INTEGRATED PEST MANAGEMENT SYSTEMS FOR SUGARCANE APHID IN GRAIN SORGHUM

By

PHILLIP JOSEPH HAAR

(Under Direction of G. David Buntin)

Abstract

Studies were conducted utilizing an integrated pest management approach to control the invasive pest the sugarcane aphid, *Melanaphis sacchari,* in grain sorghum. The study took place from 2016-2017 at Griffin, Tifton and Plains, Georgia, USA from May to October. During this research a pathogenic fungus, *Lecanicillium lecani,* was discovered attacking sugarcane aphid. Integrated tactics included four variables: planting date, insecticidal seed treatment, foliar insecticides, and plant tolerance/resistance. Early planting was effective in reducing damage and increasing yields when compared to the late planting. Additionally, the resistant variety and use of a foliar insecticide application was uniform in terms of yield despite treatment type and yielded more than the susceptible variety overall. We concluded that an earlier planting date coupled with a resistant variety and judicious use of a foliar insecticide produced the best yielding outcome.

INDEX WORDS: *Melanaphis sacchari*, sugarcane aphid, grain sorghum, integrated pest management

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Origin. The original discovery of the sugarcane aphid (SCA) *Melanaphis sacchari* (Zehntner) (Hemiptera: Aphididae) in the USA on sorghum, *Sorghum bicolor* (L.) Moench, was by Denmark (1988) in Florida. At this time, it was not considered an agronomic issue in sorghum. Long before its invasion into North America, the SCA was a serious pest of sorghum in Asian, African, Australian, and South American countries (Singh et al. 2004). The SCA is believed to have originated from Africa and is an invasive pest to the U.S mainland. Before sorghum the SCA was found only in sugarcane and first reported in North America in Florida in 1977 (Mead 1978) and Louisiana in 1999 (White et al. 2001). The first report of SCA causing significant damage to sorghum was near Beaumont, TX in 2013. At the time, the aphid infested four states and 38 counties as well as three northeastern states of Mexico, but by 2015 it infested 17 states and over 400 counties and all sorghum production regions in Mexico (Bowling et al. 2016). Currently, SCA on sorghum is recognized as a biotype or strain of *M. sacchari*, but the aphid has been recognized previously as a separate species, *Melanaphis sorghi* (Blackman and Eastop 1984).

Identification. The body color of the SCA ranges from tan to light yellow in the summer and gray during the winter and spring (Bowling et at. 2016). Some distinctive morphological characteristics for identifying SCA include dark or black cornicles, tarsi, and antennae (Villaneuva et al. 2014). The alate aphids look similar to apterous aphids with the exception that they are distinguished by black markings along the dorsal sclerites (Eastop 1955, Blackman and Eastop 1984) and are unique in their presence of black hardened structures at the base of the wings (Bowling et al. 2016). Some other aphid pests of sorghum from which the SCA can be distinguished using these characteristics include the corn leaf aphid, *Rhopalosiphum maidis* (Fitch), greenbug, *Shizaphis graminum* (Rhondani), and the yellow sugarcane aphid, *Sipha flava* (Forbes).

Host preference. The SCA can be a pest and persist not only in sorghum but also on sorghum related species including johnsongrass, sudangrass, broom corn, and pearl millet. Additionally, the aphid also has non-persistent crop hosts when the preferred host is not available which consist of corn, energycane, miscanthus, crabgrass, and napiergrass. When sorghum is not present sugarcane aphids may feed on other species and survive in warmer areas until sorghum is planted the following year.

Reproduction. In North America, all of the aphids are female and give birth to live young through asexual reproduction. However, one report of egg production from female aphids collected from three Mexican states has been documented but is rare (Peña-Martinez et al. 2016). The aphid has four nymphal instars that, with sensitivity to temperature, take about 4 to 12 days for development from birth to adult (Chang et al. 1982). Adult life can range from 10 to 37 days (Singh et al. 2004, Chang et al. 1982), with the reproductive capability ranging from 34 to 96 nymphs per female varying with environmental conditions such as nutrient acquisition and temperature ranges (Singh et al. 2004, Chang et al. 1982). Following their arrival, the colony becomes established and exponential growth of their population is possible with favorable conditions over the sorghum developmental period with populations approaching as many as 30,000 aphids on one plant (Singh et al. 2004).

Optimal Environment. The temperature, amount of rainfall, and relative humidity impact the size of the population (Chang et al. 1982). The optimal environment for SCA population growth occurs during warm and dry climatic conditions (Singh et al. 2004). Although it is largely unknown why SCA favors warm dry weather, a few theories may attribute some insight. Wet and cool environmental conditions may favor the development of entomopathogenic fungi which can drastically decrease the aphid population (Bowling et al. 2016). Heavy rainfall or dew may submerge aphids and physically weaken or kill them by drowning (Bowling et al. 2016). Rainfall may also physically remove aphids from the plant relocating them in areas where predators may take advantage of their vulnerability (Bowling et al. 2016).

Migration and infestation. The SCA has a preference for dry, warm weather. SCA does not overwinter in freezing areas and must migrate from areas such as south Florida, South Texas and Mexico where they feed on green plant tissue and then migrate northward during warmer months. Like many aphids, this migration is accomplished through alate aphids which disperse during overcrowded conditions or when nutritional resources are diminished in addition to climatic conditions. In order to survive the winter, the aphids are required to find a suitable host such as remnant and ratoon sorghum or perennial grasses. Near the Texas Gulf Coast, SCA can be found during the winter on remnant sorghum and Johnsongrass, *Sorghum halepense* (L.) Persoon, and ratoon sorghum grown in the Rio Grande Valley of Texas and Mexico (Bowling et al. 2016). Even when the temperature periodically drops to freezing and most of the vegetation has degraded, SCA were still found in January and February of 2015 in north central Texas on Johnsongrass (Bowling et al. 2016). Migration usually occurs to southern Georgia around April into May and persists throughout the summer when populations peak and then crash in September (Buntin unpublished data). The dissemination of the winged SCA is most likely due to wind aided migration throughout North America. Observations of alate aphids in mass (Brewer et al. 2016) and published aphid movement of other aphid species (Irwin and Thresh 1988) reinforces the assumption that the SCA also utilizes the wind for its dispersal (Bowling et al. 2016). The migration via wind aid is important for the SCA as is for most aphids due to their weak flying capabilities and the need to relocate to a new food source. Following migration, SCA produces apterous aphids which are solely for reproduction and colonization which enables the high rate of birth and productivity. Upon arrival to the new sorghum field, the alates are usually found on the underside of upper leaves in the canopy of the sorghum (Wallin and Loonan 1971, Irwin and Thresh 1988, Bowling et al. 2016). Infestations, however, usually begin on the bottom canopy leaves and move upwards as aphid populations increase.

Plant Injury and Damage. SCA feeds on plant phloem tissue and extracts plant photosynthates as most aphids do. Feeding can cause desiccation, discoloration and necrosis of the plant tissues and leaves, stunting of the seedlings, heading prevention or sterile grain heads, and if damage is severe enough, death of the plant can occur. The stress related injury caused by the SCA all lead to grain yield losses and total loss of biomass in the crop stand. Additionally, secondary economic impacts are caused by the sticky honeydew secretions as well as the aphid biomass when harvest occurs. Harvesting proves to be much more difficult due to sticky leaves impeding the movement of parts within the combine and causing mechanical failure. Honeydew not only leads to mechanical failure but also promotes the growth of black sooty mold that accumulates on the leaf surface and can inhibit the plant's photosynthetic capabilities. In commercial production of sorghum in south Texas, 10,000 aphids on a single plant have been found (Brewer et al. 2016). After reaching such numbers, the plant quality declines very rapidly resulting in biomass reduction and a severe yield deficit occurs. Symptoms of aphid damage begin with discoloration and purpling of young plants that can lead to chlorosis, stunting, and finally necrosis of maturing leaves and the stalk of the plant resulting in death of the plant if feeding ensues (Singh et al. 2004). Sorghum can be resilient to show symptoms, depending on the variety, even as populations of aphids initially surge upon arrival. The leaves can remain green despite infestations of aphids on the undersides of foliage. As the aphids begin to reach damaging numbers and plant injury initiates, leaves change color from yellow, purple, and, finally, brown as leaf health declines (Bowling et al. 2016).

The sugarcane aphid can vector three viruses, two of which can infect sorghum. Millet red leaf virus (Blackman and Eastop 1984) is not a pathogen to sorghum but may pose a threat to millet. Sugarcane yellow leaf virus can be a pathogen on both sorghum and sugarcane which are both agronomically important crops (Schenck 2000). Also sugarcane mosaic virus (SMV) can be vectored by the sugarcane aphid on sorghum (Bhargava et al. 1971; Kondaiah and Nayudu 1984; Setokuchi and Muta 1993). Demonstrated by Yang (1986), the sugarcane aphid was effective at transmitting SMV on not only sorghum but also corn and sugarcane. The incubation periods for SMV on corn and sweet sorghum were 30 and 20 days, respectively (Yang 1986). It was also noted by Yang (1986) that symptoms of SMV transmitted by *M. sacchari* took a longer time to develop on sweet sorghum than on sugarcane or corn. As of recently, no new plant pathogens have been discovered to be vectored by the SCA and no damage resulting from phytotoxins in the SCA's oral secretions while feeding has been confirmed. Although these viruses have been identified in sorghum transmitted by the sugarcane aphid, they have not been of agronomic importance in commercially grown sorghum to date (Schenck 2000; Bhargava et al. 1971; Kondaiah and Nayudu 1984; Setokuchi and Muta 1993; Yang 1986).

Grain loss may occur if the pre-flowering stage of sorghum becomes infested by SCA as well as a yield loss if the aphids are numerous during the developmental stage of the grain. A decrease in heading, lower plot grain weight, delayed maturity, and even the death of the entire plant may occur from an exorbitant amount of aphids (Bowling et al. 2016). In addition to direct loss of grain due to feeding injury caused by the aphid, potential losses of grain can occur during harvest as the sticky honeydew secretions on the leaves and heads of the sorghum accumulate in the separator of the combine and inhibit the retrieval of the grain and delay harvesting leading to as much as a 50% reduction in the recovery of grain and delay in harvest (Bowling et al. 2016). Similarly, the accumulation of honeydew can cause mechanical issues to ensue during cutting and bailing of sorghum grown for forage or hay, as well as decrease the quality due to sooty mold buildup, and delay drying down time of the cut foliage (Bowling et al. 2016).

Sampling. Insecticides are another tool that can be used to minimize the losses caused by SCA. In early planted sorghum around mid-May in Georgia, neonicotinoid insecticide treated seed, which can provide systemic protection for the seedlings from SCA for up to one month (Knutson et al. 2016, Buntin unpublished data), but may have limited efficacy due to initial infestations arriving after this period of effectiveness. In this case, foliar insecticides would be optimal in order to control the aphid upon its arrival rather than spending the extra money on seed treatment that may be of little to no use on the SCA. However, in later planted sorghum, the potential for infestations to occur during the seedling stage is more likely and in this case the seed treatment could provide early protection for the plants and avoid the need for a foliar spray until later in the growing season.

For initially detecting aphids, protocols developed by Bowling et al. (2016) suggest to inspect the leaves (undersides of upper and lower canopy) and the grain heads if present along the field edges as deep as 7.62 meters (25 feet) into the field. Scouting in this manner needs to be conducted weekly at the least until aphids are found or the seed starts to harden. Typically, 15 to 20 plants are chosen in 50 feet of row for inspection at each sampling site (Bowling et al. 2016). Honeydew is a good indicator of aphid presence and can expedite the process of locating aphids, however, just because honeydew is not present does not mean that the aphids are not present as well. Aphids may aggregate in the lower canopy when insecticidal sprays are applied and alates may also inhabit the plant recently with no signs of presence such as honeydew. Field edges that are consistently hit by oncoming wind and/or are next to a field that is unmanaged should be an area of high priority scouting due to the possibility of the adjacent field serving as an refuge site and wind aiding the alates to migrate to the field of interest.

Following the infestation of a field, the aphids should be monitored twice on a weekly basis in order to determine the use of insecticide treatment. Previous threshold data and field observations have implicated economic thresholds for SCA in North America; these thresholds include either aphids per leaf or the percent of plants infested with established colonies (Brown et al. 2015; Catchot et al. 2015; Seiter et al. 2015; Knutson et al. 2016). A protocol has been designed to assess a quick estimate of aphids/leaf based on plant response to aphid presence gathered from experiments in south Texas, Louisiana, Arkansas, Oklahoma, and Georgia (Bowling et al. 2016). For each, sampling site the underside of 10 developed green leaves from the upper canopy and 10 from the lower canopy (not including the flag leaf and unhealthy leaves which are discolored) are sampled. On each of the leaves, the aphid load (aphids per leaf) is approximated and recorded. Then, the overall estimate is attained by averaging the estimates from the individual leaves at each sampling site.

