IMPACT OF SPATIAL AND TEMPORAL FACTORS ON TOMATO SPOTTED WILT DISEASE TO REFINE PEANUT Rx

by

CLARENCE B. CODOD

(Under the Direction of Robert C. Kemerait, Jr.)

ABSTRACT

Spotted wilt disease, caused by the thrips-vectored *Tomato spotted wilt virus* (TSWV), is an important disease affecting peanuts in the southeastern United States. Peanut Rx is a risk index that allows growers to determine and avoid combinations of production practices that are conducive severe spotted wilt epidemics. However, the intensity of spotted wilt disease varies among fields having the same risk category depending on location and year as documented in this study. To account for the variability in spotted wilt intensity, a ‘thrips risk factor’ was created based on location- and year-specific predictions of peak thrips dispersal from the ‘Thrips Infestation Predictor Tool for cotton’. A ’modified Peanut Rx’ was developed through the integration of the ‘thrips risk factor’ into the risk index which provided a better risk assessment than Peanut Rx. With it, peanut growers can directly account for the thrips vector in assessing their risk of spotted wilt in order to determine the suitable production practices that would help them avoid severe epidemics and yield losses.

INDEX WORDS: Spotted wilt, TSWV, thrips, risk index, peanuts, forecast

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DEDICATION

To my wife, Bencie, and our daughters, Ieza Wren and Saphira. You inspire me to dream big. Thank you very much for your love, support and understanding.

To my parents, siblings, and friends who never ceased to encourage and support me in all my endeavors.

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CHAPTER 1

LITERATURE REVIEW

The peanut industry worldwide and in the United States.

Peanut (*Arachis hypogaea* L.) is an important commodity worldwide. It is an important food, oil, and feed legume crop grown in over 100 countries (Janila et al., 2013). World peanut production reached 41.5 million metric tons of in-shell peanuts in the 2017 cropping season. Throughout the last decade, China led the global production of peanuts. In 2017, China produced 17.4 million metric tons, which were equivalent to 42% of the total world production. This was followed by India (13%), Nigeria (7%) and the U.S.A. (6%) (INC, 2017).

World exports of shelled peanuts in 2015 amounted 1.6 million metric tons. India was the main exporting country with the majority of their shipments destined to Southeast Asia. Argentina and the U.S.A. were also important exporters of peanut. Argentina's main importer was the Netherlands, while the main importers of peanuts from the U.S.A. were Canada, Mexico and the Netherlands (INC, 2017).

In the U.S.A., peanuts are produced mainly in eleven states with about 50% of the peanuts grown in Georgia. In the 2016 Agricultural Commodity Ranking for Georgia, peanuts ranked fifth behind broilers, cotton, eggs, and timber with a farm gate value of $624,380,318 (UGA-CAES, 2017). Peanuts are also produced in other states to include Texas (10%), Alabama (10%), Florida (9%), North Carolina (7%), and South Carolina

(7%) (APC, 2017). Mississippi, Virginia, Oklahoma, Arkansas, New Mexico, Louisiana, and Missouri produce collectively six percent of the U.S.A. peanut (National Peanut Board, nd).

There are four types of peanuts grown in the U.S.A., each having distinctive size and flavor (Guerena and Adam, 2008). Runner-type peanuts account for 80% of total U.S.A. production. Runner-type peanuts are grown mainly in Georgia, Alabama, Florida, Texas, and Oklahoma. Virginia peanuts, grown mostly in southeastern Virginia, northeastern North Carolina and western Texas, account for 15% of the nation's peanut production. Primarily grown in Oklahoma and Texas, spanish-type peanuts account for 4% of U.S.A. peanut production. Valencias, less than 1% of peanuts produced in the U.S.A., are grown mainly in New Mexico (APC, 2017).

Examples of runner-type peanut varieties include 'Georgia-06G', 'Georgia-12Y', 'Georgia-09B', 'Georgia-14N', 'TUFRunner™ 511', 'Florida-07', and 'AU-NPL 17'. Virginia-type peanuts include 'Bailey', 'CHAMPS', 'Emery', 'Georgia 11J', 'Sugg', 'Sullivan', and 'Titan'. Spanish-type peanuts include 'OLin', 'Schubert', and 'Tamnut OL 06'. An example of valencia-type peanuts is the variety 'TamVal OL14' (The Peanut Grower, 2019). When choosing a variety to use, it was recommended to choose one that will achieve a rapid and uniform stand, resistant to major diseases, and provide good yields and grades considering the conditions and operations in each field locations (The Peanut Grower, 2019; Kemerait et al., 2018).

Major pests and diseases of peanuts

Pests and diseases, when not managed, can hinder peanut production. Some of the most common and economically important arthropod pests of peanuts include thrips, lesser cornstalk borers, three-cornered alfalfa hoppers, southern corn rootworms, potato leafhoppers, velvetbean caterpillars, and two-spotted spider mites. Occurrence and damage by these arthropods can vary from field to field and year to year (Abney, 2018).

Fungal diseases such as early and late leafspots, southern stem rot, *Aspergillus* crown rot, *Cylindrocladium* black rot, and *Rhizoctonia* limb rot are concerns in peanut production (Kemerait, 2018). Early and late leaf spot in peanuts are caused by *Passalora arachidicola* and *Nothopassalora personata* (Chu et al., 2019). Based in the 2016 crop loss estimates in Georgia, leaf spots caused 1% reduction in crop value with an estimated $6.2 million worth of damage (Little, 2016). Little (2016) also reported a 7.5% reduction in crop value worth $46.8 million due to southern stem rot (*Sclerotium rolfsii*). An estimated $0.6 million worth of damage due to limb rot (*Rhizoctonia solani*) was recorded in the same year (Little, 2016). Spotted wilt disease, caused by *Tomato spotted wilt virus* (TSWV), is another disease that has been a major concern in peanut production in the southern United States for the past three decades (Srinivasan et al., 2017; Culbreath & Srinivasan, 2011).

Spotted wilt disease

The thrips-transmitted TSWV causes spotted wilt disease. TSWV is one of the most widespread plant viruses and occurs in countries of Africa, Asia, Central America and the Caribbean, Europe, North America, Oceania and South America (EPPO, 1999).

The virus has a wide host range, infects more than 900 plant species that include numerous crops and weeds (Pappu et al., 2009). Peanuts and other important crops such as tomato, pepper, potato, cucurbits, lettuce, eggplant, and tobacco are susceptible to TSWV (Hagan and Week, 1998). TSWV can also infect plant species growing around agricultural fields. In Georgia U.S.A., weed species found to be most commonly infected with TSWV during winter and spring, include narrow leaf cudweed (*Gamochaeta falcata* Lam.), dogfennel (*Eupatorium capillifolium* Lam.), chickweed (*Stellaria media* L.), and purple cudweed (*G. purpurea* L.) (Mullis and Ochoa, 2009). From the same study, the weed species most commonly infected with TSWV during summer and fall include smallflower morningglory (*Jacquemontia tamnifolia* L.), redroot pigweed (*Amaranthus retroflexus* L.), entireleaf morningglory (*Ipomoea hederacea*), and false daisy (*Eclipta prostrata* L.) (Mullis and Ochoa, 2009).

Peanut plants infected by TSWV exhibit variable symptoms such as concentric ring spots, smaller leaves with various patterns of chlorosis, general chlorosis, and wilting (Culbreath and Srinivasan, 2011). Asymptomatic infection is also common based on results of immunoassay testing of root tissue from field-grown plants. In severe cases, stunting of aboveground plant parts and reduction in number and size of pods also occur (Culbreath and Srinivasan, 2011). By reducing the size and number of pods in infected peanuts, severe infection reduces the yield potential, thus reducing income for the growers.

In the U.S.A., spotted wilt disease was first observed on peanuts in southern Texas in 1971 (Halliwell and Philley, 1974) but did not cause significant damage and yield losses until 1984 (Black et al, 1986). The disease caused an estimated $3-million worth of yield loss to growers in a single county in Texas in 1986 (Hagan and Weeks, 1998). In 1986, spotted wilt disease was found in peanuts in Mississippi and further spread to other southeastern states. By 1988, peanut plants showing symptoms of spotted wilt were common in Alabama, Florida, and Georgia. Yield loss to spotted wilt on peanuts in Georgia was first reported in 1990 (Hagan and Weeks, 1998, Culbreath and Srinivasan, 2011). In 2016, an estimated 3.5% yield loss amounting to $18-million was reported in Georgia. Such loss is evidence that spotted wilt is still a concern for peanut production in the U.S.A. (Kemerait et al., 2018). This is why the application of management strategies to prevent severe epidemics and to minimize yield losses is important to peanut growers.

Taxonomy of *Tomato spotted wilt virus*

Tomato spotted wilt virus (TSWV) was the first member of the genus *Tospovirus*. *Tospoviruses* are the only genera in the *Bunyaviridae* family of viruses that infect plants. All the other members of this family of viruses are pathogens of humans and other mammals (Moyer et al., 1999; Pappu et al., 2009; Kulshrestha et al., 2013).

Prior to 1990, TSWV was considered a monotypic group of plant viruses. It was first described in 1919 after its first detection in tomatoes in Australia in 1915 (Brittlebank, 1919). It was named as "*Tomato spotted wilt virus*" after it was characterized and identified as the causal pathogen of the disease by Samuel et al. (1930). In 1990, *Impatiens necrotic spot virus* (INSV), a new member of the *Tospovirus* genus was characterized (Law and Moyer, 1990). Since then, increased molecular analysis of virus isolates has led to a rapid expansion in knowledge regarding the diversity of members of this genus. As of 2015, the genus *Tospovirus* is known to include 11 officially recognized distinct virus species (Oliver and Whitfield, 2016). Species within the genus *Tospovirus* are determined based on their vector specificity and plant host range as well as the serological relationships of the nucleocapsid (N) protein. To be recognized as a distinct species within the genus, an isolate's N protein sequence should show less than 90% amino acid identity with that of any other *Tospovirus* species (Plyusnin et al., 2012).

All viruses belonging to the genus *Tospovirus* share the same morphology and genomic organization. The membrane-bound quasi-spherical virus particles measure 80 – 120 nm. The genome includes three RNAs strands which are classified through their size as “large” (L RNA), “medium” (M RNA), and “small” (S RNA). The L RNA codes for RNA-dependent RNA polymerase (RdRp) which serves as a multifunctional, replication-associated enzyme. The M RNA codes for the precursor of two glycoproteins (GN and GC) and a non-structural protein (NSm). The NSm is a distinct characteristic of *Tospovirus* species; it aides in the movement of the nucleoprotein in plants from cell-to-cell through the plasmodesmata. The determinants for thrips transmission are localized on the glycoprotein-containing envelope as TSWV mutants lacking the envelope were not thrips-transmissible. Further, the M RNA was also shown to carry determinants for host adaptation and overcoming host plant resistance. The S RNA codes for the N protein and another non-structural protein (NSs) which play important roles in the TSWV infection cycle. The N protein serves a role in modulating the transcription and replication of the virus. The nonstructural protein, NSs, encoded by the S RNA was shown to be a suppressor of RNA silencing (Sherwood et al., 2003, Pappu, 2008).

Vectors of TSWV

TSWV is transmitted in a propagative and persistent manner by thrips species in the order *Thysanoptera.* Nine species of thrips were identified to transmit TSWV out of 5850 species of thrips known worldwide which include *Frankliniella fusca, F. occidentalis, Thrips tabaci, F. schultzei, F. intonsa, F. bispinosa, T. setosus, F. gemina,* and *F. cephalica* (Riley et al., 2011).

Frankliniella fusca (tobacco thrips) and *F. occidentalis* (western flower thrips) are the two major vectors associated with spotted wilt disease epidemics in peanuts in Georgia (Mandal et al., 2001). Both thrips species occur in peanut fields throughout the southeastern United States. Between the two thrips species, *F. fusca* is considered the more important vector because it reproduces better on peanuts (Culbreath and Srinivasan, 2011, Todd et al., 1995). In a study conducted on peanuts, thrips larvae were collected from the foliage of peanut seedlings and were reared to adult for identification. Out of 875 larvae, 486 survived to become adults. Among these adult thrips, 484 were *F. fusca* and 2 were *F. occidentalis* (Todd et al., 1995). Being an important vector, understanding the biological activities of *F. fusca* could help in managing spotted wilt disease in peanuts.

TSWV transmission process

Thrips acquire TSWV from infected plant hosts and transmit it to healthy plants in a propagative and persistent manner. A propagative and persistent manner of virus transmission involves replication of the virus inside the vector after acquisition from infected plant hosts, and then persisting through the growth stages of the vector from larva to adult (Whitfield et l., 2005 and Margaria et al., 2014). The first and second instar immature thrips acquire TSWV from infected host plants when feeding. To be transmissible, the TSWV should be acquired by either of these two larval stages of thrips. TSWV replicates in the epithelium and then in the muscle fibers surrounding the foregut and midgut of the larvae. The virus spreads to the salivary glands where it also replicates to achieve a high virus titer in the saliva. TSWV replicates and persists through insect molts from larval to adult stages. It is then transmitted to the plants during feeding. Viruliferous adults spread the virus when they move and feed on other plants (Dietzgen, 2016, Nagata et al., 2002, Moritz et al., 2004). The virus is excreted during feeding through the salivary glands. It will then infect the plant and replicate if it is a suitable host (Mullis et al., 2009).

When thrips acquire the virus at the adult stage, the virus is found in the midgut and muscle cells around the midgut, but not in the salivary glands. Thus, it cannot be transmitted (Cho et al., 1988, Mullis et al., 2009). Moreover, there is no evidence that TSWV can be passed from parent to offspring (Pappu, 2008 and Ogada et al., 2016). Further, TSWV is not seed-transmissible which means that seeds from infected plants do not get infected by the virus (Pappu, 2008). Therefore, each generation of thrips must re-acquire and spread the virus for the spotted wilt disease epidemic to occur.

TSWV infected plants occur in a weakly aggregated clusters that are randomly distributed around the field (Camann et al., 1995). This spatial distribution pattern was consistent with a spatial process that influence disease transmission dynamics as described by Campbell and Noe (1985). Accordingly, viruliferous thrips are capable of re-dispersing over a short distance after landing on a plant in the field, which causes primary infection in aggregated plants. The close spacing and intertwining branches of peanuts may aid in short distance migration of thrips to adjacent plants. This movement and consequent feeding and virus transmission may contribute to the aggregation of infected plants without secondary infection.

Thrips population dynamics and pattern of thrips dispersal

The epidemics of *Tospoviruses*, such as TSWV, are dependent upon the coexistence of vector populations and plant hosts. Because TSWV has such a wide host range, the thrips vector has great potential for spreading the virus across the landscape. Aside from transmission by thrips species, there is no evidence of seed or pollen transmission or any other significant type of transmission of *Tospoviruses* (Mumford, et al., 1996).

The number of thrips and age of peanut plants play an important role in TSWV transmission (Shrestha et al., 2015). Transmission of TSWV by individual tobacco thrips (*F. fusca*) was sufficient to cause systemic infection in peanut plants but inoculation using multiple thrips (3-5 adults) resulted in a higher percent infection on tests plants (Shrestha et al., 2015). In the same study, it was also found that higher percent infection was observed on one-week old plants compared with two and four-week old plants. According to Taiz and Zeiger (2010), the increased susceptibility of younger plants could be associated with less leaf thickness and higher concentrations of nutrients such as nitrogen.

Dispersing thrips are critical for the development of spotted wilt epidemics. In a study conducted in North Carolina, the peak of crop susceptibility to TSWV infection coincided with the peak magnitude of migrating *F. fusca* (Groves et al., 2003). The potential window for the greatest chance of spread of TSWV occurs from April to May when the magnitude of dispersing *F. fusca* is at its peak (Groves et al., 2003). In Georgia, immature thrips were most prevalent between January and May with peak populations occurring between March and May. Adult thrips were most prevalent between March and August with peak populations occurring between April and June (Olatinwo et al., 2011). The aforementioned period when thrips were most prevalent coincide with the peanut planting season. That is why thrips feeding damage occurs soon after planting (Culbreath et al. 2003, Culbreath and Srinivasan 2011). As thrips-transmission is the only means of spread of TSWV in the natural environment, it is possible that when young peanuts are growing during the peak of dispersing thrips coincide, greater thrips feeding and TSWV infection would occur. For this reason, the implementation of effective management strategies is necessary to prevent severe spotted wilt epidemics and subsequent yield losses.

Management strategies

The most effective management strategy for spotted wilt disease in peanut is a preventive approach. This includes decisions that the growers need to make even before planting peanuts. These decisions include variety selection, when to plant, choice of in-furrow insecticide, tillage type, and row pattern (Kemerait et al., 2013).

The use of resistance genes has been widely used for managing spotted wilt disease in pepper and tomatoes. A single dominant gene (*Tsw* gene) from *Capsicum chinense,* was found to confer hypersensitive response and resistance against spotted wilt in *C. annuum* (Black et al., 1996). This resistance, however, was shown to break at temperatures higher than 28°C (Pennazio, 1995). Another single dominant gene *SW-5* was used to confer resistance against TSWV in tomatoes (Stevens et al., 1992). However, resistance-breaking strains of TSWV against *Tsw* in pepper plants in Italy (Roggero et al., 2002) and *SW-5* genes in tomatoes in Australia have been reported (Latham and Jones, 1998). The use of single dominant gene resistance, such as *Tsw* and *SW-5*, results in heavy selection pressure to the pathogen leading to the development of strains of the pathogen that can infect cultivars with that resistance, thereby overcoming resistance (Branch and Culbreath, 2015). Thus, breeding efforts and continuous research to find resistance genes are necessary because a single dominant gene type of resistance does not offer a long-term stability.

For peanuts, no single dominant genes have been identified to confer resistance to TSWV (Branch and Culbreath, 2015). Through a series of screening and breeding efforts the first generation resistant cultivars were developed, which included ‘Georgia Browne’, ‘Georgia Green’, ‘Tamrun 96’, and ‘ViruGard’. Under moderate to heavy virus pressure, these cultivars displayed less severe symptoms and produced higher yields than susceptible cultivars (Culbreath et al., 2003). Observations on the runner-type peanut cultivar ‘Georgia Green’ (Branch, 1996) indicated that the type of resistance to TSWV in peanuts is a quantitative type of resistance as indicated by the partial level of field resistance to the disease. These characteristics suggested that the field resistance of

‘Georgia Green’ is relatively stable (Branch and Culbreath, 2015). The use of peanut cultivars having field resistance to TSWV has been a primary means of reducing yield losses in peanuts to spotted wilt disease but the mechanism of resistance was not completely identified. The group of Shrestha (2013) suggested that the field resistance on peanut genotypes could be due to tolerance against the TSWV. They found that even though TSWV can infect and cause typical symptoms in both TSWV-resistant and susceptible genotypes, some resistant genotypes had reduced quantities of virus particles than did the susceptible genotypes.

Breeding efforts continued and led to the development of second generation resistant cultivars with greater levels of field resistance. ‘Georgia-06G’, ‘Georganic’, and ‘Tifguard’ were some of the released second-generation cultivars. ‘Georgia-06G’ is currently the most widely used cultivar. It was planted on more than 80% of the entire peanut acreage in Georgia in 2016 (Srinivasan et al., 2017). With further breeding efforts, the third-generation cultivars were developed including ‘Georgia-10T’, ‘Georgia-12Y’, ‘Georgia-13M’, ‘Georgia-14N’, and ‘FloRun™ 107’. These cultivars exhibit a several-fold increase in field resistance to TSWV than the cultivars that were grown, before the first generation cultivars were released, such as ‘FloRunner’ and ‘SunOleic 97R'. More so, resistant varieties released earlier, such as Georgia Green, are currently used as susceptible checks while screening for resistance (Srinivasan et al., 2017).

Cultural practices, in addition to the use of resistant cultivars, were used to manage spotted wilt disease on peanuts. Prior to severe outbreaks in Georgia, it was observed in Texas that peanuts planted early and late in the normal planting season tended to have more spotted wilt than peanuts planted in the middle of the planting season. Researchers observed a similar trend in the relationship between planting date to the intensity of spotted wilt in peanuts in Georgia. Although the optimum planting date and magnitude of planting date effect vary from year after year, avoidance of early and late planting dates reduce spotted wilt incidence in general (Brown et al., 2005). The mechanism behind the planting date effect was not fully understood, but it was suggested to be related to the activity of thrips vectors. In Georgia, the peak of thrips flight is usually observed during the latter part of April (Wells et al., 2002). Peanuts planted before this period resulted in greater spotted wilt incidence compared to peanuts planted after the peak of thrips flight. Considering this, the optimal planting time window, widely adopted by growers, is from May 10 to May 31 (Srinivasan et al., 2017, Brown et al., 2005).

Reduced tillage is another cultural approach associated with less spotted wilt incidence when compared with conventional tillage. Application of wheat straw to the soil surface prior to peanut emergence reduced spotted wilt severity compared with that of peanut grown on bare ground. It was suggested that the ground cover and debris from the previous crops that remain on the soil may interfere with the ability of dispersing thrips to visually locate host plants (Brown et al., 2005). The effect of reduced tillage was also observed in several studies (Culbreath et al., 1999; Johnson et al., 2001). Similar effects believed to lower spotted wilt incidence are observed on peanuts planted in a twin-row pattern as compared to planting on single-row pattern at the same seeding rates per acre. The more rapid ground coverage in twin-row patterns may affect the ability of thrips to locate a seedling host (Brown et al., 2005).

Plant population is another important consideration in spotted wilt management. Peanut plants in plots with sparse population or "skippy stand" were observed to have a greater probability of being infected with TSWV than do plants in dense populations. A plant stand of >13 plants/m of a row is recommended for Georgia to minimize yield losses from spotted wilt disease. 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 the amount of seed planted (Culbreath and Srinivasan, 2011).

The use of insecticides to control the thrips and spotted wilt disease was tested in several studies. In North Carolina, it has been reported that application of imidacloprid insecticide suppresses transmission of TSWV by reducing probing and feeding by adult thrips on treated tobacco plants, thereby reducing the probability of transmission by infectious thrips (Chappell and Kennedy, 2018; Groves et al., 2001). In peanuts, however, while insecticide applications reduced larval feeding damage, it did not result in a significant reduction of spotted wilt incidence (Chamberlin et al., 1993, Brown et al., 2005). This suggested that insecticide applications were ineffective in preventing transmission of TSWV by viruliferous adult thrips that have migrated from areas outside the field (Culbreath and Srinivasan, 2011). This could be explained by the result of a study done with *F. occidentalis* on *Petunia* and *Datura*, which showed that viruliferous thrips could transmit the TSWV in 5-minute feeding-inoculation time (Wijkamp, 1995). Whereas, it takes 15.42 hours of exposure to imidacloprid insecticide to cause mortality on 50% of *F. occidentalis* population based on a study conducted on green bean pods (*Phasaeolous vulgaris*) (Gholami et al., 2015). It is possible that the TSWV transmission by thrips could be completed before the insecticide takes effect against the thrips. In such a case, even though these insecticides provide adequate thrips control against the thrips, the incidence of spotted wilt disease may not be reduced significantly.

Despite the overall lack of control of TSWV from use of insecticides, in-furrow applications of phorate (Thimet® 20G) granules have provided consistent, low-level suppression of spotted wilt (Todd et al., 1995, Brown et al., 2005). Phorate is an acetylcholinesterase-inhibiting, organophosphate pesticide used for the control of insects, mites, and nematodes. In a study conducted on peanuts, it was found that systemic spread of TSWV in field-grown plants was reduced following phorate application. Further, a dose-dependent increase in ascorbic acid content and in activities of the oxidative stress-related enzymes catalase and superoxide dismutase was evident following treatment with phorate (Jain et al., 2015). The said enzymes are involved in providing plant defense against oxidative stress from environmental and biotic factors such as insects and pathogens (Demidchick, 2015). Thus, by application of phorate insecticide at planting, the growers could reduce thrips damage and spotted wilt disease intensity in their peanut crop.

Spotted wilt risk assessment

The intensity of spotted wilt disease has been variable in Georgia's peanut fields. A number of production practices that affect disease severity have been identified and categorized into a risk index (Brown et al., 1996). Based upon results from research trials, risk points with numerical weight values were assigned to each category based on the relative importance of each factor. The weighted risk points associated with each category can then summed to calculate the total risk. Higher point totals were indicative of higher levels of risk. By identifying high-risk situations, growers can avoid those combinations of cultural practices that are conducive to greater spotted wilt severity and yield loss. The original version of the risk index was developed in 1996 and was called Spotted Wilt Risk Index (Brown et al., 2005). The risk index was updated to include risk indices for leaf spot, white mold, and limb rot. It was then called the Peanut Rx (Kemerait et al., 2013). The factors accounted for in calculating the risk to spotted wilt disease in Peanut Rx include cultivar, planting date, plant population, insecticide usage, tillage, and Classic herbicide application (Kemerait et al., 2018). However, other factors not accounted for in the risk index may also impact the incidence and severity of spotted wilt in peanut fields. These are previous crops, immediately adjoining crops, irrigation practices, and weather (Brown et al., 2005).

The use of the Peanut Rx risk index is an example of integrated pest management where a combination of production practices are used to manage spotted wilt disease. By accounting for the impact of production practices, the level of exposure or risk to spotted wilt can be estimated. However, one aspect that is not directly accounted for in Peanut Rx is the thrips vector. Nevertheless, because thrips are critical in the epidemiology of spotted wilt disease, accounting for the thrips vector could potentially improve the risk assessment and management of spotted wilt disease.

Predictive models developed for spotted wilt disease

Weather conditions prior to and during the peanut growing season affect the population dynamics of the thrips vectors. By affecting the vector, these weather factors may influence the spread of TSWV in the natural environment (Olatinwo et al., 2008). Temperature and precipitation are the major weather factors that affect thrips populations. The increasing temperature throughout the spring favors increased thrips activity, development, and population growth (Morsello et al., 2008). Precipitation affects the thrips population in two ways. The occurrence of hard or prolonged precipitation leads to the mortality of young thrips larvae thus reducing the population (Kirk, 1997). This event can also suppress the dispersal of adult thrips (Lewis, 1963).

A predictive model was developed for peanuts in Georgia, which was able to account for up to 61% of the variability in spotted wilt severity in peanuts, as a function of the factors accounted for by Peanut Rx and multiple weather factors. The weather factors accounted in this predictive model include the average daily temperature in April, average daily minimum temperature between March and April, accumulated rainfall in March, accumulated rainfall in April, number of rain days in April, evapotranspiration in April, and number of days from 1 January to the planting date (Olatinwo et al., 2008). This is an example of how weather parameters and production practices can be accounted for in order to predict the incidence of spotted wilt during the season.

In North Carolina, a weather-based predictive model was also developed to predict tobacco thrips dispersal and estimate spotted wilt incidence in tobacco crops. It was called the Thrips and TSWV Risk Forecasting Tool (TTRF). It contains independent variables that include prior-year thrips (PYT) population estimates, average winter temperature (AWT), and March precipitation (MP). Each of these factors impacts spotted wilt intensity and transmission on a season to season basis (Chappell et al., 2013; Morsello et al., 2010). The TTRF model was tested in predicting spotted wilt incidence in tobacco crops in Georgia and it showed a promising result. It accounted for up to 54% variation in spotted wilt disease in tobacco in Georgia (Williams, 2015). This model provides a platform of a predictive tool that directly accounts for the thrips vector through the estimated magnitude of the thrips population. If properly adjusted, this model could provide a resource for spotted wilt disease management in other crops such as peanuts.

The most recent predictive model for spotted wilt on peanuts, developed in 2015, is a combination of the traditional Peanut Rx and estimated magnitude of thrips population from the TTRF model. It was called the Peanut Rx 2.0. With this model, 26.24% of the variability was accounted for (Williams, 2015). With the Peanut Rx 2.0, a method of directly accounting for the thrips vector and disease pressure, as well as level of exposure to spotted wilt disease was developed. This is another example of a forecasting model that accounts for the pathogen, host, environment, and vector. Based on this example, refined models can be developed in order to improve management of spotted wilt disease in peanuts in the southeastern United States.

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CHAPTER 2

DOCUMENTING THE EPIDEMIOLOGY OF SPOTTED WILT DISEASE IN PEANUTS AT DIFFERENT LEVELS OF RISK BASED UPON PEANUT Rx[1]

[1]Codod, C.B., Kemerait Jr., R.C., Culbreath, A.K., Abney, M.R, and Kennedy, G.G. To be submitted to *Plant Disease*

Abstract

Spotted wilt disease, caused by the thrips-transmitted *Tomato spotted wilt virus*, reduces the yield potential of the peanut crop. Growers in the southeastern United States manage spotted wilt disease in peanuts by using a risk index called Peanut Rx. In this study, the epidemics of spotted wilt disease at different levels of risk based upon Peanut Rx were documented. On-station field trials were conducted at six locations in 2017 and repeated in 2018. The experimental design was a split-split-plot where whole plots were planting date (early, mid and late), sub-plots were varieties (Georgia-06G and Florun™ '157' in 2017 and Georgia-06G and Tufrunner™ '511' in 2018) and sub-sub-plots were treated with or without phorate insecticide (Thimet® 20G) at planting. These combinations created 12 different levels of risk based upon Peanut Rx. The sAUDPC and apparent infection rates were compared between different treatments through a generalized linear mixed model analysis. Results showed that the sAUDPC values and apparent infection rates were lower among treatments with lower risk point values and were higher on treatments with higher risk point values. There was a strong positive correlation between the sAUDPC and the final spotted wilt intensity. The final spotted wilt intensity varied between different risk categories and between different locations over the two years of the study. A greater variation of spotted wilt intensities between locations and years was observed within the mild, moderate, and high-risk categories as defined according to summed risk points from Peanut Rx. Additionally, the peanut yield was shown to have a significant negative linear relationship with final spotted wilt intensity, sAUDPC, and Peanut Rx risk point values through a regression analysis.

Introduction

Tomato spotted wilt, caused by the thrips-transmitted Tomato spotted wilt virus (TSWV), is an economically important disease affecting many crops and weed species worldwide (Zitter et al., 1989, Pappu et al., 2009). In the southeastern United States, peanuts are one of the economically important host crops affected by TSWV. Historical yield losses due to spotted wilt disease in peanuts have been reported. In the southeastern United States, yield losses were first reported in Mississippi in 1986 (Reed and Sukamto, 1995) and in Georgia in 1990 (Hadden, 1991). Since then, the epidemics of spotted wilt in peanut have become common and became a limiting factor in peanut production in the Southeast (Culbreath et al., 1997; Culbreath and Srinivasan, 2011). Therefore, management of spotted wilt disease is important for the peanut growers in order to protect their yield and profitability.

In 1996, the University of Georgia released the “Tomato Spotted Wilt Risk Index”. It provided a method in which growers could assess their relative risk to spotted wilt disease in peanuts. This risk index was comprised of factors that influence the incidence of spotted wilt in peanuts (Brown et al., 1996; Brown et al., 2005). The factors accounted for in predicting the risk to spotted wilt included variety selection, planting date, plant population, at-plant insecticide, row pattern, tillage system, and the use of Classic® herbicide (Kemerait et al., 2018; Brown et al., 2005). The grower identifies their risk to spotted wilt as being low, medium, or high based upon selections within each factor. Continuous research and annual refinement resulted in the development of Peanut Rx, with the addition of risk indices for leaf spot, white mold, and limb rot (Kemerait et al., 2018).

The goal of Peanut Rx is to provide a tool with which growers can minimize the risk point total for each peanut field. It does not dictate production practices for the growers, for example planting in the middle of May, or which variety to plant (Kemerait et al., 2017). It allows growers to determine how to minimize their relative risk given their own specific production considerations.

The intensity of spotted wilt can vary between locations and years. For example, in some years, lower levels of spotted wilt disease were recorded in Gainesville, Florida than those observed in Marianna, Florida and Tifton, Georgia (Culbreath et al., 2010). In another study, the incidences of spotted wilt in peanuts were lower during La Niña years than in El Niño or Neutral years (Olatinwo et al., 2010). La Niña and El Niño refer to the periodic cooling (La Niña) and warming (El Niño) in sea-surface temperatures across the central and east-central equatorial Pacific (Twine et al., 2005). La Niña and El Niño were shown to correlate with temperature and precipitation anomalies and the frequency of extreme weather events in the United States (Gershunov, 1998; Latif and Keenlyside, 2009). Findings from these studies indicate that factors other than production practices influence the intensity of spotted wilt in a given location during a given year. Weather parameters such as rain events in March, average daily minimum temperature in March, and evapotranspiration in April were found to correlate with the risk of spotted wilt disease (Olatinwo et al., 2008). It is likely that two fields having the same level of risk based on Peanut Rx could have different levels of spotted wilt depending on the location and weather conditions in each field.

The risk point values, based upon Peanut Rx, could also be associated with peanut yield. For example, a study conducted in Georgia and Florida in 2006 and 2007 showed that varieties not treated with phorate and those planted in single rows had higher final incidence of spotted wilt and greater area under disease progress curves (AUDPC) compared with same varieties applied with phorate and those planted in a twin-row pattern (Culbreath et al., 2008). Consequently, the yields in these treatments were numerically lower than the same varieties treated with phorate and those planted in a twin-row pattern. Based upon Peanut Rx, application of phorate insecticide and use of twin-row pattern reduces the risk to spotted wilt disease. In this example, it was shown that the lower risk treatments, which included use of phorate insecticide and twin-row pattern, resulted in lower spotted wilt intensity and higher yield (Culbreath et al., 2008).

There were three objectives in this study. The first objective was to compare the area under disease progress curves and apparent infection rates between different levels of risk based upon Peanut Rx. The second objective was to document the variability of spotted wilt intensity between locations and years in different risk categories. Lastly, the third objective was to assess the impact of spotted wilt intensity on peanut yield and implications that might have on Peanut Rx risk values. The findings from these objectives could provide additional information on the epidemiology of spotted wilt disease associated with different levels of risk based upon Peanut Rx. This information could be used in improving the risk index for the management of spotted wilt disease in peanuts.

Materials and Methods

*On-station field trial*s

Field trials were established at six research stations of the University of Georgia in 2017 and 2018. The research stations included the Attapulgus Research and Education

Center (Attapulgus), C.M. Stripling Irrigation Research Park (Stripling), Southwest Georgia Research and Education Center (Plains), Black Shank Farm (Tifton), Southeast Georgia Research and Education Center (Midville), and Vidalia Onion and Vegetable Research Center (Reidsville). These research stations are located across the peanut production region of Georgia.

The field trials were set-up using a split-split plot design. The whole-plot treatments consisted of three planting dates, the sub-plot treatments included two varieties of peanut and the sub-sub-plot were treatments with or without phorate (Thimet®-20G) insecticide (5.6 Kg/Ha in-furrow at planting). Twelve combinations of planting dates, varieties, and phorate application created different levels of risk to spotted wilt disease, based on Peanut Rx, and were considered as treatments (Table 2.12). Differences in final plant stand also contributed to the variation in total Peanut Rx risk point values. Each treatment was replicated four times. The same set of treatments was used in each of the six on-station field trials.

In 2017, the varieties 'Georgia -06G' and FloRun™ '157' were planted. These peanut varieties had spotted wilt risk points equivalent to 10 and 25 based on 2018 version of Peanut Rx, respectively. Due to lack of seed supply, TUFRunner™ '511' was planted in place of FloRun™ '157' in the 2018 field trials. TUFRunner™ '511' has 20-point spotted wilt risk value.

In 2017, the first planting dates were April 20, 19, 25, 27, 24, and 21 at Attapulgus, Stripling, Tifton, Plains, Reidsville, and Midville, respectively. The second planting dates were May 10, 9, 12, 16, 15, and 11 at the same locations, respectively. Finally, the third planting dates were May 30 in Attapulgus and Stripling, June 8 (Tifton), May 31 (Plains), and June 1 (Reidsville and Midville). The risk point values corresponding to these planting dates were 30-points for peanuts planted before May 1, 15-points for planting between May 1 and 10, 5-points for May 11- 25, and 10-points for May 26 – June 10.

In 2018, the first planting dates were April 17 (Attapulgus and Stripling), April 25 (Tifton and Midville), April 20 (Plains), and April 18 (Reidsville). The second planting dates were May 14, 18, 21, 11, 22, and June 6 in Attapulgus, Stripling, Tifton, Plains, Reidsville, and Midville, respectively. The third planting dates were June 5, 8, 7, 12, 20, and 19 for the same locations.

Lastly, phorate (Thimet®-20G, 5.6Kg/Ha) insecticide was either applied in-furrow or not applied in each combination of variety and planting date. Application of phorate insecticide at-planting is equivalent to a 5-point risk value, while application of any other insecticide or no insecticide at all is equivalent to a 15-point risk value.

The peanuts were planted using a two-row planter in Attapulgus, Stripling, Tifton, Plains, and Reidsville. A four-row planter was used in Midville. A single row pattern was used in all field trials with six seed/0.3m seeding rate at 2.5cm depth. The length of plots in Tifton, Plains, Attapulgus, and Reidsville was 7.62m. Plots in Midville were 9.14m long while plots in Stripling were 12.19m.

In 2017, four-row plots were established for each treatment in Attapulgus, Plains, Reidsville, and Midville. Six-row plots were set-up in Stripling, while two-row plots were set up in Tifton. In 2018 the field in Stripling had 6 rows per plot, while four-row plots were established at the other five locations. All treatments were replicated four times.

The field trials were established in irrigated fields. Drip irrigation was used in Stripling, while Tifton and Reidsville had overhead sprinkler irrigation. A center pivot irrigation system was used in the fields at Midville and Attapulgus. The field in Plains was irrigated using a lateral irrigation system.

Herbicides were applied to manage weeds in these field trials based on expert recommendations. This herbicide program involved the application of pendimethalin (Prowl 3.3EC at 1 quart /acre) before planting, followed by flumioxazin (Valor SX at 3 ounces /acre) immediately after planting. A mixture of S-metolachlor (Dual Magnum 7.62EC at 1.33 pint /acre) and bentazon + acifluorfen (Storm 4EC at 1.5 pints /acre) was applied post-emergence. To manage weeds that have escaped the previous sprays bentazon (Basagran 5EC at 1 quart /acre) followed by 2,4-DB (Butyrac 175 at 18 ounces /acre) were also recommended. Management of other pests and diseases, to include leaf spot and stem rot, were based on recommendations from University of Georgia Extension.

Spotted wilt intensity rating

The intensity of spotted wilt was assessed once every two weeks beginning at 45 days after the first planting date and continuing until near harvest. Ratings were done using the “hit-stick method" as described by Culbreath et al. (1997). This was done by counting the number of 0.3m sections along a row of peanuts that contained at least one infected plant. Infected plants were determined based on foliar symptomatology. Plants showing symptoms such as ring spots, mottling, chlorotic and smaller leaflets, and stunted plants were considered infected (Figure 2.1). In isolated cases where only chlorotic ring spots were observed in at least one leaflet, it was counted as a half-hit. The total number of hits per row of peanuts was then divided by the row length in order to get the proportion of spotted wilt intensity. Skips (missing plants within a plot) due to seedling mortality from other diseases, planter equipment failure, and damage from pivot irrigation tracks were discounted from the total row length.

Disease progress over time at different levels of risk based on Peanut Rx

The spotted wilt disease intensity ratings throughout the growing season were used to calculate the area under the disease progress curve (AUDPC) and the apparent infection rate for each treatment. The AUDPC is determined through a simple midpoint (trapezoidal) rule that breaks up the disease progress curve into a series of trapezoids, calculating the area of each, and then adding up the area (Simko and Peipho, 2012). The formula for calculating AUDPC is described by the following equation:

$$AUDPC = \sum_{i=1}^{n-1} \frac{y_i + y_{i+1}}{2} \; x \, (t_{i+1} - t_i)$$

where y_i is an assessment of a disease (percentage, proportion.) at the *i*th observation, t_i is time (in days, hours, etc.) at the *i*th observation, and *n* is the total number of observations.

The number of evaluations and number of days from planting to the evaluation period differed among locations during the two years of the study as affected by differences in planting dates. For this reason, the standardized area under the disease progress curve (sAUDPC) was calculated by dividing the AUDPC by the time in days between the first and last evaluation dates (Fry, 1977; Culbreath et al., 2011; Madden et al., 2007). This was conducted in order to allow comparison among epidemics of different duration (Craven and Fourie, 2011).

A regression analysis was conducted for the spotted wilt intensity ratings and the number of days from planting to the date of disease assessments per treatment. From the result of the regression analysis, the slope parameter, equivalent to the apparent infection rate, were recorded (Plaut and Berger, 1981; Shaner and Finney, 1977).

The sAUDPC and apparent infection rate of spotted wilt disease were compared between treatments trough a generalized linear mixed model procedure (PROC GLIMMIX) in SAS 9.4 software. This analysis was conducted at each location for each year. Replications within a trial were considered as a random effect and mean separation was computed based on Tukey's HSD test at 0.05 level of significance. From the result of the GLIMMIX analysis, treatments with the same risk values were also compared for each location per year.

Regression of sAUDPC, apparent infection rate, and final spotted wilt intensity (%) with Peanut Rx risk points

The sAUDPC values, apparent infection rate, and final spotted wilt intensities combined across locations and over years were regressed with the Peanut Rx risk point values using PROC REG in SAS 9.4 software. The probability values (p), coefficient of determination (R^2), and slope parameter are listed in Table 2.13.

Correlation of sAUDPC and final spotted wilt intensity

The association between the final spotted wilt intensity and sAUDPC was analyzed through correlation analysis using PROC CORR in SAS 9.4 software. This analysis was done per location and year. The probability values (p) and correlation coefficients (r) were summarized in a table (Table 2.7). A scatter plot with trend lines was also produced to show the correlation between final spotted wilt ratings and the sAUDPC values per location and year using PROC SGPLOT in SAS 9.4 software.

Data analysis for variability of spotted wilt intensity between locations and years

The Peanut Rx risk value for each treatment was calculated based on different combinations of three planting dates, two varieties, and phorate insecticide application. The final plant population (measured as plant stand) also contributed to the total risk value in each plot. The risk point values for row pattern and tillage type were also added. The total Peanut Rx risk values calculated for each combination of variety, planting date, use of phorate and plant stand were categorized using redefined risk categories as low (≤60 risk points), mild (65-75 risk points), medium (80-95 risk points), or high risk (100-120 risk points) to spotted wilt disease.

To evaluate the variability of spotted wilt intensity at the same level of risk across location and years, the data were analyzed using the generalized linear mixed models (PROC GLIMMIX) in SAS 9.4 software. Location, year, and risk categories were treated as fixed effects. The response variable was the observed spotted wilt intensity. Prior to analysis, the response variable was transformed using the logit transformation to normalize residuals to meet the assumptions of the generalized linear model procedure.

The logit transformation is the logarithm of the odds, as described by the equation logit (p) = log (p/1-p) where "p" is the probability of an event and (1 – p) is the probability of not observing the event (Schlotzhauer, 1993; Holland, 2017). Multiple comparisons were done using Tukey's HSD test.

For presentation and interpretation purposes, the untransformed data were used in generating graphs, while the Tukey groupings were based on the analysis done using the logit-transformed data. The graphs were created using the PROC SGPANNEL in SAS 9.4 software.

Yield data

The peanuts were inverted between 120 and 140 days after planting. They were left to dry in the field for at least three days before they were picked. The peanuts in each plot were harvested, weighed, and yields were recorded. Percent moisture content was determined at harvest for each planting date. The final weight of peanuts per plot was then adjusted to 7% percent moisture content and yield was converted to kilograms per hectare. A regression analysis was conducted to determine the linear relationship between yield (kg/ha) and final percent spotted wilt intensity and sAUDPC values. The regression analysis was conducted per location and year.

Further, the yield was also regressed against the summed Peanut Rx risk point values per location and year. This was conducted to determine if there was a significant linear relationship between risk points and peanut yield.

Results

Disease progress over time in different levels of risk based on Peanut Rx

On-station field trials were conducted at six UGA research stations in 2017 and 2018. In each field trial, 12 treatments were created based on different combinations of three planting dates, two varieties, and treatment with or without phorate insecticide. These combinations created different levels of risk to spotted wilt disease based upon Peanut Rx (Table 2.12). The final spotted wilt intensity varied between the different treatments. In 2017, the final spotted wilt intensity ranged from 0-12.64%, 0.66-18.02%, 0-12.05%, 2.13-41.67%, and 3.13-39.39%, 5.83-50.83% in Attapulgus, Stripling, Tifton, Plains, Reidsville, and Midville, respectively. In the same locations, the final spotted wilt intensity ranged from 1-27.55%, 1.88-28.13%, 0-37.18%, 5.21-59.57%, 0.83-43.33% in 2018. Spotted wilt intensity ratings at each location were used to calculate the sAUDPC and apparent infection rate for each treatment per location and year.

Based on the result of a generalized linear mixed model analysis, the sAUDPC and the apparent infection rate varied between different treatments in each location per year (Tables 2.1- 2.6). The sAUDPC values and apparent infection rates were generally lower among treatments with lower risk point values containing the resistant variety 'Georgia-06G'. For example, in Attapulgus, the sAUDPC was highest in FloRun™ '157', planted early without phorate insecticide ('Treatment 10') which had the highest TSWV risk point value of 120 points in 2017 (Table 2.1). In contrast, the lowest sAUDPC values were recorded in the middle ('Treatment 2') and late-planted ('Treatment 3') 'Georgia-06G' treated with phorate as well as in the late-planted

‘Georgia-06G’ without phorate (‘Treatment 6’). These treatments had risk point values of 65, 55, and 65, respectively.

The apparent infection rate also varied between different treatments. For example in Attapulgus in 2018, ‘Treatment 12’ comprised of late-planted TUFRunner™ ‘511’ without phorate had the highest apparent infection rate. Conversely, the middle-planted ‘Georgia-06G’ treated with phorate (‘Treatment 2’) had the lowest apparent infection rate as shown in Table 2.1.

In another example, the early-planted FloRun™ ‘157’ without phorate (‘Treatment 10’) had the highest sAUDPC and apparent infection rate in 2017 in Midville (Table 2.6). The lowest sAUDPC values and apparent infection rates were recorded in middle (‘Treatment 2’) and late-planted (‘Treatment 3’) ‘Georgia-06G’ with phorate during the same year. ‘Treatment 10’ had the highest risk point value of 100-points while ‘Treatment 2’ and ‘Treatment 3’ had 50 and 55 risk point values, respectively (Table 2.6).

Further, some combinations of planting date, variety, and phorate insecticide usage resulted in equal risk point values based upon Peanut Rx. The sAUDPC values and apparent infection rates in treatments with the same risk point values were compared from the result of generalized linear mixed models (PROC GLIMMIX) analysis (Tables 2.1 – 2.6). The sAUDPCs and apparent infection rates did not differ significantly among most pairs of the treatments having equal risk point values.

