INTEGRATED MANAGEMENT OF COTTON WILT DISEASES

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Introduction

Verticillium wilt is the most important pathogen of cotton, causing worldwide losses of about 1.5 million bales from potential production (3). Fusarium wilt occurs in most cotton growing regions of the world, but it is notably absent from west Africa, Turkey, and until recently from Australia. In 1997, Verticillium wilt caused an estimated 1.37% crop loss and Fusarium-wilt 0.32% in the US. These losses persist in spite of intense efforts to control the wilt diseases. Considerable progress has been made in improving resistance to both pathogens, but even the most resistant cultivars can become affected by defoliating strains of *V. dahliae* if mean soil temperatures fall below 25°C (2, 3, 12). No single method is highly effective in controlling the wilt diseases. Consequently, an integrated management system is necessary to minimize losses and control the wilt diseases (7).

Control begins with the selection of a cultivar that has some level of resistance to wilt, good agronomic characteristics and adaptation to the geographical location. A combination of cultural practices are then adapted for this cultivar to minimize the losses from wilts. Chemical controls can be effective, but are generally not used because of their prohibitive cost. Biological controls are used to a limited extent only in Russia and India. Several workers have presented detailed reviews of Verticillium and Fusarium wilts (2, 3, 4, 7, 11, 16, 23, 26, 29, 30). This paper presents conceptual models and practical application for integrated management and control of cotton wilt diseases.

Verticillium Wilt

A conceptual model for Verticillium wilt (Figure 1) was developed that integrates and links our knowledge of system components: host resistance and its genetic potential, fruit set, other pests in the system, pathotypes and inoculum density of the pathogen, disease progress, temperature and moisture, and rhizosphere and phylloplane environments to plant health, yield and quality (7). The system adjusts biological activities in response to environment and management tactics.

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Epidemiology

Factors important in the epidemiology of Verticillium wilt of cotton are inoculum density and pathotype (defoliating and non-defoliating) of *Verticillium dahliae* Kleb. in soil, plant age, host resistance and its genetic potential, air and soil temperature, soil moisture, plant density, and nitrogen and potassium availability to growing plants.

Causal Organism. The *V. dahliae* fungus has a wide host range and survives as microsclerotia in soil and in decomposed plant debris for several years. Strains of *V. dahliae* are known to attack more than 400 plant species in 40 different families (3, 26). The fungus includes several strains; some are rather host-specific while others attack many plant species. At least five strains were reported to attack American Upland (*Gossypium hirsutum*) cotton cultivars (26). Vegetative compatibility (V-C) tests and isozyme analyses have been used to show that there are four genetically isolated populations (V-C groups) within the species *V. dahliae*, and that each V-C group has at least two subgroups (3).

Fungus propagules (microsclerotia) in the rhizosphere are usually dormant and are stimulated to germinate by root exudates. There is a time interval of about 14 days between root infection and detection of disease symptoms in leaves.

Inoculum Density, Disease Progress and Severity. The severity and rapidity with which disease symptoms progress depend primarily on the cultivar, pathotype of *V. dahliae*, inoculum density, growth stage of the host, fruit load, and soil moisture and temperature (Figure 1).

Increasing virulence or inoculum density of the pathogen can offset effects of host resistance (2, 3, 4). Pathogen density and virulence levels for specific sites and fields can be estimated, especially when the history of the disease is known. The number of microsclerotia of *V. dahliae* can be quantitatively determined with the modified Anderson sampler technique (5, 22) or the wet sieve method (17). The number of microsclerotia recovered by the Anderson method averages 2.8 times higher than that recovered by wet sieving (5).

The effect of initial inoculum density of 5, 20, 40, and 60 propagules/gram (p/g) of soil of *V. dahliae* on foliar disease symptoms and on disease progress in time is presented in Figure 2 (7, 22). An increase in inoculum density from 5 to 60 p/g resulted in an increase in the percentage of infected plants as the season progressed, causing 95% foliar symptoms at 60 p/g and 15% at 5 p/g. The fungal population density required for 50% disease is approximately 22 p/g of soil. Also, with 60 p/g symptoms appeared early, 50-60 days after planting, compared to 90 days with 5 p/g.