Insecticides. Previous insecticides that were effective on sucking insects in sorghum were not effective on the SCA. Within one year of the known presence of SCA in North America, insecticides that targeted phloem-sucking insects and were compatible with sorghum were identified to combat the SCA (Bowling et al. 2016). Two foliar insecticides proved to be effective against SCA on sorghum in the US. The first, sulfoxaflor (Transform 50% wg) was produced by Dow AgroSciences, Indianapolis, IN, and received a Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) section 18 emergency use registration in most of the southern states where the SCA is a significant issue on sorghum in 2014, 2015, 2016, 2017 and 2018 (Buntin pers.) (Bowling et al. 2016). Later, in 2015, flupyradifurone 17.09% (Sivanto Prime), developed by Bayer CropScience, Leverkusen, Germany, an insecticide within the group 4D (butenolides), received EPA approval for commercial use in sorghum (Bowling et al. 2016). Both sulfoxaflor and flupyradifurone perform very well on sorghum, these insecticides have an efficacy of greater than 98 percent mortality of the SCA and residual remaining a minimum of 7 to 10 days (Bowling et al. 2016, Buntin et al. 2018). Sulfoxaflor and flupyradifurone are classified for use against sap sucking insects and have low toxicity to non-target organisms and beneficial arthropods, enabling them to work synergistically with biological control (Michaud et al. 2016). The spray formulation of imidaclorprid, a neonicotinoid, is available in Mexico and is also an effective insecticide for control of SCA on sorghum (Bowling et al. 2016). Insecticides used for seed treatments of sorghum also have proven effective especially in the later planted sorghum following aphid infestations. Neonicotinoid seed treatments clothianidin, thiamethoxam, and imidacloprid all display systemic activity against the sugarcane aphid in the field for up to one month following planting.

Biological Control. Various insect natural enemies are known to prey upon SCAs in sorghum. Natural enemies can usually be observed while aphids are present in the fields, increasing as the aphids reach and surpass economic thresholds. Even in the presence of natural enemies, SCAs still exceed economic thresholds, however, as the natural enemies become more acclimated to the SCA and more aphid resistant sorghum cultivars are grown, the natural enemies may contribute greater to the control of the SCA.

Predators. The natural enemy populations increased along with greater diversity from 2014 to 2015 (Maxson and Brewer, pers. obs.). A survey of the natural enemy species complex in sorghum was conducted in south (Nueces County) and central (Burleson County) Texas in 2015 (Bowling et al. 2016). Both areas had similar species complexes with the most natural enemies, eight species of lady beetles (Coleoptera: Coccinellidae), were found: *Coccinella septempunctata* (L.), *Coleomegilla maculata* (De Geer), *Cycloneda sanguinea* (L.), *Harmonia axyridis* (Pallas), *Olla v-nigrum* (Mulsant) and two morphospecies of dusky lady beetles *Scymnus spp.* (Coccinellidae: Scymninae). Brown lacewings (Neuroptera: Hemerobiidae) of the genus *Hemerobius* were present, as were the green lacewings (Neuroptera: Chrysopidae) *Ceraeochrysa valida* (Banks), *Chrysopa quadripunctata* (Burmeister), *Chrysoperla externa* (Hagen), *Chrysoperla rufilabris* (Burmeister), and *Chrysoperla plorabunda* (Fitch). The hoverflies (Diptera: Syrphidae) that were found included *Allograpta obliqua* (Say), *Pseudodoros clavatus* (Fabricius), and *Eupeodes americanus* (Wiedemann) (Syrphidae: Syrphini). The minute pirate bug, *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) was also detected in the fields.

All aphidophagous predator species were present on aphid-infested sorghum in both juvenile and adult life stages, suggesting that these natural enemies are successfully utilizing sugarcane aphid as a prey item and reproducing. Colares et al. (2015), found that four predatory species located in the south and central Texas region (*Coleomegilla maculata, Hippodamia convergens*, *Chrysoperla carnea*, and *Orius insidiosus*) were reared on SCA as well as the greenbug (*Schizaphis graminum*). It has also been reported in other states that similar predator taxa in SCA-infested fields (Buntin, Kerns, Sieter, pers. obs.) are present, indicating that existing populations of aphidophagous taxa are adapting to SCAs that are invading sorghum in North America.

Parasitoids. The most prevalent parasitoid that was reared from the mummies of the sugarcane aphid in Texas was *Aphelinus nigritus* (Howard) (Hymenoptera: Aphelinidae) (Bowling et.al 2016). The mummy is oval and shiny black in color very much different from a live aphid (Bowling et al. 2016). *Lysiphlebus testaceipes* (Cresson) (Hymenoptera: Braconidae) is another generalist aphid parasitoid that parasitizes the sugarcane aphid but was not as abundant and successful as *Aphelinus nigritus* (Bowling et al. 2016). *Lysiphlebus testaceipes* is more of a tan to brown hue in color with a globular shaped mummy.

Entomopathogenic fungi. Entomopathogenic fungi have been found in the field on sugarcane aphid cadavers in Tifton, Williamson, and Plains, Georgia in 2017 as well as Texas in both in 2016 and 2015 (Haar et al. 2018). The fungus was identified as *Lecanicillium lecanii* (Zimmerman) Zare & Gams (Hypocreales: Clavicipitaceae) (Haar et al. 2018). This pathogen appears to be contributing to the patterns of boom and busts that the aphid populations experience periodically throughout the growing season. Following a severe drop in aphid numbers cadavers covered with the white mycelium can be found still fresh on the leaves which they were feeding.

Host plant resistance. Genetic host plant resistance in sorghum to aphid pests, including SCA, provides an effective management strategy because it can work in concert with the beneficial arthropod populations as well as offer an affordable and easy to use alternative to insecticides (Brewer and Elliott 2004). Many sorghum hybrids have already been developed and used for control of greenbug in North America (Michels and Burd 2007). Parental lines showing resistance to the sugarcane aphid as well as commercially available hybrids have already been established and efforts to release more varieties are underway (Singh et al. 2004). Sorghum parental types SC110 and SC170, parental line RTx2783 and Texas A&M sorghum lines and hybrids B11070, B11070, AB11055-WF1-CS1/RTx436, and AB11055-WF1-CS1/RTx437 have displayed high levels of resistance to sugarcane aphid both in greenhouse and field tests (Armstrong et al. 2015, Mbulwe et al. 2015). Sorghum for the most part has displayed both antibiosis and tolerance as resistance mechanisms. Antibiotic properties of sorghum do not kill aphids but rather slow down their reproductive speed when compared to susceptible varieties. Tolerant properties of resistant sorghum allow the plant to grow and produce yield even under aphid stress and feeding. While both of these mechanisms are not well understood in resistant sorghum lines they appear to both be responsible for resistance to the sugarcane aphid. Sorghum variety trials in Georgia have shown differences in susceptibility to sugarcane aphid infestations that affect sorghum yield in commercially available sorghum hybrids for grain and forage production (Buntin et al. 2017). However, currently hybrids for silage production are susceptible to sugarcane aphid injury (Buntin et al. 2017).

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CHAPTER 2

EPIZOOTICS OF THE ENTOMOPATHOGENIC FUNGUS *LECANICILLIUM LECANI* (HYPOCREALES: CLAVICIPITACEAE) IN SUGARCANE APHID (HEMIPTERA: APHIDIDAE) POPULATIONS INFESTING GRAIN SORGHUM

Haar, P.J., R. Bowling, W. A. Gardner, and G. D. Buntin. 2018. Epizootics of the Entomopathogenic Fungus *Lecanicillium lecani* (Hypocreales: Clavicipitaceae) in Sugarcane Aphid (Hemiptera: Aphididae) Populations Infesting Grain Sorghum in Georgia and Texas. J. Entomol. Sci. 53(1):104-105. Reprinted here with permission of the publisher.

Introduction

The sugarcane aphid, *Melanaphis sacchari* (Zehntner) (Hemiptera: Aphididae), occurs worldwide on a variety of grass species (Poaeceae), sugarcane (*Saccharum officinarum* L.), and several species of *Sorghum* (Singh et al. 2004). The sugarcane aphid was first reported in the U.S. on sugarcane in Florida (Mead 1978) and later in Louisiana (White et al. 2001). While it was reported on sorghum in Florida (Denmark 1988), it had not been recognized as an economic pest of grain sorghum, *Sorghum bicolor* (L.) Moench, until 2013 when Villanueva et al. (2014) reported yield losses due to sugarcane aphid infestations along the Texas Gulf Coast and Louisiana. The pest rapidly spread into 15 other states in the U.S. and all sorghum production regions in Mexico by the fall of 2015 (Bowling et al. 2016).

Yield losses in sorghum caused by sugarcane aphid are attributed to extraction of plant nutrients and sap when infestations of the aphid feed on the ventral surface of the leaves and along the stalk (Bowling et al. 2016). Losses are greater when large infestations are present during pre-flowering grain development. To date, there is no evidence of sugarcane aphid transmitting plant pathogens. Sooty mold growth on the honeydew produced by the aphids also reduces photosynthetic activity in the leaves and can reduce harvest efficiency (Singh et al. 2004).

When warranted by market conditions and infestation levels, two insecticides are currently available for use by growers to manage sugarcane aphid infestations on sorghum (Bowling et al. 2016). Results of initial testing of sorghum lines and hybrids for genetic resistance to the sugarcane aphid are promising and could be a viable management tactic (Armstrong et al. 2015). The presence of immature and adult stages of a variety of generalist aphid predators on sugarcane aphid-infested sorghum indicates that these predators are successfully using the aphids as prey. Aphelinid and braconid parasitoid wasps also have been detected and reared from aphid mummies. However, these natural enemies have not been recognized as significant natural mortality factors for the aphid pest (Bowling et al. 2016).

Materials and Methods

No naturally-occurring entomopathogens had been reported from sugarcane aphids infesting sorghum in the U.S. until the observations reported herein. In February 2015, a fungus was observed on overwintering sugarcane aphids in an abandoned sorghum field at Odem, TX (San Particio Co., 28.003174N; -97.536717W). In September 2016, an epizootic of the same fungus was identified as the cause of an observed "crash" in the population of sugarcane aphids on sorghum in Beasley, TX (Fort Bend Co., 29.491105N; -95.990170W). Fungal epizootics were subsequently observed in sugarcane aphid populations in sorghum plantings at three locations in Georgia in September 2017 – the UGA Bledsoe Research Farm (Williamson, Pike Co., 33.1773N; -84.4984W), the UGA Southwest Research and Education Center (Plains, Sumter Co., 32.0361N; -84.3692W), and the UGA Lang Research Farm (Tifton, Tift Co., 31.5202N; -83.5506W).

Results

Examination of aphid cadavers on the sorghum leaves collected from the three Georgia locations showed that aphid cadavers were often anchored to the leaf substrate by the fungal mycelia emerging from the cadaver. As is frequently symptomatic of fungal infections in insects and other arthropods, the cadavers were hardened but appeared in pristine state sometimes with the proboscis inserted into the plant tissue. The sporulating fungus on the cadavers was white (void of hue or grayness) in coloration with globular collections of spores on the cadaver surface (Fig. 1). Microscopic examination of the spores revealed them to be short and ellipsoidal in shape, and all were homogenous in size and shape. Using an ocular micrometer, the mean (±SE) measurements of 100 spores from the three locations in Georgia were 2.46 ± 0.12 μm L x 1.0 ± 0.01 μm W. The fungus was identified as *Lecanicillium lecanii* (Zimmerman) Zare & Gams (Hypocreales: Clavicipitaceae) using the key of Humber (1997) and the descriptions based on the taxonomic revision of *Verticillium* by Zare and Gams (2001).

Discussion

Lecanicillium lecanii, formerly known as *Verticillium lecanii* (Zimmerman) Viegas, is now phylogenetically considered to be the type species of a complex including *L. lecanii*, *L. muscarium* (Petch), and *L. longisporum* (Petch) (Zare and Gams 2001). Research with *V. lecanii* prior to the taxonomic revision found that naturally-occurring infections of insects via airborne spores are not likely and that epizootics of the fungus probably originate from fungal spores residing in the crop soils that are splash-dispersed onto the crop foliage (Hall 1981). Previous research with *V. lecanii* also shows that successful infection and epizootic initiation are highly dependent upon temperature and humidity. Hall (1981) reported that the optimal temperature range for *V. lecanii* is 18 to 31°C, depending on the source of the fungal isolate, and that *V.*

lecanii spores require high levels of humidity (near saturation) in the microhabitat for successful germination.