In Attapulgus, there were three (2017) and five (2018) pairs of treatments that had equal risk point values; the corresponding sAUDPC values were not significantly different (Table 2.1). In Stripling, there were three (2017) and four (2018) pairs of treatments with the same risk point values. The sAUDPC did not vary significantly between each pairs of treatments (Table 2.2.). Two pairs of treatments had equal risk point values and non-significantly different sAUDPC values in Tifton in 2017 (Table 2.3). While the sAUDPC values were non-significantly different, the apparent infection rates were variable for some of the treatments having equal risk point values. For example, 'Treatment 1' (early-planted 'Georgia-06G' with phorate) and 'Treatment 12' (late-planted TUFRunner™ '511' without phorate) had equal risk point values in Attapulgus and Stripling in 2018 (Table 2.1 and 2.2). However, the apparent infection rate was higher in 'Treatment 12' than in 'Treatment 1' at both locations.

The variability in apparent infection rates between pairs of treatments having equal risk point values was also observed with sAUDPC values in some treatments in other locations. In 2018, three pairs of treatments had the same risk point values in Tifton (Table 2.3). While the sAUDPC values and apparent infection rates did not vary significantly between two out of three pairs of treatments, they were significantly different for one pair of treatments. 'Treatment 4' (early-planted 'Geogia-06G' without phorate) and 'Treatment 7' (early-planted TUFRunner™ '511' with phorate) had a total risk point value of 90 points, but the sAUDPC and apparent infection rate were higher in 'Treatment 7' compared with 'Treatment 4'.

Significant differences in sAUDPC and apparent infection rates among treatments with equal risk point values were also observed in 2018 in Plains ('Treatments 4 and 11' and 'Treatments 1 and 8'), Reidsville in 2018 ('Treatments 6, 9, and 11'), and Midville in 2018 ('Treatments 1 and 9' and 'Treatments 4 and 12') and in 2017 ('Treatments 1 and 11'). These were shown in Tables 2.4- 2.6, respectively. Despite having equal risk point values, the sAUDPC values and apparent infection rates were higher among treatments containing the susceptible varieties FloRun™ '157' and TUFRunner™ '511' than were those from treatments containing the more-resistant variety 'Georgia-06G'.

The sAUDPC and apparent infection rates among treatments having the same variety and treatment with or without phorate were also compared between different planting dates. Early-planted peanuts had higher sAUDPC and apparent infection rates while the middle-planted ones have lower values of sAUDPC and apparent infection rates in general. For example, in Stripling in 2017, the early planted FloRun™ '157' where phorate was applied at planting ('Treatment 7') had a significantly higher sAUDPC and apparent infection rate than did those of late-planted peanuts ('Treatment 9') (Table 2.2). In Tifton (2018), the early-planted TUFrunner™ '511' with phorate ('Treatment 7') had higher a sAUDPC value than did the middle-planted peanuts of the same variety with phorate ('Treatment 8') as shown in Table 2.3. This was also observed in Reidsville and Midville as shown in Tables 2.5 and 2.6.

Additionally, the effect of phorate application on the sAUDPC and apparent infection rates as compared among treatments containing the same variety and planting date. The was no effect except for 'Treatment 10' (early-planted FloRun™ '157' without phorate) which had higher sAUDPC than 'Treatment 7' where phorate was applied in Reidsville in 2017 (Table 2.5). In Midville (2017), the apparent infection rate was higher in 'Treatment 11' (middle-planted TUFRunner™ '511' without phorate) than in 'Treatment 8' (middle-planted TUFRunner™ '511' with phorate) (Table 2.6).

Regression of sAUDPC, apparent infection rate, and final spotted wilt intensity (%) with Peanut Rx risk points

A regression analyses was conducted using spotted wilt data combined across six on-station field trials over two years. The sAUDPC and final spotted wilt intensity had a significant positive linear relationship with Peanut Rx risk point values at the 0.05 level of significance (Table 2.13). The Peanut Rx risk points accounted for 5.16% and 4.95% variability in sAUDPC values and final spotted wilt intensities across different levels of risk. The apparent infection rate did not have a significant linear relationship with Peanut Rx risk points, but the slope of the regression line had a positive value.

Correlation of sAUDPC and final spotted wilt intensity

The association of sAUDPC values and final spotted wilt intensities were assessed through a correlation analysis (Table 2.7). The sAUDPC of spotted wilt disease across different treatments had a strong positive correlation with the final spotted wilt intensities in all locations in 2017 and 2018 (Table 2.7) as illustrated in Figure 2.2. Greater final spotted wilt intensities correlated with greater sAUDPC. In contrast, lower sAUDPC values were calculated among treatments with lower spotted wilt intensities.

Space and time variability of spotted wilt intensity

The variability of final spotted wilt intensity between locations and between years was assessed. There was a significant effect of year, location, and risk category (p <.0001) and a significant interaction between location and year (p <.0001) for the intensity of spotted wilt disease (Table 2.8). The interactions were not significant between year*risk category, location*risk category, and year*location*risk category.

The effect of risk category was analyzed per location in each year. Lower spotted wilt intensities were observed in situations with low risk categories while higher intensities were observed in higher risk categories, as expected from Peanut Rx (Figure 2.3).

The intensity of spotted wilt disease was also investigated between locations in two years at each risk category. At the low risk category (Figure 2.4), the intensity of spotted wilt at a single location did not vary significantly between 2017 and 2018, except for Attapulgus. The intensity of spotted wilt disease was higher in 2018 than in 2017.

When compared between different locations and over years, there was higher spotted wilt intensity in Reidsville (2018) and Midville (2017) than was observed in Tifton, Stripling, and Attapulgus in 2017. Out of 66 possible combinations of six locations and two years of data, 12 combinations of location and years were significantly different from each other, as summarized in Table 2.9 and indicated by blue lines in the diffogram shown in Figure 2.4. The intensities in other location and year combinations were not significantly different, although there were nominal differences.

In the mild risk category, spotted wilt intensity at a single location varied between 2017 and 2018 in Attapulgus, Stripling, Plains, and Tifton (Figure 2.5). Spotted wilt intensity was higher in 2018 than in 2017 at Attapulgus, Stripling, and Tifton. Conversely, the intensity of spotted wilt was higher in 2017 than 2018 in Plains. When compared between locations over years, the highest spotted wilt intensity was recorded in Midville in 2017. The lowest spotted wilt intensity was observed in Attapulgus (2017), Stripling (2017), and Plains (2018). Thirty-four combinations of location and years were significantly different (Figure 2.3 and Table 2.9).

The intensity of spotted wilt varied between 2017 and 2018 in Attapulgus, Stripling, Tifton, and Midville at the moderate risk category (Figure 2.6). Higher spotted wilt intensities were recorded in 2018 than those in 2017 in Attapulgus, Stripling, and Tifton. In Midville, higher spotted wilt intensity was recorded in 2017 than 2018. Between locations, thirty-three location and year combinations were significantly different with each other (Figure 2.6 and Table 2.9). The highest spotted wilt intensity, at moderate risk category, was observed in Midville in 2017, while the lowest was recorded in Attapulgus, Stripling, and Tifton in 2017.

At the high-risk category, spotted wilt intensity at a single location varied between 2017 and 2018 in Attapulgus, Stripling, Tifton, and Midville (Figure 2.7). Higher spotted wilt intensities were recorded in Attapulgus, Stripling, and Tifton in 2018 than those in 2017. In Midville higher spotted wilt was recorded in 2017 than 2018. When compared between locations in two years, 20 combinations were significantly different from each other (Figure 2.7 and Table 2.9). The highest spotted wilt intensity was observed in Midville in 2017 while the lowest was observed in Attapulgus in 2017.

The difference between the highest and lowest spotted wilt intensity across location over years varied at each risk category. At the low-risk category, the intensity of spotted wilt varied by 12.4%. Spotted wilt intensity varied by 20.9, 25.4, and 40.6% at the mild, moderate, and high-risk categories (Table 2.9).

Regression of yield with spotted wilt intensity and sAUDPC

A simple linear regression was performed for peanut yield and percent spotted wilt intensity for each location per year. Peanut yield had a significant negative linear relationship with percent spotted wilt intensity in Attapulgus, Stripling, and Midville in 2017, and in Attapulgus, Plains, and Midville in 2018 (Table 2.10). Based on R^2 values, the intensity of spotted wilt accounted for up to 31.03% variation in yield in Midville (2018). In other locations, it accounted for 22.84, 16.64, 15.72, 10.95, and 10.12% variation in yield in Midville (2017), Attapulgus (2017), Stripling (2017), Plains (2018), and Attapulgus (2018), respectively. The steepness of the slope was variable from one location to another. The value of the slope parameters were -192.57, -144.08, -67.98, -64.57, -51.66, and -37.21 in Stripling (2017), Attapulgus (2017), Attapulgus (2018), Plains (2018), Midville (2018) and Midville (2017), respectively (Table 2.10).

There was a significant negative linear relationship between the sAUDPC values and peanut yield in on-station field trials at Attapulgus, Stripling, and Midville in 2017 (Table 2.14). In 2018, a significant negative linear relationship between the sAUDPC values and peanut yield was also observed in Midville and Attapulgus. Among the on-station field trials where there was a significant linear relationship between the sAUDPC values and peanut yield, the sAUDPC accounted for 7.99 to 24.55% variation in peanut yield based upon the R^2 values listed in Table 2.14.

Regression of yield with spotted wilt risk point values

Yields were also regressed against the summed Peanut Rx risk point values (Table 2.11). This was conducted to determine how much yield loss was associated with each increase in the total risk points. The peanut yield had a significant negative linear relationship with Peanut Rx risk points in 2017 at Attapulgus, Stripling, and Tifton and in 2018 at Attapulgus and Midville (Table 2.11). The steepness of the slopes (Kg/Ha reduction in yield for every 1 point increase in risk point) were -81.67, -66.40, -42.84, -35.83, and -24.55 for Stripling (2017), Attapulgus (2018), Tifton (2017), Midville (2018), and Attapulgus (2017), respectively. Conversely, there was a significant positive linear relationship between Peanut Rx risk point values and peanut yield in Stripling in 2018 (slope = 42.05) as shown in Table 2.11.

Based on the R^2 values from the regression analysis, the Peanut Rx risk point values accounted for 12.01 to 49.08% variation in peanut yield among the on-station field trials where there was a significant negative linear relationship between the yield and risk point values (Table 2.11).

Discussion

The result of this study showed that the sAUDPC values and apparent infection rates of spotted wilt were higher among treatments with the highest risk point values but lower on treatments with lowest risk points as expected from Peanut Rx (Table 2.1-2.6). This was consistently observed at all six locations in both years of the study. This finding is another example of the importance of achieving a low risk levels based on Peanut Rx similar to what was reported by Kemerait et al. (2015). Accordingly, as little as 5% TSWV intensity was observed in plots where multiple management practices were used to create a “low risk” situation. Conversely, over 60% TSWV intensity was observed in high-risk situations. It was also reported that a yield difference of over 2000 lbs. per acre was recorded in some cases (Kemerait et al., 2015).

The findings from the current study show that the disease progress over time and the rate of infection are lower in low risk situations when compared with situations having higher risk point values. Thus, by achieving a low level of risk, growers can significantly slow the epidemics of spotted wilt in their peanut crop. This is important because plants that show symptoms earlier in the season typically yield less compared with plants infected later in the season (Culbreath et al., 1992). Therefore, with the ability to slow down the disease progress by choosing production practices that result in low levels of risk, growers can reduce the risk of yield loss.

Among treatments having the same variety and phorate application, the early- and late-planted peanuts had higher sAUDPC values and apparent infection rates than did those planted during the "mid-planting" dates. These results were similar with findings from previous studies that reported higher spotted wilt intensities with early- and late-planted peanuts compared with those planted during the recommended planting window (Brown et al., 1996; Brown et al., 2005; Culbreath and Srinivasan, 2011; Tillman et al., 2007; Nuti et al., 2014). Additionally, among the treatments having the same variety and planting date, the sAUDPC values and apparent infection rates between treatments with and without phorate insecticide applied at planting were generally not significantly different. However, there were two cases where the sAUDPC values and apparent infection rates were significantly lower among treatments where phorate was applied at planting on the more-susceptible varieties (Tables 2.5 and 2.6). Several studies have also reported lower intensity of spotted wilt in peanuts treated with phorate at-planting

(Brown et al., 2005; Kemerait et al., 2018; Herbert et al., 2007; Marasigan et al., 2015; Tubbs et al., 2013). Hence, the use of resistant varieties, planting during the recommended planting window and application of phorate insecticide at-planting continue to be important factors that reduce the risk of spotted wilt in peanuts.

Using Peanut Rx, there are multiple combinations of production practices that can result in the same number of risk points and risk category. Use of Peanut Rx allows growers to select different combinations of production practices to achieve a desired risk point total. For example, a grower who needs to plant in late April can still achieve a satisfactory point total by adjusting other parts of the index, such as the selection of a more resistant variety (Kemerait et al., 2013). Where the combination of production practices resulted in the same risk point values, the sAUDPC and apparent infection rates between treatments were often not significantly different (Tables 2.1-2.6). This finding was consistent with the fact that a 10-point difference in risk point in one factor, such as planting date, is expected to equal a 10-point difference in the other factors, such as variety selection in terms of overall contribution to total risk (Kemerait et al., 2013). This allows the growers to be flexible in choosing different combinations of production practices to achieve a specific risk value without significantly affecting the severity of spotted wilt disease epidemics.

However, some treatments with the same risk point values had significantly different sAUDPC values and apparent infection rates (Tables 2.1 - 2.6). The sAUDPC values and apparent infection rates were higher among treatments where the susceptible varieties (FloRun^{TM} ‘157’ and TUFrunner^{TM} ‘511’) were used. This is an indication that the risk points assigned to susceptible may not be high enough or that the risk points assigned to the resistant varieties may not be low enough. It is also possible that the range of risk points assigned for peanut varieties and other production practices may need to be adjusted in order to maintain that a 10-point difference between two varieties is equal to a 10-point difference between different planting dates.

In the current study, the sAUDPC and apparent infection rates were compared between treatments having different levels of risk based on Peanut Rx. However, in previous studies, the final disease intensity has been generally used for comparison between different peanut genotypes (Wells et al., 2002; Culbreath et al., 2005) and production practices (McKinney 2013; Tilman et al., 2007, Cantonwine et al., 2006). Both the final ratings and sAUDPC values were used for evaluating TSWV resistance of peanut genotypes in other studies (Culbreath et al., 1993; Culbreath et al., 1997; Culbreath et al., 2008; Culbreath et al., 2011; Williams, 2015). In other studies, both the final spotted wilt ratings and sAUDPC values were used for evaluating TSWV resistance of peanut genotypes in other studies (Culbreath et al., 1993; Culbreath et al., 1997; Culbreath et al., 2008; Culbreath et al., 2011; Williams, 2015).

A question may be asked whether the relationship between peanut Rx risk points and spotted wilt in peanuts is the same when the final spotted wilt intensity, sAUDPC, or apparent infection rates were used. The result of regression analyses in the current study showed that the Peanut Rx risk point values had a significant positive linear relationship with sAUDPC and final spotted wilt intensity. The R^2 values did not have a huge difference between regression of Peanut Rx risk points with sAUDPC ($R^2 = 0.0516$) and final spotted wilt intensities ($R^2 = 0.0495$) (Table 2.13). This finding shows that a single spotted wilt intensity rating at the end of the season fits as well with the Peanut Rx risk point values as the sAUDPC, which was calculated using more than one disease rating during the growing season.

Correlation analysis has shown a strong positive correlation between sAUDPC and final disease rating of spotted wilt were in this study (Table 2.10, Figure 2.2). It is posible that there is a steady rate of spotted wilt infection throughout the growing season. If so, a greater infection early in the season would progress steadily leading to greater spotted wilt intensity at the end of the season, while lower spotted wilt intensity early in the season would lead to lower end-of-season spotted wilt intensity. This may be the reason why there was not a substantial difference between the result of regression analyses using the sAUDPC and the final spotted wilt intensity with Peanut Rx risk point values as presented earlier. As TSWV transmission by thrips is the only mode of spread of spotted wilt in the environment, the steady rate of infection could be associated with the timing of dispersal of thrips. It is known that the peak of thrips dispersal into host crops occur early in the season (Groves et al., 2003; Morsello et al., 2008). The number of dispersing thrips will then decline until the growing season is over, which means that there is a low chance of getting a sudden increase in the number of infected plants. In practice, it would be simpler to use the final ratings in comparing spotted wilt between different treatments, as it only requires a single rating. Conversely, while the sAUDPC can also be used to compare effects of different treatments, collecting data needed for the sAUDPC requires much more time and labor to rate the field several times during the season.

The application of production practices that are known to reduce risk to spotted wilt disease in peanuts is important to growers especially in area during a year with high levels of spotted wilt disease pressure. Unfortunately, there is currently no means of predicting the disease pressure in peanut fields for each location or from one year to another.

A second objective of this study was to document the variation of final spotted wilt intensity between locations and year at each level of risk. To document the space and time variation in spotted wilt intensity, both “location” and “year”, in addition to the risk categories, were treated as fixed effects in the generalized linear mixed model analysis. For this analysis, a redefined category of risk based on ranges of total risk points, defined as ‘low’ (≤ 60 risk points), ‘mild’ (65-75 risk points), ‘moderate’ (80-95 risk points), or ‘high’ risk (100-120 risk points) was used in place of the risk categories from Peanut Rx, (Table 2.12). These arbitrary risk categories were created because when the categories from Peanut Rx were used, most of the risk point values created in this study would have been categorized as ‘moderate’ risk (70 – 110 risk points). In most of the on-station field trials, none of the treatments was categorized as ‘high’ risk (≥115 points), except for one treatment at Attapulgus in 2017 which had a total risk point value of 120-points (Table 2.1). As it was necessary to have an observation in each risk category for comparison between locations per year, a redefined risk category was created in this study.

The redefined risk categories, location, year, and location by year interaction had a significant effect to final spotted wilt intensity. The intensity of spotted wilt disease varied between risk categories, locations, and years. The significant interaction between locations and years suggested that in a single location, the intensity of spotted wilt varied between the two years of study. This also indicated that spotted wilt varied between locations in a single year. There was no interaction between risk category*location, risk category*year, and risk category*location*year. This demonstrated that the effect of risk categories based on the Peanut Rx risk index was consistent across locations and years. Elevated spotted wilt intensities were observed among treatments that were categorized as high-risk. Conversely lower spotted wilt intensities were observed in low-risk category (Figure 2.4). However, it was found that the final spotted wilt intensities were more variable between location and years in plots with mild, moderate, and high risks categories when compared to the low-risk category. It is possible that between two fields with exactly the same production practices and risk level based on Peanut Rx, one field can have a severe spotted wilt epidemic while the other field may not. Further, it seems that with a low level of risk, the chance of significantly different intensity of spotted wilt from year to year, and from one location to another is reduced. The reason why there is less variation in spotted wilt at the low risk category could be associated with the fact the combination of production practices leading to a low level of exposure to spotted wilt protects the peanut crop whether there is a low or high disease pressure in a specific location and year. Whereas, with higher level of exposure to spotted wilt disease, the intensity of spotted wilt during the season could be severe when there is high disease pressure (based on number of dispersing viruliferous thrips) at each location and year. However, the intensity of spotted wilt could also be low, even with high level of risk, when the disease pressure is very low. That is why the spotted wilt intensity is more variable in situations with higher risk levels than situations with low-risk based on Peanut Rx.

The variation of spotted wilt intensity at each risk category between six geographic locations per year is presented in Figures 2.4-2.7. The variability in spotted wilt intensity observed between different locations and years observed in the current study and in previous studies (Culbreath et al., 2005; Culbreath et al., 2010; Mullis and Ochoa, 2009; Nuti et al., 2014) indicate that there may be an important factor that is not accounted for in Peanut Rx. This variability may be influenced by weather parameters, for example it was reported that spotted wilt intensity was significantly lower during La Niña when compared to El Niño or Neutral years (Olatinwo et al., 2010). El Niño years in the southeastern US coastal plain tend to be cooler and wet while La Niña years tend to be warmer and dry between October and April (Kiladis and Diaz, 1989; Sittel, 1994). In another study conducted on tobacco crops in Georgia, it was observed that TSWV was low in years where rainfall amounts were greater than five inches in the month of March when compared to those years where rainfall was less than five inches (Csinos and Mullis, 2009). It is clear that the weather parameters such as amount of rainfall and temperatures impact the intensity of spotted wilt in a specific location per year. The impact of temperature and rainfall in the intensity of spotted wilt could be attributed to their influence on the population dynamics and dispersal of the thrips vector, *Frankliniella fusca*. Warmer temperature and less rainfall favor population growth and dispersal of the *F. fusca* thrips (Chappell et al, 2013; Morsello et al., 2008, Olatinwo et al., 2011; Wells et al., 2002b). Accounting for the biological activities of thrips, such as dispersal patterns and magnitude of population, could be an area for refining the Peanut Rx risk index in order to account for effects of location and years in the intensity of spotted wilt disease in peanuts.

The objective of plant disease management is to protect the yield of the crop. Disease management strategies are applied to reduce the economic and aesthetic damage caused by plant diseases (Maloy, 2005). In the current study, the peanut yield was regressed with final spotted wilt intensity, sAUDPC, and Peanut Rx risk point values. The peanut yield was not transformed because it had a normal distribution and the residuals were also normally distributed based on visual observation of the residual histogram and quantile-quantile plot from the univariate procedure of SAS 9.4 software.

The final spotted wilt intensities and sAUDPC values had a significant negative linear relationship with the peanut yield (Table 2.10). The final spotted wilt intensity accounted for more variation in yield (10 to 31%) than the sAUDPC (8 to 24%) (Tables 2.10 and 2.14). This is likely related to the earlier observation in this study that the rate of infection is steady throughout the growing season. Lower spotted wilt intensity early in the season results to lower sAUDPC and final spotted wilt intensity. This is why management of spotted wilt disease early in the season is critical in order to avoid severe spotted wilt epidemics later in the season. Among the locations where there was a significant negative linear relationship between peanut yield and final spotted wilt intensity, it was shown that with every one percent increase in spotted wilt intensity, the yield is reduced by 37.21 up to 192.57 kg per hectare. This amount of yield loss is equivalent to $16.41 to $84.91 lost per hectare if calculated based on price of peanuts in 2018 ($0.2/lb) (USDA NASS, 2019).

When the yield was regressed with the Peanut Rx risk point values, there was a significant negative linear relationship between total risk points and peanut yield in three out of six locations in 2017 and two out of six in 2018 (Table 2.11). The Peanut Rx risk point values accounted for 12.01 to 49.08% variability in peanut yield among the on-station field trials where there was a significant negative linear relationship between yield and risk point values (Table 2.11). The Peanut Rx risk point values accounted for more variation in yield when compared with the final spotted wilt intensity and the sAUDPC values. This suggests that aside from accounting for the impact of spotted wilt disease in the peanut yield, the risk point values also account for the influence of the production practices in the peanut yield.

Among the on-station field trials where a significant negative linear relationship between total risk points and peanut yield was observed, the yield was reduced by 24.55 to 81.67 kg/ha with every point increase in the summed Peanut Rx risk point value. Previous studies have shown that the individual factors accounted for in Peanut Rx affect peanut yield. For example, better yields were recorded when TSWV resistant varieties were used (Culbreath et al., 2005; Culbreath et al., 2010; Plumblee et al., 2018), when planted in mid-May (Mahoney et al., 2018), applied with phorate at-planting (Mahoney et al., 2018; Herbert et al., 2007), or when twin-row pattern was used (Kirk et al., 2013; Lanier et al., 2004). The results of this study suggest that the summed risk points based on combinations of production practices not only provides an estimate of the relative level of exposure to spotted wilt disease, but it also could provide an idea on how much yield is "potentially" lost for every increase in risk based on choices of production practices.

Unfortunately, the significant negative relationship between yield with final spotted wilt intensity, sAUDPC values, and Peanut Rx risk points was not observed in the other on-station field trials. This is because factors other than spotted wilt disease may have affected the yield in the field trials or that spotted wilt intensities were not high enough to affect yield. According to Wells et al. (2002), cultural and environmental factors make the effects of spotted wilt on yield difficult to evaluate. In the current study, the wet and flooded conditions early in the season in 2018 stunted the peanut plants, which likely had a significant effect on the yield in Reidsville. While the slope of the regression between spotted wilt and yield was negative, the test was not significant. Conversely, the regression trend line had a positive slope in Stripling in 2018 (Table 2.11). This could be associated with the landfall of hurricane Michael before the May-planted peanuts were picked. The peanuts were dug before the hurricane hit the area. The May planted peanuts had lower risk point values compared with peanuts planted in April or June. While the peanuts were still picked after the hurricane, the yield was less compared with the yield from late or early-planted peanuts as the peanuts were blown around the field by the hurricane. This is likely the reason why there was a negative slope between yield and the summed risk point values.

Summary and Conclusion

On-station field trials were conducted in six UGA research stations in 2017 and in 2018. The epidemics of spotted wilt disease in different levels of risk based upon Peanut Rx was studied. Twelve different combinations of three planting dates, two varieties, and treatment with or without phorate insecticide created different levels of risk to spotted wilt disease based upon Peanut Rx. A generalized mixed models analysis showed that the sAUDPC and apparent infection rate of spotted wilt were higher on treatments with the highest risk but lower on treatments with lowest risk point values. The sAUDPC values and apparent infection rates did not vary among pairs of treatments with equal risk point values in general. However, in some pairs of treatments with the same risk point values the sAUDPC values and apparent infection rates were higher among treatments where the susceptible varieties (FloRun^{TM} '157' and TUFrunner^{TM} '511') were used compared with the treatments containing the resistant variety 'Georgia-06G'. This is an indication that the risk points assigned to the peanut varieties may not be high or low enough.

Through a regression analysis it was shown that the Peanut Rx risk point values had a significant positive linear relationship with sAUDPC and final spotted wilt intensity. The R^2 values did not have a huge difference between regression of Peanut Rx risk points with sAUDPC and final spotted wilt intensities. This finding shows that a single spotted wilt intensity rating at the end of the season fits as well with the Peanut Rx risk point values as the sAUDPC, which was calculated using more than one disease rating during the growing season.

Another objective in this study was to document the variation of final spotted wilt intensity between six geographic locations in two years in different risk categories. The intensity of spotted wilt disease varied between risk categories, locations, and years. The final spotted wilt intensities were more variable between locations and years in the mild, moderate, and high-risk categories when compared with the low-risk category. The variability in spotted wilt intensity observed between different locations and years indicate that there is an important factor that is not accounted for in the Peanut Rx risk index. The variability of spotted wilt intensity in space and time provides an opportunity to refine Peanut Rx by understanding and accounting for this variation in assessing the risk of spotted wilt disease.

Further, the peanut yield was regressed with the final spotted wilt intensity, sAUDPC, and Peanut Rx risk point values. The final spotted wilt intensity accounted for more variation in yield than the sAUDPC. The rate of infection appears to be steady throughout the growing season, which is probably why the final spotted wilt intensity accounts for more or as much variation in yield as the sAUDPC does. When the yield was regressed with the Peanut Rx risk point values, a significant negative linear relationship was observed. Based on R^2 values from the regression analysis, the Peanut Rx risk point values accounted for more variation in yield when compared with the final spotted wilt intensity and the sAUDPC values. This suggests that besides accounting for the impact of spotted wilt disease in the peanut yield, the risk point values also account for the influence of the production practices in the peanut yield.

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Figures and Tables

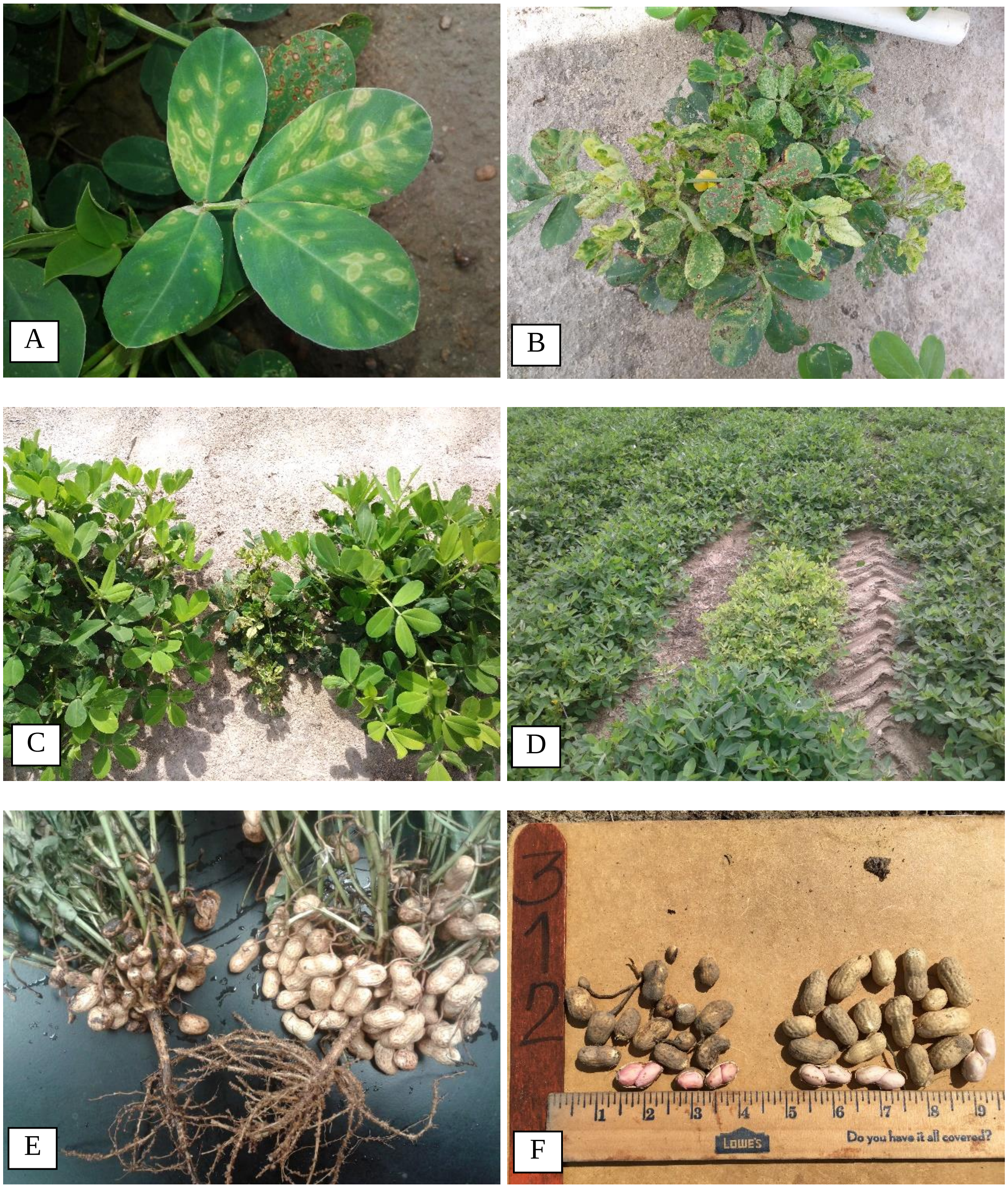


Figure 2.1. Symptoms of spotted wilt disease in peanuts. A.) Chlorotic ring spots, B.) Chlorosis and stunting on severely infected plant, C. and D.) Severely infected plants compared with healthy plants, E.) Smaller and fewer pods on infected compared with healthy plant, F.) Darker pod color and reddish discoloration on seed coats

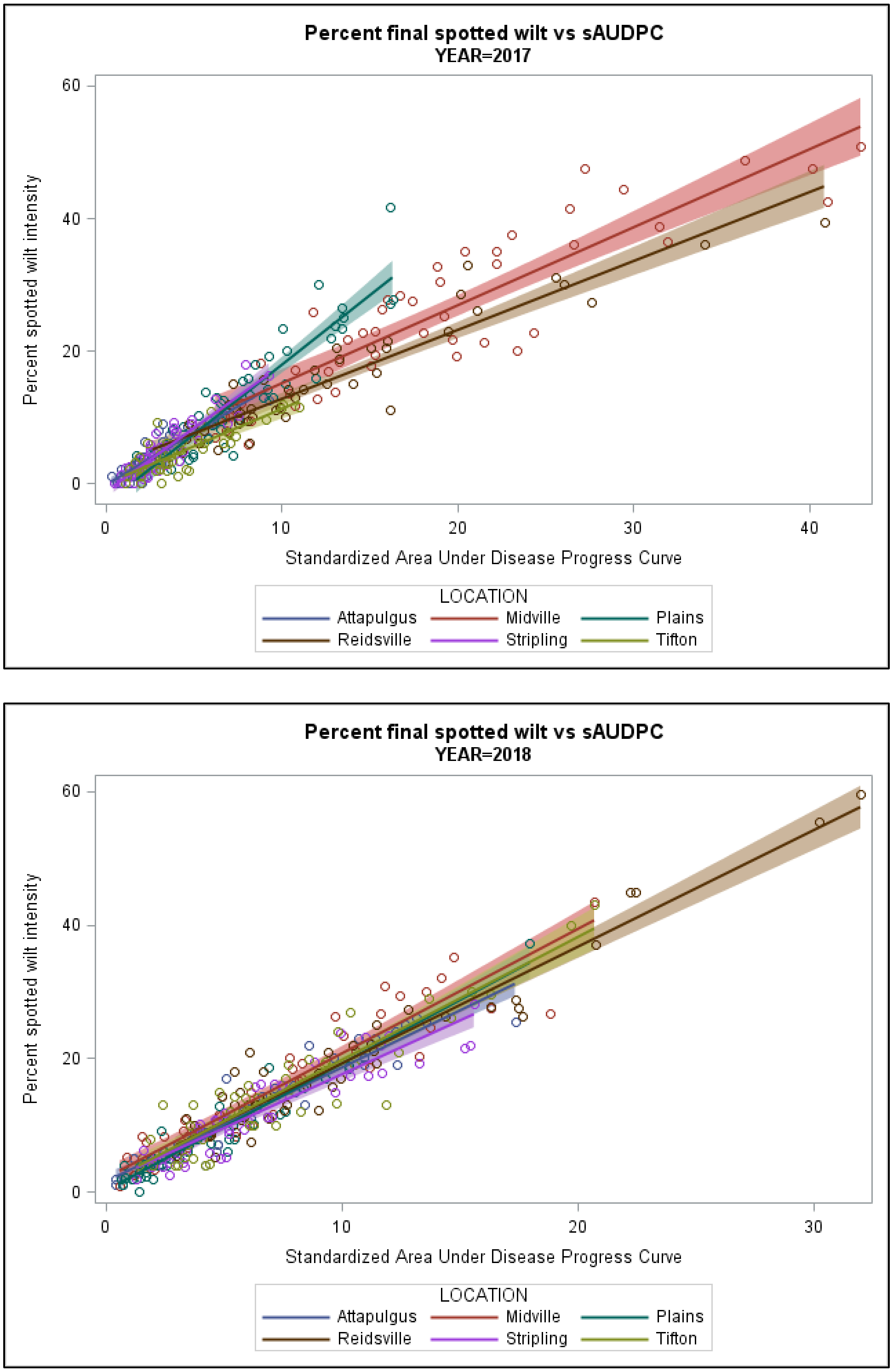


Figure 2.2. Correlation between final spotted wilt intensities and sAUDPC observed in six locations in 2017 and in 2018

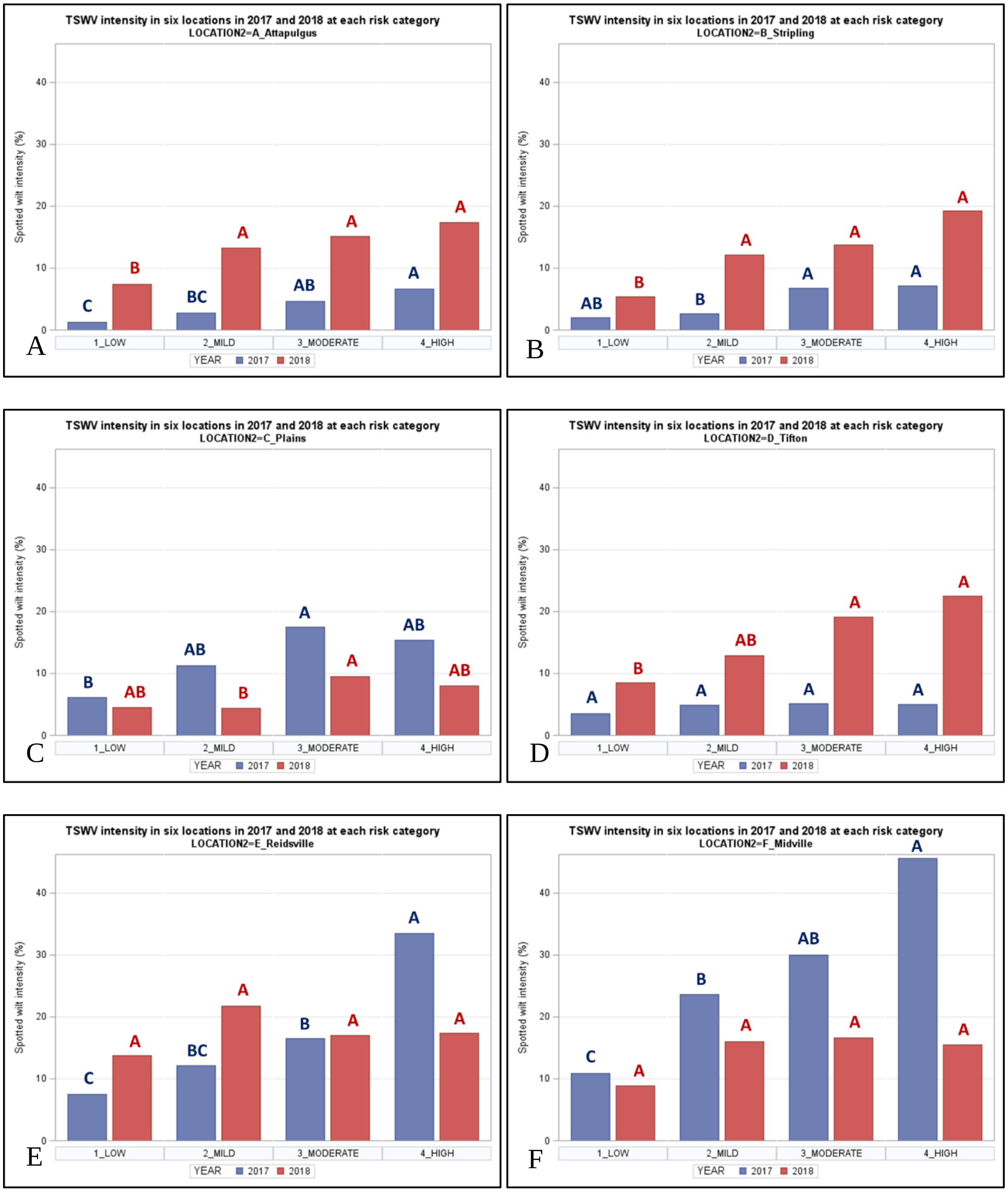


Figure 2.3. Variation of final spotted wilt intensity observed in four risk categories at each of six locations: A.) Attapulgus, B.) Stripling, C.) Plains, D.) Tifton, E.) Reidsville, and F.) Midville. *NOTE: Tukey grouping is based on logit-transformed data.*

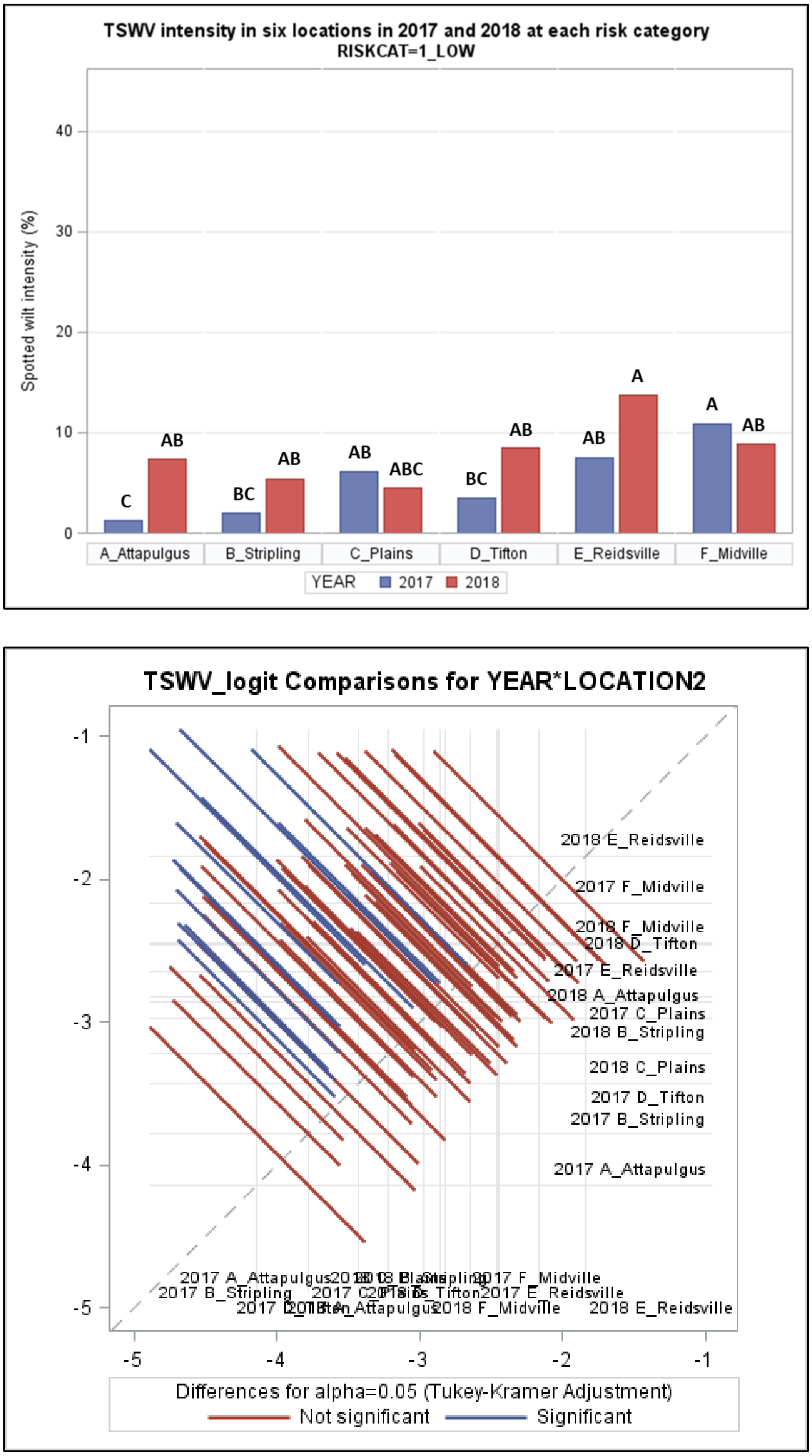


Figure 2.4. Variation of final spotted wilt intensity at "low" risk category between six geographic locations in two years. *NOTE: Tukey grouping is based on logit-transformed data.*

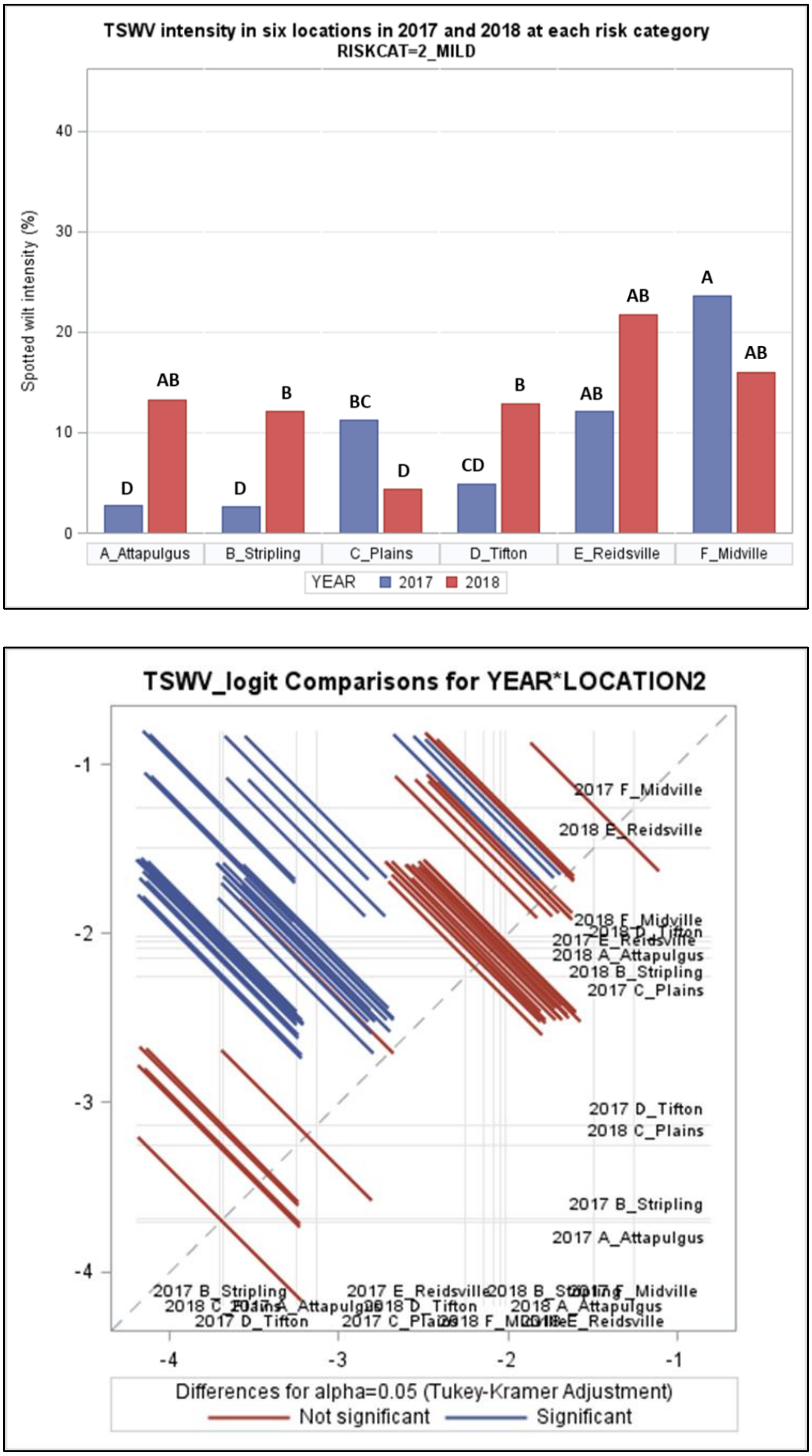
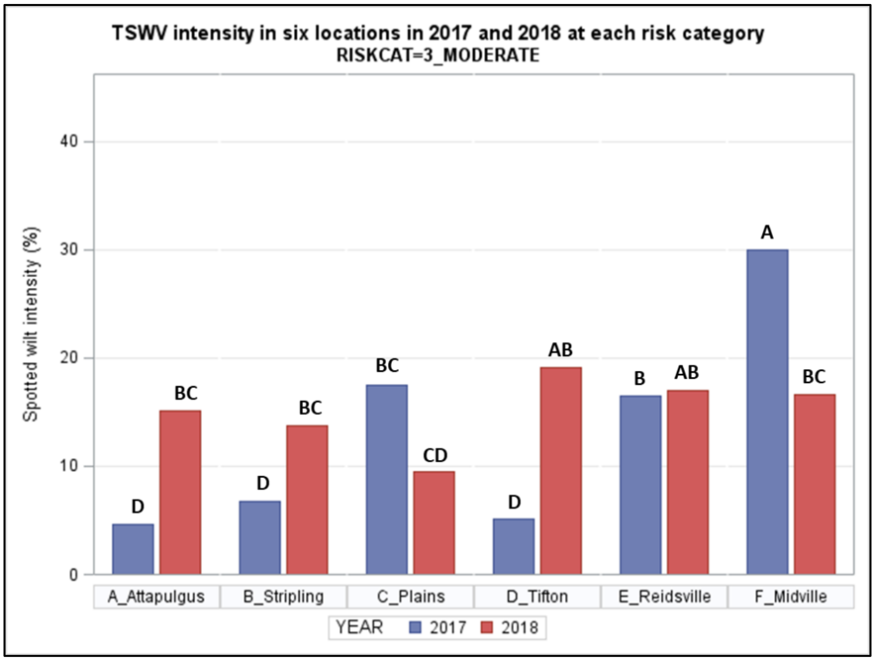