Additional studies are needed to determine the minimum number of propagules required for the initiation of systemic infection and disease incidence. This number may vary with fungal pathotype, cropping history, cultivar, soil moisture, and environmental conditions, especially temperature (7).

Temperature Effects. Cool air and soil temperatures favor Verticillium wilt of cotton. Optimum temperatures for disease development are between 22 and 25 C (2, 3, 12). Low night temperatures trigger early-season disease development, provided the maximum day temperatures do not exceed 30 C. Symptom severity and fungal colonization decrease rapidly as temperature increases from 22 to 28 C. High air temperatures (28 C) decrease the susceptibility of cotton to wilt (3, 4, 12) and restrict *in vivo* growth of the fungus. *V. dahliae* pathotypes also differ in optimum temperatures for growth. The non-defoliating SS-4 strain from cotton has an optimum of 24 C, whereas the defoliating T-1 strain has an optimum of 27 C (26). Germination and growth of *V. dahliae* are inhibited at temperatures above 30-33 C, and fungus structures die at temperatures above 36 C.

Control Measures

Effective control of Verticillium wilt can be achieved only with an integrated management system. The disease is controlled most effectively by growing adapted resistant cultivars and using cultural and management practices and options known to reduce disease severity, such as increasing crop rotation, sanitation, plant density, and soil temperature; and decreasing crop residues, weeds, nitrogen rate, and irrigation frequency and amount (7).

Figure 3 illustrates an integrated crop management system (ICMS) for cotton and control of Verticillium wilt. The system, as with all production systems, is dynamic in that it can vary according to the production region and environmental conditions. This ICMS can be used as a production model and as a checklist of key disease control tactics and options that should be considered throughout the season.

Control measures may be implemented before, at or after planting depending on the amount of inoculum in the soil (7). If the initial inoculum density is high, control measures may not lower the number of infective propagules enough to reduce disease severity and maintain yield. If inoculum density is 22 p/g of soil or higher, the main option is crop rotation. Rotation with grasses, sorghum, small grains, corn, sweet clover, alfalfa or soybeans and weed-free fallowing may reduce disease losses. In cotton, rotation sequences such as cotton/sorghum/cotton, cotton/grain/cotton, and cotton/sorghum/grain aid in reducing propagules of soil-borne pathogens. If inoculum density is 5-20 p/g, several preplanting, at-planting, and post-planting practices are available (7). Paddy rice for a single year has given substantial increases in cotton yields and marked reductions in the amount of pathogen inoculum (21).

Preplant Practices

Sanitation. Sanitation is important in preventing the introduction of the fungus into wilt-free fields and in reducing losses from wilt in infected fields. Field application of plant residues infested with the pathogen, such as gin trash, often is a source of inoculum and can spread *V. dahliae* to disease-free fields. Composting trash eliminates some of the inoculum, and early plowdown to allow thorough rotting before planting further reduces inoculum in trash.

Tillage. Verticillium wilt has been reported to be severe in sandy loam, loam and clay soils, and soils high in organic matter. The disease causes the most striking damage on clay soils. Propagules of *V. dahliae* are most prevalent in the plant bed and top 30 cm of soil. Deep plowing, particularly where the soil is completely inverted, can be effective in reducing disease losses. Deep cultivation and root pruning in the presence of the pathogen increase disease severity and should be avoided during the growing season.

Weed Control. An effective weed control program helps reduce the incidence of Verticillium wilt. Susceptible weed species of economic importance in cotton production include pigweed, annual morningglory, prickly sida, common purslane, Carolina horsenettle, and silverleaf nightshade.

