot killed an average of 40.1 per cent of the cotton plants on subsoiled plats as compared with 56.1 per cent on the untreated plats. The subsoiled plats yielded an average of 232 pounds of lint cotton per acre as compared with 212 pounds for the untreated plats. Although subsoiling resulted in an average increase of 20 pounds of lint cotton per acre, the value of this increased yield was not sufficient to pay the cost of the subsoiling operation. From a practical point of view, subsoiling to depths of 14 to 28 inches is not a promising method of controlling cotton root rot because of the expensiveness of the subsoiling operations.

Soil Amendments for Root Rot Control

Many experiments involving the use of a wide variety of soil amendments have been conducted but most of the treatments used have failed to control the disease (2, 7, 8, 9, 10, 11, 13, 18, 21, 23, 25, 29, 40, 41, 42, 49, 59). There are a number of chemicals that are toxic to root rot when they are brought in contact with the fungus. However, the problem of securing penetration and distribution throughout the soil of the material used so as to insure contact of the chemical with the fungus is very difficult. Even in some of the more porous soils, these treatments have been only moderately successful although extreme care and elaborate methods were used.

One group of soil amendments that has been extensively studied is the soil acidifying chemicals. Interest in the soil acidifying agents was developed following a laboratory demonstration that the growth of the root-rot fungus in pure culture could be controlled by changing the reaction of the media on which the fungus grew from alkaline to acid (72). It has long been known that the cotton root-rot disease is most generally distributed and most severe in neutral to basic soils and that its distribution and severity are very much restricted in low lime content soils. Detailed studies of the major soil types in Texas have shown that there is a close connection between the soil reaction and the severity of root rot (1, 2, 7, 8, 9, 10, 12, 16, 41, 42, 63, 65, 70, 71, 72).

In an effort to make practical application of this information, sulphur was used in a number of tests as one of the more economical soil-acidifying agents. In small experimental plats planted to cotton, the prevalence of the root-rot disease was considerably reduced by application of the sulphur (7, 8, 10, 13, 63, 65, 70). However, attempts to make practical the use of sulphur on a field scale to control root rot on low lime content soils were disappointing. The results secured indicated that sulphur applied to such soils was not likely to give satisfactory control of the disease, and that there was considerable danger of injury to the cotton (8). Tests made on certain high lime content soils of the Blackland region indicated that rates of sulphur application necessary to affect the soil reaction materially were far too expensive for practical use (48).

Increasing Yields of Susceptible Crops from the Use of Fertilizers

Chemical fertilizers are another class of soil amendments that have been given considerable attention. Since these materials are expected to have their influence primarily through the plant, their method of application is not so exacting as for chemicals where contact with the fungus is required. However, recent experiments show that reasonably deep placement of fertilizer in the clay soils of the Blackland region permits the fertilizers to be more effective than shallow placement (17). During the past 10 years a large number of fertilizer experiments with cotton have been conducted under root-rot conditions in the Blackland region both by the Texas Agricultural Experiment Station and the Division of Soil Fertility Investigations, United States Department of Agriculture. In general the fertilizers used have increased the yield of cotton, particularly the fertilizers high in nitrogen and phosphorus (2, 17, 49, 51). The Division of Soil Fertility Investigations has also pointed out that certain fertilizers delay the occurrence of root rot early in the summer (17). Under conditions of favorable cotton prices, the increased cotton yields obtained from fertilizers on several of the soils of the region may be quite profitable, especially if the fertilizer is used in conjunction with crop rotations.

Plant Improvement and Root Rot Control

Repeated attempts have been made and are still being made to find cotton and legume strains that are resistant to cotton root rot (2, 3, 4, 7, 8, 9, 10, 15, 59, 61, 62, 63, 65, 67, 69, 72). Although the discovery of a resistant strain of cotton might be the most effective means of controlling the disease, the results secured with cotton thus far give little indication of resistance in this crop. Some of the legumes, such as sesbania and guar, however, appear to be highly resistant to the disease, and in more recent experiments, observations have been made that certain varieties of cowpeas are less susceptible to root rot than are others (2, 69).

The development of high yielding strains of forage legumes resistant to root rot would contribute materially to the profitableness of Blackland agriculture and greatly encourage the use of crop rotation. The occurrence of some very acceptable plant material for legume breeding and the existence of apparent resistance to root rot in certain legumes offers some encouragement that this objective might be attained. The improvement recently made with non-susceptible grass crops such as rust resistance in wheat and oats and the development of more productive strains of corn and grain sorghum promise to increase the acreage planted to these crops (2). With the planting of sufficient acreages of these non-susceptible crops, the control of root rot by crop rotations will be simplified.

SUMMARY

The fungus *Phymatotrichum omnivorum* (Shear) Duggar attacks and causes the decay of the roots of cotton and many other plants, both cultivated crops and weeds.