Figure 2.5. Variation of final spotted wilt intensity at “mild” risk category between six geographic locations in two years. *NOTE: Tukey grouping is based on logit-transformed data.*



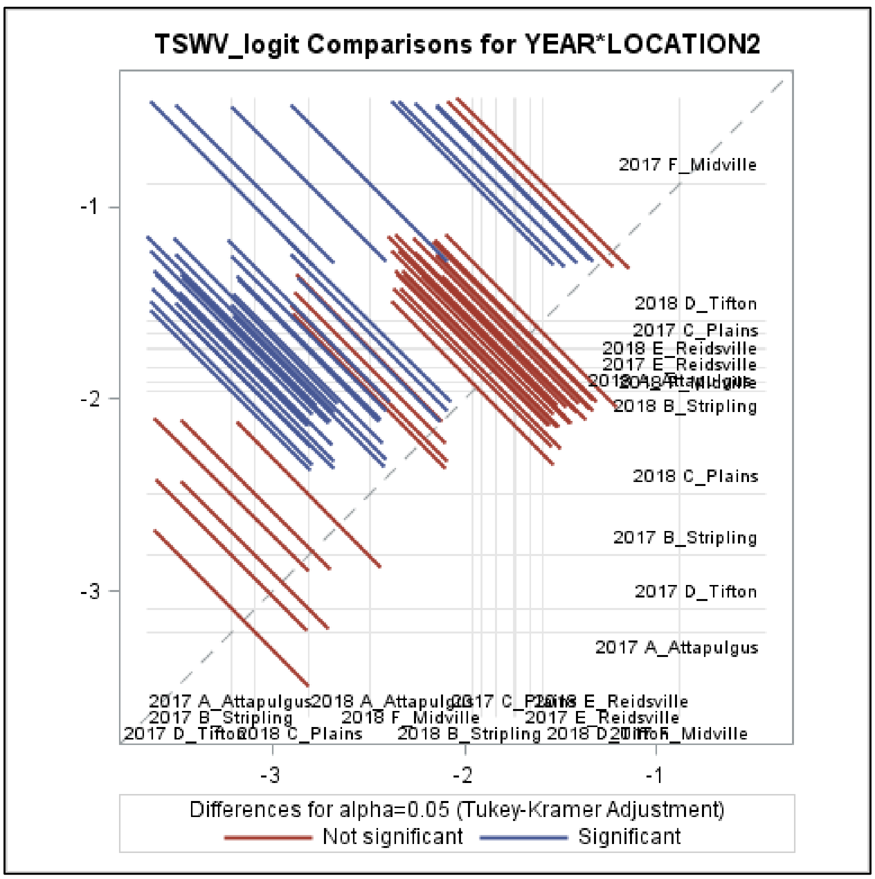


Figure 2.6. Variation of final spotted wilt intensity at "moderate" risk category between six geographic locations in two years. *NOTE: Tukey grouping is based on logit-transformed data.*

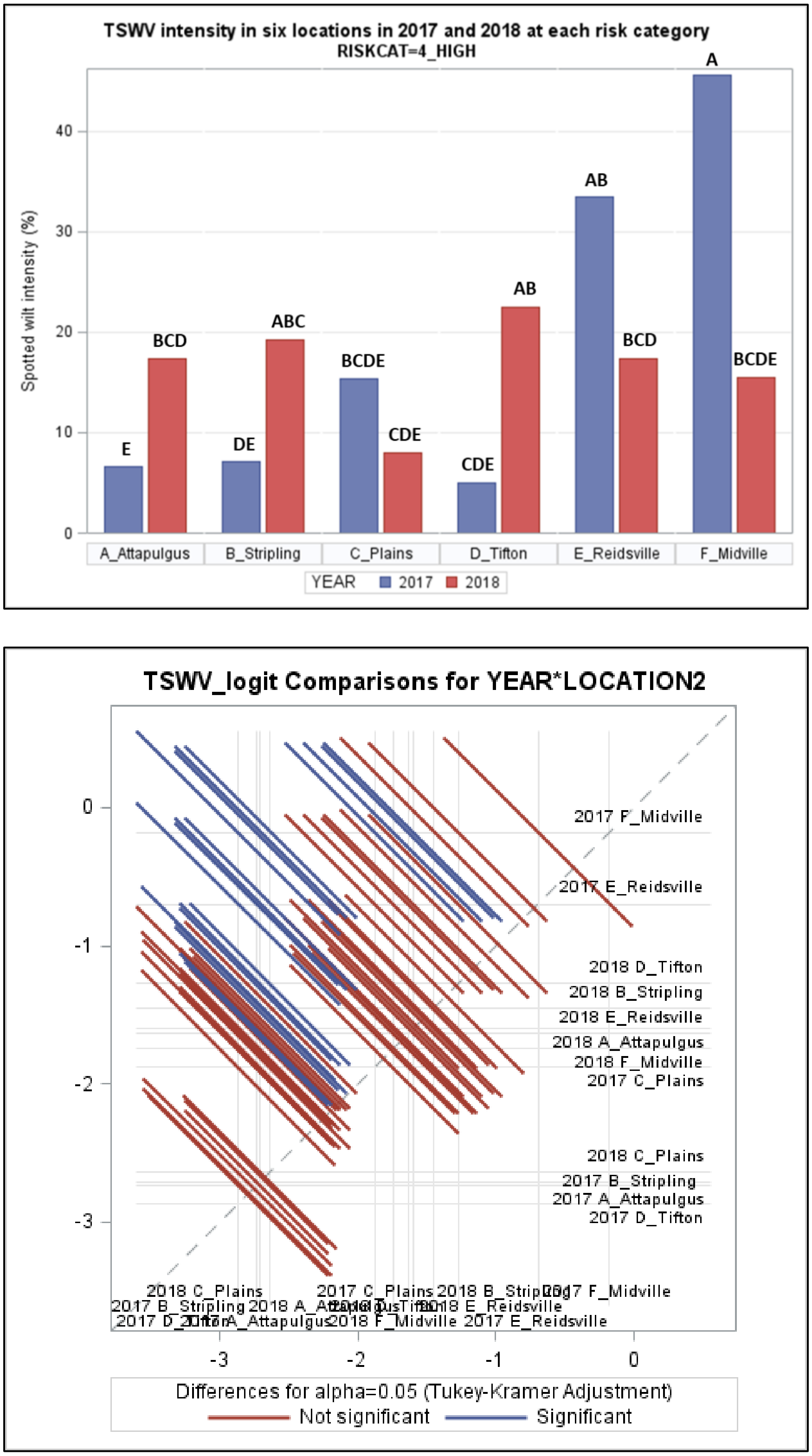


Figure 2.7. Variation of final spotted wilt intensity at “high” risk category between six geographic locations in two years. *NOTE: Tukey grouping is based on logit-transformed data.*

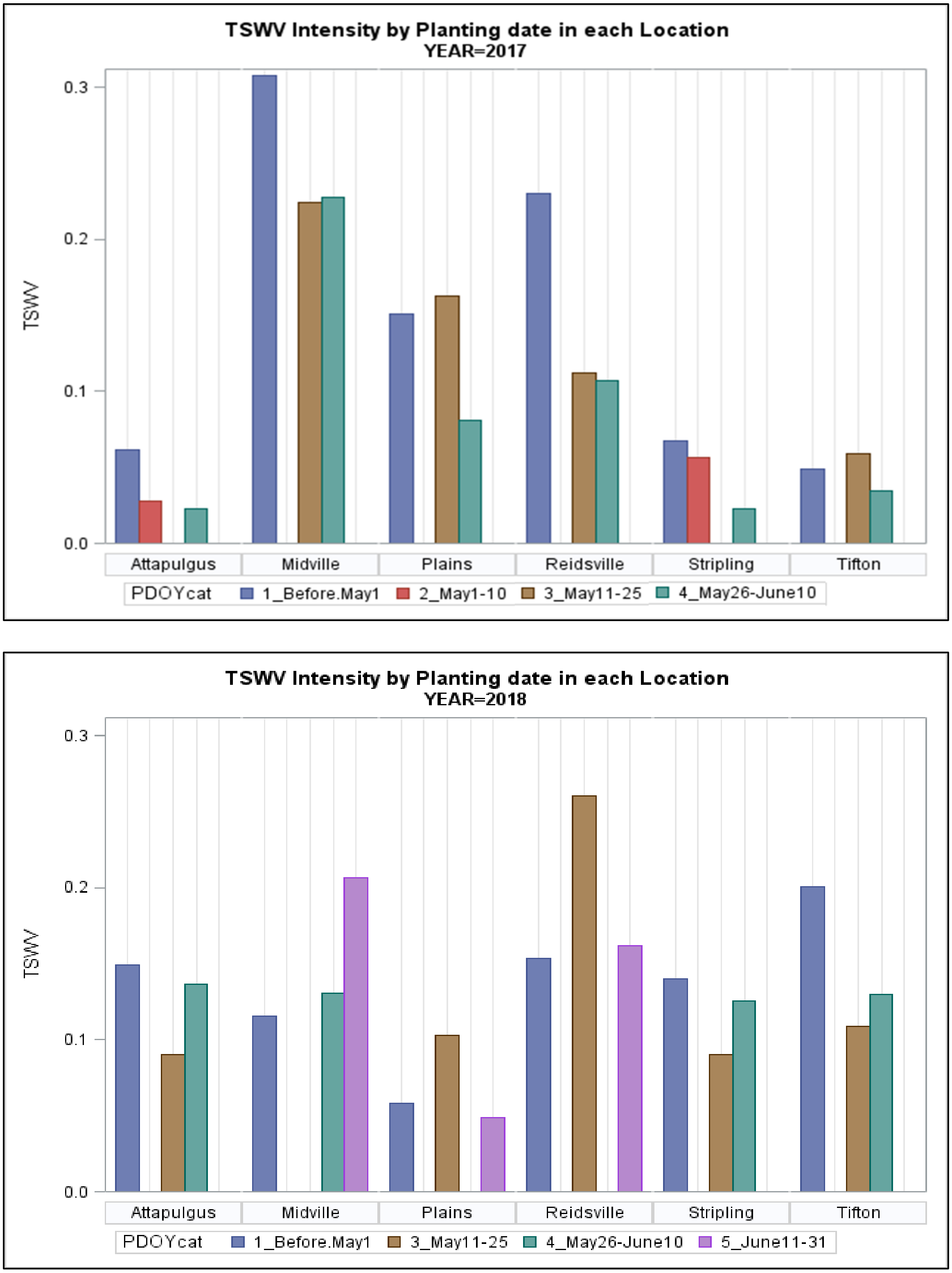


Figure 2.8. Mean spotted wilt intensity per planting date in six locations in 2017 and 2018.

Table 2.1. Standardized area under disease progress curves and apparent infection rates in different levels of risk of spotted wilt disease based on Peanut Rx in Attapulgus, Georgia.

Planting period	**Variety**	**Phorate Insecticide**	**Treatment Number**	**Peanut Rx TSWV points**		**sAUDPC**		**Apparent infection rate**	
				2017[1]	**2018[2]**	**2017[1]**	**2018[2]**	**2017[1]**	**2018[2]**
Early	Georgia-06G	Thimet® 20-G	1	95	80	2.71 abc	5.54 a	0.04a	0.10bc*
Middle	Georgia-06G	Thimet® 20-G	2	65	50	1.30 c	2.14 a	0.03a	0.05c
Late	Georgia-06G	Thimet® 20-G	3	55	60	1.44 c	3.91 a	0.02a	0.15abc
Early	Georgia-06G	None	4	105	90	3.18 abc	5.18 a	0.05a	0.08bc
Middle	Georgia-06G	None	5	75	60	1.56 c	4.39 a	0.03a	0.10bc
Late	Georgia-06G	None	6	65	70	1.78 bc	5.79 a	0.02a	0.19abc
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	7	95	90	4.63 ab	11.25 a	0.07a	0.22abc
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	8	80	60	2.46 abc	5.73 a	0.04a	0.14abc
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	9	70	70	2.44 abc	7.80 a	0.07a	0.27ab
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	10	120	100	5.46 a	10.63 a	0.07a	0.18abc
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	11	90	75	2.18 bc	5.28 a	0.04a	0.14abc
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	12	80	80	1.55 c	9.83 a	0.02a	0.33a*

[1] Peanut variety FloRun™ '157' was used. [2] Peanut variety TUFRunner™ '511'was used. * The sAUDPC or the apparent infection rate was significantly different with other treatments havinf the same TSWV risk point values

Table 2.2. Standardized area under disease progress curves and apparent infection rates in different levels of risk of spotted wilt disease based on Peanut Rx in Stripling, Georgia.

Planting period	Variety	Phorate Insecticide	Treatment Number	Peanut Rx TSWV points		sAUDPC		Apparent infection rate	
				2017[1]	2018[2]	2017[1]	2018[2]	2017[1]	2018[2]
Early	Georgia-06G	Thimet® 20-G	1	95	80	2.41 abc	3.96 ab	0.05ab	0.08b*
Middle	Georgia-06G	Thimet® 20-G	2	65	50	2.72 abc	5.18 ab	0.05ab	0.15b
Late	Georgia-06G	Thimet® 20-G	3	60	60	2.17 abc	2.59 b	0.04ab	0.10b
Early	Georgia-06G	None	4	90	90	2.57 abc	5.15 ab	0.05ab	0.09b
Middle	Georgia-06G	None	5	75	60	4.11 abc	4.14 ab	0.08ab	0.09b
Late	Georgia-06G	None	6	70	70	1.94 bc	5.00 ab	0.03ab	0.20ab
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	7	95	90	5.57 ab	10.27 ab	0.11a	0.20ab
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	8	80	65	2.96 abc	7.14 ab	0.06ab	0.15ab
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	9	75	70	1.24 c	6.96 ab	0.03b	0.23ab
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	10	105	100	4.86 abc	10.74 a	0.09ab	0.19ab
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	11	90	75	5.81 a	8.61 ab	0.10ab	0.22ab
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	12	85	80	2.52 abc	8.97 ab	0.05ab	0.30a*

[1] Peanut variety FloRun™ '157' was used. [2] Peanut variety TUFRunner™ '511'was used. * The sAUDPC or the apparent infection rate was significantly different with other treatments havinf the same TSWV risk point values

Table 2.3. Standardized area under disease progress curves and apparent infection rates in different levels of risk of spotted wilt disease based on Peanut Rx in Tifton, Georgia.

Planting period	**Variety**	**Phorate Insecticide**	**Treatment Number**	**Peanut Rx TSWV points**		**sAUDPC**		**Apparent infection rate**	
				2017[1]	**2018[2]**	**2017[1]**	**2018[2]**	**2017[1]**	**2018[2]**
Early	Georgia-06G	Thimet® 20-G	1	80	80	5.58 a	5.47 b	0.08ab	0.14b
Middle	Georgia-06G	Thimet® 20-G	2	55	55	3.42 a	5.10 b	0.06ab	0.11b
Late	Georgia-06G	Thimet® 20-G	3	60	60	2.34 a	4.74 b	0.05ab	0.20ab
Early	Georgia-06G	None	4	90	90	4.84 a	6.16 b*	0.06ab	0.14b*
Middle	Georgia-06G	None	5	65	65	4.73 a	3.41 b	0.07ab	0.09b
Late	Georgia-06G	None	6	70	70	2.04 a	3.65 b	0.03b	0.16b
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	7	95	90	4.52 a	15.69 a*	0.06ab	0.39a*
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	8	70	65	6.37 a	7.75 b	0.10ab	0.21ab
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	9	75	70	3.39 a	8.95 ab	0.08ab	0.28ab
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	10	105	100	5.08 a	10.90 ab	0.08ab	0.27ab
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	11	80	75	6.44 a	9.25 ab	0.12a	0.19ab
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	12	85	80	2.90 a	5.96 b	0.07ab	0.21ab

[1] Peanut variety FloRun™ '157' was used. [2] Peanut variety TUFRunner™ '511'was used. * The sAUDPC or the apparent infection rate was significantly different with other treatments havinf the same TSWV risk point values

Table 2.4. Standardized area under disease progress curves and apparent infection rates in different levels of risk of spotted wilt disease based on Peanut Rx in Plains, Georgia.

Planting period	Variety	Phorate Insecticide	Treatment Number	Peanut Rx TSWV points		sAUDPC		Apparent infection rate	
				2017[1]	2018[2]	2017[1]	2018[2]	2017[1]	2018[2]
Early	Georgia-06G	Thimet® 20-G	1	80	80	7.67 abc	1.88 bc	0.16ab	0.05c*
Middle	Georgia-06G	Thimet® 20-G	2	55	55	7.96 abc	3.04 abc	0.12ab	0.08abc
Late	Georgia-06G	Thimet® 20-G	3	60	65	4.82 bc	1.81 bc	0.10b	0.07bc
Early	Georgia-06G	None	4	90	90	5.05 bc	1.18 c*	0.09b	0.04c
Middle	Georgia-06G	None	5	65	65	5.91 abc	1.96 abc	0.08b	0.05c
Late	Georgia-06G	None	6	65	75	3.88 c	2.14 abc	0.07b	0.08abc
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	7	95	105	11.32 ab	5.41 abc	0.24ab	0.10abc
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	8	70	80	12.55 a	7.97 ab	0.28a	0.21ab*
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	9	70	75	6.30 abc	2.37 abc	0.17ab	0.08abc
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	10	105	100	9.95 abc	4.22 abc	0.19ab	0.09abc
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	11	80	90	10.73 abc	8.30 a*	0.18ab	0.23a
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	12	80	85	7.27 abc	2.94 abc	0.18ab	0.10abc

[1] Peanut variety FloRun™ '157' was used. [2] Peanut variety TUFRunner™ '511'was used. * The sAUDPC or the apparent infection rate was significantly different with other treatments havinf the same TSWV risk point values

Table 2.5. Standardized area under disease progress curves and apparent infection rates in different levels of risk of spotted wilt disease based on Peanut Rx in Reidsville, Georgia.

Planting period	Variety	Phorate Insecticide	Treatment Number	Peanut Rx TSWV points		sAUDPC		Apparent infection rate	
				2017[1]	2018[2]	2017[1]	2018[2]	2017[1]	2018[2]
Early	Georgia-06G	Thimet® 20-G	1	80	80	11.94 cd	5.88 b	0.11a	0.15c
Middle	Georgia-06G	Thimet® 20-G	2	55	55	4.80 d	9.59 b	0.09a	0.29abc
Late	Georgia-06G	Thimet® 20-G	3	60	65	6.09 d	6.87 b	0.08a	0.31abc
Early	Georgia-06G	None	4	90	90	15.15 bc	9.13 b	0.09a	0.15c
Middle	Georgia-06G	None	5	65	65	7.31 cd	8.54 b	0.09a	0.30abc
Late	Georgia-06G	None	6	70	75	9.67 cd	6.69 b*	0.12a	0.27abc
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	7	95	90	21.54 b	7.79 b	0.24a	0.22bc
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	8	70	65	9.26 cd	16.28 ab	0.12a	0.45abc
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	9	75	75	8.14 cd	10.90 ab*	0.13a	0.38abc
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	10	105	100	31.99 a	8.95 b	0.20a	0.24abc
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	11	80	75	13.02 bcd	22.53 a*	0.18a	0.59a
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	12	85	85	7.71 cd	12.31 ab	0.12a	0.51ab

[1] Peanut variety FloRun™ '157' was used. [2] Peanut variety TUFRunner™ '511'was used. * The sAUDPC or the apparent infection rate was significantly different with other treatments having the same TSWV risk point values

Table 2.6. Standardized area under disease progress curves and apparent infection rates in different levels of risk of spotted wilt disease based on Peanut Rx in Midville, Georgia.

Planting period	Variety	Phorate Insecticide	Treatment Number	Peanut Rx TSWV points		sAUDPC		Apparent infection rate	
				2017[1]	2018[2]	2017[1]	2018[2]	2017[1]	2018[2]
Early	Georgia-06G	Thimet® 20-G	1	75	75	14.88 cde	2.28 e*	0.14d*	0.08d*
Middle	Georgia-06G	Thimet® 20-G	2	50	55	9.03 e	3.46 cde	0.14d	0.13cd
Late	Georgia-06G	Thimet® 20-G	3	55	60	7.43 e	4.80 bcde	0.12d	0.22bcd
Early	Georgia-06G	None	4	90	85	23.48 abcd	2.92 de	0.18cd	0.07d*
Middle	Georgia-06G	None	5	65	65	14.34 cde	1.80 e	0.19cd	0.07d
Late	Georgia-06G	None	6	65	70	11.74 de	7.24 abcde	0.22bcd	0.25bcd
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	7	90	90	29.28 ab	7.42 abcde	0.33abc	0.23bcd
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	8	70	70	14.47 cde	12.22 ab	0.20cd*	0.41ab
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	Thimet® 20-G	9	70	75	21.96 bcd	14.15 a*	0.47a*	0.52a*
Early	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	10	100	100	35.55 a	5.50 bcde	0.41a	0.17cd
Middle	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	11	75	80	26.02 abc	11.47 abc	0.40ab*	0.35abc
Late	FloRun™ '157'[1] TUFRunner™ '511'[2]	None	12	80	85	16.62 cde	10.97 abcd	0.34abc	0.41ab*

[1] Peanut variety FloRun™ '157' was used. [2] Peanut variety TUFRunner™ '511'was used. * The sAUDPC or the apparent infection rate was significantly different with other treatments having the same TSWV risk point values

Table 2.7. Table of probability values and Pearson's correlation coefficients (r) values from correlation analysis between final spotted wilt (SW) intensities and standardized area under disease progress curves in 6 locations in 2017 and 2018

LOCATION	**YEAR**	**Final SW vs sAUDPC**	
		p-value	*r*-value
Attapulgus	2017	<.0001	0.8719
Stripling	2017	<.0001	0.9050
Plains	2017	<.0001	0.9170
Tifton	2017	<.0001	0.8195
Reidsville	2017	<.0001	0.9424
Midville	2017	<.0001	0.9005
Attapulgus	2018	<.0001	0.9561
Stripling	2018	<.0001	0.9216
Plains	2018	<.0001	0.9601
Tifton	2018	<.0001	0.9264
Reidsville	2018	<.0001	0.9654
Midville	2018	<.0001	0.9453

Table 2.8. ANOVA table showing effects of location, year, and risk categories on final spotted wilt intensity from PROC GLIMMIX analysis

Type III Tests of Fixed Effects			
Effect	**Num DF**	**F Value**	**Pr > F**
Year	1	27.31	<.0001
Location	5	34.94	<.0001
Year* Location	5	35.12	<.0001
Risk Category	3	36.22	<.0001
Year* Risk Category	3	1.47	0.2217
Location* Risk Category	15	0.81	0.6713
Year* Location* Risk Category	15	1.42	0.1342

Table 2.9. Variation of final spotted wilt intensities between six locations over two years in different levels of risk based on Peanut Rx

Risk Category	**Number of possible location*year combinations**	**Number of significantly different location*year combination**	**Variance (%)**
Low	66	12	12.4
Mild	66	34	20.9
Moderate	66	33	25.4
High	66	20	40.6

Table 2.10. Listing of probability values, coefficient of determination (R^2), and slope parameter from regression analysis between yield (Kg/Ha) and percent spotted wilt (SW) intensity

LOCATION	**YEAR**	**Yield vs. Percent SW**		
		Pr > F	R^2	SLOPE
Attapulgus	2017	0.004	0.1664	-144.079
Stripling	2017	0.0053	0.1572	-192.570
Plains	2017	0.5921	0.0063	17.960
Tifton	2017	0.8996	0.0004	-9.776
Reidsville	2017	0.8966	0.0004	-3.283
Midville	2017	0.0006	0.2284	-37.215
Attapulgus	2018	0.0276	0.1012	-67.978
Stripling	2018	0.5816	0.0073	13.651
Plains	2018	0.0216	0.1095	-64.569
Tifton	2018	0.0987	0.0582	32.652
Reidsville	2018	0.1269	0.0499	-22.812
Midville	2018	<.0001	0.3103	-51.657

Table 2.11. Listing of probability values, coefficient of determination (R^2), and slope parameter from regression analysis between yield (Kg/Ha) and Peanut Rx risk points

LOCATION	**YEAR**	**Yield vs. Peanut Rx Risk points**		
		Pr > F	R^2	SLOPE
Attapulgus	2017	0.0006	0.2260	-24.555
Stripling	2017	<.0001	0.4908	-81.670
Plains	2017	0.572	0.0070	-10.655
Tifton	2017	0.0158	0.1201	-42.837
Reidsville	2017	0.6514	0.0045	-7.079
Midville	2017	0.8451	0.0008	-1.964
Attapulgus	2018	<.0001	0.3493	-66.399
Stripling	2018	0.0002	0.2878	43.208
Plains	2018	0.9546	0.0001	0.700
Tifton	2018	0.6997	0.0033	4.822
Reidsville	2018	0.2651	0.0269	14.126
Midville	2018	0.0004	0.2441	-35.831

Table 2.12. Table of treatments and risk categories based on Peanut Rx and based on the redefined categories. The TSWV risk points were based from actual risk point values in on-station field trial in Attapulgus in 2018.

Treatment	Variety	Planting date	Insecticide	Total points	Peanut Rx Category	Redefined Category
1	Georgia-06G	April 25	Thimet	80	Moderate	Moderate
2	Georgia-06G	May 21	Thimet	50	Low	Low
3	Georgia-06G	June 7	Thimet	60	Low	Low
4	Georgia-06G	April 25	No Thimet	90	Moderate	Moderate
5	Georgia-06G	May 21	No Thimet	60	Low	Low
6	Georgia-06G	June 7	No Thimet	70	Moderate	Mild
7	TUFRunner ™ '511'	April 25	Thimet	90	Moderate	Moderate
8	TUFRunner ™ '511'	May 21	Thimet	60	Low	Low
9	TUFRunner ™ '511'	June 7	Thimet	70	Moderate	Mild
10	TUFRunner ™ '511'	April 25	No Thimet	100	Moderate	High
11	TUFRunner ™ '511'	May 21	No Thimet	75	Moderate	Mild
12	TUFRunner ™ '511'	June 7	No Thimet	80	Moderate	Moderate

Table 2.13. List of probability values, R^2- values, and slope parameter from result of regression between Peanut Rx risk point values with sAUDPC, apparent infection rate, and final spotted wilt intensity (%).

VARIABLES	*p*-value	R^2	SLOPE
Risk points vs AUDPC	<.0001	0.0516	0.1039
Risk points vs Infection Rate	0.1268	0.0041	0.0006
Risk points vs Final Spotted wilt intensity	<.0001	0.0495	0.1559

Table 2.14. Listing of probability values, coefficient of determination (R^2), and slope parameter from regression analysis between sAUDPC and yield (Kg/Ha)

LOCATION	YEAR	YIELD (Kg/Ha) vs sAUDPC		
		Pr > F	R2	SLOPE
Attapulgus	2017	0.0023	0.1848	-0.0007
Stripling	2017	0.0391	0.0893	-0.0003
Plains	2017	0.1902	0.037	0.0004
Tifton	2017	0.8759	0.0005	0.0000
Reidsville	2017	0.726	0.0027	-0.0003
Midville	2017	0.0515	0.0799	-0.0028
Attapulgus	2018	0.0088	0.1398	-0.0010
Stripling	2018	0.7007	0.0034	0.0002
Plains	2018	0.0634	0.0729	-0.0007
Tifton	2018	0.0405	0.0881	0.0011
Reidsville	2018	0.1358	0.0477	-0.0012
Midville	2018	0.0003	0.2455	-0.0027

CHAPTER 3

ASSESSMENT OF PEANUT Rx AND PEANUT Rx 2.0 AS MANAGEMENT TOOLS FOR SPOTTED WILT DISEASE IN PEANUTS[1]

[1]Codod, C.B., Kemerait Jr., R.C., Culbreath, A.K., Abney, M.R., Kennedy, G.G., Chappell, T.M. To be submitted to *Plant Health Progress*

Abstract

Spotted wilt disease caused by the thrips-transmitted TSWV is managed using a preventative approach. The use of a pre-plant tool such as a risk index or a forecasting model helps growers plan their production practices in order to avoid major yield losses due to spotted wilt disease. This study was conducted to compare the pre-plant tools, Peanut Rx and Peanut Rx 2.0, to account for the variability of spotted wilt intensity across risk levels. On-station field trials were conducted at six locations in 2017 and 2018. In each on-station field trial, different levels of risk to spotted wilt were created by using two varieties, three planting dates, and treatment with and without phorate insecticide. Peanut Rx 2.0 was compared with Peanut Rx in accounting for the variability in spotted wilt intensity at each of six field trials in 2017 and in 2018 through a regression analysis. Based on R^2 values, *p*-values, and slope parameters, Peanut Rx 2.0 was not better than Peanut Rx. The R^2 values were always higher, the *p*-values were significant in most field trials, and the slope parameter was always positive based on regression of spotted wilt intensities to the total Peanut Rx risk points as compared to the results of regression analysis using predictions from Peanut Rx 2.0. A second objective in this study was to revalidate the Peanut Rx risk index. This was done based on commercial field surveys in 2017 and 2018. Results showed that growers were selecting production practices that resulted in a low risk of spotted wilt disease. The fields where elevated spotted wilt intensities were observed were among the fields with higher levels of risk based on Peanut Rx. Therefore, Peanut Rx continues to be a valuable tool that helps growers to assess and reduce their risk of loss to spotted wilt disease.

Introduction

Spotted wilt disease caused by the thrips-transmitted *Tomato spotted wilt virus* (TSWV) is an important problem in peanut (*Arachis hypogaea L*.) production. This disease is difficult to manage and the thrips vectors, *Frankliniella fusca* and *F. occidentalis*, are present in the peanut producing areas of Georgia (Culbreath et al., 2003). Unlike fungal diseases, where fungicides can be applied to manage the diseases, there are no virucides available in the market that can be used to manage diseases such as spotted wilt (Waziri, 2015). For this reason, a preventive disease management approach is necessary. A pre-plant tool such as a risk index or forecasting model can be useful to help growers plan their production practices in order to prevent severe spotted wilt epidemics and major yield losses.

In peanuts, management of spotted wilt disease depends on a preventive approach (Kemerait et al., 2013). After the crop is planted, there is no known control measure that can be applied to manage the disease. Research studies conducted since 1990 have identified a number of factors affecting the severity of spotted wilt disease in peanuts. These factors include choice of cultivar, planting date, phorate (Thimet® 20-G) insecticide usage, tillage type, row pattern, final plant stand, and use Classic® herbicide. Combinations of these production practices influence the risk of losses to TSWV in a peanut crop. While some factors were found to be more important than others, management using a single factor could not provide adequate control, especially where severe epidemics occurred (Culbreath et al., 2003; Brown et al., 2005).

To help farmers assess the relative level of risk associated with individual peanut production scenarios, the Spotted Wilt Risk Index for peanuts was developed in 1996

(Brown, 1996). The risk index was developed through an ‘expert system’. Points were assigned to each production practice found to affect risk of spotted wilt disease depending on their relative effect on disease severity as observed in field studies conducted in various locations in the Southeast United States. The risk points assigned for each production practice are then summed to get an overall estimate of TSWV risk for a given field (Kemerait et al., 2017). By calculating the risk based on the production practices, the growers will have an idea of the level of exposure of their peanut crop to spotted wilt disease. With this information, they can avoid combinations of production practices that are conducive to yield loss.

Due to the dynamic nature of spotted wilt epidemics, the risk index has been and will continue to be refined annually (Brown et al., 2005). From the time of first release in 1996, continuous research and annual refinements have resulted in the development of Peanut Rx, which also includes risk indices for leaf spot and white mold (southern stem rot) (Kemerait et al., 2018). As the spotted wilt disease remains an important concern in peanut production, continued research to improve the risk index is being conducted to mitigate further yield losses.

In 2010, the importance of location effects and performance of cultivars with different levels of field resistance on the severity of spotted wilt disease were reported by Culbreath et al. (2010). In this study, lower levels of spotted wilt disease were recorded in Gainesville, Florida than were observed in Marianna, Florida and Tifton, Georgia. In another study, it was found that the incidences of spotted wilt in peanuts observed in multiple trials conducted in Georgia and Florida were lower during La Niña years than in El Niño or Neutral years (Olatinwo et al., 2010). La Niña and El Niño refer to the periodic cooling (La Niña) and warming (El Niño) in sea-surface temperatures across the central and east-central equatorial Pacific (Olatinwo et al., 2010; Twine et al., 2005). The period in the cycle when neither El Niño nor La Niña is present was referred to as the Neutral phase. The sea-surface temperatures were linked to the natural phenomenon called El Niño – Southern Oscillation (ENSO) that was shown to correlate with temperature and precipitation anomalies and the frequency of extreme weather events in the United States (Gershunov, 1998; Olatinwo et al., 2010; Twine et al., 2005; Latif and Keenlyside, 2009). Additionally, a higher probability of spotted wilt disease was observed when the number of rain events during March was greater than or equal to 10 if the peanuts were planted before May 11 or after June 5. The total evapotranspiration in April (>127 mm) and the average daily minimum temperature in March (>6.8°C) similarly increased the risk of spotted wilt (Olatinwo et al., 2008).

Weather conditions prior to and during the growing season were also critical for population dynamics and dispersal of the thrips. Late winter and early spring temperatures, rainfall amounts, and number of days with rain were found to explain the variation in the numbers of *F. fusca* captured in aerial traps at 21 sites over a 5-year period during the period of January through May (Morsello et al., 2008). These studies have shown that the weather factors can influence the severity of spotted wilt in a given location and year. When differences in weather conditions occur, the severity of spotted wilt could be variable between locations. Variability in spotted wilt intensity between locations or between years is not accounted for in the Peanut Rx risk index.

A forecasting tool, known as the ‘Thrips and TSWV Risk Forecasting Tool’ (TTRF), was developed for the management of spotted wilt disease on tobacco in North

Carolina. This forecasting model is used to predict the incidence of TSWV as well as the magnitude of population and dispersal pattern of thrips in tobacco fields. These predictions are based upon weather factors. The factors included in the TTRF tool are estimates of prior-year thrips population (Morsello et al., 2010), March precipitation, and average winter temperatures. This model was able to account for up to 89.9% of the variability in spotted wilt incidence in tobacco (Chappell et al., 2013). Outputs from the TTRF tool are distinctly different from those of the Peanut Rx risk index, and account for disease pressure (the amount of inoculum in the environment) through the estimation of the magnitude of thrips population.

A continuing effort to provide better tools for managing spotted wilt disease on peanuts lead to the development of a new a tool that accounts for both exposure (level of risk) and disease pressure. This was done through the combination of Peanut Rx and the TSWV and Thrips Risk Forecasting (TTRF) tool, which lead to the development of 'Peanut Rx 2.0' (Williams, 2015). Peanut Rx provides information on the level of exposure to spotted wilt disease based on production practices and inputs, but this method does not reflect vector population dynamics and disease pressure in each geographic location. Through the addition of the prior-year thrips population estimates, which were calculated by the TTRF tool, the disease pressure was accounted for (Williams, 2015). Independent variables from Peanut Rx and TTRF were integrated by regression analysis to develop Peanut Rx 2.0. The best-fit model accounted for cultivar, planting date, at-plant insecticide, row pattern, tillage system, March precipitation, average winter temperature, and the estimated magnitude of the prior-year thrips population. Peanut Rx 2.0 accounted for 26.24% of the variability in spotted wilt incidence in peanut fields that were included in the study (Williams, 2015). This work provided a framework of a forecasting model that accounted for the host, vector, pathogen, and environment in predicting the intensity of spotted wilt in the upcoming season.

Further work was done in 2016 (Chappell, unpublished). This resulted in a simplified Peanut Rx 2.0 model where March precipitation and average winter temperature were removed and specific parameter estimates were calculated for each variety, row pattern, tillage, and insecticide (Table 3.1). With the development of Peanut Rx 2.0, the approximate intensity of spotted wilt could be predicted for each peanut field based on production practices and estimated prior-year-thrips population. However, this model needed further assessment, testing and comparison to Peanut Rx, the current spotted wilt management tool, before it would be appropriate to release it to growers.

The current study was conducted to compare Peanut Rx and Peanut Rx 2.0 as to their ability to account for the variability in spotted wilt intensity across different levels of risk. A second objective in this study was to re-validate Peanut Rx as a tool useful for peanut farmers, accounting for the addition of new varieties with better resistance to TSWV since the initial release of the Tomato Spotted Wilt Risk Index. The results of this study are to confirm that Peanut Rx remains an appropriate tool for assessing the risk of spotted wilt and whether Peanut Rx 2.0 will provide disease management benefits to growers beyond those of Peanut Rx.

Materials and Methods

*On-station field trial*s

On-station field trials were conducted in six locations across Georgia in 2017 and 2018. The field trials were established at six research stations of the University of Georgia, which included the Attapulgus Research and Education Center (Attapulgus), C.M. Stripling Irrigation Research Park (Stripling), Southwest Georgia Research and Education Center (Plains), Black Shank Farm at the Coastal Plain Experiment Station (Tifton), Southeast Georgia Research and Education Center (Midville), and Vidalia Onion and Vegetable Research Center (Reidsville).

The field trials were established using a split-split plot design. The whole-plot treatments consisted of three planting dates, i.e., early, middle, and late. The sub-plot treatments included two varieties of peanut. 'Georgia -06G' and FloRunTM '157' were planted in 2017, and 'Georgia -06G' and TUFRunnerTM '511' were used in 2018. The sub-sub-plots were treatment with or without phorate (Thimet® 20-G) insecticide at 5.6 Kg/Ha. Combinations of these treatments created twelve different levels of risk to spotted wilt disease based upon Peanut Rx. The same set of treatments was used in each of the six field trials. Differences in final plant stand also contributed to the variation of total Peanut Rx risk points.

The intensity of spotted wilt was assessed on a biweekly schedule using the "hit-stick method" as described by Culbreath et al. (1997). This was done by counting the number of one-foot sections of a row that contained at least one infected peanut plant within a row of peanuts. The total number of "hits" was calculated for each plot. Infected plants were determined based on foliar symptomatology. Plants showing a combination of symptoms such as ring spots on leaflets, mottling, chlorotic and dwarfed leaflets, and stunted plants were considered infected. In isolated cases where only chlorotic ring spots were observed on a few leaflets, severity was measured as a "half-hit". The total number of hits was then divided by the row length in order to get the proportion of spotted wilt severity. Skips (missing plants within a plot) due to seedling mortality from other diseases, planter equipment failure, and damage from pivot irrigation tracks were discounted from the total row length.

Peanut Rx risk

The risk to spotted wilt disease was calculated based on combination of production practices. To calculate the risk, the spotted wilt points assigned to the variety (5- 30 points), planting date (5- 30 points), final plant stand per foot (5- 25 points), at-plant insecticide (5- 15 points), row pattern (5 -10 points), tillage (5- 15 points), and Classic® herbicide application (0- 5 points) were taken from the 2018 version of Peanut Rx risk index (Kemerait et al., 2018).

Peanut Rx 2.0 predictions of spotted wilt intensity

The intensity of spotted wilt was predicted using Peanut Rx 2.0. The parameter estimates that were calculated for each production practice and predicted prior-year-thrips were used to predict spotted wilt intensity as shown in Table 3.1. Specific parameter estimates have been calculated for each variety, row pattern, tillage type, and insecticide (Table 3.1). For planting date, the Julian day-of-year was taken and then multiplied with the parameter estimate. Plant population and application of Classic® herbicide were not included in Peanut Rx 2.0. In addition to production practices, the prior-year-thrips estimates from the TTRF tool were also used in predicting spotted wilt intensity. The thrips estimates were log-transformed and then multiplied with the parameter estimate. The MS Excel program was used to calculate the predicted spotted wilt intensity for each location. In the spreadsheet, formulas were entered such that if a specific production practice was entered then the corresponding parameter estimate would be used in predicting spotted wilt. The logit-value of predicted spotted wilt intensity was then calculated using the following formula:

Logit (TSWV) = (variety PE) + (row pattern PE) + (tillage type PE) + (PDOY*PE) + (insecticide PE) + {[log (PYT)]*PE} – 3.1661

where PE is the parameter estimate, PDOY is the planting day-of-year based on Julian day calendar, and PYT is the prior-year-thrips estimate.

Data analysis for comparison of Peanut Rx and Peanut Rx 2.0

A simple linear regression between the logit-transformed spotted wilt intensities and the total risk points based on Peanut Rx was conducted per location in 2017 and in 2018. This was done using the regression procedure (PROC REG) in SAS 9.4 software.

For Peanut Rx 2.0, the logit-transformed spotted wilt intensities were regressed to the predicted spotted wilt intensity (logit value) from Peanut Rx 2.0 per location in 2017 and 2018. The *p*-values, R^2 values, and slope parameters were compared between Peanut Rx and Peanut Rx 2.0.

Growers' field survey

A statewide survey was conducted in the 2017 and 2018 cropping seasons to determine growers' practices and to assess spotted wilt intensity in peanut fields across the peanut production region of Georgia. These fields were selected based on variability in production practices with assistance from county agents. In 2017, up to 4 fields were surveyed in each county. A total of 73 fields from 20 counties were surveyed in 2017. These counties included Webster, Miller, Tattnall, Irwin, Turner, Bulloch, Screven, Dooly, Randolph, Decatur, Jeff Davis, Crisp, Cook, Brooks, Peirce, Wayne, Bleckley, Jenkins, Burke, and Laurens. In 2018, 83 peanut fields in 21 counties were surveyed to include Webster, Miller, Grady, Ben Hill, Tattnall, Irwin, Bulloch, Screven, Dooly, Randolph, Jeff Davis, Crisp, Brooks, Peirce, Bleckley, Jenkins, Burke, Laurens, Worth, Appling, and Grady. Two to six fields per county were surveyed in 2018.

The information needed to calculate the Peanut Rx risk for Tomato spotted wilt, such as planting date, variety, phorate (Thimet® 20-G) application, and chlorimuron (Classic®) herbicide usage, was gathered from growers with assistance from the county agents. The type of tillage, row pattern and plant population were recorded during the actual field visits.

In each field, four 15.24 m plots were arbitrarily established within each field and then flagged for repeated ratings. Areas in the field exhibiting nematode infestation, flooded conditions, weedy zones, and areas beyond irrigation, were avoided as such would interfere with spotted wilt assessment.

The intensity of spotted wilt was measured using the "hit-stick" method described by Culbreath et al. (1997). The proportion of infected plots along a row of peanuts were measured using a hit-stick. Four plots were assessed in each field. Two rows per plot were rated for spotted wilt severity in 2017 making a total of 30.48 m row length per plot. In 2018 four rows per plot were assessed thus the total row length per plot was 60.96 m. Skips or missing plants within a plot due to seedling mortality from other diseases, planter equipment failure, and damage from pivot irrigation tracks were discounted from the total row length.

Final plant populations were counted during visits to the growers' fields. This was done by counting the number of individual plants in a 0.91 m length of row of peanuts. The canopy was opened to expose the main stem and then a yardstick was placed horizontally in the row of peanut plants. Next, the total number of main stems was counted per 0.91 m for a single or for twin rows. If the peanut plants were already inverted during at the time of the final rating, stand counts were taken by placing the yardstick along the row of peanuts and then counting the number of taproots per 0.91 m. The total number of peanut plants per 0.91 m was divided by 3 to calculate the final stand per foot of row as such is the assessment in Peanut Rx.

Data analysis for revalidation of Peanut Rx

The spotted wilt intensities observed from on-station field trials and commercial field surveys were used in revalidation of Peanut Rx. To demonstrate the relationship between risk points and spotted wilt intensity, a scatter plot with a trend line was produced showing the actual percent spotted wilt intensity on the y-axis and Peanut Rx risk point values on the x-axis. This was done using PROC GPLOT in SAS 9.4 software. The slope of the trend line was evaluated as to being positive or negative.

The production practices in the commercial peanut fields that were surveyed were recorded. This was to confirm how growers are protecting their peanut crops against spotted wilt disease and to calculate the risk based on Peanut Rx. The percentage of fields using each production practice was calculated.

