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EPIDEMIOLOGY AND MANAGEMENT OF TOMATO SPOTTED WILT IN PEANUT

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■ **Abstract** Tomato spotted wilt caused by thrips-vectored tomato spotted wilt virus (TSWV) is a very serious problem in peanut (*Arachis hypogaea* L.) production. TSWV and the thrips *Frankliniella fusca* and *Frankliniella occidentalis,* which vector the virus, present a difficult and complicated challenge from the perspectives of both epidemiology and disease management. Simply controlling the vector typically has not resulted in control of spotted wilt. No single measure can currently provide adequate control of spotted wilt where severe epidemics occur. However, interdisciplinary investigations have resulted in development of integrated management systems that make use of moderately resistant cultivars and chemical and cultural practices, each of which helps to suppress spotted wilt epidemics. Such systems have been successfully deployed in many areas for minimizing losses to this disease. The development of a spotted wilt risk index has aided greatly in relaying information on the importance of using an integrated approach for managing this disease.

INTRODUCTION

Diseases caused by thrips-vectored *Tospoviruses* cause severe problems in many of the world's plant agroecosystems (65, 97, 122, 134, 135). Spotted wilt was first described on tomato (*Lycopersicon esculentum* Miller) in Australia in 1915 (22), and was first reported to be caused by a virus in 1930 (119). The involvement of thrips in transmission of the causal agent was reported in 1927 (107). Since those early reports, *Tomato spotted wilt virus* (TSWV) and related viruses have been reported to infect over 650 species of plants, including over 50 families among both monocots and dicots (65, 134). In recent years, several distinct viruses in the *Tospovirus* genus have been identified (134), including some considered previously to be strains of TSWV (65, 110). Worldwide, TSWV is the most prevalent and collectively destructive member of the *Tospovirus* genus (97, 122, 134). Various aspects of the biology and vector relationships of the *Tospoviruses* have been addressed in previous reviews and collections (65, 99, 101, 134, 135), and reviews and proceedings on general epidemiology and management of diseases caused by *Tospoviruses* in various crops have also been published (45, 65, 75, 109, 112).

TOSPOVIRUSES ON PEANUT

Among the many diseases caused by TSWV is spotted wilt of peanut (*Arachis hypogaea* L.), first reported by Costa (48) in Brazil. Subsequent reports of spotted wilt or similar diseases in peanut were made from South Africa (61, 78), Australia (72, 116), India (46, 63, 66, 113), and the United States (71). Peanut (groundnut) bud necrosis, caused by thrips-vectored *Peanut bud necrosis virus* (PBNV), is an extremely destructive disease of peanut in Southeast Asia (1, 34, 109), particularly in India (66). Initially, PBNV was considered a strain of TSWV (110, 113), but PBNV is now classified as a distinct virus in the *Tospovirus* genus (110). Several updates or reviews of epidemiology and management of that disease have been published (31, 109). In addition to TSWV and PBNV, several *Tospoviruses* including *Peanut yellow spot virus* (PYSV) (111, 120), *Groundnut ringspot virus* (GRSV) (59), *Impatiens necrotic spot virus* (INSV) (12, 103, 145), and *Peanut chlorotic fan-spot virus* (PCFV) (44, 47) occur on peanut. *Watermelon bud necrosis virus* (WBMV) has been reported to cause nonsystemic crinkling symptoms on peanut leaflets after mechanical inoculation (124). This review concentrates on TSWV on peanut, but may address peanut bud necrosis or other diseases caused by *Tospoviruses* where key findings with those viruses have served as aids in managing spotted wilt in peanut, as illustrations for comparisons or contrasts to the spotted wilt situation in peanut, or where the presence of those viruses in addition to TSWV may complicate epidemiological studies and disease management.

OCCURRENCE, SYMPTOMOLOGY, AND IMPACT ON PEANUT PRODUCTION

Although spotted wilt occurs on peanut in production areas of South America (48, 49), impact of the virus in larger peanut-producing areas there has not been as great as in North America. Since spotted wilt was first observed in Texas in 1971, it has become one of the most serious diseases of peanut in the United States (9, 15, 17, 43, 54, 64, 69, 93, 114). In 1985, approximately 50% of the peanut crop in the production area of southern Texas was lost to spotted wilt, with losses near 100% reported in some individual fields (15, 17). In the southeastern United States, estimated losses to spotted wilt in peanut increased from the late 1980s through 1997, when losses were estimated to be 12% of the crop for Georgia alone, representing an approximate value of $40 million (7). More recently, significant reductions in severity and losses have been noted (145).

TSWV causes a wide array of symptoms on peanut. These include concentric ringspots; various patterns of chlorosis on leaflets; stunting of all above-ground plant parts; small and/or misshapen geocarpophores, pods, and kernels; and reddish discoloration and cracking of the seed coats (48, 53, 54, 71). Symptoms range in severity from minor spotting on one or a few leaflets to severe stunting and death of entire plants. Number of pods produced, kernel size, and yield produced per plant can be greatly reduced by spotted wilt, and these effects have been correlated with time at which initial symptoms appear (53). Plants showing symptoms early in the season typically yield less than those that develop symptoms later (53). TSWV has been associated with a general chlorosis and wilting of peanut plants that may not be accompanied by typical above-ground symptoms of spotted wilt (50). This malady has been referred to in Texas as peanut yellowing syndrome (91).