The observed epizootics of *L. lecanii* in sugarcane aphids infesting sorghum in Texas and Georgia reported herein followed periods of precipitation and accompanied temperatures within the optimal temperature range for the fungus. The crop canopy also likely contributed in retaining high levels of humidity under the canopy and on the ventral surfaces of leaves where sugarcane aphids were feeding. The future occurrence of epizootics of this fungus in sorghum cropping systems will depend upon the proper combination of abiotic and biotic conditions (i.e., temperature, humidity, precipitation, aphid population density, etc.). The impact that any epizootic may have on crop protection will depend upon the timing of the event in relation to critical growth stages of the crop.

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Figure 2.1. Sugarcane aphid cadaver covered with sporulating *L. lecanii*. (Image provided Margarita Martínez de Jesús, Maestría en Ciencias Agropecuarias, División de Ciencias Biológicas y de la Salud, Universidad Autónoma Metropolitana, Mexico).

CHAPTER 3

EVALUATION OF CONTROL TACTICS FOR MANAGEMENT OF SUGARCANE APHID IN GRAIN SORGHUM

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Abstract

Studies were conducted utilizing an IPM approach to control the invasive sugarcane aphid *Melanaphis sacchari* in grain sorghum. The study took place from 2016-2017 at Griffin, Tifton and Plains Georgia, USA during the growing season of grain sorghum from May to October. Integrated tactics included four variables: planting date, insecticidal seed treatment, foliar insecticides, and plant tolerance/resistance. We found that the early planting was effective in reducing damage and increasing yields when compared to the late planting. Additionally, the resistant variety and use of a foliar insecticide application was uniform in terms of yield despite treatment type and yielded more than the susceptible variety overall. Foliar application of flupyradifurone when aphids reach an economic threshold also was an effective management tactic. We concluded that an earlier planting date coupled with a resistant variety and judicious use of a foliar insecticide produced the best yielding outcome.

INDEX WORDS: *Melanaphis sacchari*, sugarcane aphid, grain sorghum, integrated pest management.

Introduction

The sugarcane aphid (SCA), *Melanaphis sacchari* (Zehntner) (Hemiptera: Aphididae), is an invasive pest to the U.S mainland believed to have originated and migrated from Africa. The original discovery of SCA on sorghum, *Sorghum bicolor* (L.) Moench, was by Denmark (1988) in Florida where it was not considered a pest of sorghum at the time. Before this it was found only in sugarcane and first reported in North America in Florida in 1977 (Mead 1978) and Louisiana in 1999 (White et al. 2001). Later, near Beaumont, TX in 2013, the SCA was first reported to be causing significant damage to sorghum. At the time, the aphid was found in four states and 38 counties as well as three northeastern states of Mexico, but by 2015 it infested 17 states and over 400 counties and all sorghum production regions in Mexico (Bowling et al. 2016). Long before its invasion into North America, the SCA was a serious pest of sorghum in Asia, Africa, South America and Australia (Singh et al. 2004). Found around the world on many grasses in the family (Poaeceae), sugarcane, *Saccharum officinarum* L., and sorghum are the primary targeted hosts which are of extreme agronomic importance. The SCA affects greater than 90% of the sorghum production areas of North America with the 17 U.S. states that had SCA on sorghum in 2015 estimated to include 97% (2,996,697 hectares) (7,405,000 acres) of the sorghum area and 98% 15,687,000 tons (US) (560,253,000 bushels) of the total production of sorghum in the U.S. (Bowling et al. 2016, USDA-NASS 2016).

SCA feeds on plant phloem tissue as most aphids do and can cause desiccation, discoloration and necrosis of the plant tissues and leaves, stunting of the seedlings, heading prevention or sterile grain heads, and if damage is severe enough, death of the plant. The stress related injuries caused by the SCA can lead to grain yield losses and total loss of biomass in the crop stand. Additionally, secondary economic impacts are caused by the sticky honeydew secretions as well as the aphid biomass when harvest occurs. Harvesting proves to be much more difficult due to sticky leaves impeding the movement of parts within the combine and causing mechanical failure. Honeydew not only leads to mechanical failure but also promotes the growth of black sooty mold that accumulates on the leaf surface and can inhibit the plant's photosynthetic capabilities. Viral transmission is also possible but has not been shown to be agronomically important to date.

The SCA, in the U.S., is an anholocyclic, parthenogenic, viviparous species, feeding on its annual hosts in the spring and summer, and then surviving through the fall and winter months on an alternate host when the sorghum dies (Brewer et al. 2016). The SCA undergoes parthenogenic reproduction at a much faster rate (nearly double) than that of other aphid pest species such as the greenbug, (*Shizaphis graminum* (Rondani)), enabling the colonization of the host plant very rapidly (Colares et al. 2015). Sugarcane aphids have a doubling time of about every 1.5 days and live on average about 28 days and can give birth to 2-3 live nymphs per day (Michaud 2015). Temperature, amount of rainfall and humidity impact the size of the population (Chang et al. 1982). The optimal environment for SCA population growth occurs during warm and dry climatic conditions (Singh et al. 2004). SCA does not overwinter in freezing areas and must migrate from areas such as south Florida, South Texas and Mexico where they feed on live plant tissue and then migrate northward during warmer months. Like many aphids this migration is accomplished through alate aphids which disperse during overcrowded conditions, diminishing nutritional resources and climatic conditions.

Previous research and field observations have implicated economic thresholds for SCAs in North America which include either aphids per leaf or the percent of plants infested with established colonies (Brown et al. 2015, Catchot et al. 2015, Seiter et al. 2015, Knutson et al.

2016). A protocol has been designed to assess a quick estimate of aphids/leaf based on plant response to aphid presence gathered from experiments in South Texas, Louisiana, Arkansas, Oklahoma, and Georgia (Bowling et al. 2016). Two insecticidal sprays are effective against SCA on sorghum in the US. The first, a 50 % formulation of sulfoxaflor (Transform 50WG) received a Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) section 18 emergency use in most of the southern states on sorghum in 2014, 2015, 2016, 2017, and 2018 (Buntin pers. Observ.). Later, in 2015, flupyradifurone 17.09% (Sivanto Prime 1.67SL) received EPA approval for commercial use on sorghum (Bowling et al. 2016). Both sulfoxaflor and flupyradifurone have an efficacy of greater than 98% mortality of the SCA (Bowling et al. 2016, Buntin et al. 2018). A diversity of natural enemies has also been well documented including 18 predator species, 2 parasitoid species (Colares et al. 2015, Bowling et al. 2016) and an entomopathogen (Haar et al. 2018). Natural enemies play a considerable role in integrated pest management and may delay aphids from reaching threshold but usually natural enemies alone do not prevent economic damage by SCA.

Grain sorghum is an important row crop across the southeast including Georgia. Its use as a semi drought tolerant livestock feed for animals has been and is still currently being jeopardized by the sugarcane aphid. The research conducted here implements and assesses the use of integrated pest management tactics to provide a sustainable and effective management strategy for the invasive sugarcane aphid on grain sorghum. Field experiments from this study reveal results about the use of host plant resistance, insecticide seed treatment, foliar insecticide application and planting date in an integrated pest management strategy to control sugarcane aphid. The overall goal is to develop an economically stable integrated pest management system worthy of adoption by sorghum growers so that sustainable management of this pest can be achieved.

Materials and Methods

Field experiments were conducted at three University of Georgia Research farms including the Bledsoe Plant Science Farm near Griffin, the Southwest Research and Education Center near Plains and the Lang Research farm near Tifton. Trials were conducted in 2016 and 2017 at the Griffin and Tifton sites and in 2016 at Plains. All trials were planted at the standard seeding rate of 197,684 seeds per hectare (80,000 seeds per acre) using either a pneumatic planter or a small-plot packet planter. Plots in Griffin measured 9.14 meters (30 feet) with four rows at 76.2 cm (30 inch) row spacing. Plots in Tifton and Plains measured 12.2 meters (40 feet) with 6 rows at 91.4 cm (36 inch) row spacing and were planted with an air planter. Planting dates for each trial are listed in Table 1.

Standard agronomic practices for each location were used in all trials. Tillage was conventional with disk harrowing or chisel plowing plus disk harrowing. All trials were fertilized preplant and incorporated with 44.5 or 55.6 kg per ha (40 or 50 lbs per acre) of nitrogen in a 7-14-21 (N-P-K) blend of granular fertilizer. Sidedress liquid nitrogen was applied about 30 days after planting at 111.2 kg per ha (100 lbs of nitrogen per acre). All seed was treated with Concep III safener (Syngenta Crop Protection, RTP, NC) and S-metolachlor (Dual Magnum® 7.62EC, Syngenta Crop protection) was applied as a pre-emergence herbicide after planting at 1.74 Liters per ha (1.5 pints per acre) to prevent emergence of annual grass and broadleaf weeds. Atrazine (Aatrex 4L) was applied at 1.98 kg per ha (32 ounces per acre) as a post emergence herbicide when plants were approximately 0.3 meters (1 foot) tall for the control of small broadleaf weeds. All plots in the early planting at Griffin in 2016 were sprayed with chlorantraniliprole (Prevathon®, DuPont, Wilmington, DE; now FMC Company, Philadelphia, PA) at 0.86 kg per ha (14 fl. oz. per acre) on 1 June at 3-4 leaf stage to control fall armyworm, *Spodoptera frugiperda* (J.E. Smith), in the whorls. No other pesticides were applied in all trials. Trials were irrigated as needed to establish stands and to prevent drought stress.

There were four variables analyzed in this study including planting date, insecticide seed treatment, plant tolerance/ resistance, and foliar insecticide applications. The insecticide seed treatment, plant tolerance/ resistance and the foliar insecticide applications were arranged in all possible combinations for a maximum of eight different treatments. Hybrid and foliar spray treatments in all trails were organized in a 2x2 factorial arrangement in a randomized complete block design with four replications. Each whole plot was split and either treated or not with an insecticidal seed treatment.

The planting date was assessed by planting the early and late trials roughly one month apart in a side by side arrangement, each of which contained four replications of the eight treatments for a total of 32 plots within each trial. Early and late trials were conducted at Griffin in 2016 and 2017 but only a late trial was conducted at Plains and Tifton in 2016. In 2017 the Tifton location had both the early and late plantings but severe bird damage during the first trial and hurricane before maturity prevented yield from being taken. Specific planting dates and harvest dates are listed in Table 3.1. Two border rows of DKS 3888 (susceptible hybrid, no seed treatment) were planted on both sides of the early and late planting at Griffin to control for possible edge effects that may occur from infesting aphids. Four border rows of DKS 3888 were planted on both sides of the late planting at Tifton and Plains with an additional 21.3 m (70 feet) of border on the front and back of Tifton.

Two sorghum hybrids were used, Dekalb DKS 3888 and DKS 3707 (Dekalb Seeds, Monsanto/Bayer Inc. St. Louis, MO). DKS 3888 is susceptible to SCA while DKS 3707 is partly tolerant / resistant to SCA (Brewer et al. 2017, Michaud and Zukoff 2017, Buntin et al. 2017). The nature of the resistance to SCA is not known but includes a degree of plant tolerance. Insecticide seed treatment was clothianidin (Poncho 600, Bayer CropScience, RTP, NC) at the rate of 0.18 kg per 45 kg of seed (6.4 fl. oz. per 100 lb of seed). All seed also was treated with the fungicides metalaxyl, mefenoxam, and fluxothanin. Foliar insecticide treatment was untreated or treated with flupyradifurone (Sivanto prime 1.67SL, Bayer CropScience, RTP, NC) at 0.30 kg per ha (4 fl. oz. per acre). Flupyradifurone was applied when SCA infestations reached the tentative economic threshold of 50 aphids per leaf (Bowling et al. 2016, Brewer et al. 2016). Foliar sprays were applied with a CO_2 backpack sprayer equipped with flat fan TeeJet 8004 nozzles that delivered 140 liters per hectare (15 gpa) at 275 kilopascal (40 psi) and 4.8 kilometers per hour (3 mph). The timing of application of flupyradifurone varied among treatments because the seed treatment and variety tolerance affected the rate of increase of SCA populations. Specific application dates are listed in Table 3.1.

Insect Sampling

SCA were sampled in early stages of plant growth up to about V5-6 by inspecting 20 leaves taken from the mid canopy leaves at random within each plot. At the later growth stages, the aphid counts were taken from 10 upper and 10 lower canopy leaves at random within each plot. Total aphid of alates and apterae were numerically counted between 1 - 50 aphids per leaf.

Infestations exceeding about 50 aphids per leaf were estimated by counting the number of square centimeters of infested leaf area and multiply the leaf area by 20 aphids per cm^2. The conversion amount was based on initial samples of heavily infested leaves and estimating aphids per cm^2. Plots were inspected weekly for presence of aphids and then sampled weekly to measure aphid numbers. Sampling continued in each trial until aphid populations had declined to nearly zero in all plots except at Plains in 2016 where only four weekly samples were taken.