Results

Regression of spotted wilt intensity with Peanut Rx risk values and predicted spotted wilt intensity from Peanut Rx 2.0

The linear relationship between spotted wilt intensities and Peanut Rx risk points versus Peanut Rx 2.0 predictions were compared. Based on the probability (p) values, the total risk points from Peanut Rx had a significant positive linear relationship with spotted wilt intensities observed in five out of six trials (Table 3.2; Figure 3.1A) in 2017. In comparison, Peanut Rx 2.0 predictions had a significant positive linear relationship with spotted wilt intensities in all six trials in the same year (Table 3.3; Figure 3.2A). In 2018, a significant positive linear relationship between spotted wilt intensities and Peanut Rx risk points was observed in five out of six trials (Figure 3.1B). In contrast, the regression between observed and predicted spotted wilt intensity based upon Peanut Rx 2.0 did not have a significant linear relationship in any trials in 2018 (Figure 3.2B).

Peanut Rx and Peanut Rx 2.0 were also compared based on the R^2 values from the regression analysis. The R^2 values from regression analysis with Peanut Rx were always greater than those from Peanut Rx 2.0. Peanut Rx risk values accounted for up to 50.11% variation in spotted wilt intensity in Reidsville in 2017 (Table 3.2) while Peanut Rx 2.0 accounted for up to 43.55% variation in spotted wilt intensity at the same location and year (Table 3.3). In 2018, the summed risk points based on Peanut Rx accounted for up to 29.69% variation in spotted wilt intensity in Stripling. In comparison, the predicted spotted wilt intensities from Peanut Rx 2.0 accounted for up to 5.45% variation in spotted wilt intensity in Tifton.

The slope of the trend line between observed and predicted spotted wilt intensity was also calculated. In 2017 and 2018, the slope of the trend lines from the regression of spotted wilt intensities observed at six locations and total Peanut Rx risk points were positive. While there was a positive slope between observed and predicted spotted wilt intensities based on Peanut Rx 2.0 from all six locations in 2017 a negative slope was observed at Midville, in 2018.

Table 3.4 demonstrates an example of observed versus predicted spotted wilt intensities based on Peanut Rx 2.0. In cases where the observed spotted wilt intensities were low, the predictions from Peanut Rx 2.0 were close to observed values. However, Peanut Rx 2.0 under-predicted values in cases where higher spotted wilt intensities were observed.

Revalidation of Peanut Rx risk index in commercial fields

In 2017 and 2018, 73 and 83 commercial fields were surveyed across the peanut production region of Georgia, respectively. ‘Georgia-06G’ was grown in 63.01 and 74.7% of the fields surveyed in 2017 and 2018, respectively (Table 3.5). The rest of the fields that were surveyed in both years were planted with newer varieties such as ‘Georgia- 09B’, ‘TUFRunner^{TM} 297’, ‘FloRun 107’, ‘FloRun^{TM} 157’, ‘Georgia-16HO’, ‘Georgia Green’, ‘TifNV-HiOL’, ‘Tifguard’, ‘Georgia 12Y’, ‘TUFRunner^{TM} 511’, ‘Georgia - 14N’ and ‘Georgia -13M’ (Figure 3.4).

The majority of the fields (34%) were planted from May 11 to 25 in 2017 (Figure 3.5). In 2018 the majority of the fields (33.7%) were planted between May 1 and 11. In both years, phorate was applied in the majority of the fields surveyed (54.79% in 2017 and 57.8% in 2018) as shown in Figure 3.6. Conventional tillage was practiced in more than 70% of the fields surveyed in 2017 and in 2018 (Figure 3.6). All other production practices are presented in Table 3.5 including planting dates, insecticide application, tillage type, row pattern, Classic herbicide usage, and final plant stand.

Among the commercial peanut fields that were surveyed, 60.27 and 65.06% had low level of risk based on Peanut Rx in 2017 and 2018, respectively (Figure 3.14). A positive slope was observed from trend line created from the total Peanut Rx risk values and the observed spotted wilt intensities in commercial fields surveyed in 2017 and 2018 (Figure 3.10 and 3.11). The total risk points ranged from 40 to 90 points in commercial fields surveyed in both years. In fields with the lowest risk value of 40 TSWV points, the intensity of spotted wilt was lower than five percent. Fields with an elevated intensity of spotted wilt disease were observed among the fields with the highest risk point values of 90 TSWV points in both years.

In 2017, elevated spotted wilt intensities (≥20%) were recorded from two fields in Irwin and Tattnall County (Figure 3.12, Table 3.6). In 2018, elevated spotted wilt intensities were observed in one field in Worth County and one field in Appling County (Figure 3.13, Table 3.6).

Discussion

Decision support systems (DSS) assist a decision maker by providing recommendations on certain management options and/or allowing exploration of the consequences of making different decisions (Knight, 1997). The Peanut Rx risk index is an example of a DSS that provides information about choices of production inputs and practices that affect the risk of exposure to spotted wilt disease on peanuts. As spotted wilt continues to be a concern in peanut producing areas in the southeastern United States, research continues to be conducted to improve the risk index. In a study conducted by Williams (2015) and Chappell (unpublished), Peanut Rx 2.0 was developed by combining factors accounted for in Peanut Rx and the TSWV and Thrips Risk Forecasting (TTRF) tool developed for North Carolina. The development of Peanut Rx 2.0 was an innovation in managing spotted wilt in peanuts. It provided a method of accounting for exposure to spotted wilt, through the production practices accounted for in Peanut Rx, and disease pressure, through the estimated magnitude of thrips population from the TTRF tool (Williams, 2015 and Chappell, unpublished). Peanut Rx 2.0 provided a framework for a forecasting model that takes into account the estimated population of the thrips vector, weather, and production practices also found in Peanut Rx. A primary objective in this study was to compare Peanut Rx 2.0 to the Peanut Rx risk index in accounting for the variability of spotted wilt intensity across different levels of risks in on-station field trials.

A regression analysis was conducted to compare Peanut Rx and Peanut Rx 2.0. The *p*-values from the regression analyses showed that the risk points based on Peanut Rx had a significant positive linear relationship with the observed spotted wilt in almost all field trials in 2017 and 2018. This was expected because it is known that greater risk points result in greater exposure to spotted wilt disease (Brown et al., 2005 and Kemerait et al., 2018). Hence, a greater intensity of spotted wilt was expected with greater risk point values. In comparison, while predictions from Peanut Rx 2.0 had a significant positive linear relationship with observed spotted wilt intensities in six on-station field trials in 2017, the relationships were not significant in 2018. This indicates that the predicted spotted wilt intensity from Peanut Rx 2.0 were not always statistically associated with the observed spotted wilt intensities in on-station field trials.

Further, comparison of the R^2 values showed that Peanut Rx accounted for more variation in spotted wilt intensity than did Peanut Rx 2.0 across different levels of risk to spotted wilt disease (Tables 3.2 and 3.3). This result was as expected for Peanut Rx as it is a well-developed risk index currently being used to assess the risk of spotted wilt by peanut growers. However, this result was not an expected result from Peanut Rx 2.0. It has been shown that Peanut Rx 2.0 accounted for more variation (26.24%) in spotted wilt intensity when compared to Peanut Rx (4.44%) (Williams, 2015). Chappell (unpublished) also showed that Peanut Rx 2.0 accounted for 35.9% while Peanut Rx accounted for 6.5% variation in spotted wilt incidence based from field trial data collected in south Georgia and north Florida from 2010-2014. While Peanut Rx 2.0 showed promising results based from historical data (2010-2014), the findings from this study based on current spotted wilt data (2017 and 2018) showed that Peanut Rx 2.0 was not better than Peanut Rx in accounting for the variability of spotted wilt at different risk levels. Unfortunately, many plant disease forecast models have not lived up to the expectations that they would play a major role in projecting disease outbreaks (Seem, 2001 and

Fernandes et al., 2011). But attempting to develop such a model is useful in guiding research in disease epidemiology. Predictive models can highlight deficiencies in our knowledge about a disease (Kerr and Keane, 1997). With increasing knowledge, the predictive value of a model can be improved.

Peanut Rx 2.0 was designed to predict approximate spotted wilt intensity. Therefore, if the predicted values for disease intensity were close to the observed values from the field ratings, then the trend lines from the regression analysis for all field trials should follow a single line. This was not observed in this study as shown in Figure 3.2. Results in this study showed that Peanut Rx 2.0 could closely predict spotted wilt when the observed intensity was low; however, it under-predicted in cases where elevated spotted wilt intensities were observed. This is a problem because the purpose of using a forecasting model, such as Peanut Rx 2.0 is to predict the amount of disease that will likely occur in a field under a certain set of conditions. When accurate, such predictions allow the growers to determine the best production practices to limit spotted wilt incidence. Because it was not able to accurately predict when the intensity of spotted wilt would be elevated, the Peanut Rx 2.0 model must be adjusted to make it a more functional pre-plant tool that identifies situations where the intensity of spotted wilt will be either low or high.

To understand the reason why Peanut Rx 2.0 predictions were not closer to the observed spotted wilt intensities, the factors included in the model were examined. Predictions from Peanut Rx 2.0 are based upon cultivar, planting day of the year (Julian day), row pattern, tillage type, insecticide, and prior-year-thrips estimates, as shown in Table 3.1 (Chappell, unpublished). The parameter estimates calculated for each factor were used to estimate spotted wilt intensity. Parameter estimates describe the magnitude of the contribution of an explanatory variable. A large value parameter estimates indicate that the variable strongly influences the probability of disease occurring, while a near-zero parameter estimate indicates that variable has little influence on the probability disease occurring. A positive sign indicates that the explanatory variable increases the probability of disease from occurring, while a negative sign indicates that the variable decreases the probability of disease from occurring (Park, 2013; Langner et al., 2003).

In Peanut Rx 2.0, a parameter estimate was calculated for each cultivar, tillage type, row pattern, and insecticide through the GLMSELECT procedure of the SAS software (version 9.4) during the model development (Chappell, unpublished; Williams, 2015). The Peanut Rx 2.0 was developed using data from spotted wilt trials in peanuts conducted across south Georgia and north Florida from 2010 to 2014. The same was done for each tillage type, row pattern, and insecticide. However, this procedure only provided parameter estimates for varieties included in the analysis during the model development. This procedure could be a problem when newer varieties are used such as FloRun™ '157' and TUFRunner™ '511', which were used in this study. These varieties did not have parameter estimates because data were not available during the model development. To deal with this limitation, parameter estimates for cultivars with the same risk point values ('Georgia Green' and FloRun™ '107'), based upon Peanut Rx were used to estimate spotted wilt intensity in this study. As for Peanut Rx, a risk value was assigned to a new cultivar as soon as data were available from field trials conducted by researchers. The risk value assigned to each cultivar, during the annual Peanut Rx meeting, is based on observations from multiple studies. This is an advantage of Peanut

Rx over Peanut Rx 2.0 because the risk points are easily and regularly updated. In comparison, it would require statistical expertise and greater effort to update the parameter estimates for Peanut Rx 2.0.

Another point to consider about Peanut Rx 2.0 was the integration of planting date into the model. Planting date is one factor that can have a significant impact on spotted wilt epidemics in peanut (Brown et al., 2005; Culbreath et al., 2003; Culbreath et al., 1999; Tillman et al., 2007). Results from our study were consistent with previous reports that the optimum planting dates and the magnitude of the planting date effect vary slightly from year to year, but in general, avoiding the early and late planting periods reduces the incidence and severity of spotted wilt in peanuts (Brown et al., 2005; Kemerait et al., 2018). Thus, it is important to properly account for the effect of planting date in predicting the intensity of spotted wilt disease. Further studies need to be conducted to determine what factors drive the yearly variation in the magnitude of the planting date effect in spotted wilt epidemics.

From Table 3.1, there was only one parameter estimate for planting date (-0.017994) as it was treated as an interval variable not a categorical variable as it was in Peanut Rx where different ranges or categories of planting dates had different risk-point values. Because the parameter estimate for planting date is negative, Peanut Rx 2.0 predicts lower spotted wilt intensity for late-planted peanuts and greater spotted wilt for early-planted peanuts. This was not the case for Peanut Rx. While the risk points are lowered from April to May planting dates, the risk points are increased when planting occurs after the recommended planting date, which is May 11 to 25. Peanuts planted beyond this window will have increased risk to tomato spotted wilt (Kemerait et al., 2018).

In 2017, higher spotted wilt intensities were observed in early-planted as compared to late-planted peanuts (Figure 3.3). This was consistent with the presumption from the Peanut Rx 2.0 model that there is lower risk spotted wilt in late-planted peanuts. In 2018, however, elevated intensities of spotted wilt were recorded in both early and late-planted peanuts (Figure 3.3). This may be one reason why the predicted and observed spotted wilt intensities did not have a significant positive linear relationship in all field trials in 2018.

Additionally, the slope from the regression plot of predicted versus observed spotted wilt intensity was negative in Midville in 2018 from Peanut Rx 2.0. At this location, the second and third planting dates were in June due to very wet conditions in May. There were higher spotted wilt intensities in peanuts planted in June; however, the Peanut Rx 2.0 model predicted lower values. This result demonstrated the complicated effect of planting date on the intensity of spotted wilt, especially for later-planted peanuts. It was shown that spotted wilt intensity on late-planted peanuts is variable and can be either higher or lower from one year to another (Figure 3.3). Currently, there is no means of predicting whether the spotted wilt epidemics will be severe or not from one year to another. Peanut Rx 2.0 may be improved by treating the planting date as a categorical variable like it was in Peanut Rx and not a continuous variable. By categorizing the planting dates, a specific parameter estimate can be calculating for each category or range of dates. With Peanut Rx, a range of planting dates were grouped such that planting prior to May, May 1-10, May 11-25, May 26- June 10, and after June 10 were assigned different risk point values (Kemerait et al., 2018). While this may lead to false positive predictions when spotted wilt intensity is low on late-planted peanuts, as observed in 2017, the risk of potentially elevated intensities (observed in 2018) will be accounted for (Figure 3.3). Thus, growers can apply necessary preventive management strategies to avoid potential severe spotted wilt epidemics and subsequent yield loss.

Peanut Rx 2.0 uses estimated magnitude of prior-year-thrips population from the TSWV and Thrips Risk Forecasting tool (TTRF) in predicting the intensity of spotted wilt disease (Williams, 2015). The TTRF tool is a web-based forecasting tool developed in North Carolina to predict TSWV incidence in tobacco crops based on weather parameters and estimated magnitude of prior-year-thrips populations (Chappell et al., 2013). In 2015, the TTRF tool was assessed in terms of predicting spotted wilt intensity in tobacco crops in eastern Georgia and has shown promising results. A regression analysis between observed and predicted spotted wilt from TTRF tool had an R^2 value of 0.54 (Williams, 2015). However, by the time that the Peanut Rx 2.0 was developed, the TTRF tool has not been validated for estimating the magnitude of thrips population in peanut fields in Georgia. The ability of the TTRF tool to closely estimate the magnitude of thrips population in each location per year could affect the performance of Peanut Rx 2.0 in predicting the intensity of spotted wilt in peanuts. The accuracy of the TTRF tool in estimating the magnitude of prior-year-thrips population in southern Georgia was assessed in the following chapter of this manuscript.

The development of Peanut Rx 2.0 was an innovation in managing spotted wilt in peanuts as it provided a method of accounting for both exposure and disease pressure through a combination of Peanut Rx and the TTRF tool (Williams, 2015 and Chappell, unpublished). Based on current spotted wilt data from on-station field trials conducted across the peanut producing areas in Georgia, the Peanut Rx 2.0 did not perform better than Peanut Rx as a spotted wilt management tool. This was shown by result of regression analyses, where Peanut Rx accounted for more variability in spotted wilt across risk levels. In order to move forward with Peanut Rx 2.0, it needs to be improved. This may be done by categorizing planting date, calculation of parameter estimates for every peanut variety (if data are available), and adjusting the thrips predictive component to work specifically in predicting magnitude of thrips population in peanut fields in Georgia.

As Peanut Rx was first developed over 20 years ago, questions have been raised as to its utility now, especially with the release of newer varieties. From the result of regression analysis in this study, it was shown that Peanut Rx remains to be an effective management tool that allows growers to assess their risk of spotted wilt disease. The summed risk points based on Peanut Rx had a significant positive relationship with spotted wilt intensities observed in the on-station field trials, and accounted for 8.53 - 50.11% variability in the observed spotted wilt across risk levels (Table 3.2).

To confirm that the Peanut Rx continues to be a useful tool in prediction risk of spotted wilt in commercial peanut fields, a survey was conducted in 2017 and 2018. In this study, it was shown that the growers were practicing recommended production practices that result in lower levels of risk to spotted wilt disease (Figures 3.4 – 3.9). The majority of the fields that were surveyed (60.27% in 2017 and 65.06% in 2018) had a low-risk of spotted wilt disease based on Peanut Rx as shown in Figure 3.14. None of the commercial peanut fields that were surveyed was categorized as “high-risk” (≥ 115-

points) based on Peanut Rx. The growers were protecting their peanut crop from spotted wilt disease by selecting production practices that result in low levels of risk such as using resistant varieties, planting during the recommended planting window, application of phorate insecticide, and achieving higher plant population per foot of row (Table 3.5).

The percentage of fields with single and twin-row patterns did not vary greatly among the fields that were surveyed (Figure 3.8). The row-pattern was not included in the original version of the risk index that was released in 1996, but was soon included in the 1999 version (Brown et al., 2005). Fifty percent of Georgia's total peanut acreage in 2001 was planted in twin rows compared with an average of only 10% during 1992 to 1996 (Brown et al., 2005). Consistent with the previous report, result of this study indicated that 50% of the fields surveyed have adopted the twin-row pattern based on the survey conducted in 2017 and 2018 (Table 3.5, Figure 3.8).This is another example that growers recognize the benefits and adopt recommended production practices.

Tillage type is another factor that was not included in the original Spotted Wilt Risk Index (Brown, 1996). It was added in the risk index in the 1999 version (Brown et al., 2005). After 19 years (1999- 2018) since its addition as a factor in the risk index, only 23 and 28% of the fields surveyed in 2017 and 2018 were prepared using a reduced tillage (Figure 2.7). More than 70% of the commercial peanut fields surveyed in 2017 and 2018 were prepared in a conventional tillage even though it has a higher risk point value based on Peanut Rx. It seems that the percentage of fields being prepared with reduced tillage has not changed much since year 2000. According to Brown et al. (2005), the acreage utilizing strip tillage in Georgia was approximately 20% in 2003 compared with approximately 5% in 1995. A report by Wright et al. (2002) in Florida indicated that peanut farmers have been slow to adopt conservation or reduced tillage due to the belief that plant residue left on the soil surface causes increased disease problems on peanut or that digging will be hard. Despite practicing a conventional tillage, however, growers still achieve low-risk of spotted wilt by using other low-risk production practices such as resistant varieties and planting during the recommended planting window.

There is a positive trend between total risk points from Peanut Rx and observed spotted wilt intensity (Figure 3.10 and 3.11). As the Peanut Rx risk increases, the associated spotted wilt intensity also increased. Lower spotted wilt intensity was recorded among fields with low-risk points while the cases with elevated spotted wilt intensities were among the fields with the greatest total risk point values. This is an evidence that after more than 20 years from the development of the original risk index in 1996, with the yearly updates and refinement, the Peanut Rx remains useful in determining the risk to spotted wilt disease in commercial peanut fields. This was reflected by the average yield losses incurred by growers then and now. When the original Spotted Wilt Risk Index was released, an average of 12% yield loss due to spotted wilt disease in peanuts has been recorded amounting to more than $40 million in 1997 (Brown et al., 2005). As of 2018, the average yield losses due to spotted wilt in peanuts in Georgia was 3.5% (Kemerait et al., 2018). This shows that the application of integrated management practices based upon the Peanut Rx risk index has helped growers avoid yield losses due to spotted wilt disease.

Among the commercial peanut fields that were surveyed, the variety ‘Georgia-06G’ was widely grown. This could be attributed to its high TSWV resistance with medium maturity and excellent yield, grade, and dollar value return per acre (The Peanut

Grower, 2018; Monfort, 2018). Newer varieties such as ‘Georgia-12Y’ and ‘TifNV-HiOL’ were also being grown in other fields (Figure 3.4). This shows that growers continue to adapt to growing promising cultivars with disease resistance and good yield potential developed through breeding efforts.

The development and use of peanut varieties with high-levels of resistance to TSWV was the biggest change in peanut production in terms of managing spotted wilt disease in the southeastern United States. Choice of cultivar is the largest single factor affecting disease progress and severity that a peanut grower can control (Culbreath and Srinivasan, 2011). When the original Spotted Wilt Risk Index for peanuts was developed in 1996, the varieties having the highest risk-point value of 40-points were ‘Georgia Runner’, ‘Florunner’, ‘Sunrunner’, ‘Andru 93’, ‘MarcI’ (Brown et al., 2005). ‘Georgia Green’, ‘Southern Runner’, and ‘Georgia Browne’ were the peanut varieties with the lowest risk-point value of 20-points in the original risk index. In the 2018 version of Peanut Rx, the variety ‘Georgia Green’ had the highest risk-point value (30-points), while ‘Georgia-12Y’ had 5-point risk to spotted wilt disease (Kemerait et al., 2018). The widely grown variety ‘Georgia-06G’ has a risk-point value of 10-points.

With the availability of peanut varieties having high-levels of resistance to TSWV, one might ask whether other production practices still matter in managing spotted wilt disease. None of the currently available peanut varieties are immune to TSWV (Srinivasan et al., 2018; Shrestha et al., 2013). The peanuts varieties with resistance to TSWV could still get a significant infection under high TSWV pressure, even though the incidence and severity of spotted wilt are less than half that shown in susceptible cultivars (Murakami, 2003; Brown et al., 1999). Result of the commercial field survey showed that even though the TSWV resistant variety ‘Georgia-06G’ was used, elevated spotted wilt intensities occurred when it was not combined with other production practices that are known to reduce risk of spotted wilt disease. There were four fields where 20% or more spotted wilt intensities were recorded during the survey conducted in 2017 and 2018 (Table 3.6). While ‘Georgia-06G’ was planted in three out of four fields having ≥20% spotted wilt, the peanuts were planted prior to May 1 and after May 25, which were outside the recommended planting window based on Peanut Rx. ‘Georgia-09B’ was planted in the 4th field having ≥20% spotted wilt. Even though ‘Georgia-09B’ is resistant to TSWV (Monfort, 2018), it was also planted earlier than the recommended planting window. In three out of the four commercial peanut fields with elevated spotted wilt intensities (≥20%), conventional tillage and single row pattern were practiced, and phorate (Thimet®-20G) was not applied. Therefore, it is still important to combine other production practices accounted for in Peanut Rx in managing spotted wilt disease in peanuts.

Overall, this study has provided information on the limitations and potential areas of improvement in using Peanut Rx 2.0 model to predict the intensity of spotted wilt during the growing season. Of equal importance, the Peanut Rx was shown to uphold its usefulness in determining the risk to spotted wilt in research and commercial peanut fields.

Summary and Conclusion

On-station field trials were conducted at six research stations in 2017 and 2018. In each on-station field trial, different levels of risk to spotted wilt were created by using two varieties, three planting dates, and treatment with and without phorate insecticide. Peanut Rx 2.0 was compared with Peanut Rx to account for the variability in spotted wilt intensity at each field trial through regression analysis. The predicted spotted wilt intensities from Peanut Rx 2.0 had a significant positive linear relationship with observed spotted wilt intensities in six on-station field trials in 2017. However, the predictions from Peanut Rx 2.0 did not have a significant linear relationship with the observed spotted wilt intensities in 2018. In contrast, the summed Peanut Rx risk points were significantly related to the observed spotted wilt intensity in five out of six locations in 2017 and in five out of six locations in 2018. In terms of the R^2 values, Peanut Rx always accounted for more variation in spotted wilt intensities across different risk levels than Peanut Rx 2.0. Overall, Peanut Rx 2.0 did not perform better than Peanut Rx.

Through commercial field surveys conducted in 2017 and 2018, the Peanut Rx risk index was revalidated to account for time since the first release and for the addition of new varieties with better resistance to TSWV. Results showed that growers were selecting production practices that result in a low risk of spotted wilt disease. Varieties with resistance to TSWV were being grown in commercial peanut fields during recommended planting dates. The use of phorate insecticide at-planting, reduced tillage, twin-row pattern, and higher plant populations were also being practiced among the commercial peanut fields that were surveyed. As expected from Peanut Rx, lower intensities of spotted wilt were observed among the commercial peanut fields with lower Peanut Rx risk point values, while elevated intensities were observed among fields with greater risk point values. More than 20 years after the development of the original risk index and with the addition of varieties with greater resistance to TSWV, Peanut Rx remains to be a useful tool that helps the growers to assess and reduce their risk to spotted wilt disease in peanuts.

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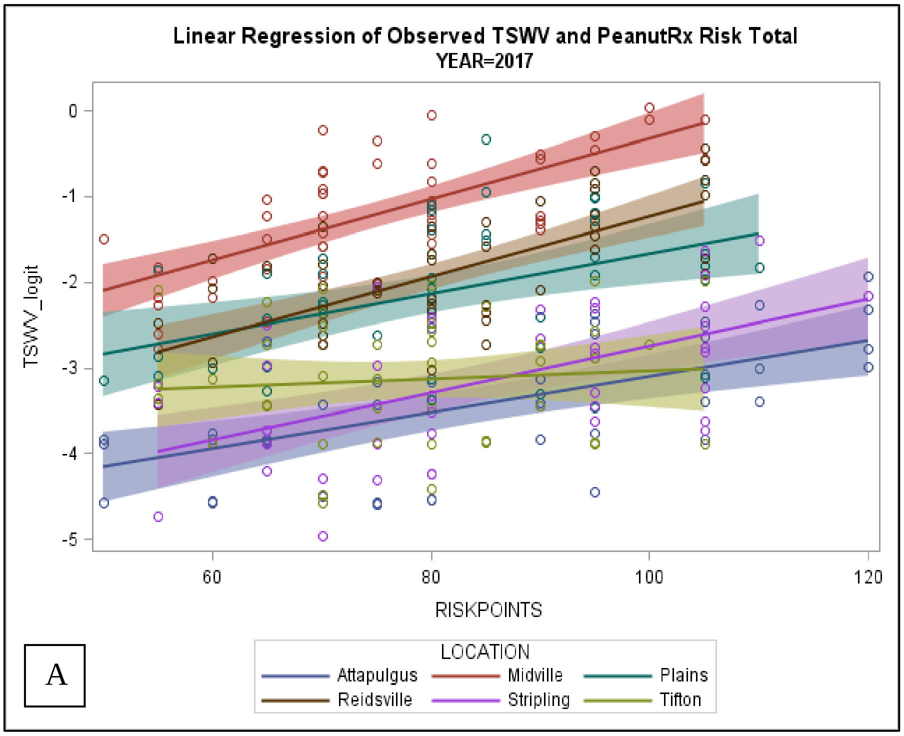
Figures and Tables



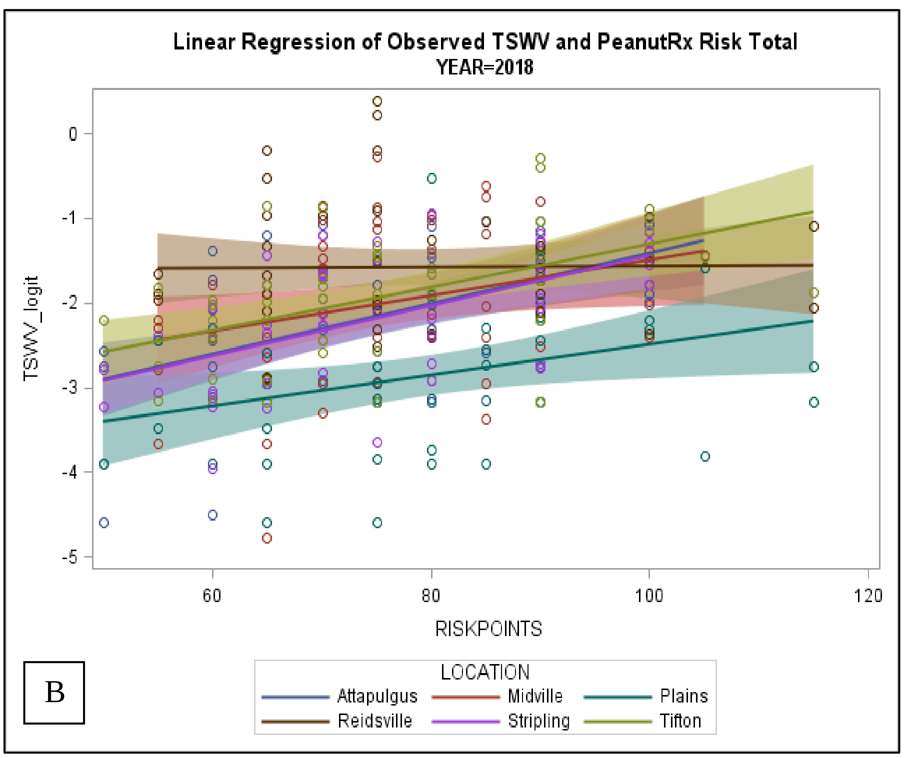
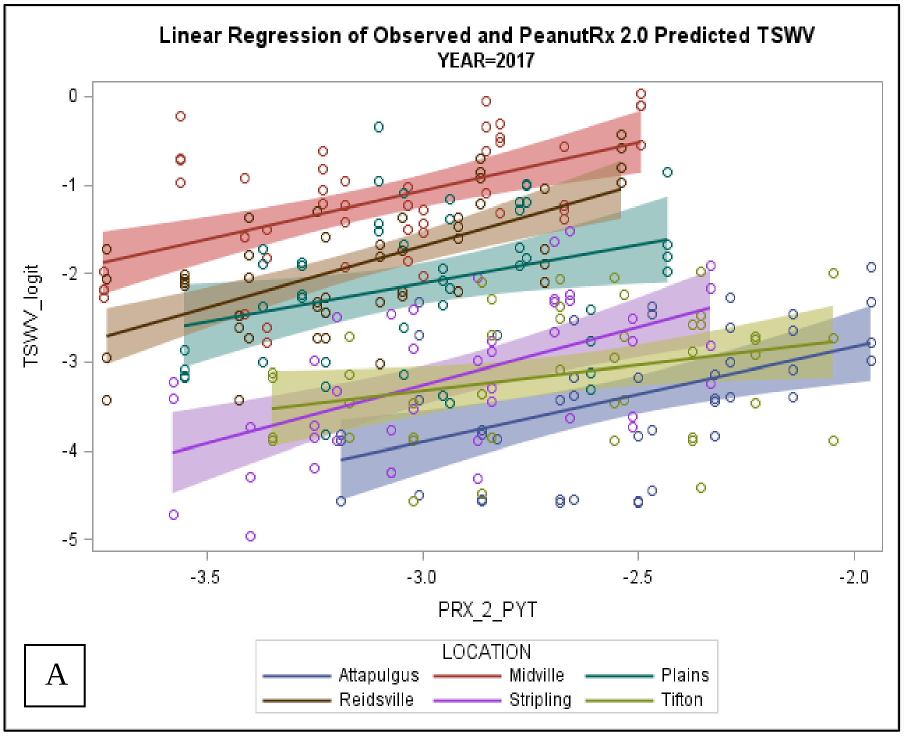


Figure 3.1. Trend lines between logit-transformed potted wilt intensity with Peanut Rx risk points for each location in 2017 (A) and 2018 (B).



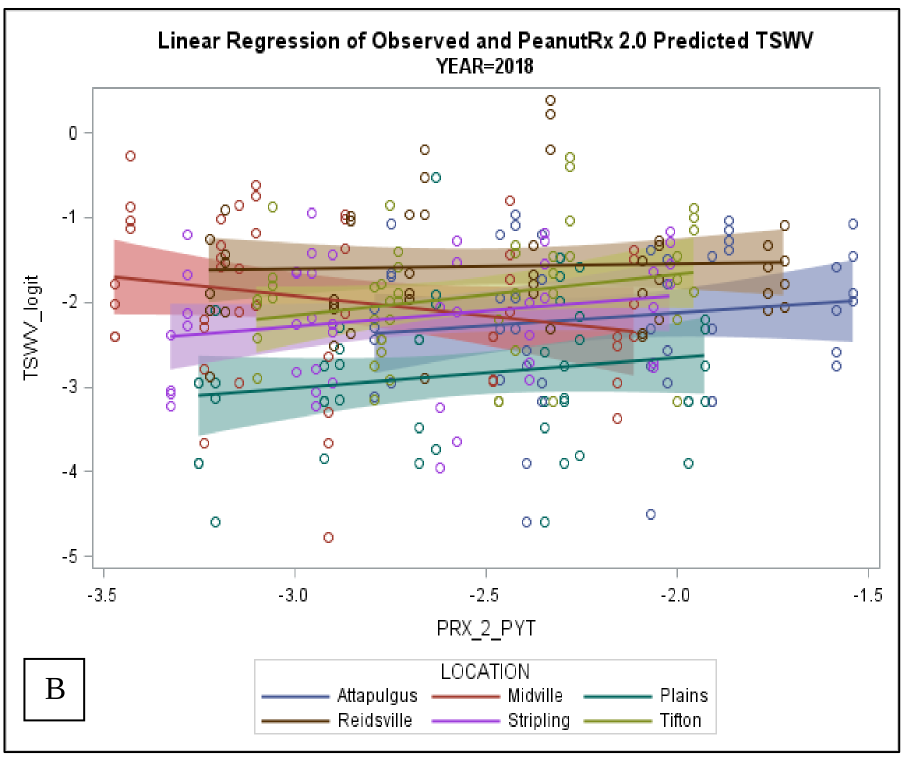
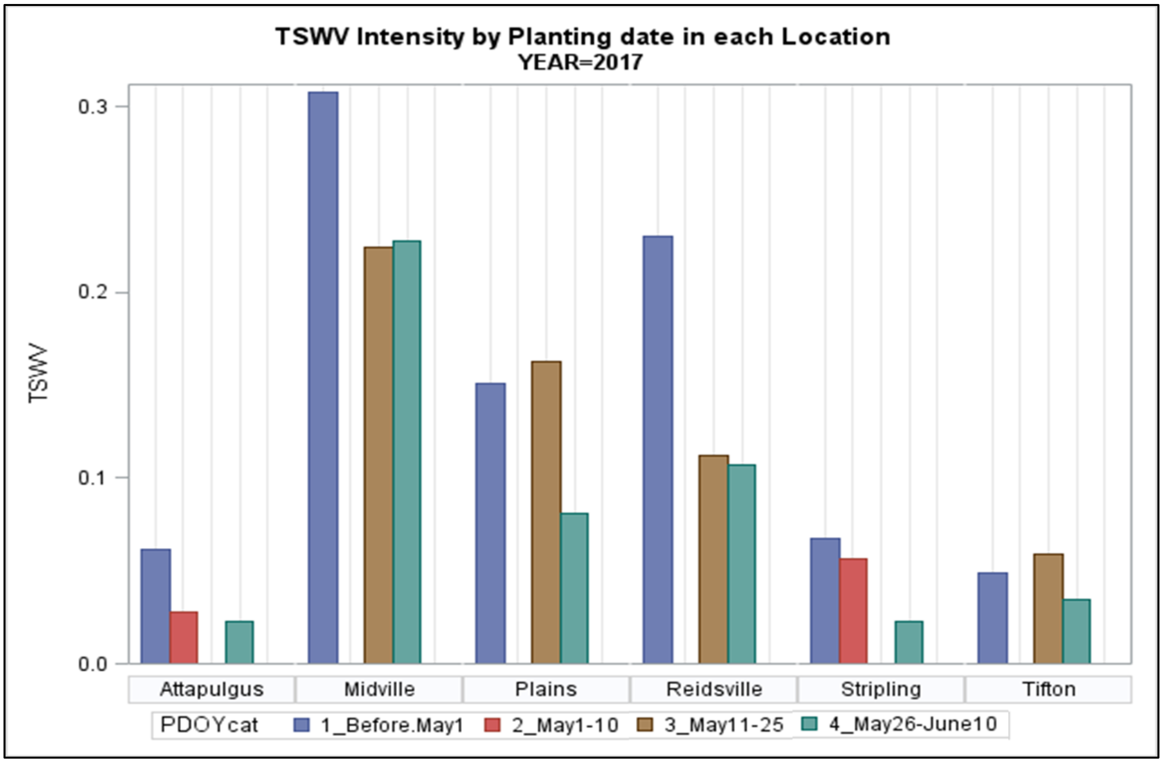


Figure 3.2. Trend lines between logit-transformed spotted wilt intensity with predicted logit values of spotted wilt from Peanut Rx 2.0 for each location in 2017 (A) and 2018 (B).



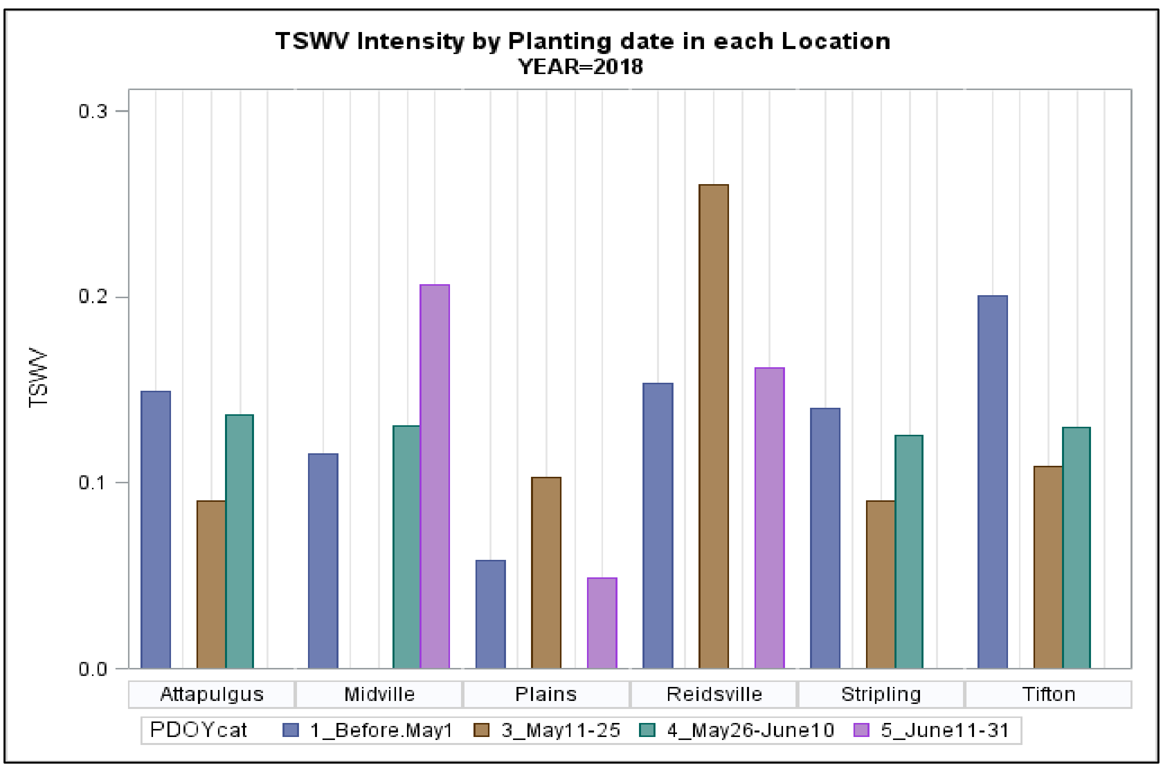


Figure 3.3. Mean spotted wilt intensity per planting date in six locations in 2017 and 2018.

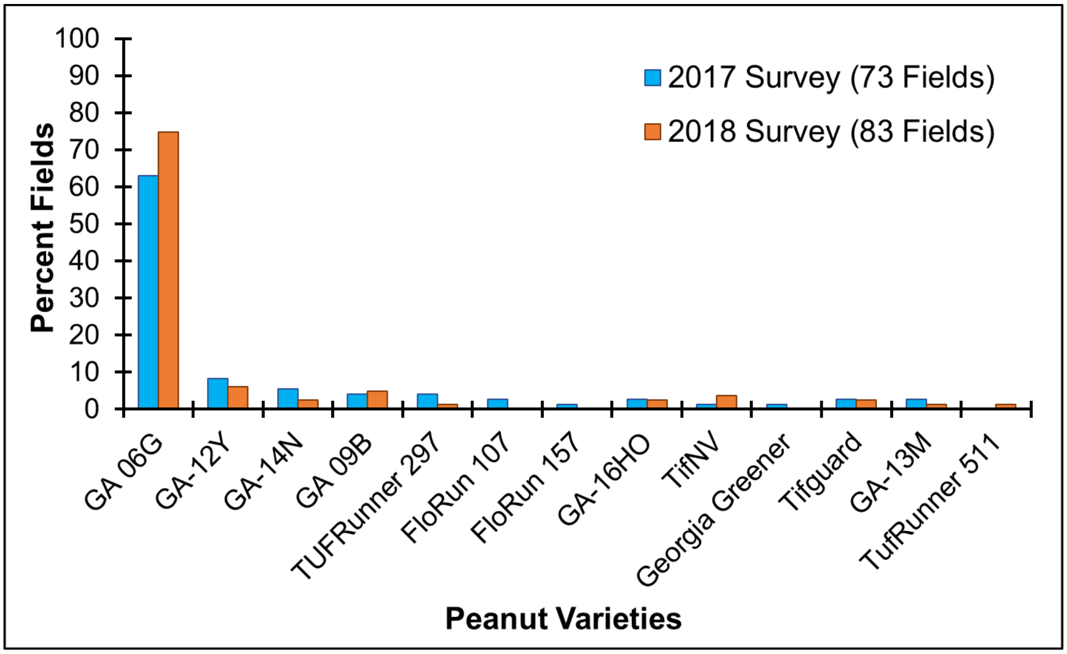


Figure 3.4. Percent fields planted with different peanut varieties among commercial peanut fields surveyed in Georgia in 2017 and 2018.

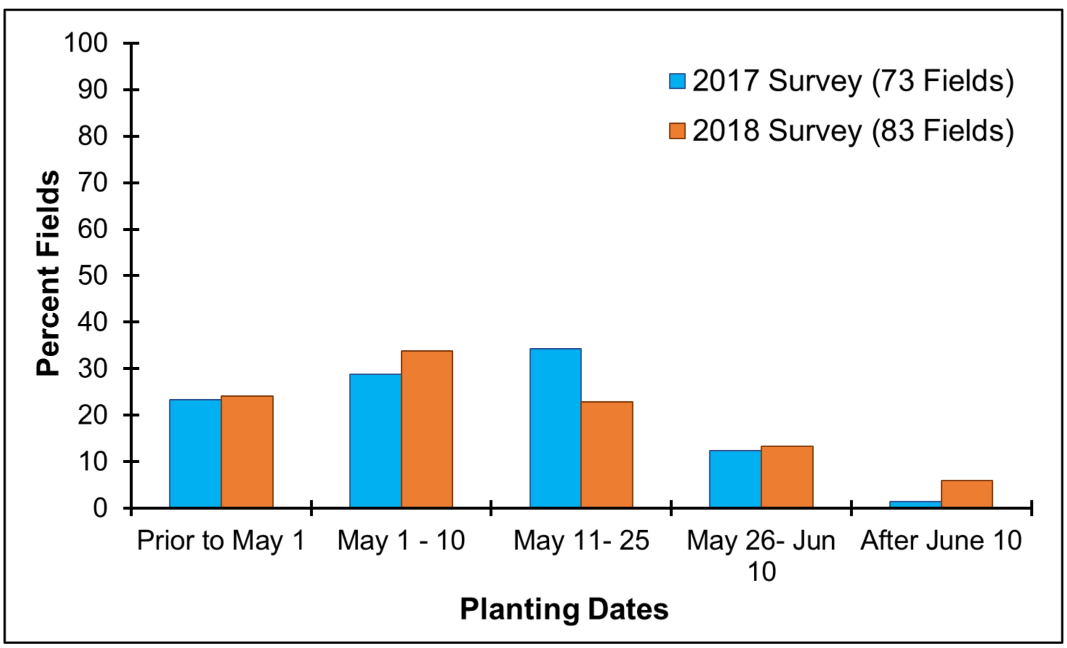


Figure 3.5. Percent fields planted within difference range of planting dates among commercial peanut fields surveyed in Georgia in 2017 and 2018.

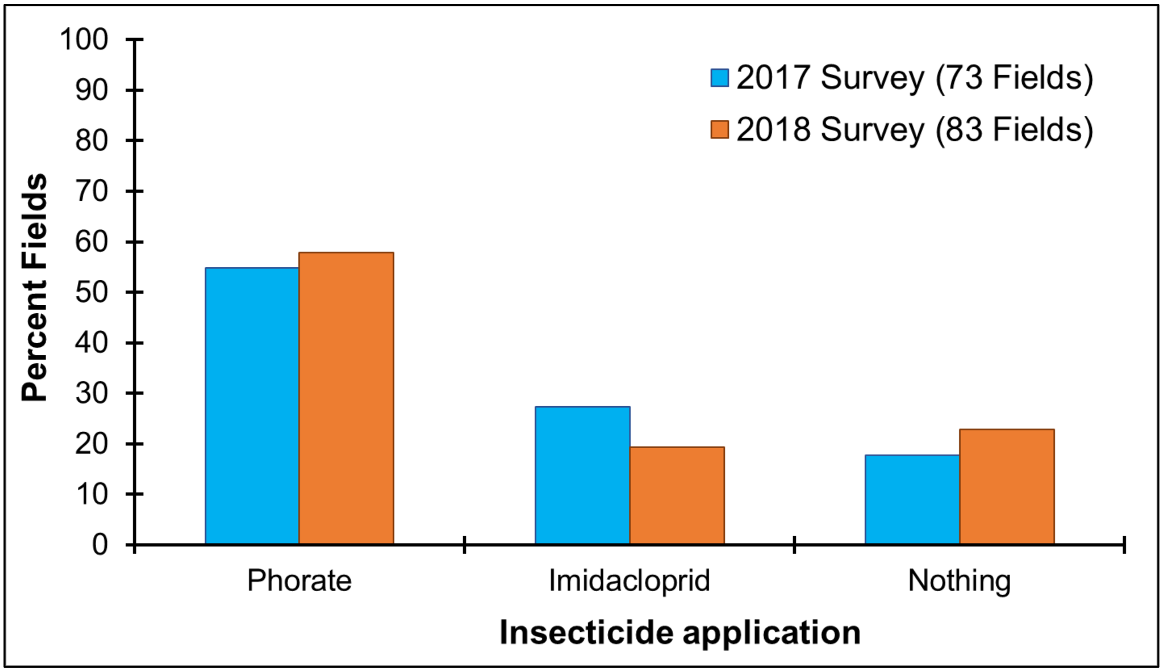


Figure 3.6. Percent fields applied with and without phorate insecticide among commercial peanut fields surveyed in Georgia in 2017 and 2018.