Roots of affected plants typically show varying degrees of necrosis, which can result in death of the entire plant (50). Other pathogens may be involved in the destruction of peanut root systems of those plants (50, 91). Mitchell et al. indicated that infection by TSWV was not essential for plants to develop peanut yellowing syndrome but infection with TSWV exacerbated the problem (91). However, research in Texas and Georgia showed that measures such as those recommended for management of tomato spotted wilt in peanut also reduced occurrence of general yellowing and wilting of peanut plants (58, 91).

Asymptomatic infections may also occur. Based on immunoassays of root tissue from field-grown plants, Culbreath et al. (52) reported incidence of asymptomatic infections as high as that of disease incidence based on visible foliar symptoms.

INITIAL INOCULUM AND THRIPS VECTORS

Spotted wilt and the thrips that vector TSWV present a perplexing challenge in epidemiology and disease management in peanut. Transmission of TSWV by viruliferous thrips appears to be the only significant means of inoculation in natural epidemics (93, 117, 118, 131, 134). TSWV can be mechanically inoculated into peanut, but not always easily (87, 105), and physical contact of plants does not appear to be of importance in natural epidemics. There is no indication that seed transmission occurs in peanut. Recent studies revisiting the potential for transmission of TSWV via peanut seed corroborate works by Costa (48) on TSWV and results reported by Ghanekar et al. (66) on the virus now classified as PBNV. TSWV can be found in the pods and testae of seed from infected plants, but planting seed infested with TSWV has not resulted in plants infected with the virus (104).

Tobacco thrips, *Frankliniella fusca* Hinds, and western flower thrips, *Frankliniella occidentalis* (Pergande), are confirmed vectors of TSWV (117, 118), and both species occur in most peanut producing areas of the United States (80–82, 93, 129, 131, 132, 137). Onion thrips, *Thrips tabaci* (135), is a vector of TSWV that occurs in the southern United States, but has not been implicated as a significant vector of TSWV in peanut. The initial emergence of spotted wilt as a problem in peanut in the southeastern United States in the mid-1980s followed shortly after initial reports of western flower thrips in those areas (8, 15, 69, 131). It has not been confirmed that western flower thrips were responsible for the introduction of

TSWV into the eastern United States. However, the timing of the initial detection of western flower thrips and TSWV has prompted speculation that the two events were related (8, 68, 131). Although the western flower thrips occurs on peanut in much of the southeastern United States, typically it does not occur in as high a number, does not reproduce as well on peanut as the tobacco thrips, and has different preference for feeding sites (80, 129, 131). Regardless of how TSWV was introduced, the tobacco thrips endemic to the southeastern United States is a competent vector of the virus. In most of the southern United States, tobacco thrips are the predominant vector species in peanut (82, 129, 131, 137). Sources of potential primary vectors and TSWV inoculum have been identified, but the relative importance of these sources for epidemics in peanut remains largely to be determined. TSWV, western flower thrips, and tobacco thrips occur on a large number of crop and noncrop plant species that occur in peanut-growing areas (39–41, 64, 92, 94, 129, 131, 132).

For a plant to be a significant source of inoculum: (*a*) the plant must be a host of TSWV; (*b*) the plant must support reproduction of at least one of the vector species since the virus is acquired by the larvae; (*c*) thrips must be able to acquire the virus from the plant; and (*d*) the plant must be present at a time that would complement disease cycles.

Volunteer peanut plants could potentially serve as a bridge for both TSWV and thrips vectors (39, 40). However, destruction of volunteer peanuts (41) or long-term rotations even to grass crops will not prevent spotted wilt from occurring in subsequent peanut crops. Detection of TSWV in brachypterous (wingless) adults and larvae of *F. fusca* in harvested peanut fields indicated that both TSWV and vectors may not require hosts outside the field, since neither the brachypterous thrips nor larvae are capable of movement over any large distance (40). Wells et al. (142) found no difference between brachypterous and macropterous (winged) *F. fusca* in the ability to transmit TSWV, but in field studies found a greater number of macropterous than brachypterous thrips on potted plants placed in fields at discrete intervals, and a higher percentage of macropterous thrips than brachypterous thrips tested positive for a TSWV nonstructural protein that is an indication that the thrips are viruliferous (5). They concluded that macropterous thrips had the greatest potential as initial vectors, but could not determine the source of the winged thrips. In tests in which emergence traps were used to determine whether primary thrips infestations were coming from within fields or from other sources, Barbour et al. (6) found very few thrips emerged from the soil compared with the number of thrips collected on open sticky-cards, and concluded that soils from peanut fields were not a major source of thrips infesting emerging peanuts in North Carolina.