Plant measurements

Plant measurements in all trials including seedling plant population, plant growth stage, SCA plant injury ratings, percentage of grain head emergence, final grain panicle density, grain yield and test weight. Seedling plant population was estimated by counting the number of plants in two meters of row in the second and third rows of each plot. Seedling plant counts were done at 21 - 30 days after planting in each trail before colonization of plants by SCA. When plants had reached milk to soft dough stage in plots with Sivanto spray plus seed treatment and aphid population in plots had declined, plants in plots were visually rated for plant growth stage (KSU pub) and percentage plants with grain panicles. The same person or two people rated all plots in a trail. SCA plant injury and chlorosis also were measured using injury using a modified 1 to 9 scale of Burd et al. (1993) where: 1 = no visible injury or a few isolated chlorotic spots, 2 = isolated chlorotic spots, 3 = <15% chlorotic leaf area, 4 = 16 - 25% chlorotic leaf area, 5 = 26 – 40% chlorotic leaf area, 6 = 41 – 55% chlorotic leaf area, 7 = 56 - 70% chlorotic leaf area, 8 = 71 - 85% chlorotic leaf area, and 9 = >85% chlorosis and/or all plants dead.

At maturity, the final number of grain panicles measured by counting all grain panicles with viable mature grain in one row per plot. Grain panicle number was converted to number per square meter. Plots were harvested with a 2-row small-plot combine by harvesting all seed in the two center rows of each plot. Grain were cleaned of debris and weighed. Grain test weight and moisture content were measured using a Dickey-John moisture meter. Grain yields were calculated and adjusted to 14 % moisture content. Grain yield was not measured in the early and late planting trials at Tifton in 2017, because of severe bird damage in the early trial and plant lodging in the late trial caused by Hurricane Irma on 11 Sept 2017.

Statistical analysis

Aphid counts were averaged among top and bottom leaves to calculate the mean number of aphids per leaf. Aphid-days for each plot were calculated using the equation, cumulative aphid-days = $\sum[(X_i + X_{i-1})/2] \times (t_i - t_{i-1}) / 2]$, where X_i and X_{i-1} are two progressive sample periods and (t_i and t_{i-1}) are the number of days between the two respective sample periods (Ruppel 1983, Kiechhefer et al. 1995). Cumulative aphid-days for the entire sampling time of each trial were calculated for each plot.

Response variables were cumulative aphid-days (CAA), plant stand, plant injury ratings, plant growth stage, percentage grain head after aphid numbers declined to low levels, final panicle density, grain yield and grain test weight. Initial full analyses of most variables with planting date found numerous significant interactions between planting date and the other study factors so results were analyzed by year and planting date trial. The effects of sorghum hybrid resistance, foliar spray application, and insecticide seed treatment and the interactive effects of these factors were examined in using a three-way ANOVA with a split-plot design where hybrid and foliar spray combinations as whole plots and seed treatment as a subplot factor. Resulting plant stand, cumulative aphid-days, percent heading, and final panicle density were analyzed using PROC GLIMMEX with a log adjustment and a negative binomial or Poisson distribution

(SAS 9.4, SAS Institute 2012), with hybrid, spray and seed treatment and their interactions as fixed effects and block and residual as random effects. The SLICE option was used to compare seed treatment means within foliar x hybrids. Plant damage ratings, plant growth stage, grain yield and test weight were analyzed with PROC MIXED with hybrid, spray and seed treatment as main effects and block and residual as random effects. If needed, data were transformed with either natural log or square-root transformations where appropriate to meet assumptions of normality. Aphid numbers also were analyzed within sample dates in each trial using the same experimental design with a log transformation. When overall *F* values indicated differences, treatment means were separated using pairwise T test groupings in PROC PLM. Actual LS means and SEM are presented.

Table 3.1. Dates for planting and harvest and chemicals applied throughout the season in each trial.

Year	Location	Planting date	Atrazine application date	Application dates of flupyradifurone				Harvest date
				Treatment 1 sus-nst	Treatment 2 sus-st	Treatment 3 res-nst	Treatment 4 res-st	
2016	Griffin -Early	16-May	9-Jun	28-July	28-July	12-Aug	12-Aug	1-Sep
2016	Griffin - Late	15-Jun	28-Jun	28-July	5-Aug	5-Aug	5-Aug	6-Oct
2016	Tifton - Late	3-Jun	30-June	18-July	18-July	10-Aug	10-Aug	13-Sep
2016	Plains - Late	21-Jun	7-Jul	2-Aug	12-Aug	12-Aug	22-Aug	5-Oct
2017	Griffin – Early	16-May	2-Jun	5-July	12-July	12-July	19-July	1-Sep
2017	Griffin – Late	14-Jun	11-July	19-July	19-July	27-July	27-July	5-Oct
2017	Tifton - Early	15-May	1-June	29-June	6-July	6-July	6-July	--
2017	Tifton - Late	6-July	27-July	11-Aug	16-Aug	11-Aug	24-Aug	--

Sus = susceptible hybrid, res = resistant hybrid, nst = no seed treatment, st = seed treatment applied.

Results

Aphid days and first and peak occurrence

2016 Griffin. At Griffin in 2016, aphids were first detected on July 13 in the early planting and July 20 in the late planting (Figure 3.1). But aphids reached peak numbers in the susceptible no spray treatments on Aug. 9 in both plantings. In the early planting, aphids reach the economic threshold (ET) in all of the susceptible hybrid plots on July 27, whereas aphids all resistant plots peaked and reached the threshold level in the no spray, no seed treatment plots on Aug. 9, which was about 2 week later than on the susceptible plants. For the resistant hybrid, only the no spray, no seed treatment reached threshold, the no spray with seed treatment did not reach the ET. In the late planting, the seed treatment substantially reduced peak aphid numbers in the susceptible hybrid without foliar spray and delayed aphids from reaching threshold by 8 days. The resistant hybrid spray treatments also reached threshold 8 days after the susceptible hybrid. Aphid numbers declined sharply by Aug. 25 in both plantings.

2017 Griffin. In the early planting Griffin 2017, aphids were first detected on June 16 and peaked in the susceptible, no spray without seed treatment plots on July 12 (Figure 3.2). The seed treatment delayed the peak in the susceptible, no spray treatment by one week compared to the no seed treatment, and peak aphid numbers were greater in the seed treatment than without the seed treatment. The seed treatment also delayed peak aphid numbers and the reaching the treatment threshold in the susceptible, spray plots by one week compared to the no seed treatment. The resistant variety also delayed aphids reaching the ET by one week and the resistant hybrid with seed treatment did not reach threshold even in the absence of spray. In the late planting, aphids were first detected on June 28 and peaked on July 26 about two weeks later than in the early planting (Figure 3.2). All no spray treatments had considerably higher in aphid number than the spray treatments. Aphids reached threshold in the susceptible and resistant plots without seed treatment on July 19 and 7 days later in plots with seed treatment on July 26. Plant resistance did not delay aphids reaching the ET in this trial. Aphid declined to low levels by Aug. 2 in the early planting and by Aug. 17 in the late planting.

2017 Tifton. In the early planting, first aphid detection occurred on June 22 and aphid peak was on July 13 in the susceptible, no spray without seed treatment plots (Figure 3.3). The susceptible, no spray treatments had considerably higher aphid numbers than all other treatments. The aphid peak and threshold were delayed one week by the seed treatment in the susceptible spray plots. Aphids also reach threshold on the resistant hybrid one week later than on the susceptible hybrid. Aphids on the resistant hybrid with seed treatment reached but did not exceed the threshold on July 6.

In late planting, first detection of aphids occurred on July 28 and peaked on August 16 for the susceptible, no spray without seed treatment plots (Figure 3.3). The seed treatment delayed the peak by one week in the susceptible hybrid treatments. Plant resistance without the seed treatment also delayed aphids reaching threshold by 5 days, and the resistant hybrid with seed treatment plots were below threshold the entire season. Aphid numbers declined to nearly zero on Aug. 3 in the early planting and Sep. 8 in the late planting.

2016 Tifton and Plains. In late planting at Tifton 2016, aphid presence was first detected on June 30. Aphids reached a peak on July 21 for the susceptible, no spray without seed treatment and again on Aug. 10 (Figure 3.4). Aphids were sprayed below threshold on July 18 in the susceptible, spray plots with and without seed treatment. Aphids on the resistant hybrid were delayed by the seed treatment from reaching threshold by one week but did not prevent aphids from reaching threshold the resistant, spray with seed treatment plots. No spray, susceptible plots had the highest number of aphids while the resistant, no spray plots did not reach threshold.

At Plains in 2016, aphids in susceptible hybrid plots increased above threshold after Aug. 2. Plant resistance delayed aphids from reaching threshold by 10 days. The trial was not sampled after Aug 22 when the resistant spray seed treatment plots were sprayed.

Aphid-Days

Cumulative aphid-days were not significantly affected by planting date in any trial (F = 2.73 – 7.46, df = 1, 3; P = 0.1978 - 0.0718), but interactions with other variables with planting date usually occurred. Cumulative aphid-days were significantly affected by hybrid in all trials (F = 26.23 – 55.40; df = 1, 46; P < 0.0001) with the resistant hybrid having fewer aphid-days than the susceptible hybrid (Figure 3.5). Foliar spray also significantly reduced aphid days in all of the susceptible hybrid plots in all trials (F = 26.62 – 121.81; df = 1, 21; P < 0.0001), and also reduced aphid-days of resistant hybrid in all trials (F = 5.17 – 101.06; df = 1, 21; P = 0.0335 - <0.0001), except in the Plains and Tifton trials in 2016 (F = 2.51 and 1.16; df = 1, 21; P = 0.1279 and 0.7959) (Figure 3.5). The effect of seed treatment on aphid-days was variable and was only significant (P > 0.05) in the no spray plots for the susceptible and resistant hybrids in 2 and 3 of 8 location x planting date trials, respectively. In all trials except the late planting at Griffin 2017, aphid-days were greatest for the susceptible hybrid, no-spray treatments. On resistant hybrids, aphid-days were greater in the no spray, no seed treatment plots than the other resistant hybrid treatments in 5 of the 8 trials.

Effect of SCA on plant measurements

Seedling plant numbers were not significantly ($P > 0.05$) affected by hybrid, foliar spray or seed treatment in any trial (Table 3.2). An exception was that the resistant hybrid had less plant stand than the susceptible hybrid in the 2017 Tifton late trial. Although significant, the difference in stand was not large and most likely did not affect sorghum growth, development and yield.

2016 Griffin. In the early and late plantings at Griffin in 2016, the susceptible, no spray, treatments had the highest injury ratings with the seed treatment significantly reducing plant injury in both plantings by about one rating point. The other treatment combinations had significantly lower ratings but some other combinations were statistically different in plant injury. In the late planting, plant injury ratings were much lower in all other treatment combinations with the resistant hybrid, no spray and no seed treatment having the most injury among these other combinations. Overall analysis of the early planting results found that plant injury ratings were affected significantly by foliar spray treatment ($F = 18.10$; df = 1, 21; $P = 0.0004$), but the hybrid and seed treatment did not significantly affect plant injury ratings ($F = 1.13$; df = 1, 21; $P = 0.2996$; $F = 1.13$; df = 1, 21; $P = 0.2996$, respectively). However, there was a significant interaction between hybrid and spray ($F = 51.55$; df = 1, 21; $P < 0.001$) and three-way interaction among hybrid, spray and seed treatment also was significant ($F = 4.53$; df = 1, 21; $P = 0.0454$). In the late planting, plant injury ratings were significantly affected by hybrid ($F = 78.76$; df = 1, 21; $P < 0.0001$), foliar spray ($F = 124.11$; df = 1, 21; $P < 0.0001$) and seed treatment ($F = 4.31$; df = 1, 21; $P < 0.05$), and most 2-way and the 3-way interactions also were significant (Table 3.3).

In the early planting, the number of grain panicles per area and percentage of plants with grain heads were similar in all treatments and not statistically different ($P > 0.05$) (Table 3.4 and

Figure 3.6). In the late planting, grain head numbers and percentage of grain heads also were not statistically different among treatments, except for the susceptible hybrid, no spray treatments (Table 3.4 and Figure 3.6). This treatment without a seed treatment had very few grain heads in the late planting and with a seed treatment had about half the number of grain heads as the other treatment combinations. The susceptible hybrid, no spray treatments had statistically fewer grain heads than the other treatments combinations, while the other combinations were not statistically different. These results produced significant ($P < 0.05$) main effects for hybrid, foliar spray and seed treatment, and significant 2-way and the 3-way interactions (Table 3.4).