Row Spacing. In the United States, cotton traditionally has been grown in rows spaced 102 cm apart and requires about 150-180 days to produce a crop. Attention in recent years has focused on the use of narrow-row spacing in a short-season production system as a means of controlling late-season pests and reducing production costs. Several row spacings and patterns have been studied. In the San Joaquin Valley of California, the 76-cm row spacing increased lint yield 19% over that with the conventional 102-cm spacing (8). This increase represented 173 kg/ha for the Acala cultivars. In addition to higher yields, the percentage of plants showing foliar symptoms of Verticillium wilt was lower in cotton grown in narrow rows (51 and 76 cm) than in that grown in conventional 102-cm rows (9, 10). In Texas, the percentage of wilt was decreased significantly in close single-row spacing of 13, 25, and 51 cm (19).

Fertilization. A balanced nutrition of the major elements (nitrogen, phosphorus, potassium) and the minor elements is very important in minimizing plant stress and susceptibility to pests. The amount, form, and time of application of fertilizers used in cotton production have a bearing on the incidence and severity of the disease and its control. Excessive use of nitrogen induces rank growth and delays maturity, often increases disease incidence and yield loss, and enhances insect problems. Ammonium increases Verticillium wilt more than does nitrate or urea (3, 9, 23). Thus, nitrogen fertilization should be limited to levels for optimum yield. Potassium deficiency or unavailability greatly increases disease severity. The effects of phosphorus and micro-nutrients are variable and depend on nitrogen and potassium levels (23). However, manganese and zinc were reported to be the micronutrients that most frequently reduced disease severity.

At-Planting Practices

Soil Temperature. Management tactics and practices that raise soil temperature, such as planting on beds, skip-row planting, and alternate furrow irrigation, reduce disease severity and crop loss.

Planting Date. It is important to plant as early as possible to escape the effects of Verticillium wilt late in the season. Serious damage usually occurs during the latter third of the growing season, especially when soil temperature is below 28 C. Economic loss may be minimized when a high percentage of the crop is set and matured during the first two-thirds of the growing season.

Plant Density. Several studies (7, 9, 19, 23) have shown that increasing plant populations to about 120,000-150,000 plants per hectare increased yield and reduced the incidence of Verticillium wilt. Increasing the seeding rate, however, requires a positive control of the seedling disease complex.

Cultivars. The choice of cultivar is probably the single most important decision the grower makes in an integrated crop management system. The cultivar sets the framework for the level of susceptibility to pests, the tactics applied to manage the crop, and production costs (7). Differences in the resistance of *Gossypium* species and cultivars and sources of resistance to Verticillium wilt have been reviewed (1, 2, 3, 30). Although progress has been made during the past 30 years in developing cultivars resistant or tolerant to *V. dahliae*, higher levels of resistance are still needed. Examples of resistant American Upland (*G. hirsutum*) cultivars are Acala Prema, Acala 1517V, and Paymaster 266. In the former Soviet Union, the Tashkent cultivars show resistance to the pathogen. Verticillium wilt affects fiber properties as well as lint yield. As the percentage of plants with foliar symptoms increased, lint yield decreased, and fiber length and strength were reduced (1,7).

Post-Planting Practices

Fertilization, irrigation, and promotion of rapid boll set and early maturity are the main post-plant options for disease control (Figure 3). Soil moisture, in the form of irrigation or rainfall, can influence both the host and the soil microflora and fauna. Irrigation practices that reduce soil temperature increase disease losses. Excessive moisture and nitrogen fertilization encourage rank growth, delay fruit set and maturity, and increase incidence of Verticillium wilt.

Fertilization. A split application of nitrogen can reduce disease severity and increase yield. Multiple application avoids excessive levels of nitrogen early in the growing season. If the need to correct nitrogen deficiency arises as the season progresses, nitrogen can be easily side-dressed or applied as a foliar fertilizer or in irrigation water.