This disease is particularly destructive to cotton in the Blackland region of Texas where the soil, climate, and flora are generally favorable for the spread and perpetuation of the fungus.

Three stages in the life history of the fungus are known: (1) the active growing strand or vegetative stage, (2) the resting or sclerotial stage, and (3) the spore stage.

The strand growth of the root-rot fungus is the destructive stage, and it spreads and perpetuates the fungus by continuous growth of the strands, chiefly along the live roots of susceptible plants and from one plant to another where continuous culture of cotton is practiced and close stands of susceptible weeds occur. Roots of susceptible perennial weeds may harbor and perpetuate the strand growth of the fungus for long periods.

Root rot sclerotia are formed in the strands of the fungus and serve to perpetuate the fungus in a dormant but viable condition over long periods, even in the absence of susceptible plants. Sclerotia may be found in the soil as deep as roots of susceptible plants grow and are infected with root rot. Sclerotia may remain viable in the soil for many years, although the majority apparently lose their vitality by the end of three years.

The further spread of root rot into a previously uninfested portion of a cotton field may be prevented by growing a barrier of sorghum between the infested and the uninfested parts of the field. The sorghum must be planted in the same location year after year as long as protection from root rot invasion is desired. Under practical field conditions the sorghum barrier should be at least 30 feet wide. Corn, small grain, and many other immune crops will not make effective barriers, since their root systems permit the invasion of the roots of adjacent susceptible crops.

The value and requirements of crop rotations in controlling root rot were pointed out by the Experiment Station as early as 1888. Since that time rotation experiments at San Antonio and Temple have confirmed and further demonstrated the factors essential to the control of root rot by crop rotations. Marked and consistent control of cotton root rot was secured in rotations of cotton with non-susceptible crops in which cotton was grown only 1/4 of the time. A non-susceptible crop period of at least two years between cotton crops was required to control the disease. Simple alternation of susceptible and non-susceptible crops was of little value in controlling root rot.

The control of susceptible weeds was a prerequisite to the control of root rot by crop rotations.

Yields of cotton on rotated areas were generally higher than on non-rotated areas. At Temple the increases in the yield of rotated cotton compared with non-rotated were greater the less frequently cotton was planted and the major increases were associated with the degree to which root rot was controlled. Outstanding increases in yield of cotton over that of continuous cotton were secured in rotation in which cotton was planted only 1/4 of the time.

The yields of corn and sorghum were increased by rotation. Rotations of short durantion were as effective as long rotations in increasing the yields of these crops. The yield of oats was practically as high when grown continuously as when rotated.

Increased acreages of non-susceptible crops are frequently needed on the farms of the Blackland region to enable farmers to secure the maximum benefit from crop rotations in controlling root rot. Plant improvement projects now in progress promise to make available in the near future new strains of the root-rot immune crops that should attract farmers to grow these crops more extensively. Higher yielding strains of wheat and oats are already in the possession of state and federal plant breeders. Higher yielding and more dependable strains of corn and sorghum are being developed. Improved strains of pasture grasses may also be expected.

Increased farm incomes from the root-rot immune crops may be secured on most of the Blackland farms where sufficient stock water is available by marketing these crops through salable livestock. Grazed by livestock, weeds and grass in corn fields may be converted into farm income. Winter grazing of small grains may materially increase the value of these crops. Increased markets for sorghum, a well adapted, inexpensive, and high yielding crop in the Blacklands, may be greatly extended through the use of livestock. Sorghum for grain, bundle feed, and silage is well suited to cattle feeding. Greatly increased acreages of sorghum may be grown for silage to be stored in inexpensive trench silos to insure the abundance of cheap feed. Increasing acreages of sudan may furnish excellent and dependable summer pasture for livestock and when used to supplement other feed resources may be a source of considerable farm income. The sodding of eroded areas and waste land along drainage ways to permanent pasture grasses may easily add revenue-producing acreage to many Blackland farms where livestock are kept. The classes of livestock that may be kept advantageously depends on the physical resources available, the location of the farm with reference to markets, and the aptitude of the individual farmer.

Methods of controlling root rot other than by crop rotations are less applicable to Blackland conditions. Clean fallows of sufficient duration to control the disease are no more effective than crop rotations and make poor use of land and labor. Deep tillage is usually very effective but requires the use of expensive machinery and is costly to perform. Soil amendments are seldom effective under practical field conditions. Commercial fertilizers are of most value when used in conjunction with crop rotations. The use of heavy applications of animal manure, although successful in irrigated sections, has failed to control root rot under dry land conditions. Control of root rot by green manuring practices is uncertain and the crops and land used in such a practice usually have their highest value when used in conjunction with a crop rotation and livestock program. While root-rot resistant varieties of cotton may be found, the prospects are not as encouraging as are those for the further improvement of root-rot immune crops that may be grown in rotation with cotton.

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