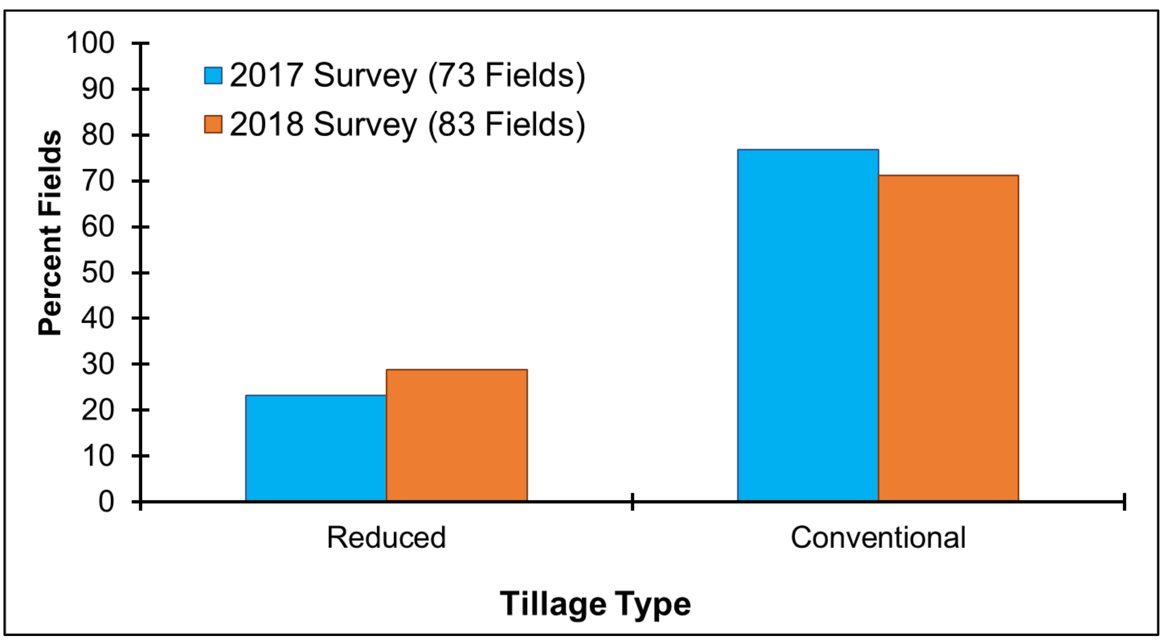


Figure 3.7. Percentage of fields prepared with conventional or reduced tillage among commercial peanut fields surveyed in Georgia in 2017 and 2018.

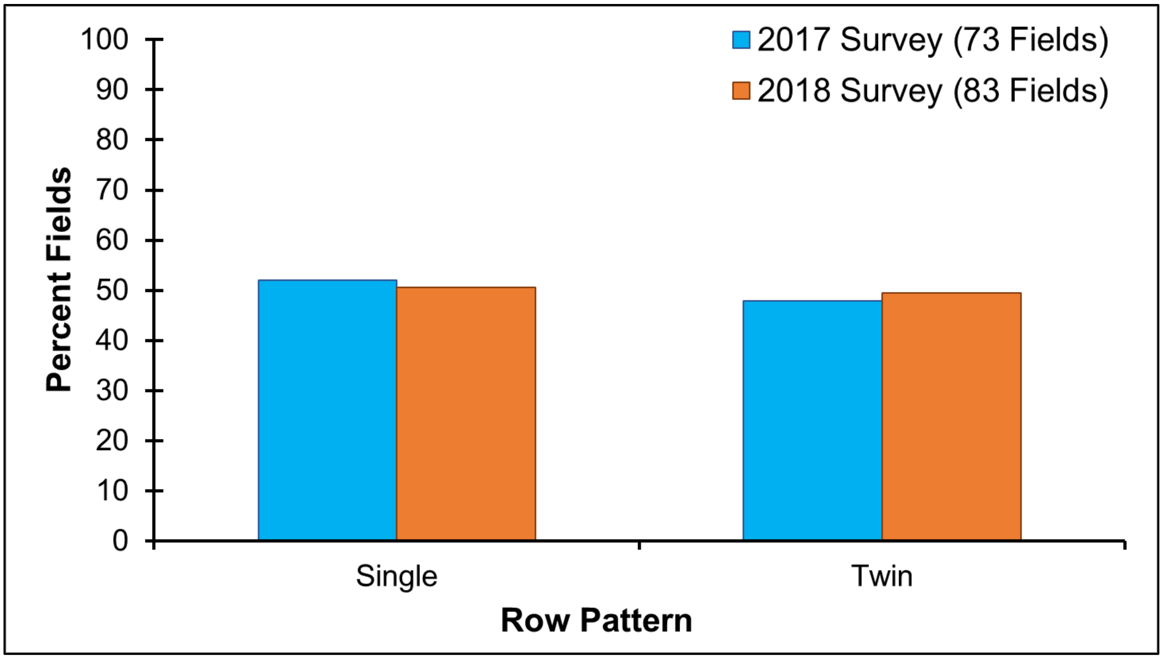


Figure 3.8. Percentage of fields with single or twin row pattern among commercial peanut fields surveyed in Georgia in 2017 and 2018.

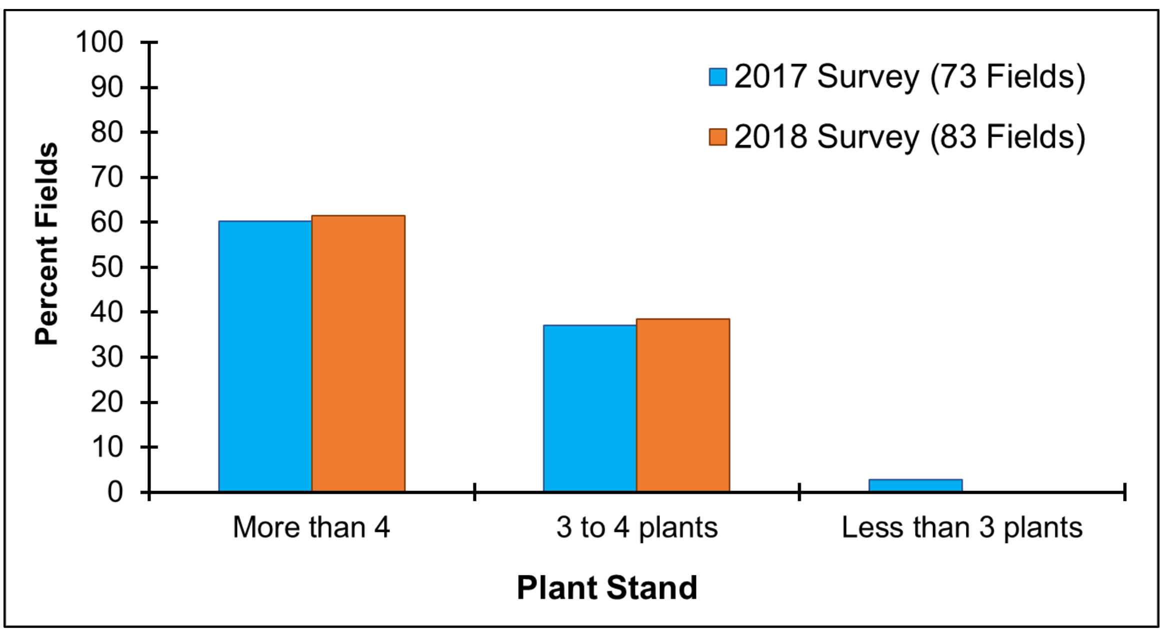


Figure 3.9. Final plant stands in commercial peanut fields surveyed in Georgia in 2017 and 2018.

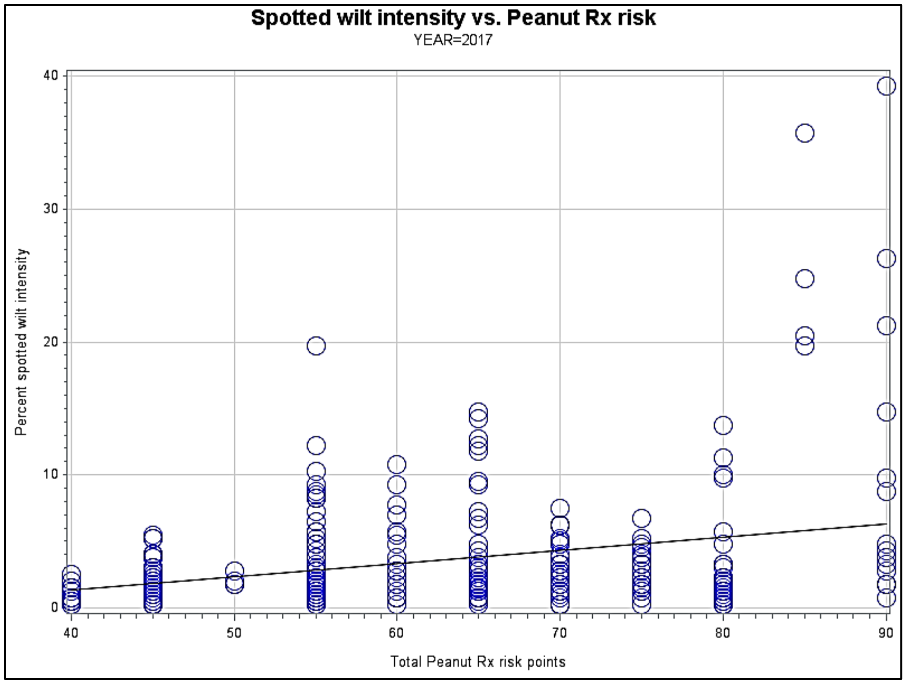


Figure 3.10. Plot of percent spotted wilt intensity and total Peanut Rx risk point values in commercial peanut fields in Georgia (2017).

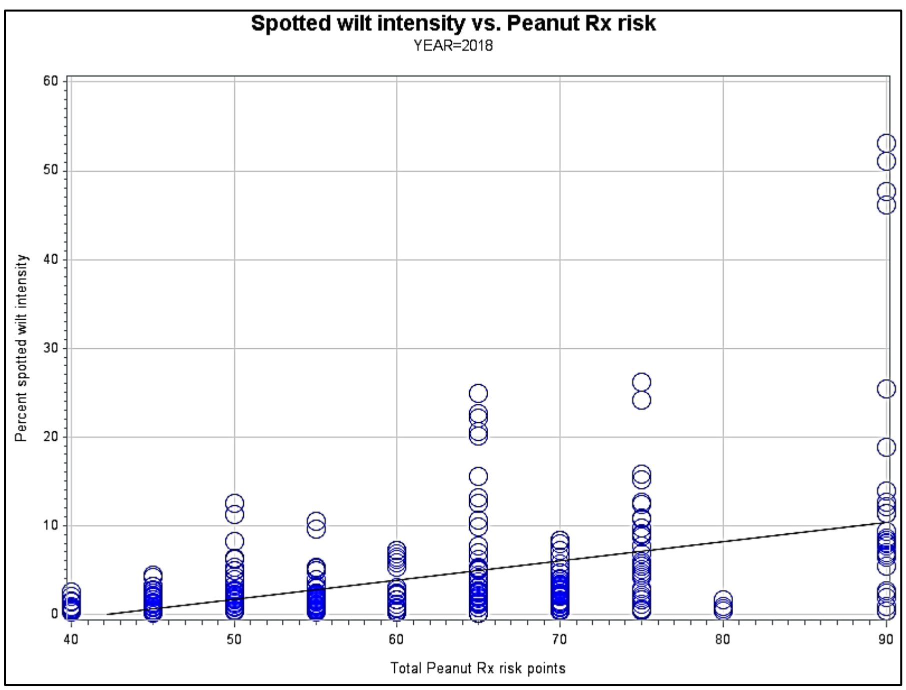


Figure 3.11. Plot of percent spotted wilt intensity and total Peanut Rx risk point values in commercial peanut fields in Georgia (2018).

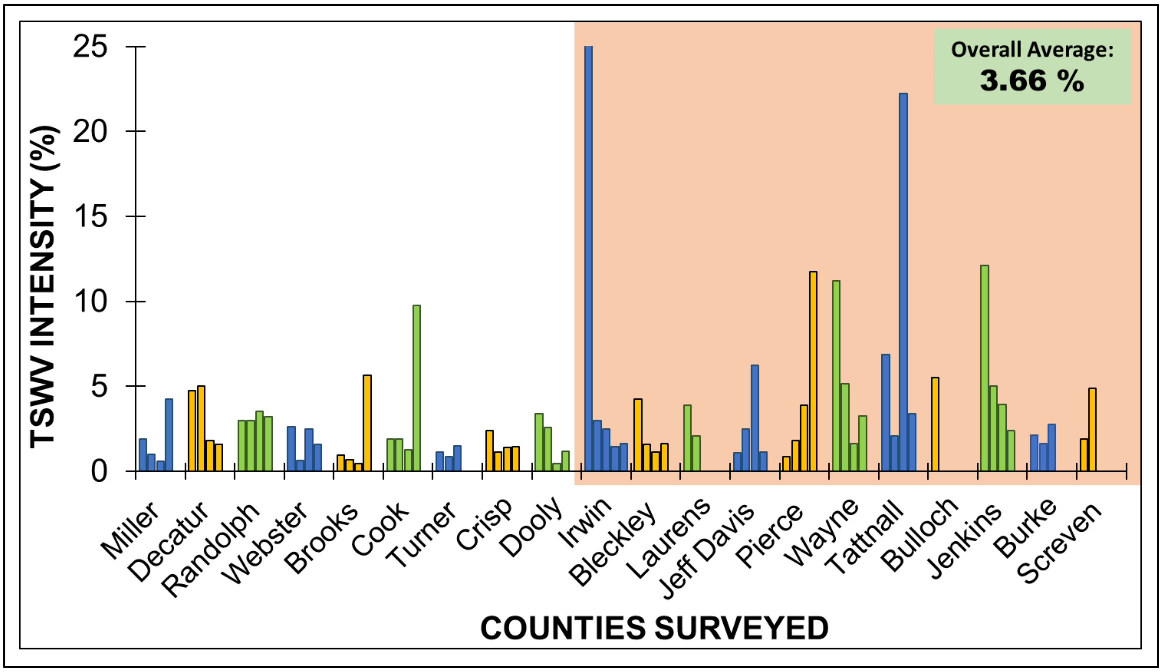


Figure 3.12. Spotted wilt intensity in commercial peanut fields surveyed per county in Georgia in 2017.

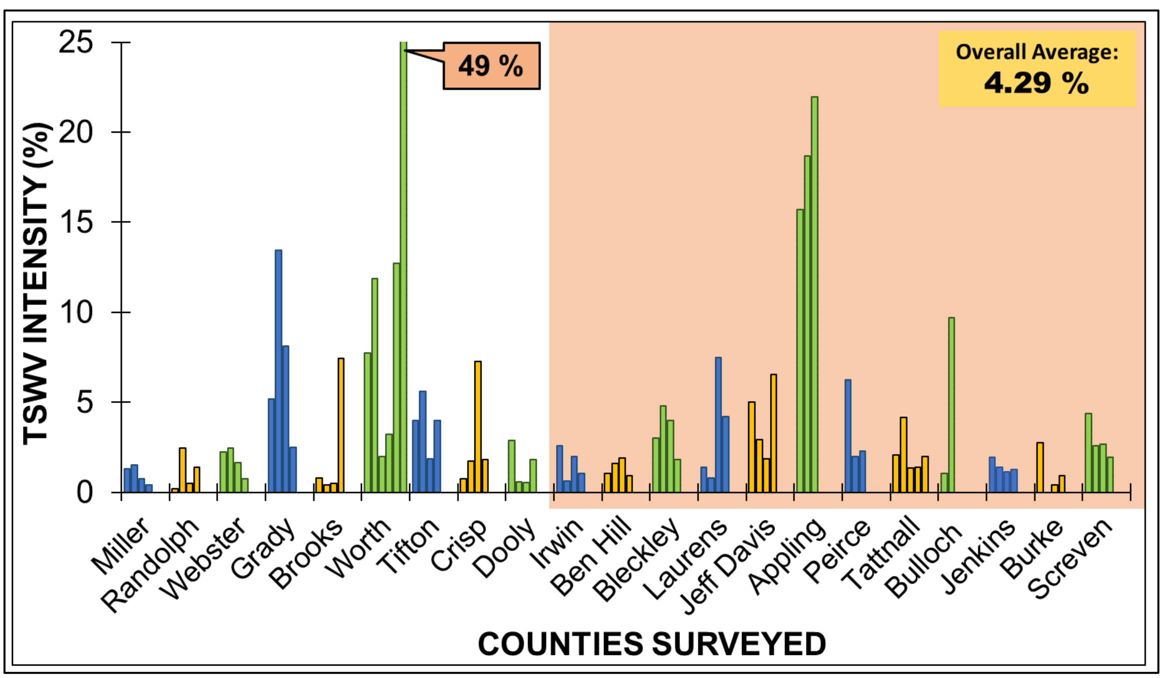


Figure 3.13. Spotted wilt intensity in commercial peanut fields surveyed per county in Georgia in 2018.

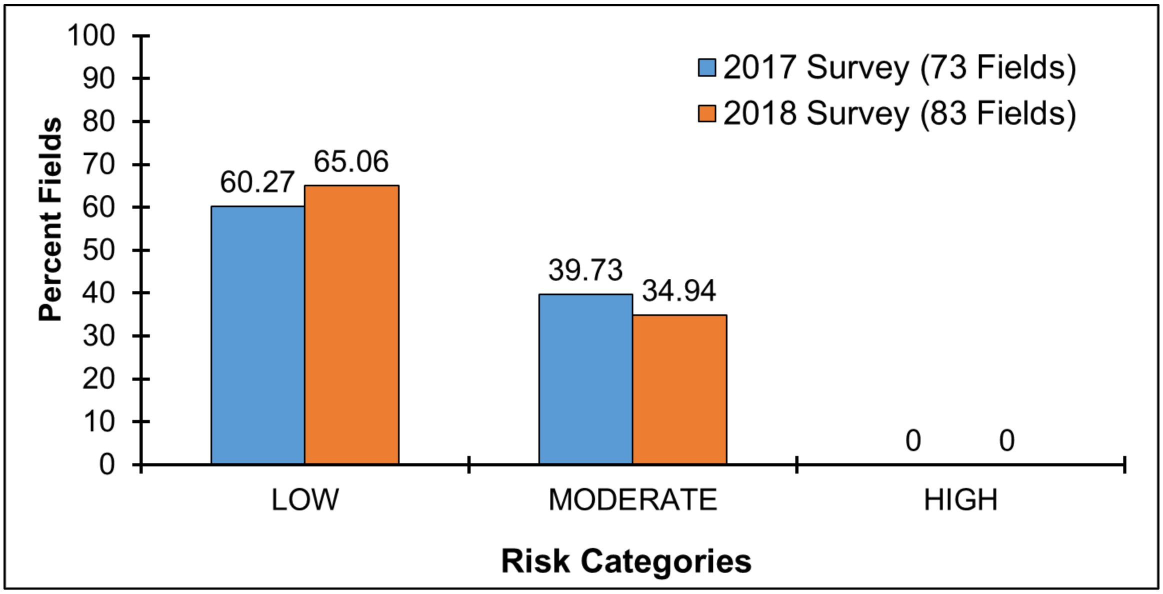


Figure 3.14. Percent fields per Peanut Rx risk categories based on commercial peanut fields surveyed in Georgia in 2017 and 2018.

Table 3.1. Parameter estimates calculated for each peanut production practices and inputs used in Peanut Rx 2.0 (Chappell, unpublished)

Parameter	Estimate	Standard Error	t Value	Pr > |t|
Intercept	-3.166119801	0.30904137	-10.24	<.0001
cultivar AP4	-0.46789709	0.29378482	-1.59	0.1114
cultivar BAILEY	0.798741234	0.18982106	4.21	<.0001
cultivar C99R	0.307077246	0.28271876	1.09	0.2775
cultivar FL07	0.664189066	0.20948846	3.17	0.0015
cultivar FLORUN107	0.581869317	0.12363828	4.71	<.0001
cultivar GA06G	0.539234504	0.08421382	6.4	<.0001
cultivar GA07W	0.026071605	0.12976085	0.2	0.8408
cultivar GA09B	0.595841821	0.10578403	5.63	<.0001
cultivar GA12Y	-0.1777272	0.10490049	-1.69	0.0904
cultivar GAGR	0.142181563	0.11787899	1.21	0.2279
cultivar GG	0.718485648	0.10345973	6.94	<.0001
cultivar TIFGUARD	0 .	.		.
ROWPAT SINGLE	0.451494426	0.05477105	8.24	<.0001
ROWPAT TWIN	0 .	.		.
TILLAGE CONV	0.454582609	0.05429433	8.37	<.0001
TILLAGE STRIP	0 .	.		.
planting_DOY	-0.017994529	0.00186263	-9.66	<.0001
logPYT	0.351726917	0.02476385	14.2	<.0001
INSECTICIDE ADMIREPR	0.00907069	0.15789539	0.06	0.9542
INSECTICIDE CRUISER	-0.028630134	0.0854836	-0.33	0.7377
INSECTICIDE THIMET	-0.326452819	0.05344357	-6.11	<.0001
INSECTICIDE NONE	0 .	.		.

Table 3.2. Table of *p*-values and coefficient of determination (R^2) values from regression analysis of final spotted wilt intensity (logit) with Peanut Rx risk points in each field trial location per year.

LOCATION	YEAR	Peanut Rx Risk Points		
		p-value	R^2	SLOPE
Attapulgus	2017	0.0001	0.2936	0.021
Stripling	2017	<.0001	0.3186	0.027
Plains	2017	0.0017	0.1937	0.023
Tifton	2017	0.5633	0.0078	0.005
Reidsville	2017	<.0001	0.5011	0.035
Midville	2017	0.0001	0.4924	0.035
Attapulgus	2018	0.0003	0.2487	0.030
Stripling	2018	<.0001	0.2969	0.030
Plains	2018	0.0256	0.1059	0.018
Tifton	2018	0.0003	0.2496	0.025
Reidsville	2018	0.9373	0.0001	0.001
Midville	2018	0.0439	0.0853	0.021

Table 3.3. Table of *p*-values and coefficient of determination (R^2) values from regression analysis of final spotted wilt intensity (logit) with Peanut Rx 2.0 predictions in each field trial location per year.

LOCATION	YEAR	Peanut Rx 2.0 Predictions		
		p-value	R^2	SLOPE
Attapulgus	2017	0.0012	0.2234	1.075
Stripling	2017	0.0001	0.3059	1.315
Plains	2017	0.0226	0.1079	0.871
Tifton	2017	0.0410	0.0936	0.582
Reidsville	2017	<.0001	0.4355	1.394
Midville	2017	<.0001	0.3059	1.097
Attapulgus	2018	0.3445	0.0194	0.306
Stripling	2018	0.1580	0.0448	0.365
Plains	2018	0.2275	0.0322	0.358
Tifton	2018	0.1101	0.0545	0.483
Reidsville	2018	0.7780	0.0017	0.061
Midville	2018	0.1136	0.0535	-0.472

Table 3.4. Example of observed and predicted spotted wilt intensity, based on Peanut Rx 2.0, in treatments with highest total risk values from on-station field trials

Location	Year	PDOY	Variety	Insecticide	Predicted SW (%)	Observed SW (%)
Attapulgus	2017	20-Apr	FloRun™ ‘157’	NoThimet	12.32	12.64
Stripling	2017	19-Apr	FloRun™ ‘157’	NoThimet	8.84	12.80
Tifton	2017	25-Apr	FloRun™ ‘157’	NoThimet	11.41	12.00
Plains	2017	27-Apr	FloRun™ ‘157’	NoThimet	8.07	30.00
Reidsville	2017	24-Apr	FloRun™ ‘157’	NoThimet	7.31	39.39
Midville	2017	21-Apr	FloRun™ ‘157’	NoThimet	7.63	50.83
Attapulgus	2018	17-Apr	TUFRunner™ ‘511’	NoThimet	17.66	25.51
Stripling	2018	17-Apr	TUFRunner™ ‘511’	NoThimet	11.73	23.75
Tifton	2018	25-Apr	TUFRunner™ ‘511’	NoThimet	12.39	29.00
Plains	2018	20-Apr	TUFRunner™ ‘511’	NoThimet	12.70	10.00
Reidsville	2018	18-Apr	TUFRunner™ ‘511’	NoThimet	15.18	25.00
Midville	2018	25-Apr	TUFRunner™ ‘511’	NoThimet	10.79	18.33

Table 3.5. Production practices in commercial peanut fields surveyed in 2017 and 2018

Categories	Inputs	**2017 SURVEY**		**2018 SURVEY**	
		No. of growers	Percentage	No. of growers	Percentage
Variety	Georgia- 06G	46	63.01	62	74.7
	Georgia-12Y	6	8.22	5	6.0
	Georgia-14N	4	5.48	2	2.4
	Georgia- 09B	3	4.11	4	4.8
	TUFRunner™ '297'	3	4.11	1	1.2
	FloRun ™ '107'	2	2.74	*nd*	*nd*
	FloRun ™ '157'	1	1.37	*nd*	*nd*
	Georgia-16HO	2	2.74	2	2.4
	TifNV-HiOL	1	1.37	3	3.6
	Georgia Greener	1	1.37	*nd*	*nd*
	Tifguard	2	2.74	2	2.4
	Georgia-13M	2	2.74	1	1.2
	TufRunner ™ '511'	*nd*	*nd*	1	1.2
Planting date	Prior to May 1	17	23.29	20	24.1
	May 1 to 10	21	28.77	28	33.7
	May 11 to 25	25	34.25	19	22.9
	May 26 to Jun 10	9	12.33	11	13.3
	After June 10	1	1.37	5	6.0
Thimet	Phorate	40	54.79	48	57.8
	Nothing	13	17.81	19	22.9
	Imidacloprid	20	27.40	16	19.3
Row Pattern	Single rows	38	52.05	42	50.6
	Twin rows	35	47.95	41	49.4
Tillage	Reduced	17	23.29	24	28.9
	Conventional	56	76.71	59	71.1
Plant population/ft	More than 4	44	60.27	51	61.4
	3 to 4 plants	27	36.99	32	38.6
	Less than 3 plants	2	2.74	0	0.0

nd = No data from fields that were surveyed

Table 3.6. Production practices in commercial peanut fields where 20% or more spotted wilt intensities were recorded surveys conducted in 2017 and 2018

Location	Field	Variety	Planting date	Tillage	Row pattern	Insecticide	Plants/ ft	% TSWV	Peanut Rx summed risk points
Tattnall county	1	GA-06G	May 26, 2017	conventional	twin	no thimet	10	6.88	55
	2	GA-12Y	May 26, 2017	conventional	twin	no thimet	9	2.06	50
	3	**GA-09B**	**April 27, 2017**	**conventional**	**single**	**thimet**	**4**	**22.25**	**90**
	4	GA-13M	May 1, 2017	conventional	single	no thimet	4	3.38	75
Irwin county	**1**	**GA-06G**	**April 25, 2017**	**conventional**	**twin**	**no thimet**	**4**	**25.19**	**85**
	2	GA-06G	May 26, 2017	conventional	single	thimet	2	3.00	70
	3	GA-06G	May 11, 2017	conventional	twin	thimet	6	2.50	45
	4	GA-12Y	May 11, 2017	conventional	twin	thimet	7	1.44	40
	5	GA-06G	May 1, 2017	conventional	twin	thimet	5	1.63	55
Worth county	1	GA-06G	April 26, 2018	conventional	single	no thimet	4	7.75	90
	2	GA-06G	April 24, 2018	conventional	single	no thimet	4	11.88	90
	3	GA-06G	May 8, 2018	reduced	twin	no thimet	5	1.97	55
	4	GA-06G	May 24, 2018	conventional	single	thimet	4	3.22	65
	5	GA-06G	June 18, 2018	reduced	twin	no thimet	3	12.74	75
	6	**GA-06G**	**April 13, 2018**	**conventional**	**single**	**no thimet**	**4**	**49.38**	**90**
Appling county	1	TufRunner 511	May 24, 2018	conventional	twin	no thimet	6	15.69	65
	2	GA-06G	May 7, 2018	conventional	single	no thimet	4	18.69	75
	3	**GA-06G**	**June 14, 2018**	**reduced**	**single**	**no thimet**	**3**	**21.94**	**65**

CHAPTER 4

ASSESSMENT OF THRIPS PREDICTIVE TOOLS DEVELOPED FOR TOBACCO AND COTTON FOR USE IN PEANUTS[1]

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Abstract

Thrips are economically important pests affecting crops worldwide. Tobacco thrips *(Frankliniella fusca)* are important species of thrips that serve as vectors of TSWV in peanut and other crops in the southeastern United States. Predictors of *F. fusca* population and dispersal patterns were developed to help growers design and implement management practices in order to avoid losses associated with thrips damage. Examples of tools developed for thrips include the TSWV and Thrips Risk Forecasting (TTRF) tool for tobacco and the Thrips Infestation Predictor (TIP) for cotton. This study was conducted to assess whether these thrips predictor tools can be utilized in Georgia on the peanut crop. Aerial thrips traps were installed at six locations in 2017 and at eight locations in 2018 across southern Georgia. The predicted number of thrips based on the TTRF tool was compared to the observed number of thrips from aerial traps. The result indicated that the TTRF tool was not able to closely predict the magnitude of thrips in locations included in this study. Temperature and precipitation events from December to May were correlated with the observed magnitude of thrips populations. The correlation of the magnitude of thrips populations and these weather parameters were consistent with previous reports. The observed peak of thrips dispersal was also compared with the predicted peaks from TTRF and TIP tools. The TIP tool was able to provide location and year specific prediction of peak of thrips dispersal. Thus it was considered to be a better predictor of the peak of thrips dispersal that can be used for peanut fields in Georgia.

Introduction

Thrips are minute insects that are widespread throughout the world in habitats ranging from forests to grasslands and farms (Ullman et al., 1992). At present, approximately 5000 species have been identified. A few hundred of these thrips species, are recognized as economically important crop pests. Thrips feeding on crops can cause direct damage leading to injury at the feeding site or indirect damage by serving as vectors of plant pathogens (Ullman et al., 1992; Brunner et al., 2002). Eleven species of thrips were found to vector *Tospoviruses* to a wide range of plants (German et al., 1992; Mound, 1996).

Tomato spotted wilt virus (TSWV), one of the *Tospoviruses*, was ranked second among the top ten economically important viruses in the world (Scholthof et al., 2011). It is one of the most important pathogens affecting peanut production in the southeastern United States (Culbreath and Srinivasan, 2011). Among the nine species of thrips known to transmit TSWV, *Frankliniella fusca* (tobacco thrips) was found to be more predominant in peanuts. This is because *F. fusca* can reproduce well on that crop and it is known to be the earliest invader of crops planted in the spring in the southeastern United States (Todd et al., 1995; Joost and Riley, 2005).

Adult *F. fusca* has brown to a dark brown or black body coloration. Males and females that have recently emerged from pupae are a paler brown or gray color (Hodges et al., 2009; Riley et al. 2011). They have an eight-segmented antenna with a smooth pedicel at the base of antennal segment III and setae arising from antennal segment II do not form stout spines. The ocellar III setae (large pair nearest the ocelli) do not arise between posterior ocelli (Cluever and Smith, 2017). The pronotal anteromarginal setae are shorter than anteroangular setae and postocular seta IV is reduced or absent (Riley et al. 2011; Cluever and Smith, 2017). The comb on tergite VIII is absent or weakly developed (Moritz et al. 2001, Mound et al. 2009). Based on these morphological features, *F. fusca* can be distinguished from other thrips species.

Tomato spotted wilt virus is transmitted by thrips in a persistent and propagative manner. To be transmissible, TSWV must be acquired by the first or second instar immature thrips from infected host plants during feeding. When thrips acquire the virus at an adult stage, the virus can be found in the mid gut and muscle cells around the mid gut, but not in the salivary glands. Thus, these adults do not transmit the virus (Cho et al., 1988; Mullis et al., 2009). After acquisition, TSWV replicates and persists through insect molts from larval to adult stages. The virus spreads to the salivary glands where it also replicates to achieve a high virus titer in the saliva. Viruliferous adult thrips transmit the virus when they move and feed to other plants (Dietzgen et al., 2016; Nagata et al., 2002; Moritz et al., 2004). Furthermore, there is no evidence of trans-ovarian transmission of TSWV (Ogada et al., 2013). Therefore, each generation of thrips must reacquire the virus for the disease epidemic to continue. As thrips are known to disperse from weeds into the peanut crop during the growing season, the availability of weeds that host both the thrips and TSWV is critical in the epidemiology of spotted wilt.

Transmission of TSWV from thrips to susceptible crops can be widespread. The efficiency of the spread and dispersal of the virus makes spotted wilt difficult to manage. Studies have shown that even when viruliferous thrips comprise <3% of the total population, severe spotted wilt damage can occur (McPherson, et al., 2005). Hence, the thrips vectors play a very important role in the epidemiology of spotted wilt disease. A thorough understanding of the population dynamics of thrips, including factors that affect it, is necessary for developing effective management strategies.

In the southeastern United States, peanut and tobacco growing seasons coincide with active *F. fusca* generations. In a study conducted in Georgia, immature thrips were most prevalent between January and May with peak populations occurring between March and May. Adult thrips were most prevalent between March and August with peak populations occurring between April and June (Olatinwo et al., 2011). Because peak generations of thrips occur during tobacco and peanut planting windows, effective management practices are necessary for controlling spotted wilt epidemics.

Dispersing thrips are critical for the development of spotted wilt epidemics. In a study conducted in North Carolina, it was found that rainfall had both positive and negative effects on the population dynamics of *F. fusca*. Rainfall can suppress the population by killing larvae and can hinder dispersal by suppressing thrips flights. On the other hand, rainfall provides adequate soil moisture, which promotes plant growth as well as pupal survival in the soil (Morsello and Kennedy, 2009). Abundant rainfall delays senescence of winter annual plants that serve as important hosts of *F. fusca.* Delayed senescence allows for continuous population growth resulting in a greater number of adults available to disperse in late May (Morsello et al., 2010).

Temperature also affects thrips development and the availability of host plants. The minimum temperature required for degree-day accumulation for development of thrips is 10.5°C or 50.9°F. Temperatures above 10.5°C during the winter favor the population growth of thrips as they start accumulating degree-days. Warmer temperatures during late April and May favors continued growth of *F. fusca* populations but also hasten the senescence of winter host plants, which result in an increased dispersal followed by rapid decline despite further degree-day accumulation (Morsello et al., 2010). Hence, temperature and rainfall are two factors that greatly influence the biological activities and survival of the thrips vector.

In another study conducted in Georgia, it was found that a lower severity of spotted wilt was associated with average temperatures in April between 19 and 22°C, whereas higher severities were detected with higher and lower temperatures (Olatinwo et al., 2008). In the same study, it was also found that the accumulated rainfall in April was associated with higher spotted wilt severity. A thorough understanding and accounting for the effects of these weather parameters on thrips population and TSWV intensity could help explain the variability in spotted wilt intensity observed in different geographic locations and years.

According to Jones et al. (2010), predicting epidemics of a plant virus disease is challenging due to the complexity of the three-cornered pathosystem (virus, vector host) and subsequent interactions with the environment. For TSWV, predictive models have been developed based on the influence of weather factors on the vector's population dynamics, vector abundance, and vector activities (Madden et al., 1990; Morsello and Kennedy, 2009; Morsello et al., 2010; Olatinwo et al., 2011; Chappell et al., 2013). In peanuts, however, management of spotted wilt disease is informed by using Peanut Rx. It is a risk index that helps growers identify and avoid combinations of production practices that are conducive to severe spotted wilt infection and yield loss (Brown et al., 2005; Kemerait et al., 2018). A framework of a predictive model that accounts for the magnitude of thrips vector in addition to factors accounted for by Peanut Rx was developed in 2015 (Williams, 2015). But the thrips predictive component, the "TSWV and Thrips Risk Forecasting (TTRF) tool", has not been verified to effectively predict the number of dispersing thrips from April 1 to May 31 in peanut fields in Georgia.

The TTRF tool was developed to predict TSWV incidence and patterns of tobacco thrips flights in North Carolina. This web-based forecasting tool queries weather data to compute estimates for five years in the past. The average of these estimates is adjusted based on the average historical spotted wilt incidence entered at the data entry page. The predicted spotted wilt incidence for the current year is then calculated relative to this adjusted average. The tobacco thrips population size is predicted using a model that accounts for the complex effects of rainfall and temperature on thrips population growth. These predictions are based on data collected from 44 sites within 14 locations and seven years of thrips trapping and weather data collection in central and eastern North Carolina and eastern Virginia. The TTRF tool contains independent variables that impact spotted wilt intensity and transmission on a season-to-season basis. These factors include prior-year thrips (PYT) population estimates, average winter temperature (AWT), and March precipitation (MP) (Chappell et al., 2013; Morsello et al., 2010).

The "Thrips Infestation Predictor (TIP) tool for Cotton" is another tool developed at North Carolina State University used to predict risk to thrips injury on cotton seedlings (Kennedy et al., 2017). The TIP tool takes into account planting date, temperature, precipitation, and knowledge of timing and intensity of thrips infestations to predict the risk of thrips injury to cotton. The TIP model calculates those planting dates likely to result in greatest risk for thrips injury. The risk is determined based on the potential overlap of high susceptibility of cotton plants with the interval of high thrips dispersal.

For high-risk planting dates, aggressive thrips management tactics should be applied which include the use of in-furrow insecticides such as acephate, imidacloprid, and aldicarb or the use of a neonicotinoid seed treatment plus a supplemental foliar application at the 1-leaf stage. In low thrips risk environments, neonicotinoid seed treatments will generally provide acceptable control (Roberts, 2018; Kennedy et al., 2017). As most of the spotted wilt infections occurring in peanut during the season are caused by primary infections from thrips (Camman et al., 1995), avoiding the peak thrips dispersal from winter weeds into peanut crop could be important in managing spotted wilt disease.

There were three objectives in this study. The first objective was to validate the use of the TTRF tool in Georgia by comparing the predicted and observed number of thrips collected from April 1 to May 31 near plots planted to peanuts. The second objective was to determine if temperature and precipitation events between December and May could be correlated to the magnitude of thrips populations and spotted wilt intensity across the peanut production region of Georgia. The third objective was to compare the predicted peak of thrips dispersal periods calculated using the TTRF and TIP tools versus the data collected from six locations between April 1 and May 31. These objectives were established to determine if such information could be integrated into Peanut Rx to provide growers with a better tool to assess risk to this disease.

Materials and Methods

Magnitude of tobacco thrips estimates from TTRF

The magnitude of the thrips population was estimated using the web-based forecasting tool, “TSWV and Thrips Risk Forecasting Tool (TTRF)”. The estimated magnitude of dispersing thrips from April 1 to May 31 was taken from a “debug table”. The “debug table” shows the numerical values of the graphs produced by the TTRF tool.

The inputs required for running the TTRF tool were the GPS coordinates of each field location and the historical average TSWV incidence. The average spotted wilt incidences reported in Georgia, 3.5% in 2016 and 3% in 2017 (Kemerait et al., 2018), were used as average historical TSWV incidence when the TTRF tool was run in 2017 and 2018. These values were used to estimate TSWV incidence in the TTRF tool but do not affect thrips estimates. Specific GPS coordinates were used for generating thrips estimates for each thrips trapping location.

Aerial thrips traps

In this study, the number of dispersing tobacco thrips was monitored in peanut field plots established at six University of Georgia research stations in 2017 and 2018. These research stations include the Attapulgus Research and Education Center (Attapulgus), C.M. Stripling Irrigation Research Park (Stripling), Southwest Georgia Research and Education Center (Plains), Black Shank Farm (Tifton), Southeast Georgia Research and Education Center (Midville), and Vidalia Onion and Vegetable Research Center (Reidsville). At these research stations the number of dispersing tobacco thrips was monitored using aerial thrips traps. The aerial thrips traps were made following the design used by Morsello et al. (2010) and illustrated by Dr. Amanda Beaudoin from NCSU (unpublished). Sticky clear plastic was wrapped around yellow-painted PVC tube (Figure 4.1). The plastic trap dimensions were 12.7 cm long by 7.62 cm wide. It was made of stable fly-trap (Catalog Order No: OL-100-10) purchased from the Great Lakes Integrated Pest Management, Vestaburg, MI, USA. The stable fly-trap is a plastic sheet that is sticky on one side. The PVC tubes (schedule 40 PVC) were 8cm long and 3.4 cm in diameter. The PVC pipes were painted yellow (Valspar project perfect, gloss gold abundance #84207). The sticky side of the fly-trap was exposed when attached to the PVC tube. After wrapping the sticky plastic to the PVC tube, the trap was attached to a 3ft. garden stake (GroTall, Model 831442). These traps were installed at the edge of the fields.

In 2017, two traps were installed at each research sites in Tifton, Plains, Reidsville, Stripling, and Midville, while four traps were installed in Attapulgus. In 2018, four traps were installed at all locations. In addition to the six field trial sites, thrips traps were also installed in two growers' fields in Pierce and Appling counties in southeastern Georgia. The traps were collected and replaced weekly. Recovered traps were returned to the laboratory and stored in the freezer to preserve them until they could be assessed.

Tobacco thrips identification. Tobacco thrips were identified based on key features that can be recognized under a stereomicroscope. From each sticky trap, the number of tobacco thrips and other species of thrips were counted separately. A rectangular plastic plate with 1cm x 1cm grid was used as a guide to avoid erroneous counts. The traps were returned to the freezer after the thrips were counted.

Calculating magnitude of thrips from April to May

The mean number of tobacco thrips captured was calculated from all traps recovered at each location per sampling date. Following this, the cumulative mean number of tobacco thrips captured was summed from April 1 to May 31. On occasions where the traps were installed before April 1st or recovered after May 31st, the number of tobacco thrips captured during the interval was divided by the number of days between sample dates to estimate the number per trap per day. Following this, the estimated number of tobacco thrips per trap per day was summed from April 1 to the sampling date and from the sampling date to May 31. The cumulative mean number of tobacco thrips captured from April 1 to May 31 were referred to as 'magnitude of thrips' in this study.

Assessment of TTRF as predictor of magnitude of thrips populations in Georgia

The cumulative mean number of tobacco thrips captured from April 1 to May 31 was compared to the predicted magnitude of thrips based on the TTRF tool. This was done by creating a bar graph in MS Excel showing predicted and observed values. Further, a simple linear regression analysis was conducted to investigate if there was a relationship between the observed and predicted magnitude of thrips populations. This was done using the regression procedure in SAS 9.4 software. Prior to conducting the regression analysis, the natural log of both the observed and predicted magnitude of thrips was calculated to achieve a normal data distribution. The observed magnitude of thrips was then regressed with predicted values across location and over the two years of data.

Use of additional thrips data

Data from aerial thrips traps were collected by Dr. Mark Abney in the Department of Entomology at the University of Georgia, Tifton, Georgia. These data were collected in Worth, Mitchell, Attapulgus, Brooks, Colquitt, and Tift counties in 2014, 2015, and 2017. The aerial thrips traps used for capturing thrips were the same as those used in the current study. These data were used to supplement the data collected in this study in 2017 and 2018 for correlation analysis for the magnitude of thrips from April to May with weather parameters.

Weather data

The weather data used in this study were retrieved from the Georgia Automated Environmental Monitoring Network (AEMN). These data include the following weather parameters: minimum, maximum and average temperatures (ºC) during the winter (December to February) as well as monthly temperatures from January to April. The amount of rainfall (cm) and the number of days with precipitation per month from January to April were also gathered. In addition, the number of days with a minimum of 0.76 cm of rain within a month were recorded from January to May as well as the number of days with temperatures favorable for thrips flights (>20 ºC) in March, April, and May.

Correlation of magnitude of thrips populations with weather data

The relationship between the observed magnitudes of thrips populations from aerial thrips traps in different locations with weather parameters was examined. This was done using the correlation procedure in SAS 9.4 software. The log-transformed values of the observed magnitude of thrips were calculated before the correlation analysis was performed. A significance level of $p \leq 0.15$, based on Pearson correlation, was used as basis for selecting weather factors that correlate negatively or positively with the thrips data. The probability (*p*-values) and correlation coefficients (r- values) for each weather factor were summarized in Table 4.4.

Spotted wilt data

On-station field trials were conducted in six locations in 2017 and in 2018. At each location, different levels of risk to spotted wilt disease based on Peanut Rx were created. This was done by using two varieties (‘Georgia-06G’ and FloRun™ ‘157’ in 2017, and ‘Georgia-06G’ and TUFRunner™ ‘511’ in 2018), three different planting dates (early, middle, and late), and application with and without phorate (Thimet® 20G, 5 lb/A) insecticide at planting time.

Spotted wilt ratings were done based on visual symptoms of spotted wilt disease where chlorotic ring spots, mottling, different patterns of chlorosis, and stunted plants were considered infected. The proportion of spotted wilt infected plants along a row of peanuts was assessed using the “hit-stick method" as described by Culbreath et al. (1997). This was done by counting the number of one-foot sections along a row of peanuts that contained at least one infected plant. The spotted wilt ratings taken near harvest were used in this study.

Relationship of spotted wilt intensity and magnitude of thrips population

The intensity of spotted wilt observed in plots planted to the highest risk situations in the on-station field trials was regressed with the observed magnitude of thrips population using the regression procedure in SAS 9.4 software. The magnitude of thrips population is the number of *F. fusca* captured in aerial thrips traps from April 1 to May 31 at each field trial location. The highest risk situations occurred in the plots planted early with a more susceptible variety and where phorate was not applied. For this analysis, the observed intensity of spotted wilt and the magnitude of thrips was combined across six trial locations and over two years. The logit-transformed values of spotted wilt intensity and the log-transformed values of magnitude of thrips populations were used in the regression analysis. The data transformations were conducted to stabilize variance and achieve normal distribution, based on visual inspection using the univariate procedure (PROC UNIVARIATE) in SAS 9.4 software, prior to analysis.

Correlation of spotted wilt intensity with weather data

Spotted wilt intensities observed from on-station field trials were correlated with selected weather parameters. The logit-transformed values of spotted wilt intensities across locations and years were calculated prior to performing the correlation analysis. The weather parameters tested in this study included the minimum, maximum and average temperatures (ºC) in the winter (December to February) and in the months of February, March and April. The amount of rainfall (cm) and number of days with precipitation in March and April were also tested for correlation with spotted wilt intensity. Additionally, the number of days with a minimum of 0.3-inch of rain in the months of February, March and April was tested for correlation with spotted wilt intensity.