Irrigation. Water management is an effective tool to manipulate cotton growth and development and to control pests (7, 14, 15). This can be achieved by regulating the amount and the schedule of irrigations. Other water management tactics involve reducing excessive soil moisture by using raised beds and by selecting soils with good internal drainage. Earlier research on the effect of irrigation on Verticillium wilt has been reviewed (23). Outbreaks of Verticillium wilt often follow irrigation late in the growing season, particularly when irrigation lowers soil temperature. Thus, irrigation should be kept to a minimum once mean temperatures begin to decrease appreciably late in the growing season.

Promoting Rapid Boll Set and Maturity. Serious damage to plants and yield loss usually occur during the latter third of the growing season when the days are shorter, plant growth shades the soil more, and night temperatures are lower. Economic loss may be minimized by managing the crop for rapid boll set and maturity.

Protection of early fruiting forms (squares and flowers) is vital to reducing loss due to Verticillium wilt. When excessive early fruit forms are lost because of insect damage, the consequence is delayed fruit set, which extends the crop into periods when pathogen infection is more severe and damaging to production. Effective early-season insect detection and control based on economic thresholds are needed to avoid delayed fruiting and to prevent shedding of early fruit forms.

Fusarium Wilt

Fusarium wilt occurs in most cotton growing regions of the world, but is notably absent from west Africa, Turkey and until recently from Australia. The disease is rarely a problem in cotton growing areas with mean daily temperatures below 24 C, compared to Verticillium wilt which is favored by cool weather towards the end of the season. Cotton is the primary host, but there are numerous secondary hosts on which the fungus can multiply but produces only mild or no symptoms.

Epidemiology

The causal organism is F*usarium oxysporum* Schlect f. sp. *vasinfectum* (Atk.) Snyder & Hansen. Six races of the pathogen have been reported, based on their selective pathogenicity on a set of host differentials. Races 1 and 2 apparently originated in the US, race 3 is found in Egypt, race 4 in India, race 5 was identified in Sudan, and race 6 from Brazil (16).

In contrast with Verticillium wilt, evidence indicate that the Fusarium wilt pathogen is carried within the seed. Since seed transmission of the disease was first demonstrated in the

US (6), internal infection of cottonseed has been reported from several cotton producing countries. Although the soilborne fungus has a limited capacity for saprofitic survival in the soil, the pathogen survives for long periods in the absence of cotton. Pathogen clamydospores probably play an important role in survival of the pathogen in the field.

Disease symptoms may appear at any stage of crop development depending on inoculum density, temperature, and host susceptibility. Usually, symptoms begin four weeks after planting, and plants become more susceptible about the onset of flowering.

Interaction of the Fusarium wilt fungus with *Rhizoctonia solani* was reported from Egypt (24), and with *Thielaviopsis basicola* from California (25). Both fungi increased disease incidence by Fusarium.

It is established that Fusarium wilt incidence in the field is higher in the presence of root-knot nematode (*Meloidogyne incognita*). Other nematodes of importance on cotton which enhance infection by *Fusarium* are the reniform and sting nematodes.

Factors Affecting Infection and Symptom Development

High soil inoculum density and warm conditions between 30 and 32 C enhance the disease. Generally, symptom expression is most severe under hot dry conditions. Cotton plants often recover from the disease and regrow if the temperature falls below the optimum for disease development after initial infection.

The type of soil which favors the disease in cotton varies greatly with pathogenic race. In the US, where race 1 and race 2 occur, the disease is favored by sandy soils of pH 5-6.5. In contrast, race 3 in Egypt and race 4 in India are more prevalent on clay soils (16).

Control Measures

Integrated management include planting resistant cultivars, cultural management especially crop rotation and fertilization, soil solarization, and biological and chemical control.