They also reported that weather conditions are not conducive for emergence and growth of volunteer peanuts in North Carolina until mid-April (6). Since spotted wilt emerged as an important problem in peanut production in the United States, numerous studies have shown that chemical control of thrips generally fails to afford significant reduction in incidence of spotted wilt (41, 42, 98, 127–129). An exception to these findings was the discovery that in-furrow application of phorate insecticide suppressed epidemics of the disease (130, 144). The effects of phorate on spotted wilt are discussed in a later section (Insecticides and Chemical Control).

TEMPORAL AND SPATIAL ASPECTS OF DISEASE PROGRESS

Studies describing disease progress of spotted wilt in peanut have been limited. Camann et al. (35) described spatial and temporal aspects of spotted wilt epidemics in a susceptible and moderately resistant cultivar. They reported significant spatial aggregation of diseased peanut plants, but the aggregated plants often occurred at random or in nearly random clusters of infected plants. They hypothesized that a continuous immigration of viruliferous vectors dominated spatial aspects of epidemic progress. Aside from smaller incidence of disease in the resistant compared to the susceptible cultivar, no effect of cultivar was noted in relation to spatial or temporal patterns of disease development. Progression of spotted wilt epidemics was described by monomolecular disease progress models in each cultivar and year (35). The data and analyses were consistent with the hypothesis that most infections are the result of primary transmission and that there is limited secondary spread of TSWV after it becomes established in the field. Secondary spread has been indicated in other studies as well (13, 82).

Chamberlin et al. (42) indicated that there would little potential for secondary spread where a systemic insecticide reduced larval thrips populations to very low levels. The relative importance of primary spread has been evidenced as well by the lack of effect of most insecticide application regimes for preventing spotted wilt epidemics.

Shelton (121) reported that aggregation of severely affected plants was noticeable in both susceptible and moderately resistant cultivars. However, the occurrence of 0.31 m portions of row severely affected by TSWV was random within cultivars when considered for entire plots across a grid of paired plots used in comparison. She concluded that spatial aggregation on that level was not a complicating factor in evaluation of cultivars or breeding lines for resistance to TSWV (121).

Within planting dates, disease progress of spotted wilt in peanut has not been correlated directly with thrips populations or damage caused by feeding of thrips larvae on the leaves. In studies on planting date in Texas (93) and Georgia (131), however, peak populations of adult *F. fusca* were greater in peanut planted in April or June than in peanut planted in May.

INTEGRATED DISEASE MANAGEMENT

No single management tool is available that provides adequate control of peanut bud necrosis or tomato spotted wilt in peanut in the respective areas in which those diseases occur. An interdisciplinary and multifaceted research and extension approach has been employed to improve management of spotted wilt in Georgia and Florida. Research efforts have resulted in identification of critical management inputs that affect spotted wilt epidemics, and extension efforts have presented the results of that research in a manner that growers can use to avoid high-risk scenarios. The pertinent inputs employ genetic resistance and cultural practices to delay or slow development of spotted wilt epidemics. Initial experiments to elucidate the effects of these inputs were done with only one or combinations of two factors. Results from intensive cooperative research have shown that the cumulative effects of multiple management practices can significantly reduce incidence and increase yields, whereas one input alone may provide only weak or marginal suppression of spotted wilt (95, 126, 130).

Field Resistance and Cultivar Selection

The single most important factor in management of spotted wilt in the southeast is cultivar selection. Cultivars with moderate levels of field resistance to TSWV are now available and widely planted in the southeastern United States. Research in Texas during the mid-1980s found that the cultivar Southern Runner had a moderate level of field resistance to TSWV (11, 16). Subsequent epidemiological studies in Georgia corroborated those findings (54).

Intensive screening of cultivars and breeding lines has identified several sources of moderate resistance, and resulted in release of the runner-type cultivars, Georgia Browne (51), Georgia Green (55), UF MDR 98 (58), Tamrun 96 (125), and ViruGard (121), which have field resistance similar to Southern Runner. More recently, the cultivar C-99R was found to have a higher level of field resistance than Southern Runner or Georgia Green (56, 57, 141). The difference was most evident in situations where spotted wilt epidemics were most severe. Incidence of spotted wilt was similar for C-99R and Georgia Green when incidence of spotted wilt was low but was lower in C-99R in situations where incidence was higher (141).

The relative performance of most of these cultivars has been generally consistent compared with susceptible standards such as Florunner, Georgia Runner, SunOleic 97R, and GK-7. There have been indications of some differential responses of cultivars grown in different regions. Runner-type cultivar Tamrun 96 was developed in Texas and has field resistance to TSWV (125). However, in tests in Georgia and Florida it was found to be more susceptible than Southern Runner or Georgia Green (57). Further studies are needed to address relative reactions of newly released cultivars in the different production areas, as are studies to characterize any variability of TSWV isolates in different areas.

No widely used peanut cultivar has a high level of resistance. Even cultivars with moderate levels of field resistance may suffer significant damage during extremely intense epidemics.