Plant growth stage was identical among all treatments in the early planting. In the late planting, plants were less mature in the susceptible hybrid, no spray, with and without the seed treatment plots than all other treatment combinations (Table 3.5). In the late planting plant growth stage was affected by hybrid ($F = 29.16$; df = 1, 21; $P < 0.0001$) and foliar spray ($F = 29.16$, df = 1, 21; $P < 0.0001$) but not by seed treatment ($F = 2.70$; df = 1, 21; $P = 0.1152$).

Grain yields in the early planting were lower in the both susceptible, no foliar spray treatments as compared to the other treatment combinations (Figure 3.7). The seed treatment improved grain yield of the susceptible, no spray treatment without a seed treatment. The other treatment combinations had similar yields except for the resistant, spray, no seed treatment which yielded less than the highest yielding treatment. Hybrid ($F = 6.24$; df = 1, 21; $P = 0.0209$) and foliar spray ($F = 6.17$; df = 1, 21; $P = 0.0215$) significantly affected grain yields in the early planting. Grain yields in the late plating also were significantly affected by hybrid ($F = 17.93$; df = 1, 21; $P = 0.0004$) and spray ($F = 10.44$; df = 1, 21; $P = 0.004$). The susceptible hybrid without foliar spray or seed treatment essentially produced no grain yield while adding a seed treatment increased yield by about 50% compared to the susceptible hybrid with foliar spray

(Figure 3.7). The susceptible hybrid with foliar spray and all treatments with the resistant hybrid had statistically similar yields.

Grain test weights in the early planting also were significantly affected by hybrid (F = 39.96; df = 1, 21; P < 0.0001), foliar spray (F= 93.28; df = 1, 21; P < 0.0001), and seed treatment (F = 10.92; df = 1, 21; P = 0.0034) as well as all two-way interactions (hybrid x spray: F = 84.80; df = 1, 21; P < 0.0001; hybrid x seed treatment: F = 6.10; df = 1, 21; P = 0.0221; and spray x seed treatment: F = 8.90; df = 1, 21; P = 0.0071) and the three-way interaction (F = 10.09; df = 1, 21; P = 0.0045). The susceptible no spray, no seed treatment had the lowest test weight and the susceptible hybrid, no spray, with seed treatment had the second lowest test weight (Table 3.6). Both treatment combinations were statistically different and were significantly lower than all other treatment combinations, which were not significantly different. Grain test weights in the late planting were not statistically different among treatment combination at Griffin in 2016 (Table 3.6).

2017 Griffin. In the early and late planting, the susceptible, no spray with and without seed treatment both statistically differed from the rest of the treatments and had the highest plant injury ratings of all the treatments (Table 3.3). Plant injury ratings were affected by both hybrid and spray in the early planting (F = 37.66; df = 1, 21; P < 0.0001) and (F = 82.79; df = 1, 21; P < 0.0001) and the late planting (F = 94.96; df = 1, 21; P < 0.0001) and (F = 47.74; df = 1, 21; P < 0.0001), respectively (Table 3.3). The hybrid by spray interactions for the early and late planting also were significant (P < 0.0001), and the spray by seed treatment interaction also was significant for the early planting only (F = 7.57; df = 1, 21; P = 0.0120).

The early planting susceptible no spray, no seed treatment had both the fewest final grain panicle density and lowest head percent of all the treatments (Figure 3.6, Table 3.4). All other treatments had more final grain panicles and percentage of heading than the susceptible, no spray treatments and were not statistically different in the early planting grain (Figure 3.6). In the late planting the susceptible, no spray with seed treatment differed statistically from the rest of the treatments and had the fewest final grain panicles. The treatment with the second lowest head percentage statistically different from all other treatments was the susceptible, no spray, without seed treatment in the late planting. All other treatments were statistically similar. Head percentage of the early planting was significantly affected by hybrid (F = 51.09; df = 1, 21; P < 0.0001), spray (F = 32.36; df = 1, 21; P < 0.0001), seed treatment (F= 4.79 ; df = 1, 21; P = 0.0401), and, all 2-way interactions were significant statistically (P < 0.05) and the 3-way interaction was also statistically significant (F = 13.30; df = 1, 21; P = 0.0015). The head percentage of the late planting was affected significantly both by the hybrid (F = 196.91; df = 1, 24; P < 0.0001) and spray treatments (F = 190.06; df = 1, 24; P < 0.0001). There was also a statistically significant two-way interaction between hybrid and spray (F = 183.33; df = 1, 24; P < 0.0001). The early planting final panicle density also was significantly affected by hybrid (F = 19.03; df = 1, 21; P = 0.0003), spray (F = 30.30; df = 1, 21; P < 0.0001) and seed treatment (F = 7.66; df = 1, 21; P = 0.0116), as well as all two-way interactions and the three-way interaction (P < 0.01). Seed treatment was the only significant effect on heads per square meter in the late planting (F = 5.86; df = 1, 21; P = 0.0247).

The susceptible, no spray, no seed treatment was statistically different from all of the other treatments and had the most immature plant stage in the early planting (Table 3.5). The resistant, no spray, with seed treatment and the resistant, spray, with seed treatment were statistically different from all other treatments and also had the most mature plant stage in the early planting. The only treatments statistically different from each other and all other treatments in the late planting were the susceptible, no spray, with and without seed treatment, which had less mature plants. Plant stage of the early planting was significantly affected by hybrid (F = 48.84; df = 1, 21; P < 0.0001), spray (F=7.81; df = 1, 21; P = 0.0108), and seed treatment (F = 31.26; 1, 21; P < 0.0001). There was also a two-way interaction between hybrid and spray (F = 12.21; df = 1, 21; P = 0.0022). Plant stage of the late planting also was significantly affected by hybrid (F = 75.00; df = 1, 21; P < 0.0001), spray (F = 75.00; df = 1, 21; P < 0.0001) and the interaction of hybrid and spray (F = 75.00; df = 1, 21; P < 0.0001).

Grain yields in the early and late planting were lower in both susceptible, no foliar spray treatments as compared to the other treatment combinations (Figure 3.7). The seed treatment improved grain yield of the susceptible, no spray treatment in the early planting and was statistically different from the no seed treatment (Figure 3.7). The other treatment combinations in both the early and the late had similar yields statistically within each trial. Hybrid (F = 52.8; df = 1, 21; P < 0.0001), foliar spray (F = 23.11; df = 1, 21; P < 0.0001), and seed treatment (F = 4.82; df = 1, 21; P = 0.0394) significantly affected grain yields in the early planting. The susceptible hybrid without foliar spray or seed treatment essentially produce no grain yield while adding a seed treatment increased yield by about 50% compared to the susceptible hybrid with foliar spray in the early planting (Figure 3.7). The susceptible hybrid with foliar spray and all treatments with the resistant hybrid had statistically similar yields. Grain yields in the late plating also were significantly affected by hybrid (F = 34.33; df = 1, 24; P < 0.0001), foliar spray (F = 142.49; df = 1, 24; P < 0.0001) and seed treatment (F = 13.18; df = 1, 24; P = 0.0013).

Grain test weights in the early planting were significantly affected by foliar spray (F = 5.58; df = 1, 21; P = 0.0279) as well as two-way interactions between hybrid x spray (F = 4.36; df = 1, 21; P = 0.049) and hybrid x seed treatment (F = 12.70; df = 1, 21; P = 0.0018). Test weights in the late planting were significantly affected by hybrid (F = 20.69; df = 1, 21; P = 0.0002), foliar spray (F = 18.64; df = 1, 21; P = 0.0003) and a two-way interaction between hybrid and spray (F = 34.20; df = 1, 21; P < 0.0001). The susceptible no spray, no seed treatment had the lowest test weight and was the only statistically different treatment in the early planting (Table 3.6). The only statistical difference observed in the late planting among the treatments was in both the treated and untreated seed from the susceptible, no spray treatments (Table 3.6). In these two treatments the test weights were significantly lower than the rest of the treatments.

2017 Tifton. In the early planting, the only statistically distinguishable treatment was that the susceptible, no spray without seed treatment had the highest plant injury of all the treatments. The only treatments which were statistically different from the other treatments in the late planting were the susceptible, no spray with and without the seed treatment. Both of these treatments had higher injury ratings than the rest of the treatments. Plant injury ratings were affected by both spray (F = 12.00; df = 1, 21; P = 0.0023) and seed treatment (F = 15.67; df = 1, 21; P = 0.0007), and the two way interactions between hybrid and spray (F = 29.63; df = 1, 21; P < 0.0001) and spray and seed treatment (F = 17.69; df = 1, 21; P = 0.0004). The three-way interaction among hybrid, spray and seed treatment was also significant for the early planting (F = 7.41; df = 1, 21; P = 0.0128). In the late planting hybrid (F = 32.54; df = 1, 21; P < 0.0001), spray (F = 76.82; df = 1, 21; P < 0.0001) and seed treatment affected plant injury (F = 4.35; df = 1, 21; P = 0.0493). Plant injury in the late planting also was which significantly affected by all two-way interactions between hybrid and spray (F = 39.19; df = 1, 21; P < 0.0001), hybrid and seed treatment (*F* = 5.59; df = 1, 21; *P* = 0.0277) and spray and seed treatment (*F* = 6.99; df = 1, 21; *P* = 0.0152).

In the early planting the susceptible, no spray without seed treatment and this treatment had the lowest overall head percentage of all the other treatments as well as fewest final grain panicles per area (Figure 3.6, Table 3.4). In the late planting, the only two treatments which were different from each other and all the other treatments statistically were the susceptible, no spray with and without seed treatment where the no seed treatment had the lowest head percentage and with the seed treatment had the second lowest head percentage. Final panicle density of the susceptible, no spray treatments had the fewest panicles and were statistically different from all other treatments. The resistant treatments had statistically similar final panicle density in the late planting. For the late planting head percentage, hybrid, spray and seed treatment were all statistically significant (*F* = 334.72; df = 1, 21; *P* < 0.0001; *F* = 311.03; df = 1, 21; *P* < 0.0001; and *F* = 7.85; df = 1, 21; *P* = 0.0107, respectively). There were also significant two way interactions between hybrid and spray (*F* = 299.51; df = 1, 21; *P* < 0.0001) and hybrid and seed treatment (*F* = 6.11; df = 1, 21; *P* = 0.0221). Hybrid, spray and seed treatment all affected the final panicle density in the early planting (*P* < 0.01). All two-way interactions as well as the three-way interaction were significant as well (*P* < 0.001). The late planting final panicles density was affected by hybrid (*F* = 65.96; df = 1, 21; *P* < 0.0001), spray (*F* = 17.85; df = 1, 21; *P* = 0.0004), as well as the interaction between hybrid and spray (*F* = 20.31; df = 1, 21; *P* = 0.0002).

The susceptible, no spray without seed treatment had the most immature plant stage of all the other treatments in both the early and late plantings and also was statistically different from the rest of the treatments (Table 3.5). The susceptible, no spray with seed treatment and the susceptible, spray with seed treatment both had the second most immature plant stage in the late planting. For the early planting plant stage was affected by hybrid (F = 40.38; df = 1, 21; P < 0.0001), spray (F = 10.92; df = 1, 21; P = 0.0034) and seed treatment (F = 10.92; df = 1, 21; P = 0.0034). There were also three two-way interactions that were statistically significant between hybrid and spray (F = 7.82; df = 1, 21; P = 0.0108), hybrid and seed treatment (F = 14.54; df = 1, 21; P < 0.0010) and spray and seed treatment (F = 7.82; df = 1, 21; P = 0.0108). The three-way interaction also occurred among hybrid, spray and seed treatment (F = 18.67; df = 1, 21; P = 0.0003). Hybrid was the only statistically significant effect for plant stage in the late planting (F = 24.65; df = 1, 21; P < 0.0001).

Grain yield and test weight not measured at Tifton in 2017 because of severe bird damage to grain in the early planting and plant damage and lodging in the late planting caused by a tropical storm 'Irma' on Sept. 12, 2017.

2016 Tifton and Plains. For the late planting at Tifton in 2016, plant growth stage, percentage of plants with grain heads and final panicle density were not significantly (P > 0.05) affected by hybrid, foliar spray or seed treatment. Plant injury was significantly reduced by foliar spray (F = 9.71; df = 1, 21; P = 0.0052) in the susceptible hybrid. The resistant hybrid was less impacted by foliar spray. Seed treatment had no effect on plant injury in the late planting at Tifton in 2016.