Cultural

Crop Rotation. Fungus chlamydospores remain viable in the soil for several years and the pathogen is able to multiply on the roots of many weed and crop species (28). The use of crop rotation involving a non-host of *F. oxysposum* f. sp. v*asinfectum* will reduce the rate at which the fungus builds up in the soil, but the most appropriate crop may vary with the particular race of the pathogen and soil type. Graminaceous species have been considered as non-susceptible to the pathogen, and yet several of them are able to sustain high populations of the pathogen. In the former Soviet Union, planting barley, maize, mustard and clover reduced the incidence of Fusarium wilt in the following season's cotton crop (13).

Fertilization. In general, nitrogen fertilizers, particularly ammonium, tend to increase wilt incidence. Application of potassium fertilizer is recommended to reduce the incidence of both Fusarium and Verticillium wilts.

Resistant Cultivars

The first Fusarium wilt resistant cottons were developed in the US by mass selection on heavily infested soil. The cultivar 'Rivers' was selected in 1892, 106 years ago, from a field of Georgia Sea Island. Further selection resulted in 'Seabrook' which is a useful source of resistance to both Fusarium and Verticillium wilts. Variability for resistance to the Fusarium wilt pathogen occurs in both Upland (*G. hirsutum*) and Egyptian (*G. barbadense*) cottons, but resistance is more complete in the latter. Several high yielding resistant cultivars are currently available in the US and globally.

Biological

Several soils are known to be suppressive to Fusarium wilt, which is usually related to the presence of antagonistic microorganisms. In California suppressive soils contained species of *Azotobacter* (27) and in India a strain of *Trichoderma hazianum* isolated from cotton plants in the field has shown promise as a biocontrol agent, causing a decrease in wilt incidence (20).

Soil Solarization

Increase in soil temperature which occur under clear polyethylene sheeting has been shown to decrease the population of soil-borne pathogens. Soil solarization decreases the incidence of Fuarium wilt, but to a lesser effect than Verticillium wilt (18). However, the practice is costly for use on row crops.

Chemical

Verticillium and Fusarium soil populations can be decreased by soil fumigation; using for example a mixture of chloropicrin and methyl bromide. However, this treatment is expensive and usually confined to high-value crops. In fields where nematodes are prevalent, nematocide application may give an economic return.

Integrating the Components

Verticillium and Fusarium wilts of cotton exemplify the integrated crop management system (ICMS). Various factors and components originating outside the specific plant-pathogen interactions influence the course of an epidemic or pathosystem (7).

Three important precepts arise from the integral relationship between crop production, disease development and management. The first is that the integration of control practices must be based on the realization that individual pest species are single components of a complex agroecosystem. The second precept is that changes in crop production affect disease management and control. For example, replacement of tillage by herbicide application is likely to alter the activities of several microorganisms in the rhizosphere; some may become more prevalent, others less so. Other pests in the system and pesticides may directly or indirectly influence host susceptibility to the pathogen and crop productivity. The third precept is that disease management is more successful if considered during all phases of crop production (7). A management system implies an orderly and planned approach involving two or more major components. Effective management of wilt diseases requires the use of several approaches at several times during a crop cycle, and integrated into the overall crop production system.

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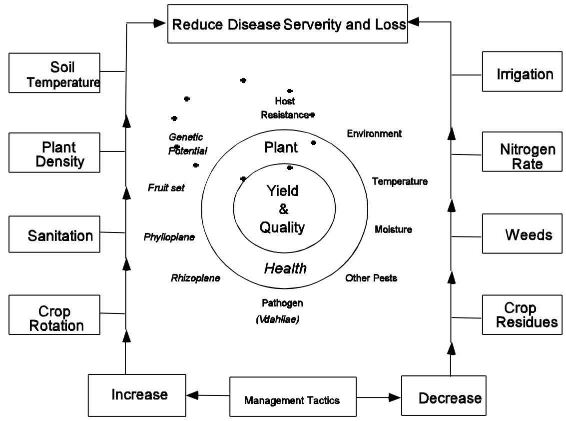

Figure 1. Conceptual model of an integrated management system for controlling Verticillium wilt of cotton. (After El-Zik 1985 (7)).