Typically, the incidence and severity of spotted wilt in Georgia Green, the currently dominant cultivar in the southeastern United States, has been approximately half of that observed in susceptible cultivars such as Florunner and Georgia Runner

(55, 57, 58), which were popular before spotted wilt epidemics became severe. During the 2002 growing season, over 90% of the peanut acreage in Georgia was planted to Georgia Green, largely because of the concern for losses to spotted wilt. New cultivars DP-1 (tested previously as F 86X43-1-1-1-1-1-1-b2-B) (56), Hull (tested previously as F 89XOL28-HO1-7-4-1-2-b3-B) (56), and Georgia 02C (J.W. Todd, A.K. Culbreath & W.D. Branch, unpublished data) have higher levels of resistance than Georgia Green. These new cultivars and other new breeding lines (56) show great potential for reducing losses to spotted wilt in peanut.

The mechanism responsible for the field resistance in peanut breeding lines has not been elucidated. Several studies have indicated that the reduced intensity of spotted wilt in these lines does not appear to be due to reduced attractiveness to thrips vectors, reproduction of vector species, or physical injury caused directly by thrips feeding (51, 54–58). The combination of moderate resistance to the thrips vector and resistance to PBNV has been reported in India (60). In addition, reduced incidence of spotted wilt in cultivars Southern Runner and Georgia Green in field studies does not correlate with results from mechanical inoculation with TSWV (73, 88, 105, 106). However, recent studies have shown that USDA-ARS breeding line C11-2-39 does have resistance to TSWV based on mechanical inoculation studies (88) as well as field resistance (56; C.C. Holbrook, A.K. Culbreath & J.W. Todd, unpublished data). Reasons for the lack of correlation between results of field tests and mechanical inoculation tests have not been determined.

Possible explanations include differential reaction to varying levels of virus titer in the vectoring thrips compared to inoculum. Differential responses to concentration of inoculum used for mechanical inoculations with PBNV have been reported (60). Several lines have shown resistance at 10^{-2} dilution of plant sap inoculum that gave a susceptible response when extracts were used at a 10^{-1} concentration in buffer solution (60). Several factors including possible temperature interactions may affect relative results from mechanical inoculations (87).

New cultivars with greater resistance to TSWV appear to have the most potential for improving disease management. Several breeding lines from the University of Georgia, University of Florida, USDA, Texas A&M, and private industry have shown greater field resistance to the disease than Georgia Green. Under severe disease pressure in multiple tests since 1997 and 1998, Florida breeding lines from crosses of F 86 × 43 and F 84 × 47 have had levels of spotted wilt that were significantly lower than those of Georgia Green (56; A.K. Culbreath et al., unpublished data). To date, the USDA breeding line C11-2-39 has the highest level of field resistance to TSWV in peanut (56; A.K. Culbreath, J.W. Todd & C.C. Holbrook, unpublished data). Most of the lines with the greater levels of field resistance to TSWV typically require longer (∼145–150 days in Georgia) to mature than Georgia Green which requires ∼135 days, depending on growing conditions. Medium maturity (requiring ∼135 days to mature in Georgia) breeding lines with greater levels of field resistance than Georgia Green have also been identified. From tests conducted in 1998 and later, the University of Florida breeding line F 90 × 7-3-5-1-b2-B (56) and new cultivar Georgia 02C (J.W. Todd, A.K. Culbreath, D.W. Gorbet & W.D. Branch, unpublished data) are among the most resistant lines of any maturity group evaluated.

The development of cultivars with greater levels of resistance to TSWV is a major objective of most peanut breeding programs. Use of resistant cultivars, particularly if greater levels of resistance could reduce the dependence on other cultural and chemical factors used currently for spotted wilt management, would be the most desirable way to manage spotted wilt in peanut. However, cultivar development is slow and requires consideration of many factors in addition to resistance to TSWV. For now, the use of moderately resistant cultivars in combination with multiple other factors that suppress spotted wilt epidemics or help minimize the damage done by spotted wilt continues to be of utmost importance in managing this extremely destructive disease.

Planting Date and Field Location

Planting date has been reported as an important factor in epidemics of peanut bud necrosis in India. Singh & Srivastava (123) reported higher incidences of bud necrosis in peanuts planted two weeks prior to the normal planting time of 1 July, and lower incidences of bud necrosis in peanuts planted in mid- or late July. Likewise, when spotted wilt occurred in peanut in the United States, the impact of planting date on spotted wilt intensity was noted first in Texas (10, 91, 93, 95). For production areas in southern Texas, peanuts planted between May 5 and June 5 were less likely to incur severe spotted wilt than those planted earlier or later (10). In addition, location of peanut fields relative to earlier planted peanut can be a significant factor. In areas where there are strong prevailing directional winds, sequentially planting peanuts in fields that are down-wind from earlier planted peanuts may have increased risks of damage by spotted wilt (10).

In most production areas of Alabama, Georgia, and Florida, wind direction typically is variable. Location relative to other fields may affect spotted wilt epidemics in those areas as well, but the effect is too inconsistent to warrant specific recommendations.