Grain yield at Tifton in 2016 was reduced in the susceptible hybrid, no spray, no seed treatment plots compared with all other treatment combinations (Figure 3.7). The susceptible hybrid, no spray with seed treatment also was lower than two of the other treatment combinations. These results produced significant effects for hybrid (F = 7.39; df = 1, 21; P =

0.0129), spray (F = 9.34; df = 1, 21; P = 0.0060) and the interaction between hybrid and spray (F = 14.98; df = 1, 21; P = 0.0009). No statistical differences were found for test weight in the 2016 Tifton late planting.

Plant injury ratings at Plains were greater in the susceptible, no spray with and without seed treatment than all other treatment combinations. Hybrid and spray were both significant for plant injury ratings (F = 20.77; df = 1, 21; P = 0.0002) and (F = 30.44; df = 1, 21; P < 0.0001), respectively, and the interaction between hybrid and spray also was significant (F = 25.37; df = 1, 21; P < 0.0001). Plant growth stage also was reduced in the susceptible, no spray treatments as compared to the other treatments (Table 3.5). Plant growth stage was significantly affected by hybrid (F = 50.03; df = 1, 21; P < 0.0001) and the interaction between hybrid and spray (F = 9.88; df = 1, 21; P = 0.0049).

The percentage of plants with grain heads and final panicle density was reduced at Plains in both susceptible hybrid, no spray treatments as compared to the other treatment combinations (Figure 3.6, Table 3.4). Hybrid and spray and the interaction of hybrid x spray significantly affected percentage of grain heads (F = 10.37; df = 1, 24; P = 0.0037, F = 7.68; df = 1, 24; P = 0.0106 and F = 6.11; df = 1, 24; P = 0.0210, respectively). Final panicle density also was greater in the resistant than susceptible hybrid (F = 12.94; df = 1, 21; P = 0.0017) and in the spray than no spray plots (F = 7.45; df = 1, 21; P = 0.0126).

Grain yield and test weights at Plains also was lower in both susceptible hybrid, no spray treatments as compared to the other treatment combination which had similar yields (Figure 3.7, Table 3.6). Seed treatment did not affect grain yield of either hybrid while test weight of the susceptible hybrid without foliar spray was lower with a seed treatment than untreated. Hybrid

(F = 35.36; df = 1, 21; P < 0.0001) and spray (F = 14.37; df = 1, 21; P = 0.0011) and hybrid x spray (F = 18.74; df = 1, 21; P = 0.0003) were significant for grain yield. Test weight also was affected by hybrid (F = 34.60; df = 1, 21; P < 0.0001) and spray (F = 5.20; df = 1, 21; P = 0.0332) and the interaction of hybrid and spray (F = 16.47; df = 1, 21; P = 0.0006). There also was a significant three-way interaction for test weight among hybrid, spray and seed treatment (F = 4.21; df = 1, 21; P < 0.05).

Discussion

Before the arrival of SCA, management of insect pests of grain sorghum was not intensive and damaging levels of insect populations were not widespread in most years in the southeastern U.S. (Buntin 2012). With the arrival of the invasive sugarcane aphid in 2014 in Georgia, sorghum production has become more difficult and expensive which has partly caused a reduction in sorghum production in the region. Since 2014, virtually every field of sorghum requires active management of SCA to prevent yield losses. Typically, in the first few years since 2014 nearly every field in Georgia was sprayed at least once and sometimes two or three times with a foliar insecticide to suppress SCA and to prevent it's damage. Initial work in the southeast and south central U.S. (Brewer et al. 2017, Bowling et al. 2016, Knutson et al. 2016) found that planting date, sorghum plant resistance, foliar-applied insecticides and insecticide seed treatments all could be used to manage SCA. In the current study these tactics were examined in various combinations in eight trials over two years and three locations for management of SCA and prevention of sorghum damage and yield loss.

SCA does not overwinter where freezing temperatures occur and typically does not overwinter in Georgia (Michaud, et al. 2018, Bowling et al. 2016, Brewer et al. 2019). The aphid is migratory and moves northward each spring to infest the southeastern U.S. The exact timing of arrival in large numbers is not currently predictable but reports of SCA on Johnsongrass typically begin in late winter in southern GA. Sorghum planting date would interact with the timing of arrival of alates. In 2016, SCA initially was detected and reached peak numbers about the same time in early and late plantings. But in 2017 aphids infested and peak a few weeks earlier in the early planting than late plantings at Griffin and Tifton. Nevertheless, the aphid arrived and reached damaging levels in sorghum at an earlier stage of plant development in the late than early plantings. Large infestations in late plantings occurred in the vegetative whorl stage before sorghum panicle emergence, whereas in the early planting large populations occur in late boot or flowering stage of development after panicles had emerged. Planting date did not have a significant effect on cumulative aphid-days in any of planting date trials but did affect final panicle numbers and grain yield. Grain yields were lower in the late than early plantings at Griffin in both years. In addition, grain yield of susceptible hybrid without foliar sprays were reduced more by SCA injury in the late than the early planting. Because of the aphid arrival in both the early and late plantings at the same time, the later planting had younger more susceptible plants than the early planting which thus reflects the yield. The later planting in both years was in the vegetative 5 to 6 leaf stage once aphids reached threshold which is a critical period for head formation and grain development. The early planting was in pre boot stage before aphids reached threshold and once they reached threshold the plants were mostly in the boot/ early heading stage which is less susceptible than earlier stages.

In all trials, the susceptible hybrid without spray regardless of seed treatment had the highest cumulative aphid-days and damage ratings and lowest percent heading, final panicle density, grain yield as compared to the susceptible hybrid with foliar spray and all of the resistant hybrids treatments. Once aphid populations began to increase on the susceptible hybrid, they increased rapidly and exceeded the economic threshold in about 1 -2 weeks in all trials. The seed treatment delayed aphids from reaching the threshold on the susceptible hybrid by about one week in most trials, but did not prevent aphids from exceeding the threshold on the susceptible hybrid in any trail.

Sorghum grain yield and quality are determined by various components that develop throughout the season including plant population, grain panicles per plant (or per area), seed number per panicle and seed size or weight. Yield components were not directly measured in this study. Comparison percent heading at dough stage, final panicle density and grain yield suggest that when aphids reach damaging levels in the early planting at Griffin in 2016 and trials at Plains and Tifton in 2016, after grain panicles had emerged, consequently SCA impacted yield presumably by reducing panicle size, seed number per panicle and / or seed weight. In all late planting trials and early planting at Griffin in 2017, aphids reached damaging levels before panicle emergence, consequently panicle density, and possibly plant mortality, was the main component affecting grain yield, although seed number and size may also have been impacted. In most trials, grain test weight also was reduced of the harvested grain in the susceptible hybrid without foliar spray suggesting a negative effect on grain size and weight, because grain test weight is determined by grain seed weight and packing efficiency of the grain (Bean 2018). Test weight is a commonly used measurement of grain quality in North America when growers deliver grain for sale.

The foliar spray was highly effective in reducing sugarcane aphid numbers to well below the economic threshold on both hybrids. In all trials, once aphid populations were controlled they did not rebound to reach the threshold in any spray treatment the remainder of the season. The efficacy of different foliar insecticides was not evaluated in this research, but previous studies (Beuzelin and May 2015; Buntin and Roberts 2016; Kerns et al. 2015; Larson et al. 2016; VanWeelden et al. 2016; Zarrabi et al. 2015, 2017a, 2017b, 2017c) of registered insecticides have shown that flupyradifurone as Sivanto prime (1.67SL) at 0.28 - 0.49 kg per hectare (4-7 fl. oz. per acre) is the most consistently effective insecticide and usually provides 21 days or more suppression. Sufloxaflor (Transform 50WG) at 0.07 - 0.10 kg per hectare (1.0 – 1.5 oz. per acre) also is efficacious against SCA for about 14 to 21 days. The organophosphate insecticide, chlorpyrifos (Lorsban 4E) also can be efficacious at the high rate of 2.24 kg per hectare (2 pints per acre) and provides suppression for about 10-14 days but is less consistently effective than flupyradifurone and sufloxaflor. But at this rate chlorpyrifos has a 60-day pre-harvest interval which limits applications to pre flowering stages of sorghum development. Flupyradifurone has become to most widely used foliar insecticide for management of SCA throughout the U.S., which creates concern about possible development of insecticide resistance by SCA.

The resistant hybrid used in this study, DKS 3707, exhibits a partial antibiotic effect on SCA and tolerance to SCA injury, although the precise mechanism of resistance is not known (Armstrong et al. 2015, 2017; Bowling et al. 2016; Szczepaniec 2018a; Trostle 2016). Aphid populations increased more slowly on the resistant hybrid and reached the economic threshold usually one to two weeks after aphids reached threshold on the susceptible hybrid. Also cumulative aphid-days were less on the resistant than susceptible hybrid in most trials except at Griffin in 2017. The foliar spray reduced aphid-days on the resistant hybrid in most trials.

Nevertheless, the plant damage, percentage of heading, final panicle density and grain yield and test weight usually were not different among the four insecticide combinations on the resistant hybrid in all trials. In some cases, SCA populations did not reach threshold on the resistant variety even in the absence of the clothianidin seed treatment. When aphid populations on the resistant DKS 3707 exceeded the economic threshold and a foliar spray was applied, final panicle density, grain yield and test weight were not significantly greater than the no-spray resistant hybrid treatments within all trials except in the late planting at Griffin in 2017 where foliar spray prevented yield loss. This suggests that for a resistant hybrid like DKS 3707 the aphid damage-loss relationship may be different than for susceptible hybrids with the resistant hybrid being able to tolerate more aphids without yield-reducing damage. Moreover, the economic threshold used in this study may be greater than the 50 aphids per leaf for hybrids with partial resistance / tolerance to SCA. Perhaps a re-evaluation of the threshold needs to be conducted for such robust varieties as DKS 3707.

The use of plant resistance and/or a foliar spray of an effective insecticide based on sampling and on economic threshold clearly are effective tools for managing SCA on grain sorghum. The need for a preventive insecticide seed treatment is less clear. Neonicotinoid insecticide of clothianidin, thiamethoxam and imidacloprid are registered for use on sorghum as a seed treatment for control of various insects including SCA. Previous studies have found that all three insecticides are effective in suppressing SCA for about 35 days after planting (Buntin, unpublished data, Jones et al. 2015, Szczepaniec 2018a, Knutson et al. 2016). The clothianidin seed treatment that was used in the current research, reduced SCA numbers and aphid-days in no spray plots of both hybrids in about half of the trials. But the seed treatments usually only had a significant effect on SCA damage and sorghum plant measurements in the susceptible hybrid without a foliar spray. Indeed, grain yield of the susceptible hybrids without a foliar spray was more than 1000 kg/ha higher with a seed treatment than without a seed treatment in both trials at Griffin in 2016, the late planting at Tifton in 2016 and the late plating at Griffin in 2017. But in the absence of a seed treatment, the foliar spray enhanced yield more than twice as much at the seed treatment without foliar spray in these trials. Nevertheless, use of a seed treatment clearly greatly reduces the risk of a complete loss of production of a susceptible sorghum hybrid by SCA. These results also suggest that the seed treatment may be useful on susceptible hybrids especially in situations of late planting and where timely sampling and foliar spray applications may not be available. Conversely the seed treatment did reduce SCA peak numbers and aphid-days in 3 of 8 trials but the seed treatment did not affect sorghum plant damage, final panicle density or grain yield and test weight of the resistant hybrid in any trial. This suggests a widespread use of a neonicotinoid seed treatment may not be useful on a hybrid with good resistance / tolerance to SCA. However, in the trial at Tifton in 2016, which had the lowest peak aphid numbers of all trials, the seed treatment on the resistant hybrid prevented SCA populations from exceeding the economic threshold. Use of a seed treatment also may help growers manage the risk of unexpected damage by SCA.

Planting date had the greatest effect on yield across all trials despite aphid presence being similar. The early planting had greater yields regardless of treatment in both 2016 and 2017 Griffin trials than the late planting complementary treatments. Resistance was found to be very robust in terms of yield and regardless of spray or seed treatment yields were similar. Only susceptible spray plots could compete with the resistant variety on its own in terms of yield. For highest yields, early planting before aphid arrival is recommended and a spray is necessary for the susceptible DKS 3888 variety or plant the resistant DKS 3707 variety. The seed treatment proved effective but only in the susceptible no spray treatments and may not be needed on hybrids with effective levels of SCA resistance.

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Table 3.2. Mean stand count with standard error for each treatment across all trials.