Predicted peak of thrips dispersal from TTRF and TIP tools

The TTRF tool provides a line graph of an estimated pattern of thrips dispersal over time. The estimated pattern of thrips dispersal is based on the location provided at the data entry page on the website: http://climate.ncsu.edu/products/tobacco_tswv/. For this study, the TTRF tool was run for each location where field plots were established and the date when the peak was predicted to occur based on the line graph showing the pattern of thrips dispersal overtime was noted.

The peak of thrips dispersal was also predicted using the Thrips Infestation Predictor (TIP) for cotton. The TIP tool was accessed on the website http://climate.ncsu.edu/CottonTIP. For each site location, the address or GPS coordinates and planting date were entered in the data entry page to run the TIP tool. Based on the information provided in the data entry page, the TIP tool provides a line graph of thrips dispersal over time. The predicted date when the peak of thrips dispersal was expected was noted from the peak of the line graph.

Assessment of TTRF and TIP tools to predict the peak of thrips dispersal over the period from April to May 30

The estimated peaks of thrips flight from the TTRF and TIP tools were compared to the sampling date when the greatest number of tobacco thrips were captured. The data used in the assessment of TTRF and TIP tools include the thrips trapping data in 2018 and thrips trapping data from southern Georgia in 2014, 2015, and 2017 provided by Dr. Mark Abney of the UGA entomology department. The predicted peak of thrips dispersal was based from the peak of a line graph showing the pattern of thrips dispersal overtime from the output of the TTRF and the TIP tool. The observed peak of thrips dispersal was considered to be closely estimated when it was within seven days before or after the predicted peak of thrips dispersal. For example, if the estimated thrips dispersal was May 15 and the most tobacco thrips were sampled on May 20, then this was considered to be closely predicted.

Results

Assessment of TTRF as predictor of magnitude of thrips in Georgia

The cumulative mean *F. fusca* captured from April 1 to May 31 were compared to the predicted magnitude of thrips from the TTRF tool (Table 4.1). The TTRF tool over-predicted the magnitude of thrips in five out of six locations in 2017 and in all eight locations in 2018 (Figure 4.2). However, the TTRF tool under-predicted the number of thrips in Midville in 2017. In both years, the TTRF tool over-predicted the magnitude of thrips at Attapulgus by a wider margin than at the other locations.

A simple linear regression analysis was performed between observed and predicted magnitude of thrips across locations and over years. The result showed no significant relationship between the observed and the predicted number of thrips ($p = 0.0998$) (Figure 4.3). The regression line of predicted and observed number of tobacco thrips had a negative slope.

Correlation of weather data to magnitude of thrips populations

The relationships between the log-transformed magnitude of thrips and a number of weather parameters were tested through correlation analysis. The minimum, maximum, and average temperatures in February had significant positive correlation with the observed number of thrips (Table 4.4). The Pearson's correlation coefficients (*r*) were 0.289, 0.315, and 0.308, respectively. The number of days with a minimum of 0.3-inch amount of rain in May also had a significant positive correlation with the magnitude of thrips, having an R-value of 0.340. The cumulative rainfall in March had a *p*-value of 0.1670, close to the significance level cut-off of 0.15. Winter temperatures were not significantly correlated to the observed magnitude of thrips. The other weather parameters that were tested did not have a significant correlation with the observed magnitude of thrips, as shown in Table 4.4.

Spotted wilt intensity vs magnitude of thrips

The result of the regression analysis was presented in Figure 4.4 and showed a positive relationship between spotted wilt intensities (logit transformed) observed at the high-risk situations and the log-transformed magnitude of thrips (p= 0.03). The observed magnitude of tobacco thrips accounted for 38.97% of the variation in the spotted wilt intensity at the high-risk situations across six locations over 2017 and 2018 (Figure 4.4).

Correlation weather data with spotted wilt intensity

The intensity of spotted wilt observed in on-station field trials had a significant negative correlation with the minimum, average, and maximum temperatures in March and April (Table 4.5). While the minimum temperature in February had positive correlation with spotted wilt, the maximum temperature was negatively correlated. The minimum, average, and maximum winter temperatures also had negative correlation with spotted wilt intensity with *r*-values of -0.2469, -0.2937, and -0.3204 respectively. The number of days with precipitation in March and April had a significant positive correlation with spotted wilt intensity. The *r*-values were 0.3778 and 0.3753, respectively. The amount of rainfall in the months of March and April did not have a significant correlation with observed spotted wilt intensity (Table 4.5). The number of days with a minimum of 0.3-inch rain in March, April, and May were positively correlated with observed spotted wilt with *r*-values of 0.1073, 0.4936, and 0.2538 respectively.

Assessment of TTRF and TIP tools in estimating the peak of thrips dispersal over the period from April 1 to May 30

The TTRF and TIP tools were assessed in estimating the peak of thrips dispersal based on the criterion that the peak of thrips dispersal is considered to be closely estimated if the observed peak was within seven days before or after the predicted peak of thrips dispersal. The observed peak refer to the sampling date when the greatest number of tobacco thrips were captured in aerial thrips traps. Both the TTRF and TIP tool were able to closely estimate the peak of thrips dispersal in 15 out of 25 observations based on aerial thrips traps in southern Georgia (Tables 4.2 and 4.3). When compared in terms of providing location and year specific predictions of peak of thrips dispersal, the TIP tool provided a more specific predictions than did the TTRF tool. In 2014, the TTRF tool predicted May 31, 2014 to be the peak of thrips dispersal in all locations. This was also observed in 2017 and 2018 where the TTRF tool predicted May 15 as the peak of thrips dispersal in all locations in both years. In comparison, the TIP tool predicted different dates of peak of thrips dispersal for each locations that were included in this study.

Discussion

The foundations of plant disease epidemiology and efficient disease management include identification, description, and quantification of the components of a disease cycle (Gent et al., 2013). Spotted wilt disease is caused by thrips-transmitted TSWV. Tobacco thrips (*F. fusca*) was found to be the dominant thrips species that transmit TSWV in the southeastern United States (Todd et al., 1995; Culbreath and Srinivasan, 2011). Transmission by thrips is the only known mode of spread of TSWV in the natural environment, which makes it important to account for the thrips vector in planning management strategies.

In peanuts, spotted wilt disease is managed using an integrated management approach in the southeastern United States. This integrated approach uses a combination of production practices that result in lower levels of risk to spotted wilt based on Peanut Rx (Kemerait et al., 2018). The Peanut Rx risk index, however, does not directly take into account the risk associated with the activities of the thrips vector. Being the only known vector and mode of spread of TSWV in the environment, it is important to search for ways to estimate the risk associated with the thrips.

This study was conducted to assess whether tools developed in North Carolina could be used as predictors of magnitude and peak dispersal of tobacco thrips in Georgia. It should be noted that the TTRF and TIP tools were developed especially for tobacco and cotton crops, respectively. This study was conducted to assess whether these tools could be used for peanuts in Georgia. Therefore, results from this study could add value to the TIP and TTRF tools if it is shown that they can be used for crops other than tobacco and cotton and beyond the boundaries of North Carolina.

Based on the comparison between predicted and observed magnitude of dispersing thrips populations, the TTRF tool overestimated the magnitude of thrips in peanut fields in Georgia (Table 4.1). Though regression analysis between predicted and observed values across locations, it was found that the TTRF tool predicted greater numbers of thrips in locations where lower numbers of tobacco thrips were captured in sticky traps (Figure 4.2). In contrast, the tool predicted a lower number of thrips in locations where an elevated number of tobacco thrips were captured. This would not have been a problem if the degree of overestimation was consistent across locations as this would be fixed by adjusting the model to fit Georgia conditions. However, the degree of overestimation of the magnitude of thrips population was not consistent in this study. It even underpredicted in Midville in 2017 where there was more number of thrips captured in aerial thrips traps.

It is important to note, however, that one of the factors that the TTRF tool accounts in estimating the magnitude of thrips population is the winter temperature. The winter of 2017 (December 2016 – February 2017) was warmer than the 12-year average winter temperatures from 2004 to 2016 in all the research stations where the study was conducted (Table 4.6). In 2018, however, the average winter temperatures did not differ much from the 12-year average. The warmer winter in 2017 could have resulted in overprediction of the magnitude of thrips population by the TTRF tool. However, this could not be established with the data in 2018 as the magnitude of thrips population was still over predicted even when the average winter temperatures were not far off with the 12-year average.

Nevertheless, this result does not invalidate the TTRF tool as it was developed for tobacco crops in North Carolina. The reason behind overestimation of the magnitude of thrips population may have been due to warmer winter temperatures in South Georgia compared to North Carolina where the TTRF tool was developed. More importantly, it should be noted that the TTRF was not designed to distinguish the magnitude of thrips population between locations according to Chappell (personal communication), one of the developers of the tool. It was designed to show a yearly trend in the magnitude of thrips population for each specific location. Moreover, the TTRF tool was developed for tobacco crops where *F.fusca* does not reproduce whereas, in peanuts, *F.fusca* can reproduce. As this study was conducted in peanut fields, it is possible that the different host plants available in the natural environment also influenced the population dynamics of the thrips. This was supported by the result of greenhouse study where *F. fusca* oviposited significantly more eggs in chickweed than tomato (Chaisuekul, 2004). Thus, while the TTRF tool did not closely predict the magnitude of thrips population in peanuts fields as seen in this study, it could have worked well in tobacco fields in Georgia. Tool also was not developed for Georgia where number of thirps generations and potential for continuous population development through the winter is expected to be different from in

North Carolina. Therefore, it is not appropriate to use the TTRF tool in differentiating the magnitude of thrips populations between different locations or peanut fields in Georgia. For this reason, it is determined that the TTRF tool at its current form cannot be adapted to determine which peanut field has greater or lesser magnitude of thrips population. Future work may be conducted to determine a way to adjust the model to make it work for the purpose of differentiating magnitude of thrips between different peanut fields or locations.

Factors other than the weather parameters accounted for by the TTRF tool may also have influenced the number of dispersing thrips observed in this study. For example, it has been shown that availability of pine pollen increased the oviposition rate of *F. occidentalis* and *F. fusca* (Riley et al., 2007). As pine trees are abundant in southern Georgia, it is possible that the pollen from these trees also influenced the population of thrips in the environment. In another study, it was observed that *F. fusca* oviposited significantly more eggs in chickweed than tomato (Chaisuekul, 2004). These examples are indication that differences in vegetation between locations, for example between North Carolina and the Coastal Plain of Georgia, could influence the population dynamics of thrips.

The estimated magnitude of thrips population based on the TTRF tool was used in developing Peanut Rx 2.0 and this addition was intended to more accurately account for disease pressure at specific locations. The lack of ability to closely estimate the magnitude of thrips across locations has likely contributed to some degree to the failure of Peanut Rx 2.0 in closely predicting spotted wilt intensity. Future studies may be conducted to adjust the TTRF tool based on thrips data from Georgia to be able to get more accurate predictions of the magnitude of thrips populations.

A correlation analysis between the magnitude of thrips population and weather parameters was conducted where a *p*-value of 0.15 was used as a cut off for significance. This significance cut-off was also used in previous studies on tobacco thrips (Morsello et al., 2010). According to Morsello et al. (2010), the correlation analysis significance cutoff of $p \leq 0.15$ is the standard minimum significance cutoff that allows examination of variables that may have explanatory power to the variation in the response variable.

Results of correlation analysis showed a positive correlation between the observed magnitude of thrips population from April 1 to May 31 and temperatures in February (Table 4.4). This was consistent with previous studies where increasing temperature resulted in increased thrips activity, development, and population growth up to the point where winter hosts began to senesce (Lowry et al., 1992; Kirk, 1997).

The number of days with a minimum of 0.3-inch rain in May was also positively correlated with the magnitude of thrips population. A threshold of 0.3-inch rain was used in this study based on earlier observations that this amount of rain could suppress the flight of thrips (L. Wells, personal communication). While it is known that rainfall can cause mortality to immature thrips and suppress flight of adult thrips, this result indicates that the number of rainy days had more of a positive effect on the thrips. According to Morsello and Kennedy (2009), the degree of population suppression by precipitation depends on timing, amount, and duration of precipitation events. The positive correlation of magnitude of thrips population and rain events in May was consistent with reports by Davidson and Andrewartha (1948) that rainfall can positively influence thrips populations by providing adequate soil moisture which foster plant growth and enhancing pupal survival.

Temperatures during the winter (December of previous year to February of current year) and the amount of precipitation in March did not have a significant correlation with the observed magnitude of thrips. This has likely contributed to inability of the TTRF tool in predicting the magnitude of thrips population in the locations included in this study. In the TTRF tool, it is assumed that the average winter temperature has positive effects, while March precipitation has a negative effect on thrips population and the amount of TSWV inoculum (Chappell et al., 2013). Winter temperatures are known to affect the abundance and persistence of annual winter weeds as well as the population dynamics of thrips. March precipitation is known to cause mortality to juvenile thrips as well as suppress the dispersal activity of adult thrips, thus reducing the transmission intensity.

While the correlation between the observed magnitude of thrips population and winter temperature was not significant, the Pearson's correlation coefficient value was positive which is consistent with the assumptions of the TTRF tool. Likewise, while March precipitation did not have a significant correlation with the observed magnitude of thrips population, the p-value (0.1670) was close to the significance level cut-off. More importantly, it had a negative correlation coefficient indicating a negative effect on the magnitude of thrips population and is consistent with TTRF assumptions. Therefore, it is possible that adjustments could be done to make the TTRF tool work well in Georgia conditions.

Nonetheless, the varying number of thrips captured on sticky traps could have been influenced by many factors beyond weather, including trap attractiveness relative to surrounding vegetation, host plant composition, thrips population size and proportion of the population that is dispersing, behavior, and agricultural practices (Morsello et al., 2008). Further studies are therefore necessary to determine whether factors other than the weather are more important determinants of thrips population in Georgia.

There was a significant positive relationship between the observed magnitude of thrips and observed spotted wilt intensity at the high-risk situations in the on-station field trials (Figure 4.4). An elevated spotted wilt intensity was observed in the location where a greater magnitude of thrips population was recorded based on insect traps. This was consistent with the result of a study conducted in North Carolina, where a strong positive relationship between final TSWV incidence and abundance of *F. fusca* was observed (Morsello and Kennedy, 2009). Further, in a study conducted on cultivated tobacco, it was found that spotted wilt incidence during the summer was influenced by weather affecting thrips activity (Chappell et al., 2013). Thus, a portion of this study investigated whether the correlation of weather parameters to the intensity of spotted wilt was consistent with correlation with the observed number of thrips caught from aerial traps. If so, the weather parameters that both influence the magnitude of thrips populations and the intensity of spotted wilt intensity could help in understanding the variation of spotted wilt epidemics between different geographic locations.

The minimum, maximum, and average temperatures during the winter (December to February) and monthly minimum, maximum, and average temperatures in February, March and April showed a negative correlation with the intensity of spotted wilt disease

(Table 4.5). This was not as expected because the temperature in the winter and in February alone had a positive correlation with the observed number of thrips (Table 4.4). This is because greater number of thrips likely would have resulted in greater intensity of spotted wilt as observed in Figure 4.4. In tomatoes in North Carolina, it was observed that the monthly average air temperature for December to February had a positive association with losses due to spotted wilt disease (Mila, 2011). However, this negative correlation between temperature and spotted wilt intensity could be related to temperature effects on overwintering hosts. In the study by Morsello et al. (2008), warm temperatures during late April and May favor continued growth of *F. fusca* populations but also hasten senescence of winter annual host plants, which results in an increase in dispersal followed by a rapid decline despite further degree-day accumulation. This was consistent with the negative correlation between spotted wilt intensity and temperatures in March and April in this study. Hence, it is possible that the thrips could have dispersed earlier, before the peanuts were planted, which could have led to a lesser number of dispersing thrips after planting. Transmission of TSWV by thrips is the only known means of TSWV spread in the natural environment. It is possible that when peanuts were exposed to fewer numbers of viruliferous thrips the resulting intensity of spotted wilt could also be lower.

There was a significant positive correlation between spotted wilt intensity and the number of days with precipitation in March and April. However, the cumulative amount of rainfall during these months did not have a significant correlation with spotted wilt. The number of days with a minimum of 0.3-inch precipitation during the months of March, April, and May was also positively correlated with spotted wilt intensity. This was consistent with the finding of Olatinwo et al. (2009) that high spotted wilt intensity was associated with the occurrence of frequent rainy days in March. In relation to the thrips vector, frequent rains that delay senescence of host plants can also result in higher total thrips populations by prolonging the period of population growth (Morsello, 2007). It was also found in this study that the number of days with a minimum of 0.3-inch precipitation in May was also positively correlated with the observed number of thrips (Table 4.4). Thus, it is possible that the number of rainy days favored population growth of thrips subsequently resulting in a greater magnitude of dispersing thrips that transmit TSWV into the peanut crops. Consequently, the observed intensity of spotted wilt was higher.

These results show the importance of accounting for the magnitude of dispersing thrips in understanding the epidemiology of spotted wilt disease. However, it was also shown that predicting the magnitude of thrips was challenging because many other environmental factors, not accounted for by the predictive tool, could influence it. Thus, until a tool that closely predicts the magnitude of thrips in Georgia is developed, other means of accounting for the thrips vector such as the timing of peak dispersal, should be considered.

In a study conducted in Virginia, the period of peak dispersal of tobacco thrips was shown to be critical in the management of spotted wilt disease in tomatoes. It was found that the incidence of spotted wilt in tomato fields was more prevalent in the spring crop than in the fall tomato crop (Nault et al., 2003). It was suggested that the less prevalent spotted wilt infection in fall-grown tomatoes was due to fewer spotted wilt inoculum sources, such as winter annuals, harboring vector species and significantly reduced flight activity of *F. fusca* during the summer (Nault et al., 2003; Groves et al., 2001; Groves et al., 2002). Hence, it is important to identify the critical periods of *F. fusca* adult dispersal and TSWV movement from weeds into crops for designing and implementing appropriate spotted wilt management strategies. Peanuts are usually planted between April to June of each year in South Georgia. Because the peak of thrips dispersal was known to occur within this period (Reitz, 2002), tools that can predict the thrips dispersal pattern such as the TTRF and TIP tools can be a useful tool that can help growers to identify and avoid the risks associated with dispersing thrips.

In terms of predicting the peak of thrips dispersal, the TTRF tool closely predicted the peak of thrips dispersal in 15 out of 25 observations. However, the predicted peaks of thrips dispersal were the same across different locations in 2014, 2017, and 2018. Having the exact same predicted peak across locations over both years was a bit troubling and may not be useful in differentiating when this period occurs between different locations. It is possible that the differences in winter and spring temperatures between the study locations were not big enough to be captured by the TTRF tool in order to provide a better location-specific prediction of thrips peak dispersal. All locations included in this study were in southern Georgia where peanuts are grown. When the TTRF tool was run for the northern most part of Georgia, with colder winters, the peaks were different from the predicted peak of thrips dispersal in southern Georgia.

Studies conducted in North Carolina have found that there was considerable spatial and temporal variation in *F. fusca* dispersal from winter hosts to crops and summer hosts each year. Significant dispersal by *F. fusca* from winter hosts begins in late March or early April and dispersing populations may peak in late May but more typically in June (Groves et al., 2001, 2003; Morsello et al., 2008). Therefore it is important to be able to predict the spatial and temporal variation in *F. fusca* dispersal in order to have a better understanding of the epidemiology of spotted wilt disease. This information may help to explain the space and time variability in spotted wilt intensity.

When the TIP tool was used in predicting the peak of thrips dispersal, the observed peaks were closely predicted in 15 out of 25 observations (Table 4.3). Unlike the TTRF tool, the TIP tool predicted a specific peak of thrips dispersal for each locations and for different years. Specific predictions for each location from one year to another was a piece of valuable information that can be used to distinguish risks associated with the thrips between locations and from one year to another. Therefore, the TIP tool is considered a reliable tool in predicting the peak of thrips dispersal in peanut fields in Georgia. With the ability to provide information on the pattern and peak of thrips dispersal for each location, the TIP tool could provide the growers with research-based information upon which to make management decisions. The predicted peak of thrips dispersal is a piece of important information that could be integrated into Peanut Rx to provide growers with a better tool to assess the risk of spotted wilt disease that accounts for the thrips vector.

Summary and Conclusion

This study was conducted to assess whether predictors of tobacco thrips population and dispersal patterns developed in North Carolina can be utilized in peanut fields in Georgia. For predicting the magnitude of tobacco thrips, the TSWV and Thrips Risk Forecasting (TTRF) tool was assessed by comparing the predicted and observed number of thrips from April 1 to May 31. The result did not show a promising prediction of the magnitude of thrips population. There was no consistency in the degree of overprediction of the magnitude of thrips population. However, it should be noted that that the TTRF was not designed to distinguish the magnitude of thrips population between locations. Instead, it was designed to show a yearly trend in the magnitude of thrips population for each specific location. Moreover, the TTRF tool was developed for tobacco crops. As this study was conducted in peanut fields, it is possible that the different host plants available in the natural environment also influenced the population dynamics of the thrips.

Based on the result of correlation analysis, there was a contradicting correlation of winter and monthly temperatures with the number of thrips and the observed spotted wilt intensity across locations and years. For example, the temperatures during winter and in February had a positive correlation with the observed magnitude of thrips but was negatively correlated with spotted wilt intensity. This showed the complexity in establishing the effect of weather parameters to thrips and spotted wilt disease.

The predicted peak of thrips dispersal, between April 1 to May 31, from the TTRF and TIP tools, were compared with the observed peak based on sampling date when the most number of *F. fusca* were captured from aerial traps. The TTRF tool closely predicted the peak period of thrips dispersal but the predicted peak was the same for all locations in 2017 and 2018. The TIP tool, on the other hand, provided location-specific predictions of peak thrips dispersal for each location per year. The TIP tool could be used to provide information on the timing of peak thrips dispersal to help the growers plan and implement management programs to avoid yield losses.

In conclusion, the TTRF tool cannot be used to identify which peanut field will have a greater or lesser magnitude of thrips population. In terms of predicting the peak of thrips dispersal, the TIP tool was considered to be a better tool than TTRF in terms of being sensitive enough to distinguish peaks of thrips dispersal between locations and years. As the predicted peak of thrips dispersal from the TIP tool differed between location and years integrating it into Peanut Rx risk index would also provide a risk assessment of spotted wilt disease that includes information on location, year, and thrips vector.

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Figures and tables

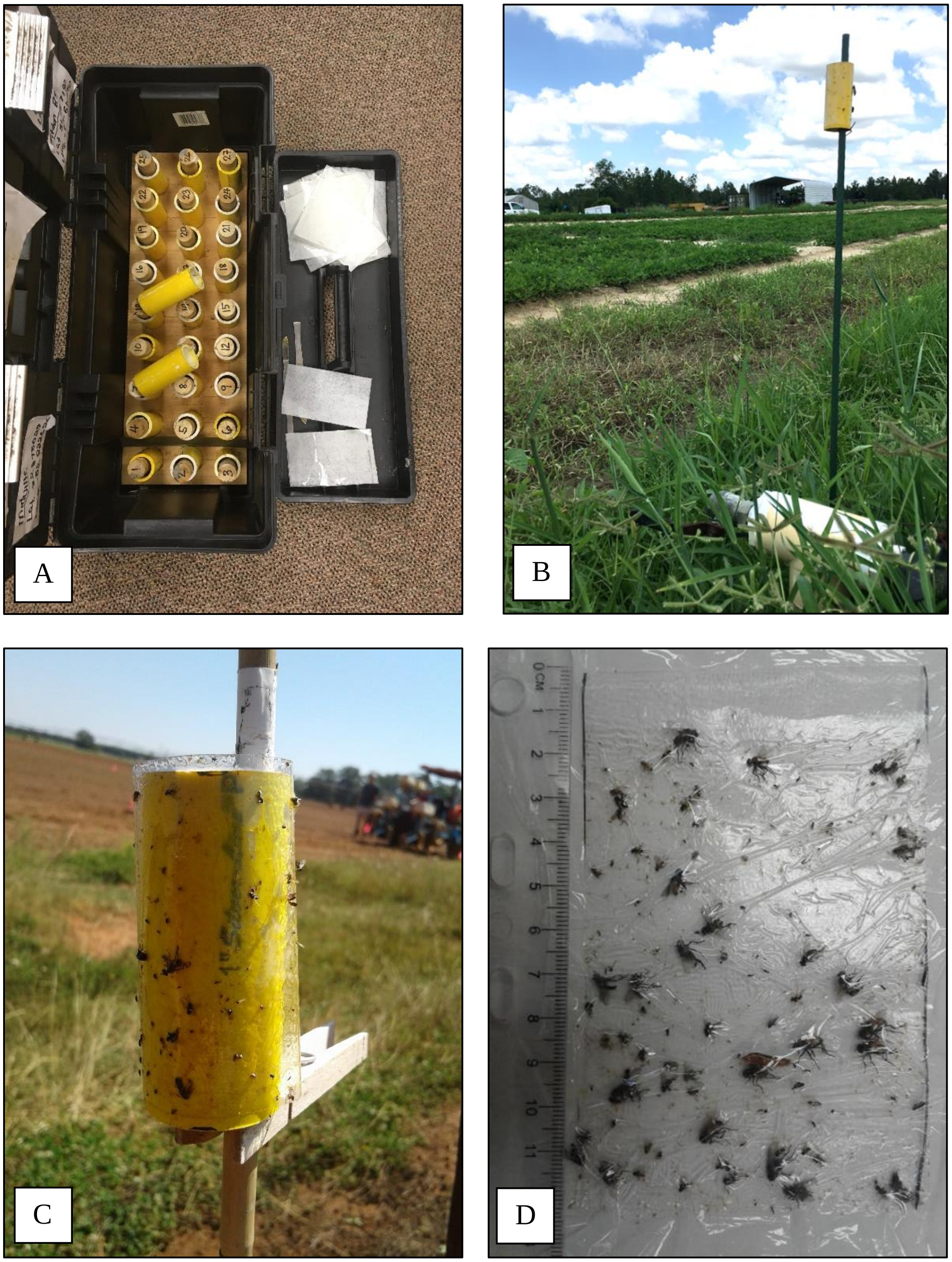

Figure 4.1. Aerial thrips trap. A.) A “Trap box” made of a toolbox fitted with a board with wooden pegs to hold the thrips traps during transportation; B.) Aerial thrips trap suspended in a 1m garden stake; C.) Yellow painted PVC pipe wrapped with a sticky plastic, sticky side out; D.) Sticky trap place into a clear plastic wrap, sticky side down

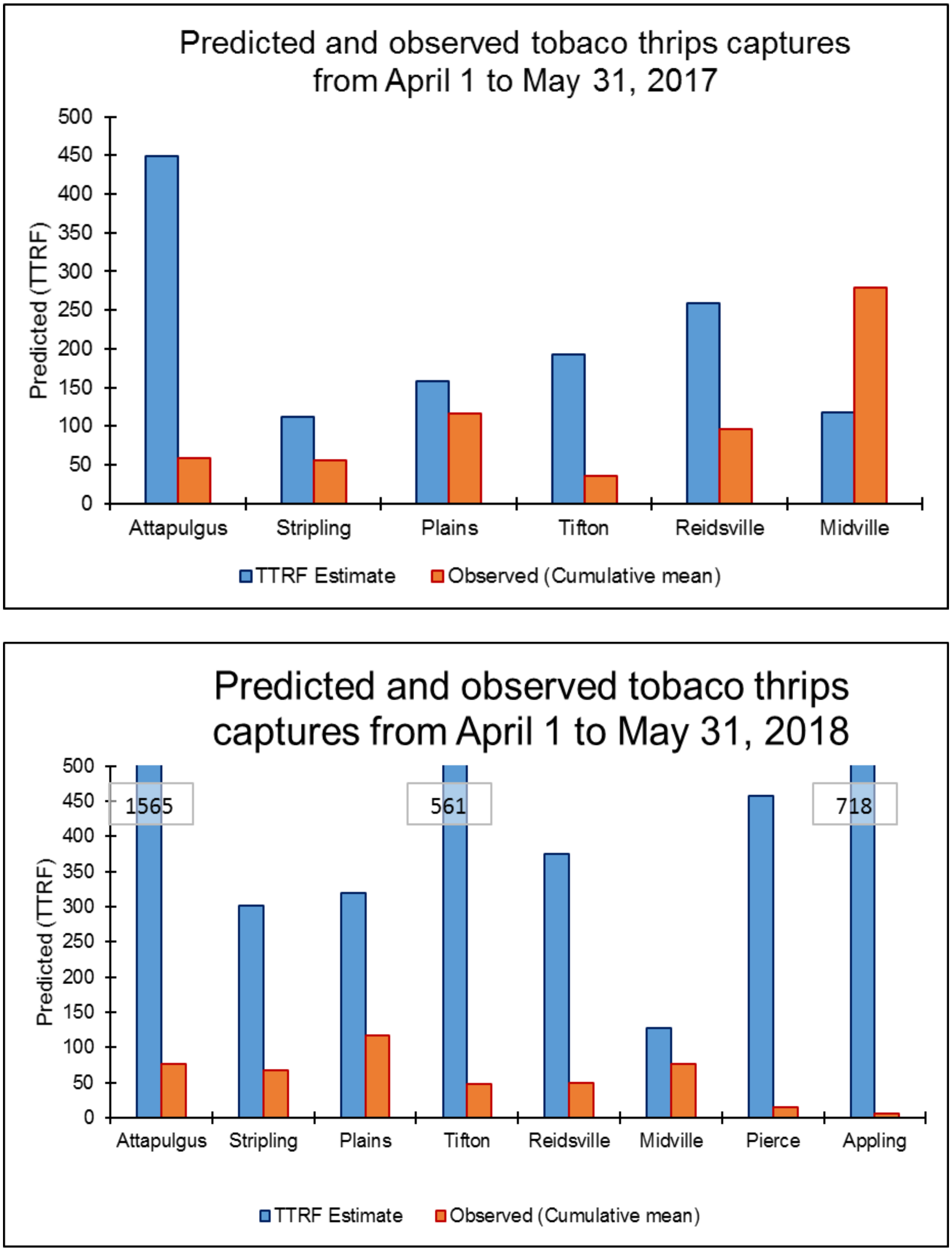

Figure 4.2. Predicted and observed number of tobacco thrips captured per sticky trap from April 1 to May 31 in 6 locations in 2017 and in 8 locations in 2018.

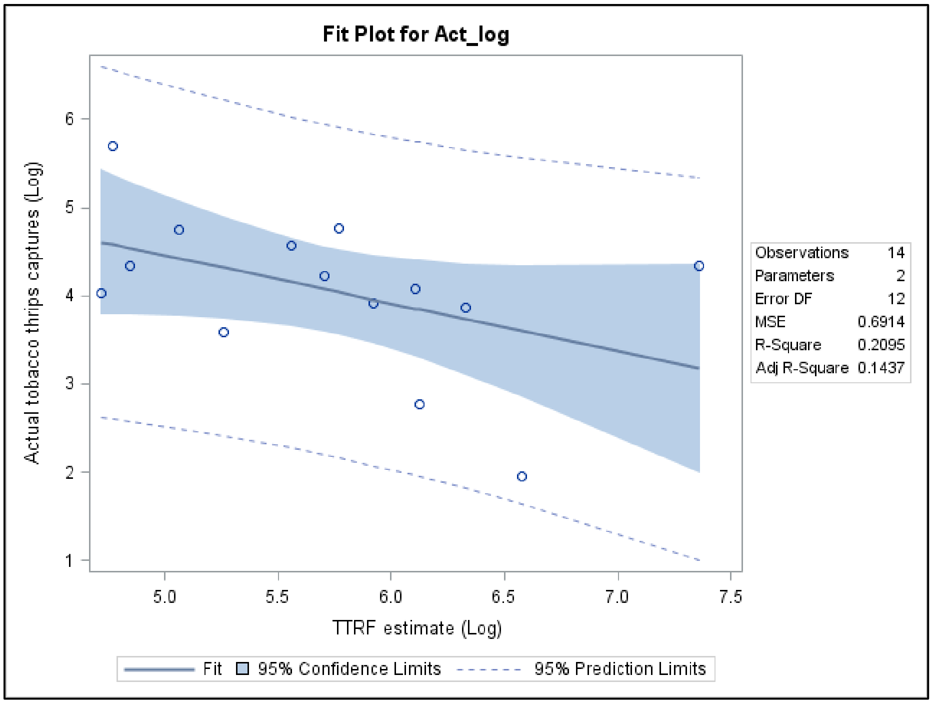

Figure 4.3. Regression of log transformed tobacco thrips counts and estimates from the TTRF tool (F=3.18, Pr > F= 0.0998).

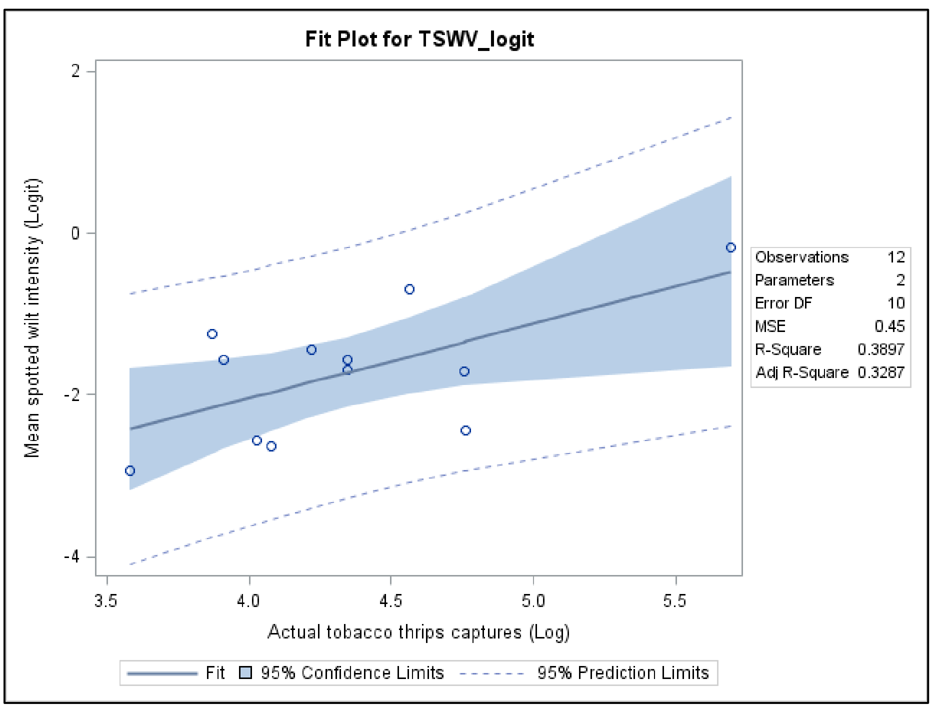

Figure 4.4. Regression of logit-transformed spotted wilt intensity and tobacco thrips counts in six locations in 2017 and 2018 (F=6.39, Pr > F= 0.0300).

Table 4.1. Predicted and observed total thrips captures per sticky trap from April 1 to May 31.

LOCATION	YEAR	Cumulative mean number of tobacco thrips from April 1 to May 31	
		TTRF Estimate	Observed
Attapulgus	2017	449	59
Stripling	2017	112	56
Plains	2017	158	116
Tifton	2017	192	36
Reidsville	2017	259	96
Midville	2017	118	279
Attapulgus	2018	1565	77
Stripling	2018	301	68
Plains	2018	320	117
Tifton	2018	561	48
Reidsville	2018	374	50
Midville	2018	127	77
Pierce	2018	457	16
Appling	2018	718	7

Table 4.2. Observed and predicted peak of thrips dispersal based on the TSWV and Thrips Risk Forecasting (TTRF) tool for tobacco

County	**Peak of thrips dispersal**		**Difference (days)**
	TTRF Estimate	**Observed**	
Worth	May 31, 2014	May 28, 2014	-3
Mitchell	May 31, 2014	May 28, 2014	-3
Decatur	May 31, 2014	May 21, 2014	-10
Brooks	May 31, 2014	May 28, 2014	-3
Colquitt	May 31, 2014	May 28, 2014	-3
Tift	May 31, 2014	May 28, 2014	-3
Worth	May 15, 2015	May 15, 2015	0
Mitchell	May 1, 2015	May 15, 2015	14
Decatur	May 1, 2015	May 15, 2015	14
Brooks	May 15, 2015	May 31, 2015	16
Tift	May 1, 2015	May 15, 2015	14
Worth	May 15, 2017	May 18, 2017	3
Mitchell	May 15, 2017	May 4, 2017	-11
Decatur	May 15, 2017	April 20, 2017	-25
Brooks	May 15, 2017	May 11, 2017	-4
Colquitt	May 15, 2017	May 4, 2017	-11
Tift	May 15, 2017	May 18, 2017	3
Appling	May 15, 2018	May 23, 2018	8
Decatur	May 15, 2018	May 14, 2018	-1
Mitchell	May 15, 2018	May 14, 2018	-1
Sumter	May 15, 2018	May 16, 2018	1
Tift	May 15, 2018	May 14, 2018	-1
Tattnall	May 15, 2018	May 11, 2018	-4
Burke	May 15, 2018	May 17, 2018	2
Pierce	May 15, 2018	May 23, 2018	8

Table 4.3. Observed and predicted peak of thrips dispersal based on the Thrips infestation Predictor (TIP) tool for cotton

County	Peak of thrips dispersal		Difference (days)
	TIP Estimate	Observed	
Worth	May 28, 2014	May 28, 2014	0
Mitchell	May 28, 2014	May 28, 2014	0
Decatur	May 20, 2014	May 21, 2014	1
Brooks	May 20, 2014	May 28, 2014	8
Colquitt	May 23, 2014	May 28, 2014	5
Tift	May 28, 2014	May 28, 2014	0
Worth	May 21, 2015	May 15, 2015	-6
Mitchell	May 18, 2015	May 15, 2015	-3
Decatur	May 10, 2015	May 15, 2015	5
Brooks	May 12, 2015	May 31, 2015	19
Tift	May 20, 2015	May 15, 2015	-5
Worth	April 28, 2017	May 18, 2017	20
Mitchell	April 21, 2017	May 4, 2017	13
Decatur	April 20, 2017	April 20, 2017	0
Brooks	April 20, 2017	May 11, 2017	21
Colquitt	April 21, 2017	May 4, 2017	13
Tift	April 29, 2017	April 6, 2017	-23
Appling	May 15, 2018	May 23, 2018	8
Decatur	May 9, 2018	May 14, 2018	5
Mitchell	May 11, 2018	May 14, 2018	3
Sumter	May 22, 2018	May 16, 2018	-6
Tift	May 16, 2018	May 14, 2018	-2
Tattnall	May 15, 2018	May 11, 2018	-4
Burke	May 25, 2018	May 17, 2018	-8
Pierce	May 11, 2018	May 23, 2018	12

Table 4.4. Probability values and Pearson's correlation coefficients (r) from correlation analysis of log-transformed number of thrips captured from April to May with weather factors

Factors	P-value	Pearson's R
Maximum winter temperature	0.3524	0.17285
Minimum winter temperature	0.2333	0.22049
Average winter temperature	0.2962	0.19381
Maximum temperature in January	0.4538	-0.13961
Minimum temperature in January	0.4321	-0.14634
Average temperature in January	0.4462	-0.14195
Maximum temperature in February	**0.0847**	**0.31466**
Minimum temperature in February	**0.1145**	**0.28925**
Average temperature in February	**0.0914**	**0.30846**
Maximum temperature in March	0.9679	0.00753
Minimum temperature in March	0.6122	-0.09473
Average temperature in March	0.7930	-0.04913
Maximum temperature in April	0.6088	0.09564
Minimum temperature in April	0.3067	-0.18973
Average temperature in April	0.7828	-0.0516
Number of days with temperatures favorable for thrips flight in March	0.8037	0.04654
Number of days with temperatures favorable for thrips flight in April	0.3133	0.18719
Number of days with temperatures favorable for thrips flight in May	0.4447	0.14242
Rainfall in January	0.1788	0.24787
Number of rainy days in January	0.4928	-0.12794
Rainfall in February	0.7355	-0.06321
Number of rainy days in February	0.8737	0.02976
Rainfall in March	0.1670	-0.25455
Number of rainy days in March	0.6036	-0.09701
Rainfall in April	0.1704	-0.25258
Number of rainy days in April	0.2774	-0.20133
Number of days with minimum of 0.3 inch of rain in January	0.3277	0.18177
Number of days with minimum of 0.3 inch of rain in February	0.5487	-0.11197
Number of days with minimum of 0.3 inch of rain in March	0.2006	-0.23632
Number of days with minimum of 0.3 inch of rain in April	0.6624	-0.08163
Number of days with minimum of 0.3 inch of rain in May	**0.0610**	**0.34038**

Table 4.5. Probability values and Pearson's correlation coefficients (Pearson's R) from correlation of logit-transformed spotted wilt intensity with weather parameters.

Weather Parameters	P-value	Pearson's R
Minimum winter temperature	<.0001	-0.2469
Average winter temperature	<.0001	-0.2937
Maximum winter temperature	<.0001	-0.3204
Minimum temperature in February	0.0214	0.0969
Average temperature in February	0.1395	-0.0623
Maximum temperature in February	<.0001	-0.3115
Minimum temperature in March	<.0001	-0.3414
Average temperature in March	<.0001	-0.3160
Maximum temperature in March	<.0001	-0.2852
Minimum temperature in April	0.0016	-0.1328
Average temperature in April	0.0003	-0.1527
Maximum temperature in April	<.0001	-0.1682
Rainfall in March	0.7228	-0.0150
Number of rainy days in March	<.0001	0.3778
Rainfall in April	0.2159	0.0522
Number of rainy days in April	<.0001	0.3754
Number of days with minimum of 0.3 inch of rain in March	0.0108	0.1073
Number of days with minimum of 0.3 inch of rain in April	<.0001	0.4936
Number of days with minimum of 0.3 inch of rain in May	<.0001	0.2538

Table 4.6. Average winter temperatures in six research stations where the study was conducted

Location	From December-1	To February-28	Average Daily Max Temperature °C	Average Daily Min Temperature °C	Average Daily Temperature °C
Attapulgus	12 year average (2004 - 2016)		17.52	4.85	10.88
	2016	2017	21.09	8.07	14.21
	2017	2018	17.85	6.53	11.82
Stripling	12 year average (2004 - 2016)		17.11	4.34	10.42
	2016	2017	20.67	7.78	13.85
	2017	2018	17.72	6.05	11.44
Midville	12 year average (2004 - 2016)		15.60	3.37	9.28
	2016	2017	18.57	6.61	12.22
	2017	2018	15.97	4.83	10.11
Plains	12 year average (2004 - 2016)		15.52	3.67	9.30
	2016	2017	19.07	7.01	12.70
	2017	2018	16.10	5.05	10.22
Tifton	12 year average (2004 - 2016)		16.36	5.39	10.72
	2016	2017	19.74	8.24	13.68
	2017	2018	16.77	6.48	11.40
Reidsville	12 year average (2004 - 2016)		16.57	4.87	10.48
	2016	2017	19.39	8.01	13.42
	2017	2018	16.78	6.23	11.17

CHAPTER 5

MODIFYING PEANUT Rx BY ADDING A THRIPS RISK FACTOR TO IMPROVE RISK PREDICTION OF SPOTTED WILT DISEASE IN PEANUTS[1]

[1]Codod, C.B., Kemerait Jr., R.C., Culbreath, A.K., Abney, M.R., Kennedy, G.G., Chappell, T.M. To be submitted to *Peanut Science*

Abstract

Spotted wilt disease, caused by the thrips-vectored *Tomato spotted wilt virus* (TSWV), is an important disease causing yield losses in peanuts in the southeastern United States. The Peanut Rx risk index was developed to help the growers to identify and implement combinations of production practices that can reduce severity of spotted wilt and protect against yield losses. However, Peanut Rx does not account for vector population dynamics and disease pressure. This study was conducted to determine if adding a ‘thrips risk factor’, based on the predicted peak of tobacco thrips dispersal from TIP tool, could improve the risk predictions of the Peanut Rx. On-station field trials and commercial field surveys were conducted in 2017 and 2018 across the peanut production region in Georgia. Late season intensity of spotted wilt was assessed using the hit-stick method. The relationship of the predicted peak of thrips dispersal periods from the TIP tool and observed spotted wilt intensity was examined by generating mosaic tables through frequency analysis. Based on this relationship, a ‘thrips risk factor’ was created and spotted wilt risk points were estimated. The ‘thrips risk factor’ was then integrated into Peanut Rx to develop a ‘modified Peanut Rx’. The ‘modified Peanut Rx’ was compared to Peanut Rx through simple linear regression, logistic regression, and ROC curves. Results from these analyses showed that the ‘modified Peanut Rx’ provided better risk assessment than Peanut Rx. The summed risk points from the ‘modified Peanut Rx’ provided greater R^2 values from the regression analysis and greater area under the ROC curve which indicated better accuracy than the Peanut Rx. Through addition of the ‘thrips risk factor’, the vector was accounted for and prediction of risk to spotted wilt disease in peanuts was improved.

Introduction

Spotted wilt disease of peanut, caused by the *Tomato spotted wilt virus* and vectored by thrips, continues to be an important disease of peanuts grown in the southeastern United States. In 2018, an estimated 3.5% yield loss due to spotted wilt was reported in peanuts grown in Georgia (The Peanut Grower, 2019). Yield losses of 3.5% and 3% were estimated previously in 2016 and 2017 (Kemerait et al., 2018).

A number of production practices associated with severity of spotted wilt disease have been packaged into a risk management tool. This was originally called the Spotted Wilt Risk Index by Brown, et al. (1996). The production practices found to add risk to spotted wilt disease include cultivar, planting date, plant population, insecticide usage, tillage, and Classic® herbicide application (Brown et al., 2005; Kemerait et al., 2016). A numeric weight was assigned to each factor so that an overall level of risk could be estimated. Higher point totals were indicative of higher levels of risk. With annual updates and integration of risk to fungal diseases, it was officially called the Peanut Rx risk index. While the production practices affect biological activities of thrips, this risk index does not directly account for the thrips vector and disease pressure in calculating risk to spotted wilt disease.