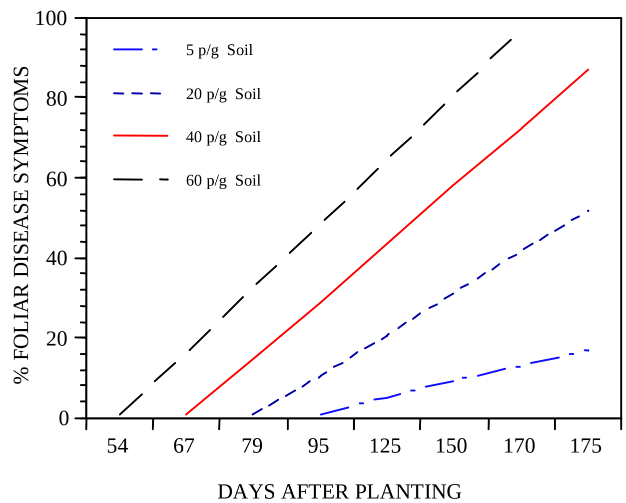

Figure 2. Relationship of initial inoculum density of *Verticillium dahliae* at 5, 20, 40, and 60 propagules per gram of soil to foliar Verticillium wilt symptoms of cotton with time. (Adapted after Pullman and DeVay [22] and El-Zik [unpublished].

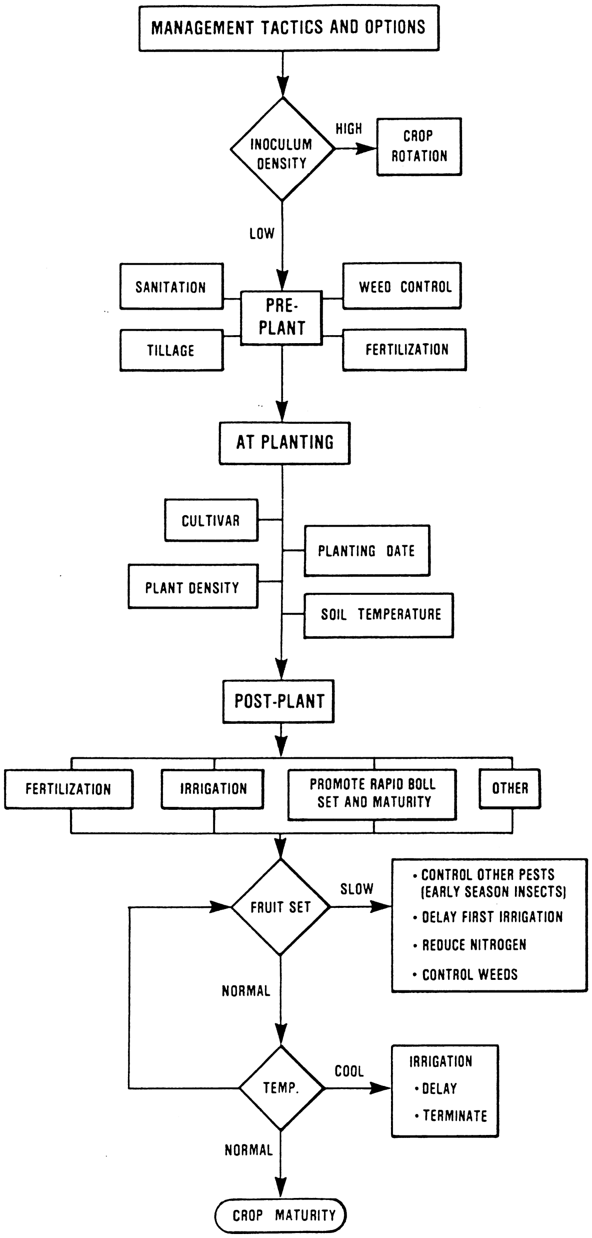

Figure 3. Integrated seasonal management tactics and options to control Verticillium wilt of cotton. [After El-Zik 1985 (7).]3