As problems with spotted wilt became prevalent in more eastern production areas, planting date was found to be critical there as well. Studies over several years on planting date in the southeastern United States indicated that planting in the first two weeks of May typically resulted in the lowest incidence of spotted wilt, whereas planting in early April resulted in greater incidence of disease (70, 89, 130). Surveys of spotted wilt infestations in production fields in Georgia have corroborated these findings, and also have documented a shift in the optimum planting dates for minimizing spotted wilt. This change is now reflected in recommendations for Georgia (28, 29). The trend toward greater infestations of spotted wilt in early planted peanuts compared with peanuts planted in early to mid-May has been consistent in the southeastern United States. Although the planting date "window" for minimizing spotted wilt incidence may vary by as much as a week from year to year, planting in the first two weeks or the middle two weeks of May has usually provided significant disease suppression relative to earlier plantings. The effects of later plantings (after June 1 in the southeastern United States) have been less consistent relative to early or mid-May plantings, but also often promote more severe epidemics (28, 29).

Explanations for the differing effects of planting date have been based on circumstantial evidence and remain speculative. A common explanation has been that thrips populations are often variable from year to year as well as across planting dates (91, 93, 131).

Over multiple-year investigations in Georgia, greatest numbers of *F. fusca* occurred on April-planted peanuts, whereas peanuts planted in May had smaller populations (131; J.W. Todd, S.L. Brown & A.K. Culbreath, unpublished data). The population dynamics of thrips in non-crop plants or volunteer peanuts early in the season have been hypothesized as a reason for these effects since these plants may serve as reservoirs for TSWV and thrips vectors (39). Dynamics of the percentage of thrips populations that are viuliferous also may be a factor. Wells et al. (142) found fluctuations between years in time of peak percentage of *F. fusca* that tested positive for nonstructural protein indicative of TSWV reproduction. Changes in environmental conditions may affect plant populations that typically occur during the range of feasible planting dates and host susceptibility and inoculation efficiency. Ambient air and soil temperatures often are much lower in mid-April than in mid-May in the southeastern United States. Soil temperatures affect rate and uniformity of seed germination and seedling emergence, as well as subsequent plant populations and vigor. Effects of plant populations on risk of losses to spotted wilt are discussed in the following sections. Temperature may also affect disease development in inoculated plants. Mandal et al. (88) reported that fewer systemic infections occurred in the field-resistant breeding line C11-239 following mechanical inoculation with TSWV at high (30–37°C) temperatures than at lower (25–30°C). Further elucidation of the reasons for shifts or fluctuation in planting date effects is needed.

Manipulation of planting date is a viable tool for suppressing spotted wilt. Because of the size and number of fields to be planted, limitations on equipment and labor, and the uncertainty of weather, growers often cannot plant all of their acreage at the optimum time.

Nonetheless, substantial changes in the planting date profile have been observed in the peanut-production areas of the southwestern and southeastern United States The shift in planting dates in Georgia in recent years has been dramatic, with fewer fields planted in April and more fields planted in May than in years before spotted wilt emerged as a serious problem. Use of later planting dates may not be feasible in areas where resultant later harvests increase the risks of frost or freeze damage prior to harvest.

The optimum planting dates for minimizing spotted wilt may vary among years and locations, and should be determined as closely as possible for the specific location or region in which peanuts are planted. Furthermore, use of even the optimum planting date for suppression of spotted wilt still may not be adequate as a sole practice to prevent significant losses to the disease.

Plant Population

Infection of an individual peanut plant with TSWV is of greater probability among sparse plant populations than among dense populations. Establishing higher plant populations does not appear to reduce the number of infections in a particular field, but likely reduces the percentage of plants that are infected. Similar observations have been reported with PBNV. Reddy et al. (109) reported that increases in plant population density resulted in corresponding decreases in incidence of bud necrosis but did not affect the number of infected plants per unit area. Field surveys in Georgia in 1992 indicated a substantial reduction in the percentage of plants infected with spotted wilt as plant density increased from <6.6 to 6.6–13 to >13 plants/m of row (S.L. Brown, J.W. Todd, J.A. Baldwin & A.K. Culbreath, unpublished data).

Wehtje and colleagues (138) reported decreased incidence of spotted wilt in peanut as seeding rates increased incrementally from 34 to 101 kg/ha. Gorbet & Shokes (67) found corresponding increases in incidence of spotted wilt as plant populations decreased in Florida. Branch et al. (19, 20) reported a significant reduction in incidence of spotted wilt and an increase in yield in several cultivars as seeding rates were increased from 10 to 23 seed/m of row (20). In that same study, incidence of spotted wilt in C-99R was lower than that of Georgia Green when both cultivars were planted at 10 seed/m, which concurred with previous results at a similar low seeding rate (54, 56). However, there was no difference in the incidence of spotted wilt between those two cultivars at the higher seeding rates.

Although seeding rate has been the primary means evaluated to increase final plant population, other factors that affect establishment of plant populations must be considered. Seed quality and environmental conditions at and following planting affect plant stand. Thus, the effects of planting date may be exacerbated by stand effects when early planting dates correspond with soil temperatures that would prevent establishment of a good stand.