Transmission of TSWV by thrips vectors is the only known mode of spreading spotted wilt disease in natural epidemics. TSWV is transmitted by 9 species of thrips (*Thysanoptera*, *Thripidae*) in a persistent propagative manner (Wijkamp, 1995; German et al. 1992, Whitfield et al. 2005; Pappu et al. 2009; Riley et al., 2011). Tobacco thrips, *Franklinella fusca* (Hinds), and western flower thrips, *Frankliniella occidentalis* (Pergande) are the two common vectors of TSWV in peanut in the southeastern United

States. Of the two, *F. fusca* is considered the more important vector as it occurs in greater numbers and reproduces more efficiently on peanut foliage than does *F. occidentalis* (Todd et al., 1995, Todd et al., 1996). In North Carolina, *F. fusca* is often responsible for vectoring TSWV from weed species to susceptible crops (Groves et al., 2003). These findings documented the significance of *F. fusca* in the spotted wilt epidemics in the natural environment.

Outside of cropping seasons, when peanuts and other host crops are unavailable, winter weeds serve as host for both thrips and TSWV. Common species of winter weeds, such as leaf cudweed, dogfennel, and chickweed have been found to be infected by TSWV in Georgia (Mullis and Martinez-Ochoa, 2009). Volunteer peanut plants can also serve as an overwintering host to thrips and TSWV. Volunteer peanuts often emerge shortly after harvest in many fields and may survive much of the winter (Culbreath and Srinivasan, 2011). It has been suggested that the variation in the distribution, abundance, and seasonal senescence of these overwintering plant hosts may contribute to the observed differences in temporal patterns and timing of dispersal of *F. fusca* and TSWV spread among locations during the spring season (Groves et al., 2003). By influencing the population dynamics of thrips vectors, ground cover and vegetation at each location could indirectly influence the disease pressure and intensity of spotted wilt during the growing season.

The intensity of spotted wilt disease can vary based on annual weather conditions. For instance, in tomatoes, warm and dry conditions in the spring can lead to earlier and more severe problems with spotted wilt disease than do cool, wet springs. This is primarily associated with the thrips population in the environment. Thrips reproduce faster under warmer conditions, while rainfall can reduce the survival of immature thrips (Morsello and Kennedy, 2009; Chaisuekul, 2004, Riley et al., 2011). Thrips require a minimum temperature of 10.5ºC for development (McDonald, et al., 1999). When this temperature is reached at certain times of the year, thrips development increases. Temperature and precipitation vary across geographic locations. Such variation in temperature and precipitation could affect biological activities of thrips as well. Such would affect the magnitude of thrips dispersing and spreading TSWV into crop hosts, including peanuts.

The TSWV and Thrips Risk Forecasting (TTRF) tool, developed for tobacco crops in North Carolina, is a web-based forecasting tool that accounts for effects of weather and magnitude of thrips population in predicting spotted wilt. This tool has shown promising results as it accounted for up to 89.9% of the variability of spotted wilt observed in tobacco (Chappell et al., 2013). While the TTRF tool accounts for disease pressure based on the estimated magnitude of thrips population, it does not take into consideration the level of exposure to spotted wilt disease. An attempt to integrate this tool as a thrips predictive component into Peanut Rx was initiated in 2015 (Williams, 2015). Peanut Rx 2.0 model was developed by integrating the estimated magnitude of prior-year-thrips from the TTRF tool, winter temperature and March precipitation data with production practices from the Peanut Rx risk index. Results from this study provided a framework in which improved models can be developed to increase spotted wilt management in the southeast United States Peanut Rx explains levels of exposure to spotted wilt while the TTRF model accounts for disease pressure. For instance, with a given risk value from Peanut Rx, a grower can determine his predicted disease level given a certain level of disease pressure (Williams, 2015). However, in this manuscript, it was found that while the Peanut Rx 2.0 closely predicted lower levels of spotted wilt intensity, it under-predicted elevated levels of spotted wilt. Additionally, accurate prediction of the magnitude of thrips population is challenging as it could be influenced by factors other than the weather parameters accounted for by the TTRF tool. Moreover, the TTRF tool was not specifically designed to discriminate the magnitude of thrips between different peanut fields but to show yearly trends of the magnitude of thrips populations in a tobacco field. Thus, other means of accounting for the thrips vector to be integrated into Peanut Rx is of interest in this study.

The temporal patterns of *F. fusca* dispersal generally show an increase and peak between April to June as reported in eastern Virginia (Nault et al., 2003), and southern Georgia (Riley and Pappu, 2004). In a study conducted by Groves et al. (2003), the peak of crop susceptibility to TSWV infection coincided with the peak magnitude of migrating *F. fusca*. From this finding, a conceptual window of opportunity for *F. fusca* movement and subsequent spread of TSWV into and among the various plant hosts was illustrated. The potential window for the greatest spread of TSWV occurs from April to May when the magnitude of immigrating *F. fusca* is at its peak (Groves et al., 2003). Moreover, younger peanut plants were found to be more susceptible to TSWV (Shrestha et al., 2015; Mandal et al., 2001). Peanuts are planted starting April through June in Georgia. Thus, it is possible that the when young peanuts are growing during the peak of migrating thrips coincide, greater thrips feeding and TSWV infection would occur.

In North Carolina, a tool called “Thrips Infestation Predictor” was developed to predict risk to thrips injury in cotton. The risk is determined based on the potential overlap of high seedling susceptibility of cotton damage from thrips with the interval of peak tobacco thrips dispersal. The pattern of thrips dispersal over time is estimated by the TIP tool and is affected by winter and spring temperatures and precipitation. Thrips dispersal begins at a low level, reaches a maximum peak and then declines (Kennedy et al., 2017). As the thrips dispersal over time is estimated based on weather parameters without regard to crop, the tool could be used to predict tobacco thrips dispersal pattern for crops other than cotton, to include peanuts.

This study was conducted to address three objectives. The first objective was to investigate the relationship between the predicted peak of thrips and spotted wilt intensity observed in peanut. The second objective was to estimate spotted wilt risk points for predicted thrips peak periods based on the relationship with spotted wilt intensity that would be consistent with other risk categories found in Peanut Rx. Lastly, the third objective aimed to modify and then re-evaluate Peanut Rx after addition of ‘thrips risk factor’.

Materials and Methods

Spotted wilt data from on-station field trials

On-station field trials were conducted in 2017 and in 2018. The field trials were established at six research stations of the University of Georgia as follows: Attapulgus Research and Education Center (Attapulgus), C.M. Stripling Irrigation Research Park (Stripling), Southwest Georgia Research and Education Center (Plains), Black Shank Farm (Tifton), Southeast Georgia Research and Education Center (Midville), and Vidalia Onion and Vegetable Research Center (Reidsville). Different levels of risk based on

Peanut Rx were created based on three different planting dates (early, middle, late), two varieties (‘Georgia-06G’ and FloRun™ ‘157’ in 2017 and ‘Georgia-06G’ and TUFRunner™ ‘511’ in 2018), and phorate (Thimet® 20-G) insecticide application at each location. The specific planting dates per location and year were listed in Table 5.5.

The intensity of spotted wilt was assessed on a biweekly schedule using the “hit-stick method" as described by Culbreath et al. (1997). The number of 0.3m portions of a row containing symptomatic plants showing concentric ring spots, various patterns of chlorosis, and stunting was counted and converted to a percentage of row length. Skips (missing plants within a plot) due to seedling mortality from other diseases, planter equipment failure, and damage from pivot irrigation tracks were discounted from the total row length. The final spotted wilt ratings, taken near harvest, were used in this study.

Predicting peak of thrips dispersal using TIP tool

The peak of thrips dispersal was predicted using the Thrips Infestation Predictor (TIP) for cotton, http://climate.ncsu.edu/CottonTIP. For each location, the address or GPS coordinates and planting date were entered in the data entry page to run the TIP tool. The predicted date of the peak of thrips dispersal was derived from a subsequent line graph generated to estimate thrips dispersal over time.

Relationship of predicted thrips peak period and observed spotted wilt intensity

The relationship between spotted wilt intensity and the period when the peak of thrips was estimated to occur, based on TIP tool, was assessed. This was done using the frequency procedure in SAS 9.4. Spotted wilt data from on-station field trials was used in this analysis. The intensity of spotted wilt was categorized as <5%, 5-14%, and >14%. The peak period when thrips dispersal was estimated to occur was also categorized as follows: on or before April 15, April 16 to 30, May 1 to 20, and after May 20. Based on these categories of spotted wilt intensities and thrips peak periods, a mosaic table was produced to show the frequency of different levels of spotted wilt at each period when the peak of thrips dispersal was estimated to occur. The peak of thrips dispersal period will be referred to as the 'thrips risk factor' in the rest of this manuscript.

Assigning risk points for thrips dispersal peak periods

Spotted wilt risk points were assigned for the 'thrips risk factor' based on the relationship between thrips peak dispersal periods and levels of spotted wilt. The highest risk point value was assigned to the predicted peak of thrips dispersal period when a ≥15% spotted wilt intensity was most frequent. Conversely, the lowest risk point value was assigned to the predicted peak of thrips dispersal period when a ≥15% spotted wilt intensity was least frequent.

A general linear model analysis (PROC GLM, SAS 9.4) was conducted to test whether the risk points assigned to the 'thrips risk factor' had a significant effect to spotted wilt intensity ($p<0.05$). This analysis was conducted separately for spotted wilt data from on-station trials and from commercial field surveys. When the assigned risk points did not have a significant effect, the risk points were re-estimated, otherwise, the risk points were used for future analyses.

Two sets of risk points were tested. In the first set of risk points, 5, 15, 20, 10 spotted wilt points were assigned when the peak of thrips dispersal was predicted to occur on or before April 15, April 16 – 30, May 1 – 20, and after May 20 correspondingly. The second set of risk points was 10, 20, 30, and 15 spotted wilt points were assigned for each period of peak thrips dispersal, respectively.

Modification of Peanut Rx and calculating risk

The ‘thrips risk factor’ was integrated into Peanut Rx to develop a ‘modified Peanut Rx’. The spotted wilt risk points corresponding to each production practices accounted for in Peanut Rx such as planting date, variety, insecticide, tillage type, row pattern, and herbicide usage was retained. Spotted wilt points, 10, 20, 30, and 15 were added when the peak of thrips dispersal was predicted to occur on or before April 15, April 16 – 30, May 1 – 21, and after May 20, respectively.

Spotted wilt data from commercial field surveys

A statewide survey was conducted in 2017 and 2018 cropping seasons to assess the levels of risk and spotted wilt intensities in commercial peanut fields across the peanut production region of Georgia. One to 5 and 2 to 6 fields per county were surveyed in 2017 and 2018 respectively. These fields were identified based on differences in production practices with assistance from county agents. A total of 73 fields in 20 counties were surveyed in 2017. In 2018, a total of 83 fields in 21 counties were surveyed.

Information needed to calculate the Peanut Rx risk, to include planting date, variety, phorate (Thimet® 20G) application, and chlorimuron (Classic®) herbicide usage, was gathered from growers by the county agents. The type of tillage, row pattern and plant population were recorded during the actual field visits.

The intensity of spotted wilt near harvest season was assessed using the "hit-stick" method. In each field, four 15.24m arbitrary plots were designated, measured, and then flagged. Two rows per plot were rated for spotted wilt intensity in 2017 making a total of 30.48m row length per plot. In 2018, four rows per plot were assessed thus the total row length per plot was 60.96m. Skips or missing plants within a plot were discounted from the total row length.

Comparing the 'modified Peanut Rx' with Peanut Rx

On-station field trial data: spotted wilt intensity over 2 years analyzed per location. For this analysis, spotted wilt data collected in 2017 and 2018 were combined for each of 6 on-station field trial locations. The logit-transformed spotted wilt intensity per location was then regressed with the total risk points from Peanut Rx and 'modified Peanut Rx'. The *p*-values, R^2 values, and mean squared errors (MSE) were then summarized in Table 5.3.

On-station field trial and survey data: spotted wilt intensity combined across locations and over two years. To further compare the 'modified Peanut Rx' with the Peanut Rx, a regression analysis was done using spotted wilt data combined across locations and over years. The regression analysis was performed separately for data from the on-station field trials and commercial field surveys. Fit plots showing the relationship between spotted wilt intensity and total risk points were produced using the regression procedure in SAS 9.4. The R^2 and MSE values were compared between Peanut Rx and 'modified Peanut Rx'.

A logistic regression analysis was conducted to test the effects of planting date risk points, thrips risk points, and risk points from other factors with logit-transformed spotted wilt intensity. The analysis was performed using the PROC LOGISTIC function in SAS 9.4. Logistic regression was conducted separately for Peanut Rx (planting date risk points and risk points from other factors) and 'modified Peanut Rx' (planting date risk points, 'thrips risk points', and risk points from other factors). This analysis was also performed using data from the on-station field trials and commercial field surveys. The AIC values and *p*-values were used to compare Peanut Rx and 'modified Peanut Rx'.

From the logistic regression analysis, a receiver-operating characteristic (ROC) curve was produced from in this analysis to investigate the sensitivity and specificity of the Peanut Rx and the 'modified Peanut Rx'. A 15% threshold was assigned for spotted wilt intensity to be a positive test. The area under the ROC curve was compared between Peanut Rx and modified Peanut Rx.

Results

Relationship of predicted thrips peak period and observed spotted wilt intensity

The TIP tool predicted specific dates of peak thrips dispersal for each location in 2017 and 2018 (Table 5.1). In 2017, the TIP tool predicted earlier peaks of thrips dispersal beginning in mid-April to early-May depending on locations. While in 2018, the predicted peaks were within the month of May across locations. In 2017, the predicted peak of thrips dispersal was earlier in two on-station field trials located in southwest

Georgia. It was April 15 in Stripling and April 16 in Attapulgus (Table 5.1). The predicted peak of thrips dispersal was in late-April in Tifton (April 28) and Reidsville (April 25). Whereas, it was early May in Plains (May 2) and Midville (May 5). Midville is located in eastern Georgia. The predicted peak of thrips dispersal in 2018 was earlier in Attapulgus (May 9) and Stripling (May 11) (Table 5.1). It was May 16 in Tifton and May 15 in Reidsville. The predicted peaks of thrips dispersal were later in Plains (May 22) and in Midville (May 25).

Using spotted wilt data from on-station field trials, combined across locations and over years, a mosaic table was produced using the frequency procedure in SAS 9.4 (Figure 5.1). Fifteen percent or more spotted wilt intensities occurred at a greater frequency of 48% when the peak of thrips was predicted to occur between May 1 and 20. A spotted wilt of 15% or greater was defined in this study as the threshold of high spotted wilt intensity. This level of spotted wilt intensity (≥ 15%) occurred at lower frequencies of 20 and 27% when the predicted peak of thrips dispersal was between April 16 and 30, and after May 20, respectively. When the predicted peak of thrips dispersal was on or before April 15, ≥ 15% spotted wilt intensity was not observed.

The frequency of spotted wilt intensities, ranging from 5 to 14%, was the same when the peak of thrips dispersal period occurred between April 16 and 30 (43%), May 1 and 20 (43%), and after May 20 (44%) (Figure 5.1). This range of spotted wilt intensities occurred at a lower frequency when predicted thrips peak period was on or before April 15 (27%). For spotted wilt intensity lower than 5%, the frequency was lowest when the predicted peak of thrips was between May 1 and 20 (9%) and was greatest when the predicted peak was April 15 or earlier (73%).

Further, mosaic tables were also produced per planting period in the on-station field trials (Figures 5.2 – 5.4). This was done to determine whether the frequency of spotted wilt intensity at each predicted peak of thrips dispersal period vary by planting period. For the early-planted peanuts (prior to May 1), 15% or more spotted wilt intensities were most frequent when the predicted peak of thrips dispersal was between May 1 and 20 (Figure 5.2). It had a frequency of 61%. The frequency of 15% or more spotted wilt was 31% and 19% when the predicted thrips peaks were between April 16-30, and after May 20, respectively. This was not observed when the predicted peak was on or before April 15.

On the middle-planted (May 1 -25) and late-planted (after May 25) peanuts (Figures 5.3 and 5.4), spotted wilt intensities of 15% or more were still most frequent when the predicted peak of thrips dispersal was between May 1 and 20 and did not occur when the predicted peak of thrips was on or before April 15. However, a 15% or more spotted wilt intensity was more frequent when the peak of thrips dispersal was predicted to occur after May 20 in the middle planted (25%) and late planted (33%) compared to when the predicted thrips peaks were between April 16 and 30 in both planting periods.

This relationship between spotted wilt intensity and the predicted peak of thrips dispersal periods was confirmed by producing mosaic tables for the commercial field survey data (Figure 5.5). While 15% or more spotted wilt intensity was observed when predicted peaks of thrips dispersal were between April 16 and 30 (3%), and May 1 and 20 (5%), it was not observed when the predicted peak was on or before April 15 and after May 20. Further, 5-14% spotted wilt intensities were most frequent when the predicted peak of thrips was between May 1 and 20. While it was least frequent when the predicted peak of thrips dispersal was on or before April 15. On the other hand, less than 5% spotted wilt intensities were most frequent when the predicted peak of thrips was on or before April 15 and were least frequent when the predicted peak of thrips dispersal was between May 1 and 20.

Risk points for thrips dispersal peak periods

Based on the relationship of spotted wilt intensities and predicted thrips peak dispersal periods observed from the mosaic tables, two sets of risk points for TSWV, as from Peanut Rx, were assigned to the predicted peaks of thrips dispersal periods. In the first set of risk points, 5, 15, 20, 10 spotted wilt points were assigned when the peak of thrips dispersal was predicted to occur on or before April 15, April 16 – 30, May 1 – 21, and after May 20 correspondingly. The second set of risk points over the same peak periods was 10, 20, 30, and 15. Each of the sets of spotted wilt points, assigned to each thrips peak period had a significant effect on spotted wilt intensity in the on-station field trial data (Table 5.2). However, compared with the first set of spotted wilt points (5, 15, 20, and 10), the second set of points (10, 20, 30, and 15) accounted for more variation in the spotted wilt data based on the R^2 value (0.1818) from GLM analysis. It also had a lower mean squared error (MSE) of 0.8546.

The risk points were retested using the spotted wilt data from commercial field surveys (Table 5.2). The first set of points did not have a significant effect on the observed spotted wilt intensity (p = 0.0653) while the second set of risk points had a significant effect (p = 0.0302). Thus the second set of points (10, 20, 30, and 15) was used for the predicted peak of thrips dispersal periods which was termed as ‘thrips risk factor’ in this study.

Peanut Rx vs ‘modified Peanut Rx’

On-station field trial data: spotted wilt intensity over 2 years analyzed per location. The total risk points based on Peanut Rx had a significant positive linear relationship with (p<0.05) spotted wilt intensities observed in 5 out of 6 on-station field trial locations. In comparison, the total risk points based on ‘modified Peanut Rx’ had a significant positive linear relationship (p-value) with spotted wilt intensities observed in all 6 locations (Table 5.3). The R^2 values were greater and MSE were lower with the ‘modified Peanut Rx’ compared with the Peanut Rx. The slope parameter was positive in all locations for both Peanut Rx and ‘modified Peanut Rx’.

On-station field trial and survey data: spotted wilt intensity combined across locations and over two years. The ‘modified Peanut Rx’ and Peanut Rx were further compared using spotted wilt data from on-station field trials and from commercial field surveys, combined across locations and over two years. The logit transformed spotted wilt intensity was regressed to total risk points with and without additional risk points based upon predicted peak of thrips dispersal (Figures 5.6 and 5.7). The totaled risk points from the ‘modified Peanut Rx’ accounted for more variation of spotted wilt intensity in the on-station field trial data set with an R^2 value of 0.1720 compared with Peanut Rx which had an R^2 value of 0.0551. The MSE was lower with the ‘modified Peanut Rx’ (0.865) compared with Peanut Rx which had an MSE of 0.987. As for the spotted wilt data from commercial field surveys (Figures 5.8 and 5.9), the R^2 values and

MSE did not vary greatly between Peanut Rx (R^2 = 0.1226) and the 'modified Peanut Rx' (R^2 = 0.1251).

The effects of planting date risk points, thrips risk points, and risk points from other factors (variety, at-plant insecticide applied in-furrow, row pattern, tillage type, Classic® herbicide usage, and plant population) were tested through logistic regression analysis. Logistic regression is used to predict the effect of a series of explanatory variables on a binary response variable. The main benefit of using the logistic regression is to avoid confounding effects by analyzing the association of all variables together (Sperandei, 2013). The observed spotted wilt intensities combined across locations and over years and a threshold of 15% spotted wilt intensity was used in this analysis. This was done in an attempt to show how addition of the 'thrips risk' points could improve how much of the variability in spotted wilt intensity is accounted for by the risk points. Without accounting for the risk points for the 'thrips risk factor' the planting date points did not have a significant effect (p= 0.1539) on spotted wilt intensities observed in on-station field trials (Table 5.4). When the 'thrips risk' points was added in the logistic regression analysis, the effect of planting date points was significant (p= 0.0174) (Table 5.4). In addition, the 'thrips risk' points also had a significant p-value of <0.0001. Risk points from other factors had a significant effect (p< 0.0001) on the observed spotted wilt intensity across locations and years when the analysis was done with and without the 'thrips risk factor'.

For data from commercial field surveys, without including the 'thrips risk factor' in the logistic regression, planting date points and risk points from other factors had a significant effect to spotted wilt intensity. With the addition of thrips risk points, the effect to spotted wilt intensity of planting date points and risk points from other factors were significant as were the thrips risk points (Table 5.4).

For further comparison, receiver operating characteristic (ROC) curves were produced using the total risk points based on Peanut Rx and ‘modified Peanut Rx’. The area under the ROC curve was 0.665 for spotted wilt intensities rated from on-station field trials (Figure 5.10). With addition of risk points from the predicted peak of thrips dispersal in the ‘modified Peanut Rx’, the area under the ROC curve increased to 0.781.

Using the same analysis, ROC curves were also produced for spotted wilt data from commercial field surveys (Figure 5.11). The area under the ROC curve was 0.828 with Peanut Rx. With the ‘modified Peanut Rx’, the area under the ROC curve increased to 0.881.

Discussion

An integrated management approach was necessary for spotted wilt disease in peanuts as no single tool provided adequate control to this disease. A risk index, now called Peanut Rx, was developed based on the combination of genetic, chemical, and cultural practices to manage this disease (Brown et al., 2005; Culbreath and Srinivasan, 2011). This risk index is well known and widely used by peanut growers in Georgia and the southeastern United States. However, research continues to identify factors that influence the severity of spotted wilt disease in individual peanut fields (Kemerait et al., 2018). Identifying factors influencing severity of spotted wilt can be used to improve management strategies, to include the use of Peanut Rx, is important to keep the yield losses minimal. One way to potentially improve Peanut Rx is by integrating a factor that directly accounts for the thrips vector into the risk index.

The significance of thrips vectors, such as *F. fusca* and *F. occidentalis*, in the epidemiology of spotted wilt in several crops has been reported in many studies (Chappell et al., 2013; Culbreath and Srinivasan, 2011; McPherson et al., 2006; Morsello and Kennedy, 2009; Riley et al., 2011; Olatinwo et al., 2009). In the paper of Groves et al. (2003), the authors illustrated a conceptual “window of opportunity” for the best management of spread of TSWV by *F. fusca* among various plant hosts from April to May. In Georgia, the peak populations of *F. fusca* adults collected from peanut plants and vegetative terminal buds occurred at 10 - 20 days after planting in April (Todd et al., 1995). The reported peak population of *F. fusca* by Todd et al. (1995) coincided with the conceptual “window of opportunity” for thrips vector to spread TSWV among plant hosts. These studies have shown the significance of the period when the *F. fusca* populations are dispersing and subsequently carrying TSWV from infected overwintering hosts into crop hosts in the epidemiology of spotted wilt disease. It is therefore possible that by accounting for the period when thrips are actively dispersing and spreading TSWV into peanut crops, the Peanut Rx risk index could be improved to directly account for the thrips vector in addition to production practices.

In this study, earlier peaks of thrips dispersal were predicted in 2017 than in 2018 across the six research stations where the field trials were conducted. This could be due to warmer winter temperatures (December of previous year to February of current year) in 2017 than in 2018 in southern Georgia. The average winter temperatures (ºC) from December, 2016 to February 2017 were 14.21, 13.85, 13.68, 13.42, 12.70, and 12.22 in

Attapulgus, Stripling, Tifton, Reidsville, Plains, and Midville respectively. The average winter temperatures from December, 2017 to February, 2018 were lower at 11.82, 11.44, 11.40, 11.17, 10.22, and 10.11 ºC in the aforementioned locations, correspondingly. Moreover, the differences in temperatures could also be the reason why the predicted peaks of thrips dispersal were different between locations. This is because the development threshold for *F. fusca* is 10.5ºC. Egg and larval development occur whenever temperatures exceed the developmental threshold (Lowry et al., 1992; Groves et al., 2001). With warm temperatures and availability of winter annual weeds in late winter and early spring, *F. fusca* populations may increase rapidly and begin to disperse (Groves et al., 2001; Morsello & Kennedy, 2009). Therefore, in a single location, the peak of thrips dispersal is likely to occur earlier during years with warm winters like 2017. The peak dispersal will be later when winter temperatures are colder as the development rate of thrips is slower.

These findings demonstrate the usefulness of the TIP tool in predicting the peak of thrips dispersal in Georgia. The TIP tool appears to work well in Georgia as it provided specific predictions for each location and year in this study. Based on data from aerial thrips traps, the predicted peak of thrips dispersal based upon the TIP tool were close to the observed peaks. Therefore it seems that the TIP tool captures the differences in weather and other conditions that influence thrips dispersal among different locations and from one year to the next in Georgia. This tool could provide useful information in the timing and peak of thrips dispersal that growers can use to plan management strategies to avoid thrips damage and subsequent TSWV spread in their crop.

The concept of risk associated with peak thrips dispersal was used in the recently developed 'Thrips Infestation Predictor' (TIP) tool for cotton in North Carolina. Based on this tool, high risk to thrips injury in cotton is expected when the peak of thrips dispersal overlaps with the susceptible (seedling) stage of cotton (Kennedy et al., 2017). In peanuts, thrips injury occurs early in the growing season (Culbreath et al., 2003) and peanut seedlings were found to be more susceptible to TSWV (Shrestha et al., 2015; Taiz and Zeiger, 2010). Thus, the concept of risk associated with overlap between seedling susceptibility and peak of thrips dispersal could be used to understand more of the effect of planting date to the intensity of spotted wilt disease in peanuts.

One objective of this study was to investigate if a relationship exists between the predicted peak of thrips dispersal from the TIP tool and observed spotted wilt intensities. To conduct a frequency analysis, the predicted peak of thrips dispersal was categorized as follows: on or before April 15, April 16 to 30, May 1 to 20, and after May 20. The period on or before April 15 was considered a category to determine the levels of spotted wilt when the predicted peaks of thrips dispersal occurred earlier than the peanut planting period. This is because the ideal planting window for peanuts is between late April and late May in regards to yield potential (Tubbs, 2018). The period from April 16 to 30 was considered as another category because most of the early planted peanuts are being planted in this period. The period from May 1 to 20 was also considered as another category. This is because, it is the period when the peanuts planted prior to May up to mid-May are emerging out of the ground. This is an important period during the growing season because one to two week old peanuts were known to be more susceptible to TSWV (Shrestha et al. 2015). Moreover, it was observed in North Carolina that the typical peak of thrips dispersal occurred during the 19^{th} week of the year (Chappell, personal communication). The 19^{th} week of the year was May 8 – 14 in 2017 and May 7-13 in 2018. The last category of predicted peak of thrips dispersal in this study was after May 20. This was considered later than the typical peak of thrips dispersal in this study.

Further, the intensity of spotted wilt was categorized as <5%, 5-14%, and ≥15%. This categorization was made based on inspection of the on-station and commercial field survey data. While there were 181 observations with 15% or more spotted wilt intensity in on-station field trials, there were only 24 observations in the commercial field survey with at least 15% spotted wilt intensity. If this threshold was increased, the number of observations (sample size) will decrease. Thus, to allow enough sample size to be able to conduct frequency analysis in on-station and commercial field survey data, 15% or more spotted wilt intensity was considered as a category. According to Culbreath (personal communication) yield losses were observed when the intensity of spotted wilt was 20% or more in peanut variety 'Georgia Green'. However, there is currently no known threshold for spotted wilt intensity in new varieties such as 'Georgia-06G'. Thus for the purpose of having enough sample size, 15% was set as a threshold for the highest category of spotted wilt in this study as it is also close to the observed economic threshold level in 'Georgia Green'.

The lowest category of <5% was based on the overall average spotted wilt intensity as observed in commercial field surveys in 2017 (3.66 %) and 2018 (4.09 %) which were less than 5%. The other category, 5-14%, was the intermediate between the two categories of spotted wilt intensity previously mentioned.

Mosaic tables from the frequency analysis showed that the occurrence of 15% or more spotted wilt intensities within a test plot occurred more often when the predicted peak of thrips dispersal was estimated to occur from May 1 to 20 (Figures 5.1 – 5.5). This was observed when the frequency analysis was done based on data combined across locations and years in on-station field trials (Figure 5.1) and commercial field surveys (Figure 5.5). When the analysis was conducted per planting period in on-station field trials (Figures 5.2 - 5.4), a spotted wilt intensity of 15% or more were most frequent when the predicted peak of thrips dispersal was between May 1 and 20 regardless whether the peanuts were planted prior to May (early), between May 1 to 25 (middle), or after May 25 (late). This was consistent with previous result when the analysis was conducted based on combined data across locations and over years. While the late-planted peanuts were planted after the predicted peak of thrips dispersal, thrips dispersal was still occurring at lower levels after the peak, and consequently feeding and transmitting TSWV on emerging peanuts. This could be the reason why 15% or more spotted wilt intensities were still observed.

The period between May 1 and 20 coincides with the time when the early-planted peanuts are emerging from the ground. Peanuts planted prior to the peak of dispersing thrips are likely to be exposed to a greater number of thrips migrating from winter hosts. This could lead to more thrips feeding and inoculating TSWV on peanut plants, consequently resulting in greater spotted wilt intensity. This is likely to be the reason why there was a greater frequency of 15% or more spotted wilt intensity when the peak thrips period occurs between May 1 and 20 because it coincides with the period when peanut seedlings are prone to TSWV inoculation. According to Shrestha et al. (2015), inoculation of 1- to 2-week-old plants by TSWV-infected thrips resulted in higher spotted wilt incidence than when 4-week old peanut plants were inoculated. In the same study, the authors found that the TSWV N-gene copy number within an infected plant, as determined by qPCR, also decreased with plant age. In another study, the most susceptible stage for mechanical inoculation was 2-3 days after germination or 6-7 days after planting (Mandal et al., 2001). Therefore, the age of peanuts relative to planting date and the period when the peak of thrips dispersal is expected to occur could provide additional information in assessing the risk of spotted wilt disease.

Moreover, the occurrence of less than 5% spotted wilt within a plot was least frequent when the predicted thrips peak period was between May 1 and 20 but was most frequent when the predicted thrips peak period was April 15 or earlier. This is evidence that risk to spotted wilt intensity during the cropping season can be better understood by knowing when the peak of thrips dispersal is expected to occur. Also, it seems that the TIP tool is an effective means to predict the timing of the peak period.

An important part of this study was to look for ways to improve Peanut Rx by directly accounting for the thrips vector. Based on the relationship between spotted wilt intensity and the predicted peak of thrips dispersal periods, spotted wilt risk points were estimated for a possible new category to be added to Peanut Rx. Greater spotted wilt points, 30 and 20, were assigned within this new category when the predicted peak of thrips dispersal was between May 1 to 20, and April 16 to 30, respectively. While 15% or more spotted wilt intensities were observed within test plots when peaks of thrips dispersal were predicted to occur after May 20 in on-station field trials, such was not observed in the commercial field survey data. This is likely because peanut growers are generally careful to avoid planting into the high-risk conditions that were created for this study. Thus, lower risk points (15) were assigned for that period so that the risk points will apply for both experimental (field trial) and commercial situations. The lowest risk points (10) were assigned for a field when the peak of thrips dispersal was predicted to be earlier than April 16, as elevated spotted wilt intensities (15% or more) were not observed when the peak of thrips dispersal was during this period.

For simplicity, the predicted thrips peak dispersal periods were referred to as the ‘thrips risk factor’ in this manuscript. Estimating risk points to factors known to influence spotted wilt disease intensity has been done successfully before in creation of the Peanut Rx risk index. Numeric values were assigned so that higher point totals were indicative of higher levels of risk to spotted wilt disease (Brown et al., 2005). Additionally, the magnitude of risk points assigned to each factor in the Peanut Rx risk index is believed to represent the same magnitude of risk to spotted wilt across categories. A 10-point difference in two varieties is equal to a 10-point difference in planting date. In this way, the growers can get the same risk point total by using different combinations of production practices, given their own needs. For example, if a grower needs to plant in late April, he or she can still achieve a satisfactory point total by making adjustments to other parts of the index, such as selection of a more resistant variety (Kemerait et al., 2013). As for the ‘thrips risk factor’, the risk points estimated in this study may need to be adjusted so that the magnitude of the risk points would be the same with the other factors.

It is understood that there is an interaction between planting date and peak of thrips dispersal, but for the simplicity of the modified peanut Rx this interaction is largely ignored. As for other categories of Peanut Rx for example variety, plant population, and use of an in-furrow insecticide, the planting date and thrips peak dispersal periods are considered independently. This allows one to maintain the simplicity of peanut Rx and yet still include the increased risk to spotted wilt disease given the timing of the peak of dispersal as related to the peanut growing season. The utility of a disease risk index for growers is a combination of accuracy in predicting risk, simplicity in usage, and opportunity to adjust production practices to reduce disease.

In this study, the risk points assigned for each thrips peak period seemed at least initially appropriate as indicated by the significant effect on the observed spotted wilt intensity (Table 5.2). Integrating these spotted wilt points based on predicted thrips peak dispersal periods into Peanut Rx could improve risk assessments. This may be especially useful in accounting for the "lower" intensity of spotted wilt that often occurs even when a "high risk" situation is predicted using Peanut Rx. It should be noted, however, that the risk points assigned to the 'thrips risk factor' were based solely on relationship of the predicted peak thrips periods with observed spotted wilt intensity. The risk points assigned to each factor in the Peanut Rx were based on expert opinion informed by research findings and experience of experts. Spotted wilt points were assigned based on knowledge and observations of peanut experts from their studies. More importantly, the magnitude and range of points for each factor determine the relative importance of each factor to the severity of spotted wilt disease. For example, spotted wilt points for variety ranges from 5 to 30, while points for at-plant insecticide range from 5-15. This means that variety has a greater impact than insecticide in mitigating risk to spotted wilt disease in peanuts. Additionally, the same point difference in one category should have the same impact as in another. For example, the difference from using Thimet®-20G to using other insecticides is 10 points. This would have the same impact as going from a “5 point” variety to a “15 point” variety (Kemerait, personal communication). With this note, further studies may be necessary to assess whether the magnitude and range of spotted wilt points assigned to the ‘thrips risk factor’ reflect its importance relative to other factors accounted for in Peanut Rx. Nonetheless, the risk points assigned to the ‘thrips risk factor’ were shown to have a significant effect on the observed spotted wilt intensities in this study.

A ‘modified Peanut Rx’ was developed by integrating the ‘thrips risk factor’ into Peanut Rx. This was compared with Peanut Rx through regression analysis. It is known that the intensity of spotted wilt varies from one year to another (Culbreath et al., 2003). This is the reason why the data from on-station trials were analyzed per location over two years to investigate how much of this variation was accounted for by the ‘modified Peanut Rx’ compared with Peanut Rx (Table 5.3). In all locations the ‘modified Peanut Rx’ accounted for more variation in spotted wilt intensities than did Peanut Rx. When the data were analyzed across locations and over years, the ‘modified Peanut Rx’ accounted for three times more of the variation than was accounted for by Peanut Rx. This means that the ‘thrips risk factor’ allows the risk index to distinguish a “good” and a “bad” year relative to the when the peak of thrips dispersal is expected to occur. It also allows the ‘modified Peanut Rx’ to account for the variability of spotted wilt associated with different locations. This allows a flexibility to the growers in terms of their peanut production practices. A grower in a location during a year when the predicted peak of thrips dispersal is expected to occur on or before April 15 (lower risk point) may opt not to apply phorate insecticide or plant a less resistant but high yielding variety. On the other hand, if the peak of thrips dispersal was predicted to occur between May 1 and 20, the grower will have to be selective in his production practices, such as use of resistant varieties or application of phorate insecticide, to minimize the risk of spotted wilt disease. This was an improvement over Peanut Rx as it does not directly account for the thrips vector.

Peanut Rx is typically very good in that where “low risk” is predicted, low amounts of spotted wilt are observed. However, small amounts of spotted wilt are often observed even at highest risk predictions (Figure 5.6). Using the new, ‘modified Peanut Rx’, one can find that there were fewer cases of low levels of spotted wilt at the highest risk predictions (Figure 5.7). This shows that by accounting the vector through the ‘thrips risk factor’, the chances of having false positive predictions with the highest risk levels are reduced. False positive predictions are described in this study as having a predicted high risk to spotted wilt but the actual level of spotted wilt was low. With a better accuracy in predicting risk, the growers can plan and implement their management strategies accordingly.

From the commercial field survey data, the addition of the ‘thrips risk factor’ to Peanut Rx did not result in a huge improvement of the R^2 value (Figure 5.9). This was likely associated with smaller variability of spotted wilt intensities in commercial fields compared with the data from on-station field trials. Different levels of risk, from low to high, were purposely created in on-station trials which resulted in variable intensities of spotted wilt. From the survey data, it is clear that growers are already adhering to the lessons taught through Peanut Rx and are working to avoid “high risk” situations. Such was proof of the effectiveness of Peanut Rx being used in commercial peanut fields. However, with a wider range of risk values, as was created in on-station field trials, the ‘modified Peanut Rx’ accounted for more variation in spotted wilt intensities than did Peanut Rx. This is the reason why the ‘modified Peanut Rx’ is important as it can be used by growers in a wider range of risk levels based on different combinations of production practices.

Based on data from on-station trials, logistic regression analysis of the data combined across locations and years showed that the planting date points did not have a significant effect on spotted wilt intensity. Note however, that this does not mean that the planting date did not affect the intensity of spotted wilt. This is because it has been observed that elevated intensities of spotted wilt is always observed on early planted peanuts compared with peanuts planted during the recommended planting window, especially where the susceptible variety (FloRun™ ‘157’ and TUFRunner™ ‘511’) were used and where Thimet®-20G was not applied. In this study, the analysis was conducted using combined data across location and years in an attempt to show how addition of a ‘thrips risk factor’ helps to account for the variability of spotted wilt across locations.

When the new thrips risk points were included in the analysis, the planting date points had a significant effect on the observed spotted wilt intensity (Table 5.4). This shows that accounting for thrips risk points complements the effect of planting date points. For example, if the peanuts were planted on April 25 (30 spotted wilt points), but the thrips peak dispersal occurred on April 13 (10 points), the resulting risk points from thrips risk factor and planting date is 40. On the other hand, if the peak of thrips dispersal was May 10 (30 points), with the same planting date (30 points), the total spotted wilt points are 60. In this way, the ‘thrips risk factor’ complements the planting date points depending on when the peak of thrips is predicted to occur based on the TIP tool. The impact of planting date on spotted wilt intensity is likely related to the biology of the thrips vector. By adding the category of ’thrips risk factor’ both the importance of planting date and thrips vector are captured in the risk index. Planting date can be viewed as an indirect measure of the importance of the thrips population dynamics to the observed incidence of spotted wilt. Addition of the ‘thrips risk factor’ further allows the tool to anticipate the impact of vector to the spotted wilt epidemics.

Further, while varieties with greater levels of resistance have been developed through breeding efforts, these varieties are not immune to TSWV. Under high thrips and TSWV pressure the resistant varieties get infected (Srinivasan et al., 2017). Therefore, a “field resistant” variety cannot serve as a ‘stand-alone’ management tool and has to be integrated with other management options (Srinivasan et al., 2017). When the pressure from thrips and TSWV are taken into account, growers can better plan other production practices in order to keep the potential losses from spotted wilt disease at a minimal level. By integrating information on the peak of thrips dispersal into Peanut Rx, a factor that can influence final disease severity, growers will be able to make further management decisions.

In Tift County, Georgia, it was observed over a two-year study that 1.1 to 3.1% of *F. fusca* collected from the foliage of tobacco plants were confirmed virus-infected vectors of TSWV (McPherson et al., 2003). In peanuts, up to 17% of tobacco thrips collected from plant terminals tested positive for TSWV (Wells et al., 2002). With greater number of dispersing thrips populations during the peak dispersal, the number of TSWV-carrying thrips vectors could also be greater. Hence, by taking into account the concept of avoiding the risk of exposing peanut seedlings to the peak of dispersing thrips, growers can achieve fewer thrips injury as well as a lower chance of inoculation from dispersing thrips. It should be noted, however, that avoiding the peak of thrips dispersal is not an assurance of zero losses to spotted wilt disease. Subsequent generations of thrips continue after the peak and viruliferous adults and can still disperse and spread TSWV into the peanut plants during the growing season.

The improvements brought about by integrating thrips risk points into Peanut Rx were supported by the ROC curves (Figures 5.10 and 5.11). The area under the ROC curve was greater when the total risk points from the ‘modified Peanut Rx’ were used as compared to Peanut Rx. This increase in the area under the ROC curve with the ‘modified Peanut Rx’ was observed when the analysis was done based on the on-station field trial and commercial field survey data. The ROC curve is a test that can be used to compare the sensitivity and specificity of different models. Sensitivity was defined as the number of true positive decisions/the number of actually positive cases while specificity is the number of true negative decisions/the number of actually negative cases. These constitute the basic measures of performance of different models (Twengstrom et al., 1998 and Park et al., 2004).

Logistic regression takes an interval and categorical inputs and fits a function that outputs odds. In this study, the fitted logistic model predicts the odds of spotted wilt intensity being above 15%. A 15% spotted wilt intensity was set as a threshold to have enough sample size for the analysis, especially for the commercial field survey data. Increasing the threshold would have reduced the sample size. Having enough sample size is important in order make inference about the result of the analysis. Moreover, based upon inspection of the commercial field survey data, majority of the fields had less than 15% of spotted wilt intensity with an average of 3.66% in 2017 and 4.09% in 2018. Further, risk points are input variables, and coefficients for each input variable are estimated as part of fitting the logistic model. Risk points are continuous variables as they increase, so do the odds that spotted wilt intensity will be above 15%, as opposed to less than 15%.

The reason ‘modified Peanut Rx’ provides an improvement in area under the ROC curve is because it effectively discards within-risk category variation in spotted wilt intensity. Within-risk category variation is the variability of spotted wilt intensity observed in the same risk level. This is reasonable for a practical purpose. For example, accounting for the difference between spotted wilt intensities in a “low” risk category is less important than accounting for the differences of spotted wilt intensities across the “low” to “high” risk categories. This is because accounting for the difference of spotted wilt across different risk categories would reduce the false positive predictions. For example, the risk index predicts high risk to of spotted wilt but the observed level of spotted wilt was the same as those observed in the low risk situations. This would count as a false positive test.

From the results of this study, the ‘thrips risk factor’ was recognized as a candidate for modifying the Peanut Rx risk index. The idea behind the ‘modified Peanut Rx’ is to maintain the simplicity of use of Peanut Rx and without adding undue complexity with addition of a ‘thrips risk factor’. This was done by estimating spotted wilt risk points associated with each of four thrips peak periods. The ‘thrips risk factor’ provided a method of directly accounting for the impact of the thrips vector in assessing the risk of spotted wilt disease when integrated as a new risk factor into the Peanut Rx risk index. Doing so, the ‘modified Peanut Rx’ could provide a more specific risk assessment based on the location of a field as the predictions of peak thrips dispersal is based on weather factors at each location.

Integrating a thrips predictive component into Peanut Rx was attempted earlier with the development of Peanut Rx 2.0, a forecasting model (Williams, 2015). This was done by accounting for the estimated magnitude of prior-year thrips population from the TTRF tool in addition to production practices for predicting the intensity of spotted wilt disease in the upcoming growing season. By doing so, a model that accounted for both disease pressure and level of exposure based on production practices in predicting spotted wilt was created. Peanut Rx 2.0 provided a framework in which improved models can be developed to increase spotted wilt management in the southeast United States (Williams, 2015). However, when compared with Peanut Rx in terms of accounting for variation of spotted wilt intensity across different levels of risk, Peanut Rx 2.0 did not perform better as shown in Chapter 3 of this manuscript. Moreover, the use of forecasting models, such as Peanut Rx 2.0, entails that the user has to run the whole model before having an estimated intensity of the disease. With a risk index, such as Peanut Rx or the ‘modified Peanut Rx’, the user can immediately tell how much each factor is contributing to the risk of spotted wilt disease based on the risk point values. This allows the grower to know which factor, such as variety or which planting interval has lower risk point and can adjust his level of risk by trying different combinations of production practices.

The result of this study allow a way to improve the current risk index by adding a 'thrips risk factor' that directly accounts for the thrips vector. By adding a new factor, it does not complicate the risk index. The 'modified Peanut Rx' maintains the structure of Peanut Rx. The risk of spotted wilt disease is calculated the same way with Peanut Rx. It allows the growers to tell the impact of each factor in the risk of spotted wilt but it also requires running the TIP tool in order to get the predicted peak of thrips.

There are two ways of using the 'modified Peanut Rx'. One is to run the TIP tool and get the predicted peak of thrips dispersal to determine the corresponding spotted wilt risk point. After which, the spotted wilt risk points will be added to the summed risk points based upon Peanut Rx to get a spotted wilt risk assessment for each peanut field. In this way, the growers can still use the printed form of Peanut Rx.

Another way of using the 'modified Peanut Rx' is by automating it to be able to package the predicted peak of thrips dispersal from the TIP tool and factors accounted for by Peanut Rx into a single application. This could be done by developing a mobile application program that can be accessed through smart phones. This is not something new because a Peanut Rx application has been developed and can be downloaded for free from the internet.

As mentioned earlier, the TIP tool can be used by growers to predict thrips dispersal over time based on the accumulation of heat units during winter and spring. The actual weather forecast contributes minimally to the accuracy of the predictions because most of the reasons why thrips disperse at certain period depend on past weather conditions (Chappell, personal communication). Thus the TIP tool, like Peanut Rx can be used as a pre-plant resource in calculating risk. By integrating the predicted peak of thrips dispersal from the TIP tool with the Peanut Rx, a risk index that accounts for disease pressure, through the 'thrips risk factor', and level of exposure, based on production practices, was developed and was termed as the 'modified Peanut Rx'.