Variety-Spray	Seed Treatment	Mean (±SE) Stand Count (plants/ meter row)							
		2016 Griffin Early	2016 Griffin Late	2017 Griffin Early	2017 Griffin Late	2017 Tifton early	2017 Tifton late	2016 Plains	2016 Tifton
Susceptible-No spray	No	14.26 ± 0.41a	17.21 ± 1.35a	19.67 ± 1.80a	21.31 ± 1.38a	20.17 ± 0.98a	16.39 ± 1.23d	22.62 ± 0.57a	13.77 ± 0.97a
	Yes	15.08 ± 1.23a	17.71 ± 1.39a	17.87 ± 0.86a	19.67 ± 2.91a	21.15 ± 1.08a	15.90 ± 1.18d	22.95 ± 1.04a	15.58 ± 0.31a
Susceptible-Spray	No	14.76 ± 0.68a	17.54 ± 0.31a	20.17 ± 0.86a	21.97 ± 2.66a	18.85 ± 1.12a	13.94 ± 0.90c	22.95 ± 0.97a	15.08 ± 0.97a
	Yes	14.26 ± 1.12a	21.15 ± 1.96a	21.48 ± 3.33a	18.36 ± 1.56a	20.17 ± 1.21a	17.87 ± 1.27bc	24.26 ± 0.54a	13.77 ± 0.46a
Resistant- No spray	No	14.59 ± 0.90a	17.38 ± 0.68a	18.52 ± 1.35a	18.69 ± 1.21a	20.17 ± 0.86a	20.49 ± 0.56ab	24.26 ± 0.60a	15.58 ± 0.31a
	Yes	14.10 ± 0.98a	20.17 ± 0.41a	16.89 ± 1.21a	14.43 ± 2.07a	18.36 ± 0.71a	21.81 ± 0.98a	24.92 ± 0.27a	14.92 ± 0.41a
Resistant-Spray	No	14.43 ± 1.44a	17.87 ± 1.27a	19.51 ± 1.12a	19.35 ± 1.79a	20.49 ± 1.18a	20.17 ± 1.18ab	23.61 ± 0.60a	15.08 ± 0.38a
	Yes	13.94 ± 0.41a	21.15 ± 2.03a	17.05 ± 1.10a	17.54 ± 2.05a	19.18 ± 1.35a	19.67 ± 1.54ab	24.76 ± 0.16a	15.90 ± 0.68a
F values									
Hybrid		0.06	0.23	1.36	3.52	0.12	9.04**	0.48	0.37
Spray		0.01	0.69	0.68	0.34	0.03	0.24	0.02	0.00
Seed treatment (ST)		0.02	2.64	0.64	3.54	0.02	0.58	0.25	0.01
Hybrid x spray		0.00	0.14	0.20	0.67	0.30	0.05	0.13	0.03
Hybrid x ST		0.06	0.10	0.35	0.09	0.75	0.29	0.00	0.00
Spray x ST		0.06	0.30	0.13	0.04	0.02	0.33	0.05	0.10
Hybrid x Spray x ST		0.06	0.18	0.38	0.63	0.00	1.20	0.00	0.72

Means within columns followed by the same letter are not significantly different (T-groupings of LS means, $\alpha = 0.05$). *, **, *** indicates significance at $\alpha = 0.05$, 0.01 and 0.001, respectively.

Table 3.3. Mean plant injury ratings with standard error for each treatment across all trials.

Variety- Spray	Seed Treatment	Mean (±SE) Plant Injury							
		2016 Griffin Early	2016 Griffin Late	2017 Griffin Early	2017 Griffin Late	2017 Tifton early	2017 Tifton late	2016 Tifton	2016 Plains
Susceptible- No spray	No	5.25 ± 0.48a	5.25 ± 0.25a	4.13 ± 0.13a	4.50 ± 0.29a	5.50 ± 0.29a	6.50 ± 0.50a	3.50 ± 0.65ab	4.75 ± 0.63a
	Yes	4.25 ± 0.48b	4.00 ± 0.20b	3.75 ± 0.32a	4.50 ± 0.29a	2.25 ± 0.48cd	4.50 ± 0.29b	3.75 ± 0.25a	5.00 ± 0.41a
Susceptible- Spray	No	2.00 ± 0.58d	1.25 ± 0.25e	1.63 ± 0.24cd	2.25 ± 0.14bc	1.50 ± 0.29d	2.13 ± 0.13c	2.25 ± 0.25c	2.00 ± 0.41b
	Yes	2.13 ± 0.43d	2.00 ± 0.00cd	2.13 ± 0.13bc	2.38 ± 0.13b	1.75 ± 0.25d	2.13 ± 0.31c	2.00 ± 0.00c	2.25 ± 0.48b
Resistant- No spray	No	3.13 ± 0.31c	2.25 ± 0.25c	2.38 ± 0.13b	2.13 ± 0.13bcd	3.25 ± 0.48bc	2.88 ± 0.43c	2.50 ± 0.50bc	2.75 ± 0.25b
	Yes	3.50 ± 0.65bc	1.75 ± 0.25cde	2.25 ± 0.14b	1.50 ± 0.29d	2.38 ± 0.24bcd	2.75 ± 0.14c	3.00 ± 0.41abc	2.00 ± 0.58b
Resistant- Spray	No	4.25 ± 0.25b	1.50 ± 0.29de	1.38 ± 0.38d	1.63 ± 0.38cd	3.38 ± 0.55b	2.13 ± 0.13c	2.75 ± 0.48abc	2.00 ± 0.41b
	Yes	3.75 ± 0.48bc	1.13 ± 0.13e	2.00 ± 0.00bc	1.50 ± 0.29d	3.25 ± 0.95bc	2.38 ± 0.24c	2.25 ± 0.25c	2.50 ± 0.50b
F values									
Hybrid		1.13	78.76***	37.66***	94.96***	1.53	32.54***	0.79	20.77***
Spray		18.10***	124.11***	82.79***	47.74***	12.00**	76.82***	9.71**	30.44***
Seed treatment (ST)		1.13	4.31*	1.12	0.78	15.67***	4.35*	0.00	0.06
Hybrid x spray		51.55***	48.81***	23.69***	30.17***	29.63***	39.19***	4.95*	25.37***
Hybrid x ST		0.64	0.32	0.40	1.54	3.92	5.59*	0.00	0.52
Spray x ST		0.07	10.30**	7.57*	0.78	17.69***	6.99*	1.78	1.44
Hybrid x Spray x ST		--	6.67*	1.95	3.00	18.67***	2.74	0.62	2.10

Means within columns followed by the same letter are not significantly different (T groupings of LS means, α = 0.05). *, **, *** indicates significance at α = 0.05, 0.01 and 0.001, respectively.

Table 3.4. Mean head percent with standard error for each treatment across all trials.

Variety-Spray	Seed Treatment	Mean (±SE) Heading Percentage							
		2016 Griffin Early	2016 Griffin Late	2017 Griffin Early	2017 Griffin Late	2017 Tifton Early	2017 Tifton Late	2016 Tifton	2016 Plains
Susceptible-No spray	No	76.2 ± 12.8a	0.0 ± 0.0c	20.0 ± 7.3c	37.5 ± 9.2b	26.7 ± 24.4b	23.7 ± 7.4c	97.5 ± 2.5a	75.0 ± 11.9b
	Yes	83.7 ± 8.9a	60.0 ± 10.0b	70.0 ± 12.2b	21.2 ± 3.1c	75.0 ± 14.4a	40.0 ± 0.0b	100.0 ± 0.0a	75.0 ± 9.5b
Susceptible-Spray	No	85.0 ± 6.4a	85.0 ± 15.0a	100.0 ± 0.0a	100.0 ± 0.0a	77.5 ± 17.8a	96.2 ± 1.2a	100.0 ± 0.0a	100.0 ± 0.0a
	Yes	93.2 ± 4.7a	81.2 ± 18.7ab	87.5 ± 12.5ab	97.5 ± 2.5a	82.5 ± 14.3a	100.0 ± 0.0a	100.0 ± 0.0a	93.7 ± 6.2a
Resistant-No spray	No	91.2 ± 8.7a	88.7 ± 8.2a	100.0 ± 0.0a	98.7 ± 1.2a	77.5 ± 22.5a	98.7 ± 1.2a	100.0 ± 0.0a	97.5 ± 2.5a
	Yes	83.7 ± 7.4a	91.2 ± 5.1a	100.0 ± 0.0a	100.0 ± 0.0a	97.5 ± 2.5a	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a
Resistant-Spray	No	95.0 ± 5.0a	97.5 ± 2.5a	100.0 ± 0.0a	100.0 ± 0.0a	95.0 ± 5.0a	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a
	Yes	78.7 ± 7.7a	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a	76.2 ± 11.4a	100.0 ± 0.0a	100.0 ± 0.0a	100.0 ± 0.0a
F values									
Hybrid		0.24	43.40***	51.09***	196.91***	3.76	334.72***	1.00	10.37**
Spray		0.64	29.05***	32.36***	190.06***	1.56	311.03***	1.00	7.68*
Seed treatment (ST)		0.14	7.12*	4.79*	2.97	1.56	7.85*	1.00	0.05
Hybrid x spray		0.84	14.94***	32.36***	183.33***	2.02	299.51***	1.00	6.11*
Hybrid x ST		3.44	4.98*	4.79*	3.88	1.42	6.11*	1.00	0.27
Spray x ST		0.14	7.71*	13.30**	1.52	3.54	3.29	1.00	0.27
Hybrid x Spray x ST		0.20	7.71*	13.30**	2.18	0.01	2.20	1.00	0.05

Means within columns followed by the same letter are not significantly different (T-groupings of LS means, α = 0.05). *, **, *** indicates significance at α = 0.05, 0.01 and 0.001, respectively.

Table 3.5. Mean plant stage with standard error for each treatment across all trials.

Variety- Spray	Seed Treatment	Mean (±SE) Plant Stage							
		2016 Griffin Early	2016 Griffin Late	2017 Griffin Early	2017 Griffin Late	2017 Tifton early	2017 Tifton late	2016 Plains	2016 Tifton
Susceptible- No spray	No	8.00 ± 0.00a	4.63 ± 0.13d	5.38 ± 0.13d	5.50 ± 0.00b	5.13 ± 0.13b	6.00 ± 0.00c	5.88 ± 0.13e	6.88 ± 0.13a
	Yes	8.00 ± 0.00a	5.63 ± 0.13c	6.13 ± 0.13c	5.30 ± 0.14c	6.90 ± 0.13a	6.30 ± 0.14b	6.00 ± 0.20de	7.00 ± 0.00a
Susceptible- Spray	No	8.00 ± 0.00a	6.38 ± 0.24ab	6.13 ± 0.13c	6.00 ± 0.00a	6.80 ± 0.14a	6.40 ± 0.13a	6.25 ± 0.14cd	7.00 ± 0.00a
	Yes	8.00 ± 0.00a	6.00 ± 0.20bc	6.50 ± 0.20b	6.00 ± 0.00a	6.80 ± 0.25a	6.30 ± 0.14b	6.25 ± 0.14cd	7.00 ± 0.00a
Resistant- No spray	No	8.00 ± 0.00a	6.13 ± 0.13abc	6.50 ± 0.00b	6.00 ± 0.00a	7.30 ± 0.25a	6.50 ± 0.00a	6.88 ± 0.13a	7.13 ± 0.13a
	Yes	8.00 ± 0.00a	6.30 ± 0.32ab	6.88 ± 0.13a	6.00 ± 0.00a	7.00 ± 0.20a	6.50 ± 0.00a	6.63 ± 0.13ab	7.00 ± 0.00a
Resistant- Spray	No	8.00 ± 0.00a	6.50 ± 0.20ab	6.38 ± 0.13bc	6.00 ± 0.00a	7.13 ± 0.13a	6.50 ± 0.00a	6.63 ± 0.24ab	7.00 ± 0.00a
	Yes	8.00 ± 0.00a	6.63 ± 0.24a	6.88 ± 0.13a	6.00 ± 0.00a	7.30 ± 0.25a	6.50 ± 0.00a	6.50 ± 0.20bc	7.00 ± 0.00a
F values									
Hybrid		--	29.16***	48.84***	75.00***	40.38***	24.65***	50.03***	2.10
Spray		--	29.16***	7.81*	75.00***	10.92**	2.74	0.62	0.00
Seed treatment (ST)		--	2.70	31.26***	3.00	10.92**	0.30	0.62	0.00
Hybrid x spray		--	6.67*	12.21**	75.00***	7.82*	2.74	9.88**	2.10
Hybrid x ST		--	0.50	0.49	3.00	14.54**	0.30	2.47	2.10
Spray x ST		--	6.67*	0.49	3.00	7.82*	2.74	0.00	0.00
Hybrid x Spray x ST		--	6.67*	1.95	3.00	18.67***	2.74	0.62	2.10

Means within columns followed by the same letter are not significantly different (T-groupings of LS means, α = 0.05). *, **, *** indicates significance at α = 0.05, 0.01 and 0.001, respectively. Stage ratings are based on Kansas State research and extension sorghum growth and development. See materials and methods for 1-9 scale.