The effects of fungicide seed treatments on plant populations and subsequent incidence of tomato spotted wilt have been examined. Brenneman & Walcott (21) reported that use of seed treatment combinations of carboxin, captan, and pentachloronitrobenzene (PCNB) increased plant stands by almost 60% compared to the nontreated control, which corresponded with an approximately 60% reduction in final incidence of spotted wilt. That combination of fungicides is a standard seed treatment used on most peanuts planted in the United States. Rideout and associates (115) reported no improvement in stand and no significant reduction in incidence of spotted wilt with in-furrow applications of the fungicide azoxystrobin in addition to the standard carboxin, captan, and PCNB fungicide seed treatment.

Although Black et al. (18) reported inconsistencies with plant population effects in Texas, the overall consistency of plant population effects and the magnitude of those effects have increased as spotted wilt epidemics in Georgia have become more severe. The establishment of uniform stands of >13 plants/m of row is recommended in Georgia for minimizing losses to spotted wilt, even with the moderately resistant cultivars available (25–30). The seeding rate required to achieve this population is a function of seed quality, proper fungicide seed treatment, soil moisture, soil temperature, and planting depth in addition to number of seed planted. New cultivars such as DP-1 (56) and Georgia 02C (J.W. Todd, A.K. Culbreath & W.D. Branch, unpublished data) and several advanced breeding lines have higher levels of field resistance that may be adequate to allow use of lower seeding rates, especially when used in conjunction with other management practices that suppress spotted wilt.

Insecticides and Chemical Control

Although TSWV is vectored by thrips, the use of insecticides to control thrips largely has been ineffective for suppressing spotted wilt in peanut (41, 42, 70, 81, 82, 98, 128, 129, 131, 133, 137, 139). Insecticide applications have been indicated for reduction of peanut bud necrosis (123), but levels of reduction in incidence often have not been substantial.

While providing good control of damage to peanut plants from thrips larval feeding, insecticide applications have been ineffective in preventing plant feeding and inoculation by viruliferous adult thrips that have migrated from areas outside the field (41, 42). Based on work with *F. occidentalis* on *Petunia* and *Datura*, only 5 minutes of feeding may be adequate for transmission of TSWV (136), whereas longer periods of exposure to insecticide may be required for mortality. Use of some insecticides has even resulted in an increased incidence of spotted wilt. Application of imidacloprid as a seed treatment or as an in-furrow treatment has resulted in substantial increases in incidence of spotted wilt relative to plots receiving other insecticide treatments or no insecticide (133). This effect may be due to modified thrips feeding behavior caused by the insecticide. Changes in feeding behavior have been noted in *F. fusca* on tomato plants treated with imidacloprid (38).

Because of the mobility of thrips vectors, the potential for interplot interference from nontreated plots to confound results from insecticide trials has been recognized (13, 42, 129). To address that possibility, tests have been conducted in which multiple entire fields were treated with in-furrow applications of aldicarb and multiple (up to 14 weekly, season-long) foliar applications of acephate with nontreated control plots randomly dispersed across the field. There was no significant reduction in incidence of spotted wilt compared with nontreated plots (129). Large field tests were conducted in which winter or spring applications of carbofuran were made in efforts to kill overwintering thrips in fallow fields or on volunteer peanut plants. Although initial populations of *F. fusca* were affected, there was no consistent reduction of spotted wilt in the subsequent peanut crop compared with strips of each field left nontreated (129).

Chapin et al. (41) reported a significant reduction in spotted wilt incidence with applications of chloropyrifos in one year of a multiyear study, but concluded after later tests that suppression of spotted wilt with chloropyrifos was inconsistent at best.

Despite the overall disappointing results with numerous insecticides, the organophosphorus insecticide phorate has provided suppression of spotted wilt in the field (4, 129, 130, 144; J.W. Todd, S.L. Brown & A.K. Culbreath, unpublished data). Aldicarb has been the standard in-furrow insecticide used for thrips control in much of the southeastern United States. Numerous tests comparing phorate and aldicarb insecticides for effects on spotted wilt have been conducted. Application of phorate in-furrow at planting resulted in reduction of spotted wilt compared with the nontreated control in 63 of 93 tests conducted in Georgia and Florida between 1987 and 2000 (J.W. Todd, J.W. Demski, S.L. Brown, D.W. Gorbet & A.K. Culbreath, unpublished data). The mechanism responsible for suppression of spotted wilt by phorate does not appear to be correlated with thrips control. Phorate typically offers no better control than other insecticides that have little or no effect on the spotted wilt epidemics (129). Phorate can be phytotoxic and often causes marginal chlorosis and necrosis on peanut leaves. It has been hypothesized that this effect on young plants may induce a host defense response or serve in some other way to inhibit virus replication or movement. Gallo-Meaher and colleagues (63) reported activation of several genes and suppression of action of several genes in peanut plants treated with phorate compared to nontreated plants. Although the specific function of the genes affected has not been determined, the physiological affects of this insecticide on plant gene action and defense systems should be investigated further.