Further validation will be needed to confirm that the performance of the 'modified Peanut Rx' in assessing risk is consistent over time and growing seasons. More work will also be needed to redefine high, medium, low-risk categories based on total risk points. Based upon Peanut Rx, the maximum total risk points possible is 130. There were three categories of risk depending on the total spotted wilt risk points in Peanut Rx. It is either low (≤65 points), moderate (70- 100 points), or high (≥115 points). With the addition of risk points (10 – 30 points) from the 'thrips risk factor', the maximum total risk points possible is 160. Hence the thresholds of total risk points per risk category will need to be adjusted. Additional studies may also need to be conducted to establish the relationship between planting date intervals and predicted peak of thrips dispersal periods. Such studies could provide additional information on the impact of each predicted peak of thrips dispersal period on early, middle, or late-planted peanuts.

Summary and Conclusion

The relationship between the predicted peak of thrips dispersal and spotted wilt intensity was investigated in this study. Mosaic tables were generated based on the predicted peak of thrips dispersal periods from the TIP tool and levels of spotted wilt intensities observed from on-station field trials and commercial field surveys conducted across Georgia in 2017 and 2018. The result showed that the occurrence of 15% or more spotted wilt intensity was most frequent when the predicted peak of thrips dispersal was between May 1 and 20. In contrast, 15% or more spotted wilt intensity was not observed when the predicted peak was on or before April 15.

Based on the relationship between spotted wilt intensities and thrips peak periods, spotted wilt points were estimated and the ‘thrips risk factor’ was created. A ‘modified Peanut Rx’ was then developed by integrating the ‘thrips risk factor’ into Peanut Rx. All other factors accounted for by Peanut Rx were retained in the modified version.

The ‘modified Peanut Rx’ was compared with Peanut Rx using regression analysis, logistic regression, and ROC curves. The ‘modified Peanut Rx’ accounted for more variation in spotted wilt intensities (logit-transformed) observed in on-station trials across locations over two years based on regression analysis. From logistic regression, it was found that the ‘thrips risk factor’ complements the effect of planting date points in determining the risk to spotted wilt. Finally, the ‘modified Peanut Rx’ risk points were more accurate in classifying whether the intensity of spotted wilt was greater or less than 15%, based on area under ROC curves.

These findings provide a way of directly accounting for the thrips vector into Peanut Rx. This was done by adding a ‘thrips risk factor’ based on predicted peak of thrips dispersal periods. The ‘modified Peanut Rx’ provides a more specific risk assessment as the predictions of thrips dispersal is based on weather parameters at each location per year. With more specific risk assessments, the growers can better plan their spotted wilt management strategies.

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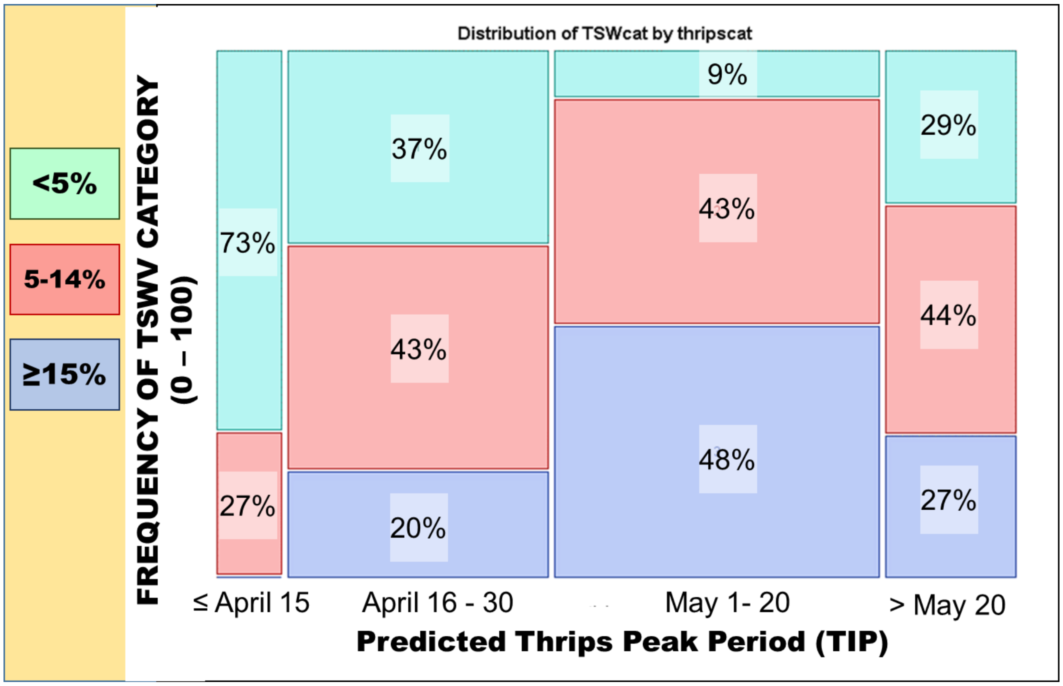
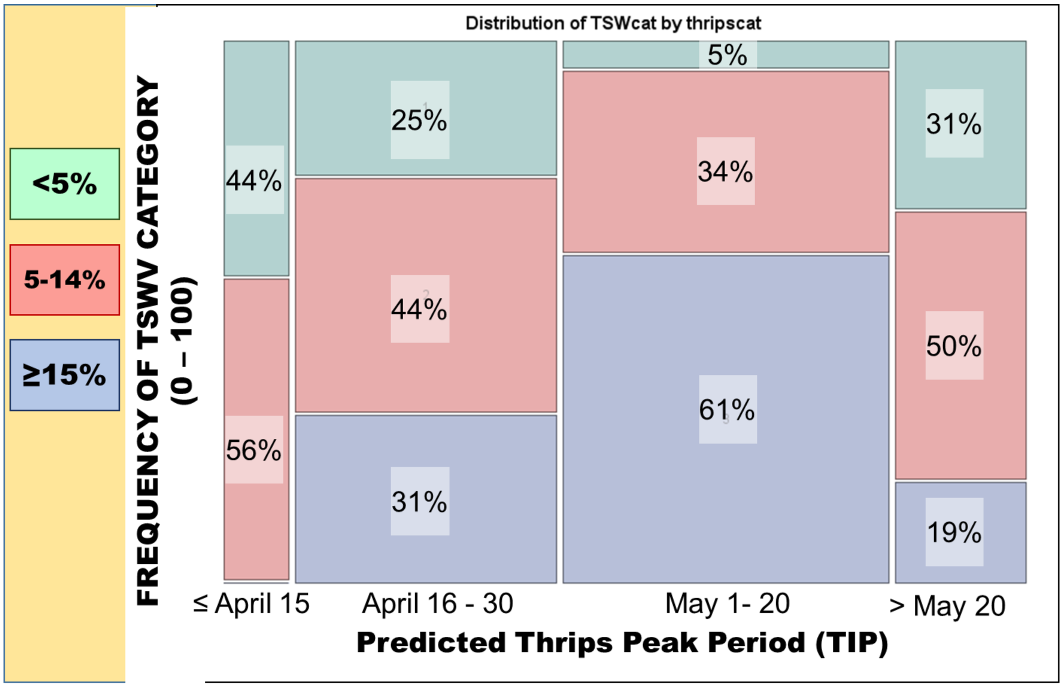
Figures and tables



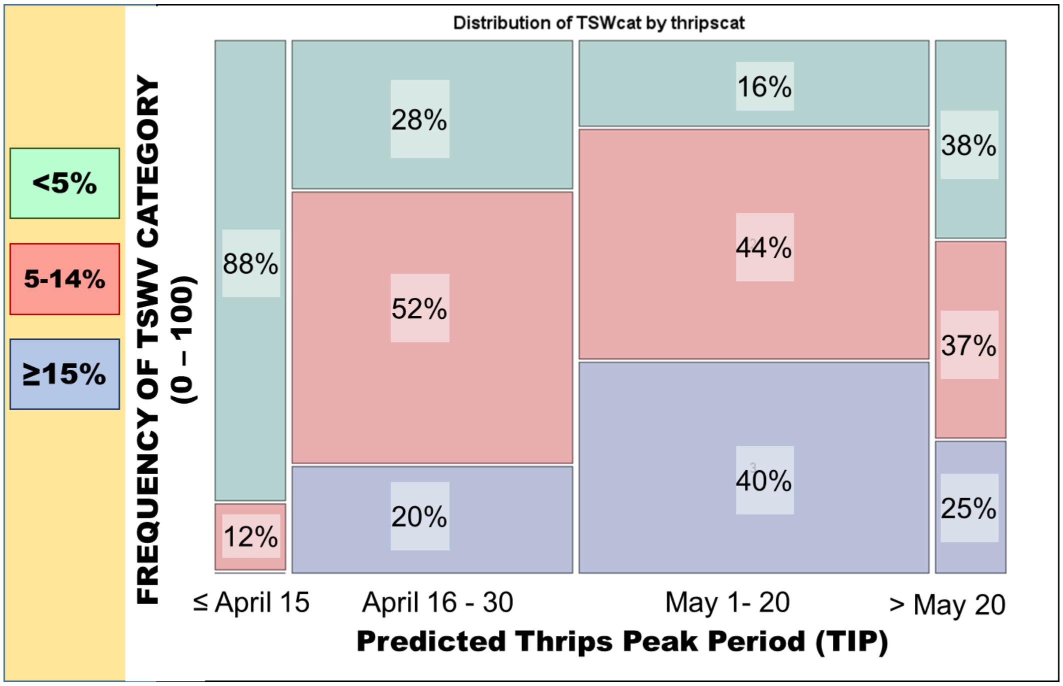
[a] TSWcat: 1 = less than 5% spotted wilt; 2= 5 to 14% spotted wilt; 3= 15% or more
[b] Thripscat: <=April 15 = peak dispersal occurred on or before April 15; April 16-30 = peak dispersal occurred between April 16 to 30; May 1-20 = peak dispersal occurred between May 1 – 20; May20+ = peak thrips dispersal occurred after May 20

Figure 5.1. Frequency of three categories of spotted wilt intensity[a] associated with thrips risk categories[b] based on on-station field trial data across six locations over two years.



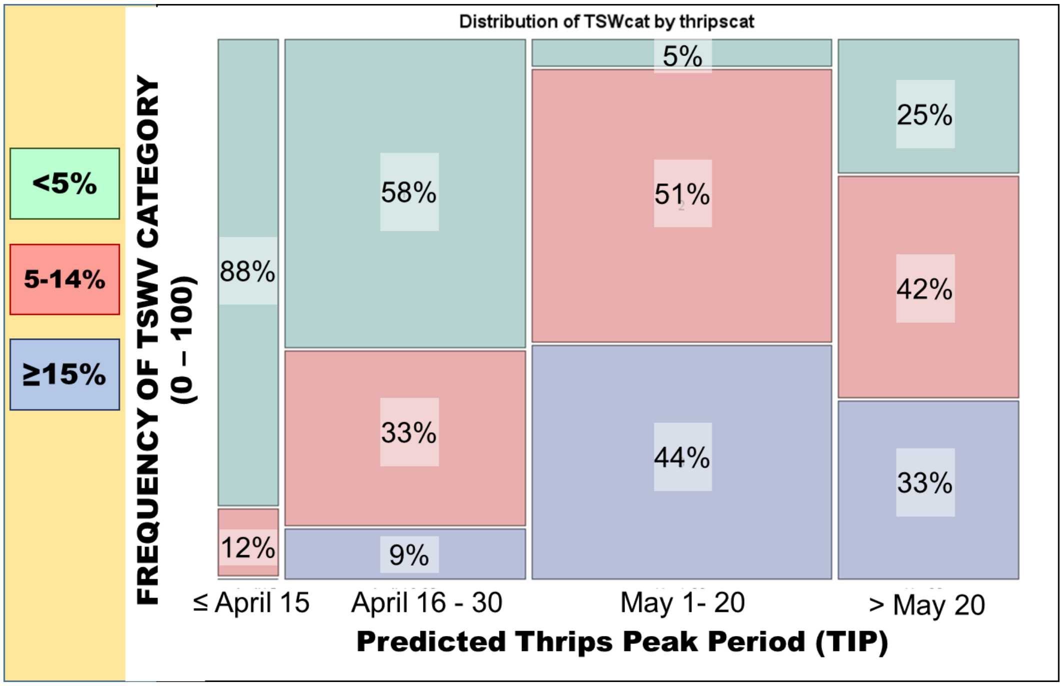
[a] TSWcat: 1 = less than 5% spotted wilt; 2= 5 to 14% spotted wilt; 3= 15% or more
[b] Thripscat: <=April 15 = peak dispersal occurred on or before April 15; April 16-30 = peak dispersal occurred between April 16 to 30; May 1-20 = peak dispersal occurred between May 1 – 20; May20+ = peak thrips dispersal occurred after May 20

Figure 5.2. Mosaic table for early-planted peanuts showing the frequency of three categories of spotted wilt intensity[a] associated with thrips risk categories[b] based on on-station field trial data across 6 locations over 2 years.



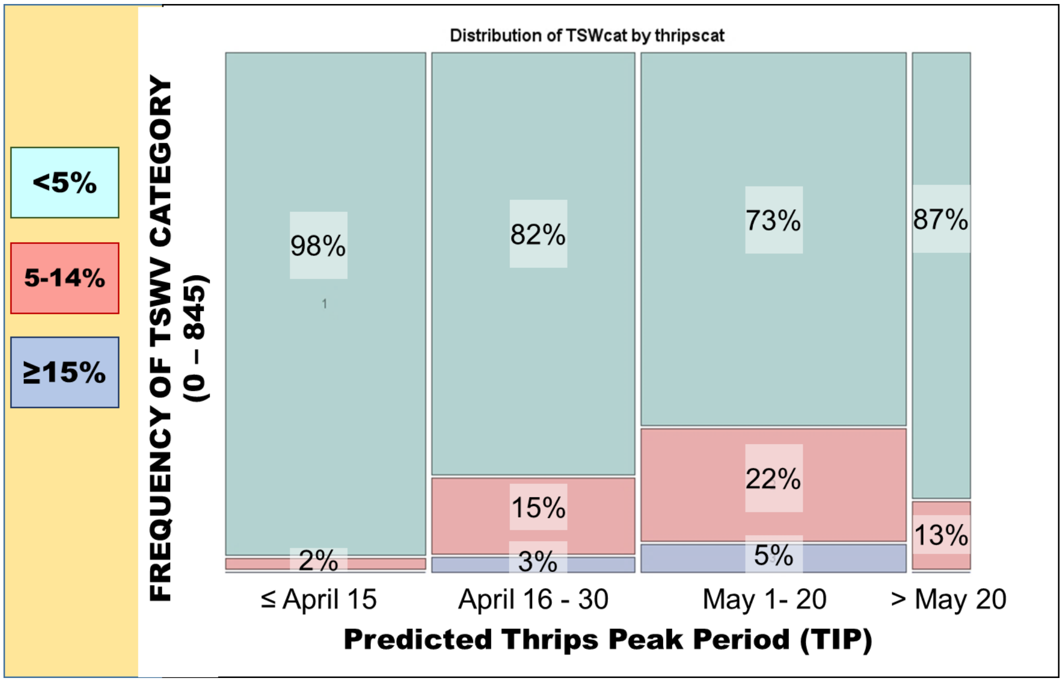
[a] TSWcat: 1 = less than 5% spotted wilt; 2= 5 to 14% spotted wilt; 3= 15% or more
[b] Thripscat: <=April 15 = peak dispersal occurred on or before April 15; April 16-30 = peak dispersal occurred between April 16 to 30; May 1-20 = peak dispersal occurred between May 1 – 20; May20+ = peak thrips dispersal occurred after May 20

Figure 5.3. Mosaic table for middle-planted peanuts showing the frequency of three categories of spotted wilt intensity[a] associated with thrips risk categories[b] based on on-station field trial data across 6 locations over 2 years.



[a] TSWcat: 1 = less than 5% spotted wilt; 2= 5 to 14% spotted wilt; 3= 15% or more
[b] Thripscat: <=April 15 = peak dispersal occurred on or before April 15; April 16-30 = peak dispersal occurred between April 16 to 30; May 1-20 = peak dispersal occurred between May 1 – 20; May20+ = peak thrips dispersal occurred after May 20

Figure 5.4. Mosaic table for late-planted peanuts showing the frequency of three categories of spotted wilt intensity[a] associated with thrips risk categories[b] based on on-station field trial data across 6 locations over 2 years.



[a] TSWcat: 1 = less than 5% spotted wilt; 2= 5 to 14% spotted wilt; 3= 15% or more
[b] Thripscat: <=April 15 = peak dispersal occurred on or before April 15; April 16-30 = peak dispersal occurred between April 16 to 30; May 1-20 = peak dispersal occurred between May 1 – 20; May20+ = peak thrips dispersal occurred after May 20

Figure 5.5. Frequency of three categories of spotted wilt intensity[a] associated with thrips risk categories[b] based on commercial field survey data over 2017 and 2018.

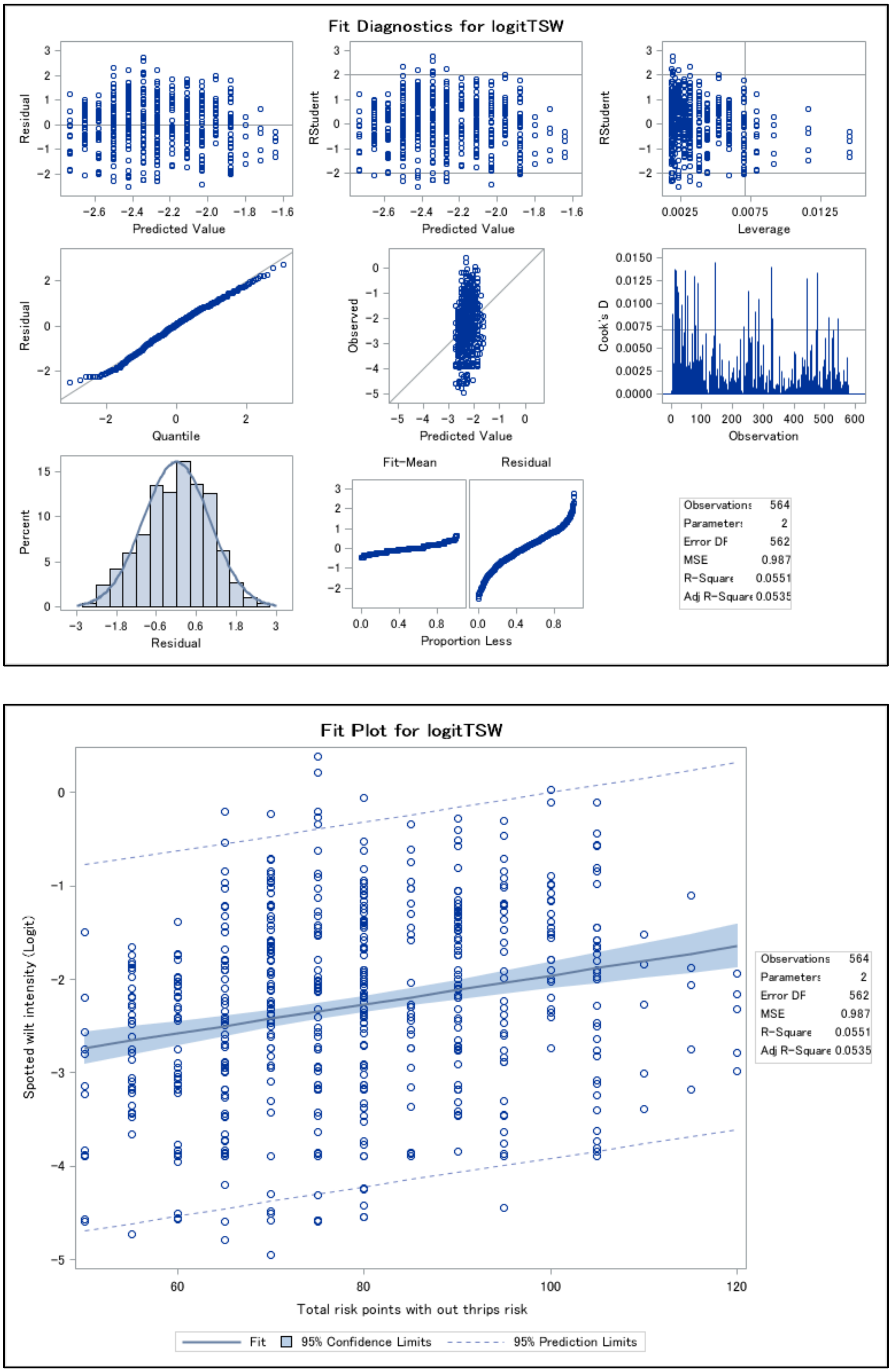
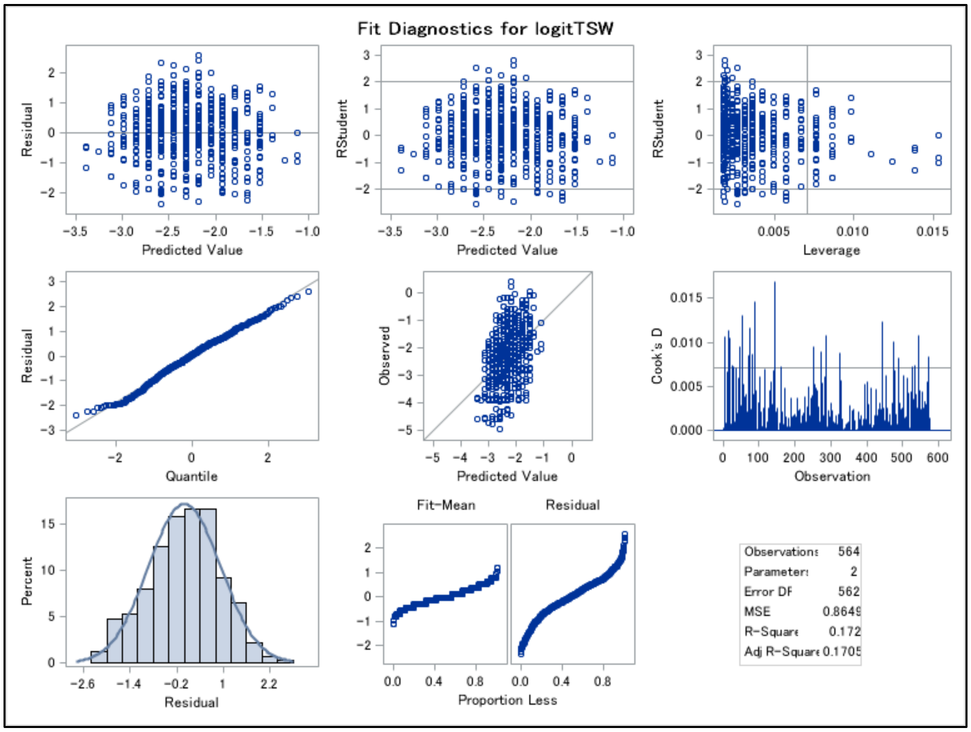


Figure 5.6. Fit diagnostics and fit plot for regression of logit-transformed spotted wilt intensity with total risk points based on Peanut Rx (F Value = 32.80, Pr > F <.0001). The data used in this analysis is from on-station field trials.



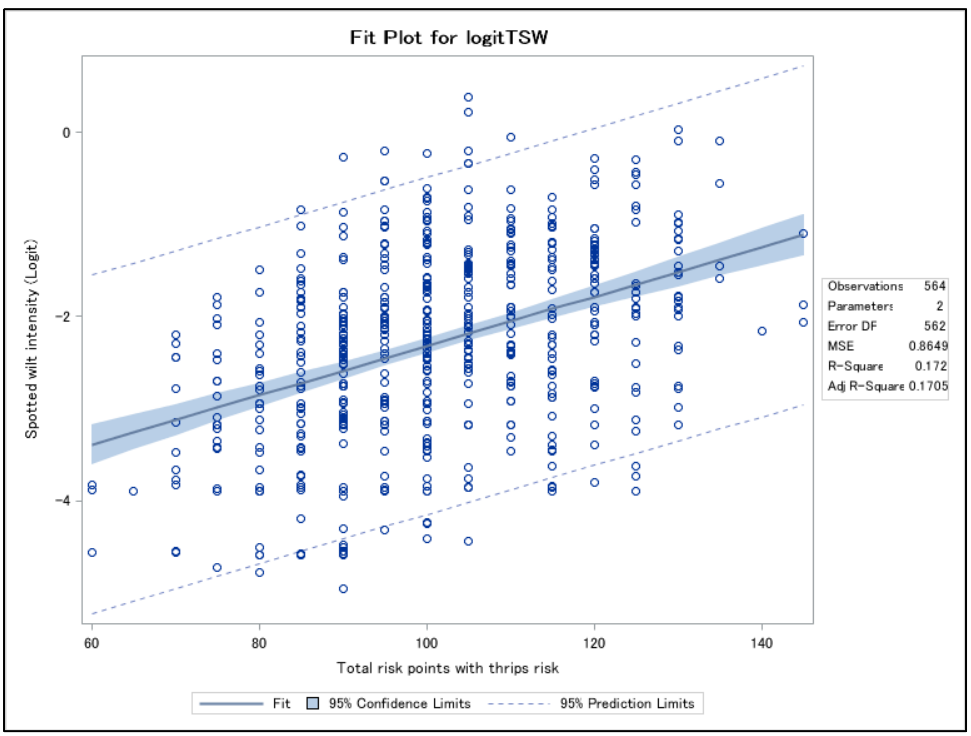
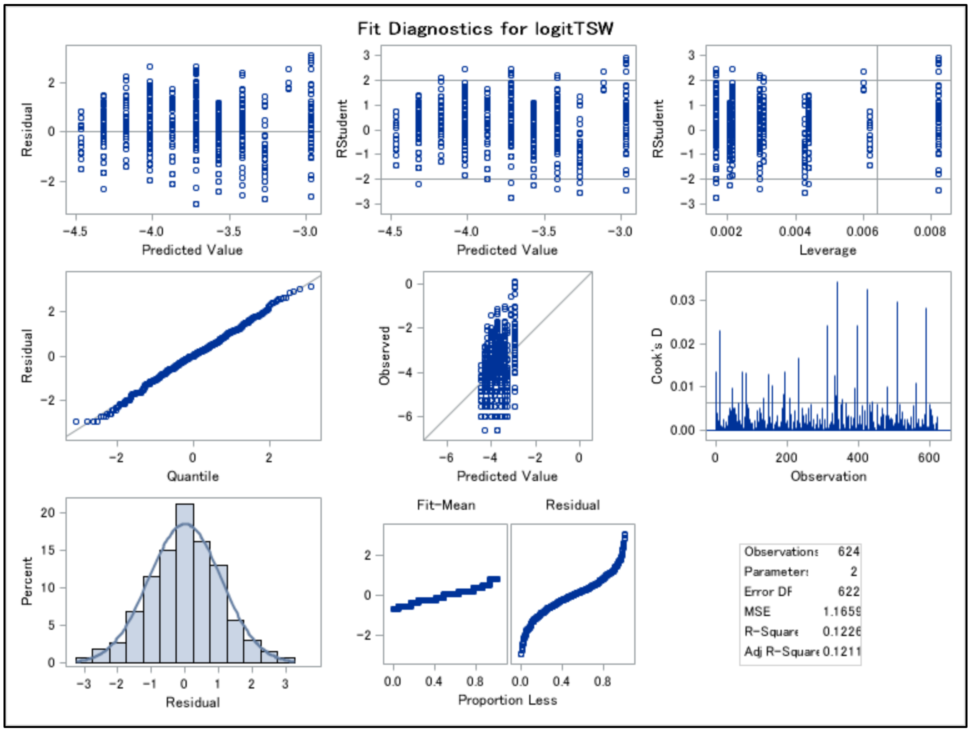


Figure 5.7. Fit diagnostics and fit plot for regression of logit-transformed spotted wilt intensity with total risk points based on 'modified Peanut Rx' (F Value =116.75, Pr > F <.0001). The data used in this analysis is from on-station field trials.



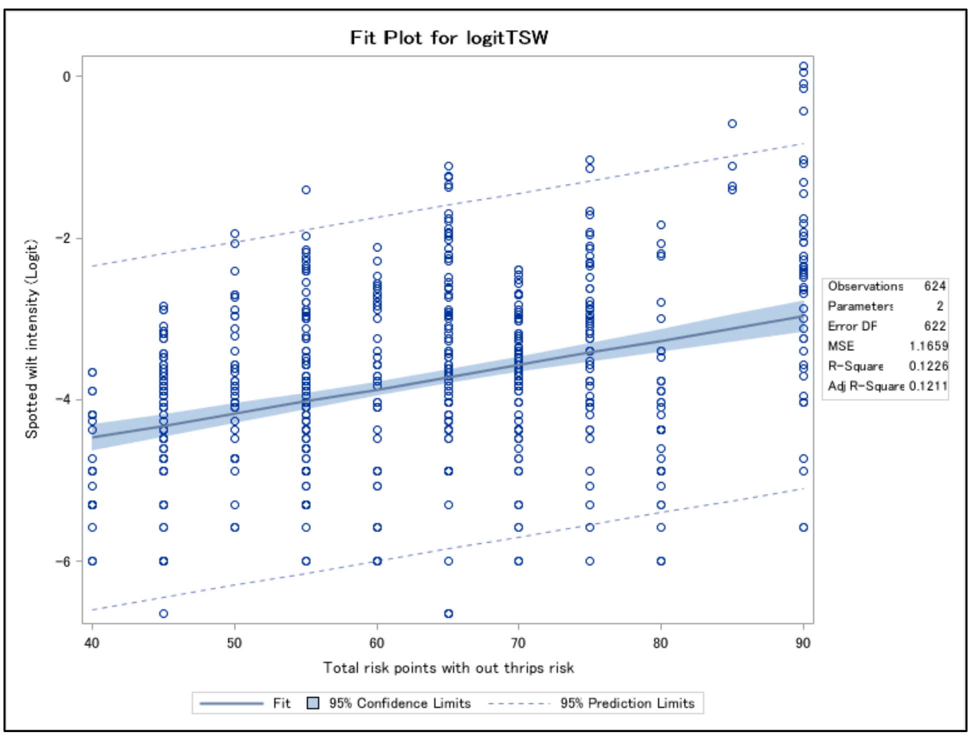
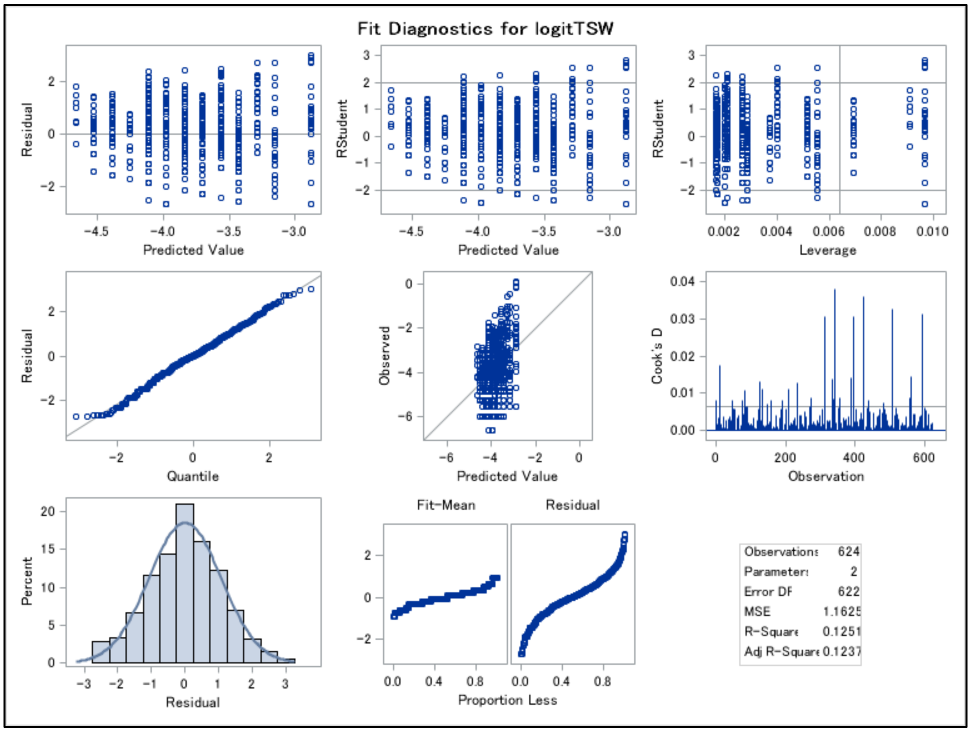


Figure 5.8. Fit diagnostics and fit plot for regression of logit-transformed spotted wilt intensity with total risk points based on Peanut Rx (F Value =86.88, Pr > F <.0001). The data used in this analysis is from commercial field surveys.



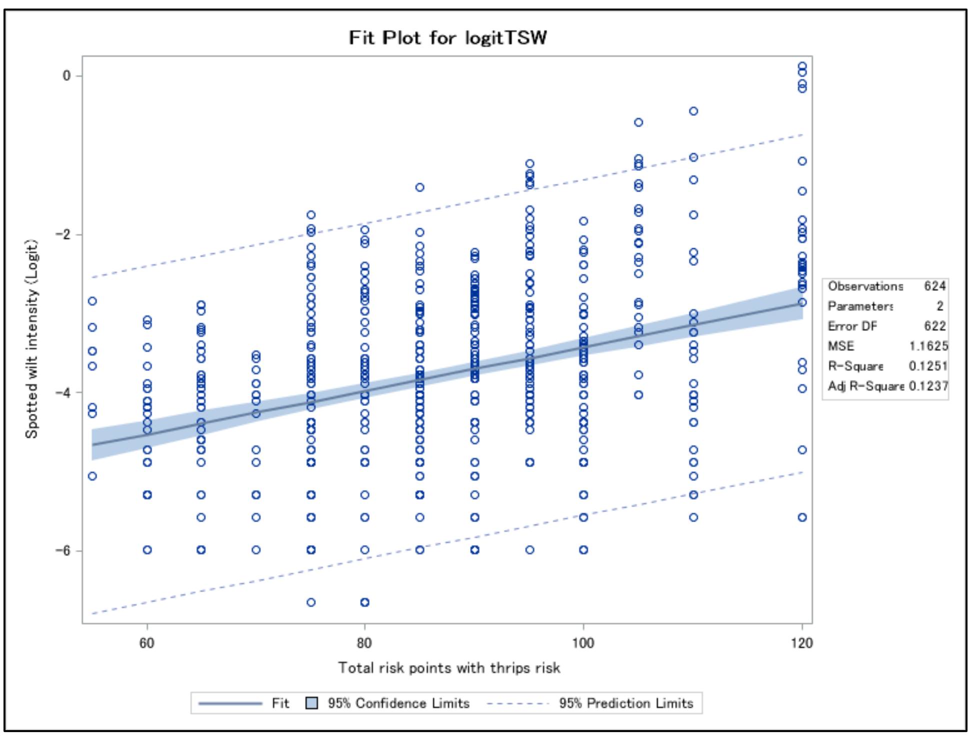


Figure 5.9. Fit diagnostics and fit plot for regression of logit-transformed spotted wilt intensity with total risk points based on ”modified Peanut Rx” (F Value =88.94, Pr > F <.0001). The data used in this analysis is from commercial field surveys.

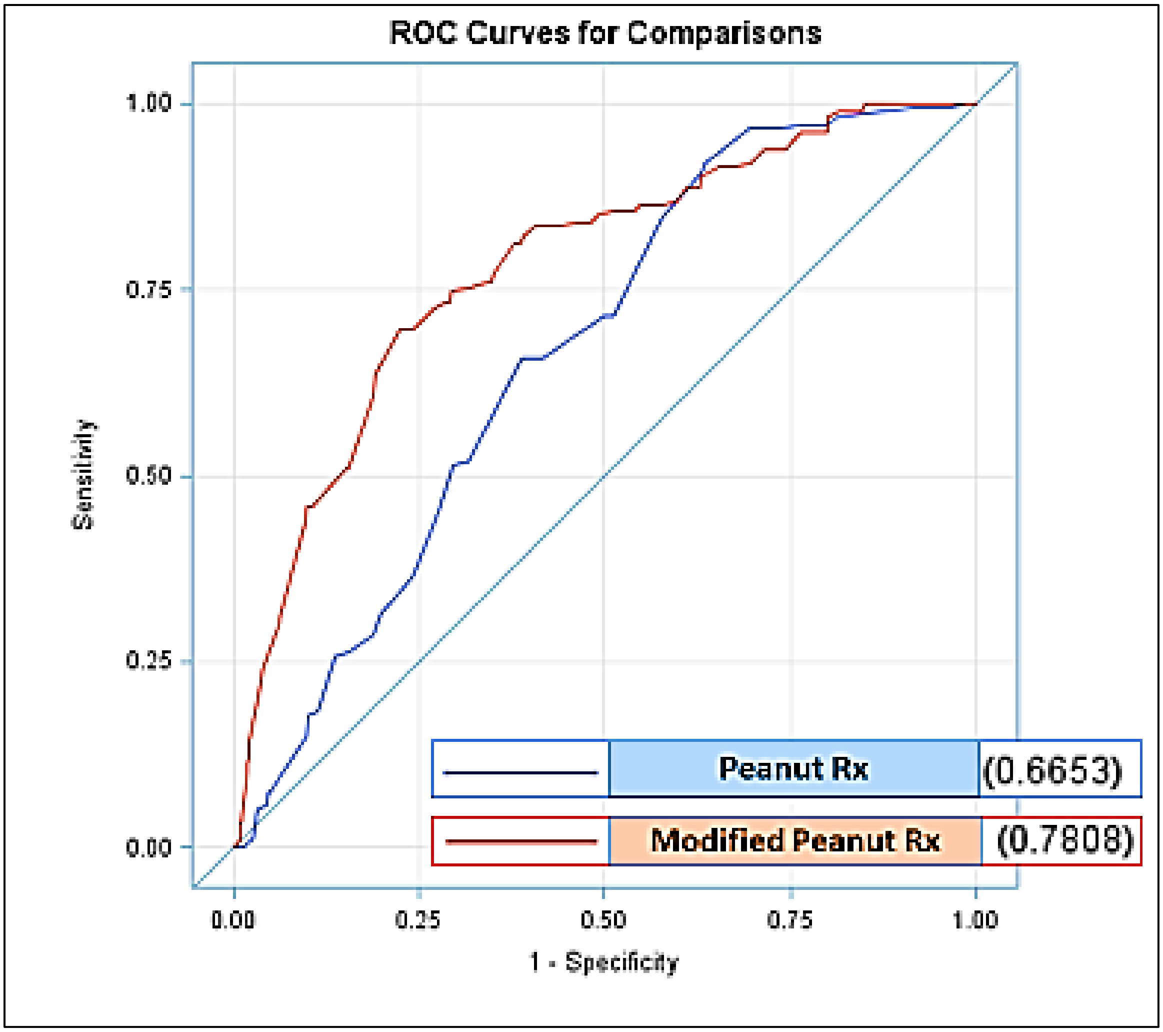


Figure 5.10. Receiver operating characteristic (ROC) curves for Peanut Rx and "modified Peanut Rx" using on-station field trial data. The blue line represents the ROC curve for Peanut Rx while the red line represents the curve for "modified Peanut Rx.

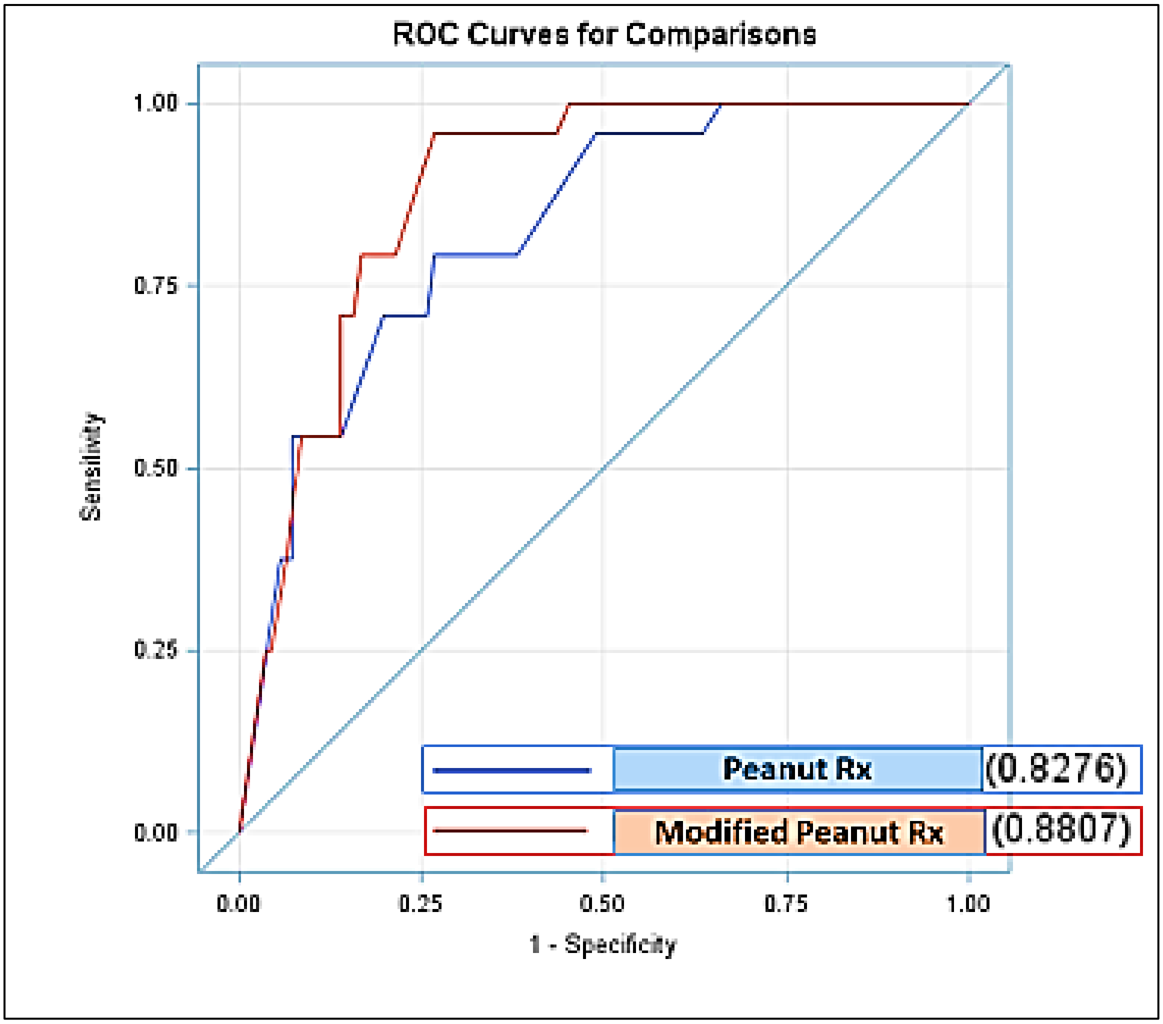


Figure 5.11. ROC curves for Peanut Rx and "modified Peanut Rx" using commercial field survey data. The blue line represents the ROC curve for Peanut Rx while the red line represents the curve for "modified Peanut Rx.

Table 5.1. Predicted peak of thrips dispersal, based on the Thrips Infestation Predictor (TIP) tool for cotton, in six research stations in 2017 and 2018.

Location	**Predicted peak of thrips dispersal**	
	2017	**2018**
Attapulgus	16-Apr-17	9-May-18
Stripling	15-Apr-17	11-May-18
Plains	2-May-17	22-May-18
Tifton	28-Apr-17	16-May-18
Reidsville	25-Apr-17	15-May-18
Midville	5-May-17	25-May-18

Table 5.2. Listing of probability values, coefficient of determination, and mean square errors for two sets of spotted wilt points evaluated using spotted wilt data from on-station trials and commercial field surveys.

	On-station trials			**Commercial field survey**		
Spotted Wilt Points	*p-value*	R-square	MSE	*p-value*	R-square	MSE
Set A (5, 15, 20, 10)	<.0001	0.1716	0.8654	0.0653	0.0055	1.3215
Set B (10, 20, 30, 15)	<.0001	0.1818	0.8547	0.0302	0.0075	1.3187

Table 5.3. Probability values, coefficient of determination, slope parameter, and mean squared errors from regression logit-transformed spotted wilt intensities with total risk points based on Peanut Rx and "modified Peanut Rx". The data used in this analysis is from on-station field trials combined over two years per location.

LOCATION	**PEANUT RX**				**MODIFIED PEANUT RX**			
	p-value	R^2	Slope	MSE	*p*-value	R^2	Slope	MSE
Attapulgus	0.0392	0.0464	0.012	1.044	<.0001	0.2992	0.031	0.767
Stripling	0.0144	0.0647	0.014	0.808	<.0001	0.1970	0.026	0.693
Plains	0.0002	0.1357	0.022	0.737	<.0001	0.1816	0.025	0.698
Tifton	0.1074	0.0282	0.011	0.882	0.0001	0.1488	0.025	0.773
Reidsville	0.001	0.1100	0.017	0.483	<.0001	0.1570	0.020	0.458
Midville	<.0001	0.1633	0.028	0.710	<.0001	0.3306	0.035	0.568

Table 5.4. Probability (*p*-values) and Akaike information criterion (AIC) values from logistic regression of spotted wilt risk points based on Peanut Rx and "modified Peanut Rx" with spotted wilt data from on-station trials and commercial field surveys.

Parameters	**On-station field trial**		**Commercial field survey**	
	Peanut Rx	Modified Peanut Rx	Peanut Rx	Modified Peanut Rx
Planting date points (*p*)	0.1539	0.0174	0.0001	0.0004
Risk points from other factors (*p*)	<.0001	<.0001	<.0001	<.0001
thrips risk points (*p*)	n/a	<.0001	n/a	0.0152
AIC value	678.17	595.74	171.55	166.79

n/a = not included in analysis

Table 5.5. List of planting dates in six locations in 2017 and 2018.

LOCATION	**Planting Dates**	
	2017	**2018**
Attapulgus	4/20/2017	4/17/2018
Attapulgus	5/10/2017	5/14/2018
Attapulgus	5/30/2017	6/5/2018
Stripling	4/19/2017	4/17/2018
Stripling	5/9/2017	5/18/2018
Stripling	5/30/2017	6/8/2018
Tifton	4/25/2017	4/25/2018
Tifton	5/12/2017	5/21/2018
Tifton	6/8/2017	6/7/2018
Plains	4/27/2017	4/20/2018
Plains	5/16/2017	5/11/2018
Plains	5/31/2017	6/12/2018
Reidsville	4/24/2017	4/18/2018
Reidsville	5/15/2017	5/22/2018
Reidsville	6/1/2017	6/20/2018
Midville	4/21/2017	4/25/2018
Midville	5/11/2017	6/6/2018
Midville	6/1/2017	6/19/2018