Other types of compounds have been evaluated, but few have shown promise for economically feasible management of spotted wilt in the United States. The plant defense activator acibenzolar-S-methyl provides significant suppression of spotted wilt in tobacco (102). Results with this material on peanut have not been as consistent. Wells and associates (139) found fewer feeding scars by *F. fusca* on excised peanut leaves treated with acibenzolar-S-methyl than on nontreated leaves. In field studies, Wells et al. (140) reported that acibenzolar-S-methyl applied in-furrow or in combination with in-furrow and foliar applications had incidence of spotted wilt similar to those treated with phorate and less than in nontreated plots in two of five tests. However, in two other tests, in-furrow applications of acibenzolar-S-methyl, phorate, or both chemicals combined failed to provide significant suppression. In field tests conducted in 2000 and 2001, final incidence of spotted wilt in peanut plots that received either foliar or in-furrow applications of harpin-protein did not differ from incidence in nontreated plots (A.K. Culbreath, M.L. Wells & J.W. Todd, unpublished data).

Neem extracts have been reported to provide suppression of peanut bud necrosis in India (123). Tests conducted in Georgia indicate that neem oil alone or in combination with the fungal entomopathogen *Beauveria bassiamna* has some suppressive activity on tobacco thrips and tomato spotted wilt epidemics (J.W. Todd & A.K. Culbreath, unpublished data). Neem oil is labeled for use on peanut in the United States, but the current cost would be prohibitive for use on peanut.

Herbicides have been reported to have both positive and negative effects on spotted wilt manifestations in peanut. MacDonald et al. (85) reported lower incidence of spotted wilt in peanut treated with the herbicide imazapic in addition to in-furrow applications of phorate than in plots treated with phorate alone or in other herbicide/insecticide combinations. Prostko et al. (108) observed that applications of chlorimuron ethyl may increase incidence of spotted wilt in peanut.

Options for chemical management of spotted wilt of peanut currently are very limited. The level of suppression provided by phorate alone is not sufficient to prevent losses to spotted wilt. Strongly encouraged is use of phorate in an integrated system with resistant cultivars and as many other management tools as are practicable (26–29, 126, 130). Prospective products that would provide economically beneficial suppression of spotted wilt in peanut are not known at this time.

Row Pattern

The planting of twin rows spaced 18–24 cm apart at the same seeding rate per ha as single rows has become increasingly popular in Georgia. Research to compare single and twin row plantings of irrigated peanut has shown a tendency for lower incidence of spotted wilt (2–4, 130), higher yields, and improved grades (percent sound mature kernels) with the twin row pattern (2–4). The reason for this reduction in spotted wilt incidence is not fully understood, but may involve visual interference with the ability of migrating thrips to recognize host plants. The ability of healthy plants to compensate for stunted plants across narrow twin rows may explain some differences in yield in the presence of spotted wilt.

Changing from single to twin rows requires considerable effort and expense. Twin rows may require adjustments in cultural practices, such as tillage, and in the digger-inverter at harvest. Furthermore, cultivars that lack a prominent mainstem and produce excessive vine growth may be extremely difficult to manage and harvest when planted in a twin-row pattern. Many growers have found that their initial investment in these adjustments is justified by lower incidence of spotted wilt and resultant increased yields.

Tillage Systems and Weed Control

Minimum tillage and no-till systems have become very attractive as conservation measures and as a means to reduce the cost of crop production. Interest in minimum tillage practices in peanut has increased dramatically in recent years across the southeastern United States. Many of the benefits and disadvantages of minimum tillage in terms of disease management remain to be determined in peanut production. However, a growing database indicates that use of minimum tillage in peanut results in lower incidence of spotted wilt as compared to conventional tillage (4, 41, 76, 96). The change to minimum tillage presents a myriad of new interactions for the host, vector, and environment. These interactions may account for the reduction in spotted wilt incidence. Lower densities in thrips populations have been reported in peanuts when minimum or no-tillage was used compared with conventional tillage peanuts (23, 36, 37), and less feeding injury by thrips has been reported for peanut produced with minimum tillage compared with conventional tillage (90). As with a twin-row pattern, the general change in architecture of the crop and environment due to the presence of stubble and/or debris from the previous crop may interfere with visual detection of host plants by migrating thrips.

The decision to produce peanuts with a minimum tillage or no-till system should not be based solely on suppression of spotted wilt epidemics. However, these tillage practices can help to minimize incidence of spotted wilt where they are compatible with the grower's production system and are economically feasible.

Management of weeds (including volunteer peanuts) that serve as hosts of TSWV and/or thrips vectors has been suggested for aiding in managing spotted wilt in peanut. Numerous studies have investigated weed hosts, and the vector species of thrips, but no high impact relationships with weed hosts have been shown (23, 39–41, 64, 77, 92, 94). An association among fall and winter rainfall and the effects on weed populations and incidence of spotted wilt in the peanut planted the following season has been noted and used as a predictive factor in southern Texas (10). *Verbesnia enceloides* is one of the few weeds targeted specifically in spotted wilt management programs in the United States. Volunteer peanut plants may be important in spotted wilt epidemics, but accurate evaluation of their impact on an individual field has been difficult to determine.

Spotted Wilt Risk Index and Integrated Management

The lack of individual tools for adequate management of spotted wilt has prompted investigations into and integration of multiple factors to minimize the effects of spotted wilt in peanut (10, 23, 70, 91, 93, 95, 130). A similar integrated management system has been necessary with peanut bud necrosis (33, 109, 112, 123) and other diseases caused by *Tospoviruses* (45, 65, 109).

The adoption of genetic, chemical, and cultural practices for management of spotted wilt of peanut has been enhanced greatly by the development and use of a spotted wilt risk index (23–32). The index has become an educational tool by which growers can assess the relative risk of spotted wilt in a particular field and identify the combination of disease-suppressive factors that best apply to their situation (31). Currently, the index has a maximum of 155 points based on cultivar selection, planting date, plant population, in-furrow insecticide, disease history, row pattern, tillage practices, and herbicide usage (29). The index is dynamic in that it has been improved annually since inception in 1996 (24–32). The relative weights of the various factors are based on research findings in Georgia, Florida, and Alabama and may require adjustment for cultivars, cultural practices, and environmental conditions before application in other regions. Each index has been validated by factorial experiments that examine the factors in various combinations and by on-farm surveys that assess the correlation between predicted relative risk and the observed incidence of spotted wilt.

Since 1997, estimated losses to tomato spotted wilt in peanut in Georgia have been less than one fourth as high as the $40 million dollar loss estimate for the state for 1997 (7, 145). This reduction was due largely to use of combinations of two or more of the following: (*a*) moderately resistant cultivars such as Georgia Green; (*b*) delaying the planting date to the low risk period of early to mid-late May; (*c*) establishing higher plant populations; (*d*) adopting phorate insecticide for suppression of the virus; (*e*) substantial increase in the use of twin-row patterns; and (*f*) significant increase in fields planted using conservation tillage systems.

The shift to planting over 90% of the peanut acreage of Georgia to Georgia Green represented the greatest sudden change in cultivars since the introduction in 1970 of the cultivar Florunner. Florunner had been the industry standard, runner-type peanut for over 20 years. In addition, there has never been a case in Georgia when such extensive changes in genetic and cultural practices were made simultaneously for any purpose, especially disease control.

Economic benefits of management of spotted wilt are difficult to estimate because numerous factors affecting yield, grade, and price must be taken into account. Significant direct benefits of individual spotted wilt management factors and combinations of factors have been reported (4, 31, 83). However, reduction in incidence of spotted wilt by changing specific components may not always result in improved economic return per hectare (84). More detailed analyses of economic aspects of management of spotted wilt are in progress.

MANAGEMENT IN THE FUTURE

Although the impact of the management package on spotted wilt has been encouraging, the disease continues to pose a serious threat to peanut production. Concerted interdisciplinary, multistate efforts in research and extension must be continued to sustain progress in understanding the factors that contribute to epidemics of the disease and in developing improved strategies for disease control. Additional sources of resistance to TSWV should help improve levels of resistance in peanut cultivars. Holbrook and associates (74) reported field resistance to TSWV in peanut lines developed from crosses of *A. hypogaea* with *A. cardenasii*. Progress in developing peanut lines with resistance to TSWV through a transgenic approach has lagged behind that in other crops, but such lines are being developed.

Li et al. (79) reported transformation of peanut with the coat protein gene of TSWV. However, in preliminary field evaluations, Spanish-type peanut lines transformed to encode for the TSWV coat protein gene had higher incidence of spotted wilt than the nontransformed standard (J.W. Todd & J.W. Demski, unpublished data). More recently, transgenic peanut lines have shown field resistance. Magbabua et al. (86) reported that lines of cultivar AT 120 transgenic for the antisense nucleocapsid gene of TSWV had lower incidence of spotted wilt transformed cultivars than the respective nontransformed cultivar. Similarly, selections of peanut cultivar MARC I transformed to include the coat protein gene for TSWV had incidence of spotted wilt as low as or lower than that in moderately resistant cultivar Georgia Green (100), where nontransformed lines of MARC I were susceptible as previously reported (51).

A combined effort of biotechnology and traditional breeding may further enhance opportunities for development of disease-resistant cultivars that meet the market requirements for peanut in the United States.

Biological control of thrips by the entomoparasitic nematode *Thripinema fuscum* has been reported to correlate with lower incidence of spotted wilt in peanut (62). However the potential for utility of this agent for management of thrips or spotted wilt has not been demonstrated.

CONCLUSION

Tomato spotted wilt continues to be a very serious problem in peanut production. It seems unlikely that any single control measure can provide adequate control of spotted wilt in peanut in the immediate future. However, integrated management systems, using moderately resistant cultivars and suppressive chemical and cultural practices, have been developed and successfully deployed for minimizing losses to this disease. Adoption of some form of integrated management regime has been extensive and rapid in peanut producing areas of the United States where spotted wilt has become a problem. Although spotted wilt has seldom been controlled completely, integrated management practices have had a huge impact on peanut production in the presence of TSWV.

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