Table 3.6. Mean test weights with standard error for each treatment across all trials.

Variety- Spray	Seed Treatment	Mean (±SE) test weight (lbs/ bushel)					
		2016 Griffin early	2016 Griffin late	2017 Griffin early	2017 Griffin late	2016 Tifton late	2016 Plains late
Susceptible- No spray	No	54.53 ± 0.31c	57.75 ± 0.68a	43.48 ± 1.91c	46.45 ± 1.49b	52.99 ± 0.71a	57.55 ± 0.68c
	Yes	56.85 ± 0.55b	55.28 ± 0.86a	50.73 ± 1.31ab	45.60 ± 1.43b	51.65 ± 0.74a	56.15 ± 0.74d
Susceptible- Spray	No	59.40 ± 0.34a	56.98 ± 0.64a	49.75 ± 1.20ab	52.75 ± 1.53a	51.62 ± 0.36a	58.43 ± 0.56bc
	Yes	59.33 ± 0.26a	54.48 ± 2.41a	52.60 ± 1.27a	53.58 ± 0.53a	51.23 ± 0.91a	58.75 ± 0.42ab
Resistant- No spray	No	58.65 ± 0.39a	56.70 ± 0.93a	51.28 ± 0.43ab	52.95 ± 0.98a	52.66 ± 0.98a	59.58 ± 0.27a
	Yes	58.78 ± 0.44a	55.90 ± 1.02a	48.60 ± 1.59b	53.70 ± 0.80a	53.42 ± 0.35a	59.58 ± 0.36a
Resistant- Spray	No	58.70 ± 0.20a	58.00 ± 0.49a	50.33 ± 1.48ab	52.45 ± 0.56a	52.01 ± 0.90a	59.35 ± 0.13ab
	Yes	58.90 ± 0.44a	57.75 ± 0.68a	50.05 ± 0.87ab	52.05 ± 0.28a	52.95 ± 0.63a	58.83 ± 0.70ab
F values							
Hybrid		39.96***	1.49	1.02	20.69***	3.32	34.60***
Spray		93.28***	0.25	5.58*	18.64***	2.24	5.20*
Seed treatment (ST)		10.92**	3.61	3.81	0.01	0.00	2.13
Hybrid x spray		84.80***	2.22	4.36*	34.20***	0.12	16.47***
Hybrid x ST		6.10*	1.53	12.70**	0.02	3.08	0.25
Spray x ST		8.90**	0.03	0.30	0.03	0.33	1.20
Hybrid x Spray x ST		10.09**	0.03	3.45	1.01	0.16	4.21*

Means within columns followed by the same letter are not significantly different (T-groupings of LS means, $\alpha = 0.05$). *, **, *** indicates significance at $\alpha = 0.05$, 0.01 and 0.001, respectively.

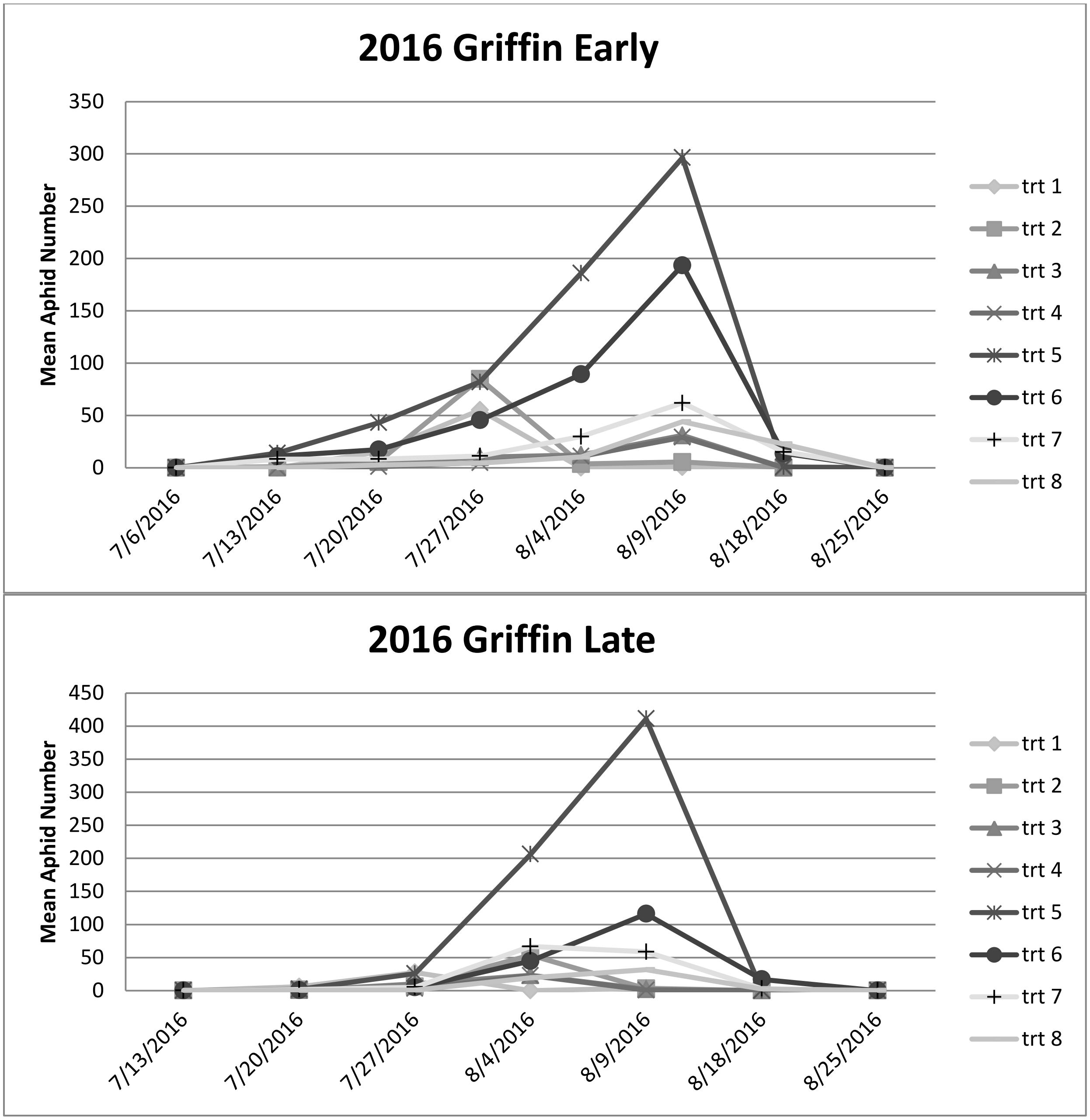
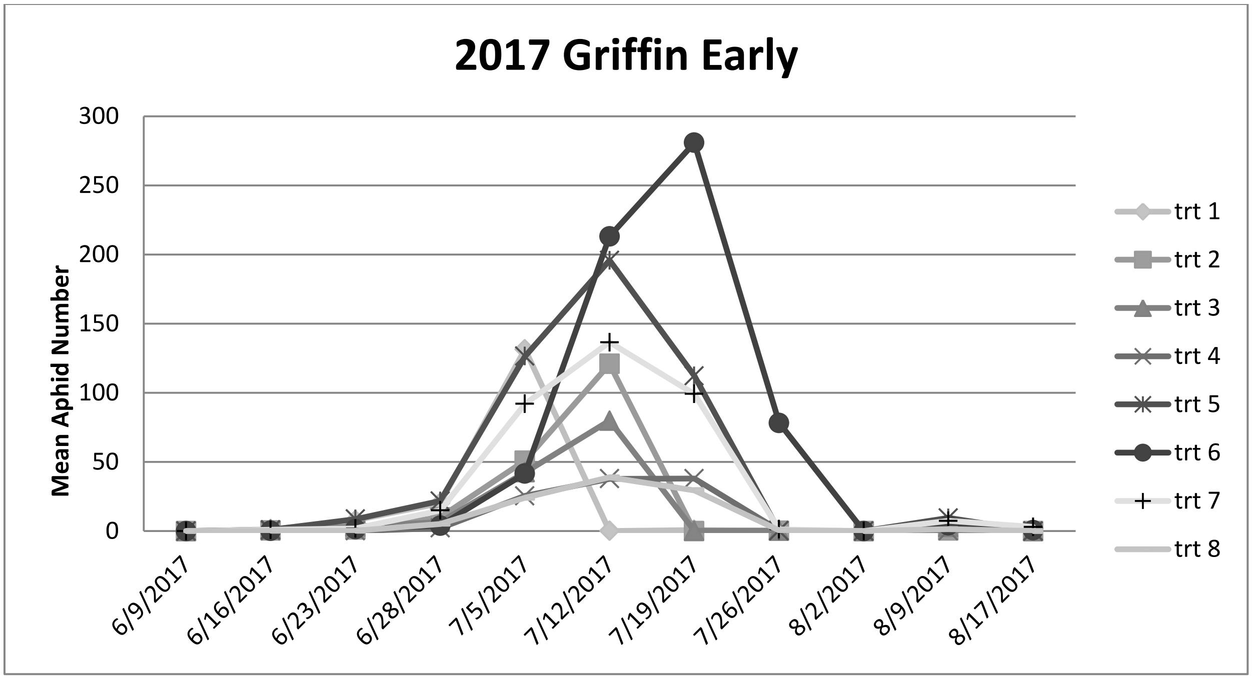


Figure 3.1: 2016 Griffin early and late planting mean aphid number by sampling date. Trt – treatment. Trt – 1 susceptible, spray, no seed treatment, trt – 2 susceptible, spray , seed treatment, trt – 3 resistant, spray, no seed treatment, trt – 4 resistant, spray, seed treatment, trt – 5 susceptible, no spray, no seed treatment, trt – 6 susceptible, no spray, seed treatment, trt – 7 resistant, no spray, no seed treatment, trt – 8 resistant, no spray, seed treatment.



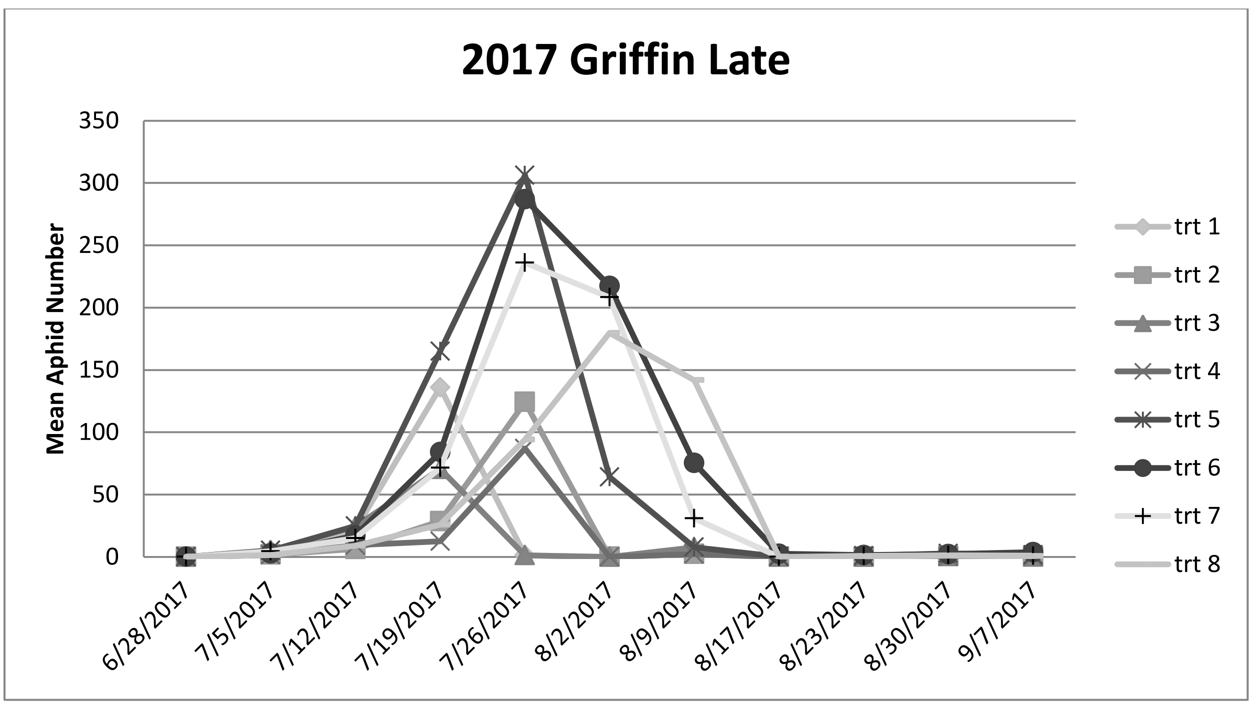
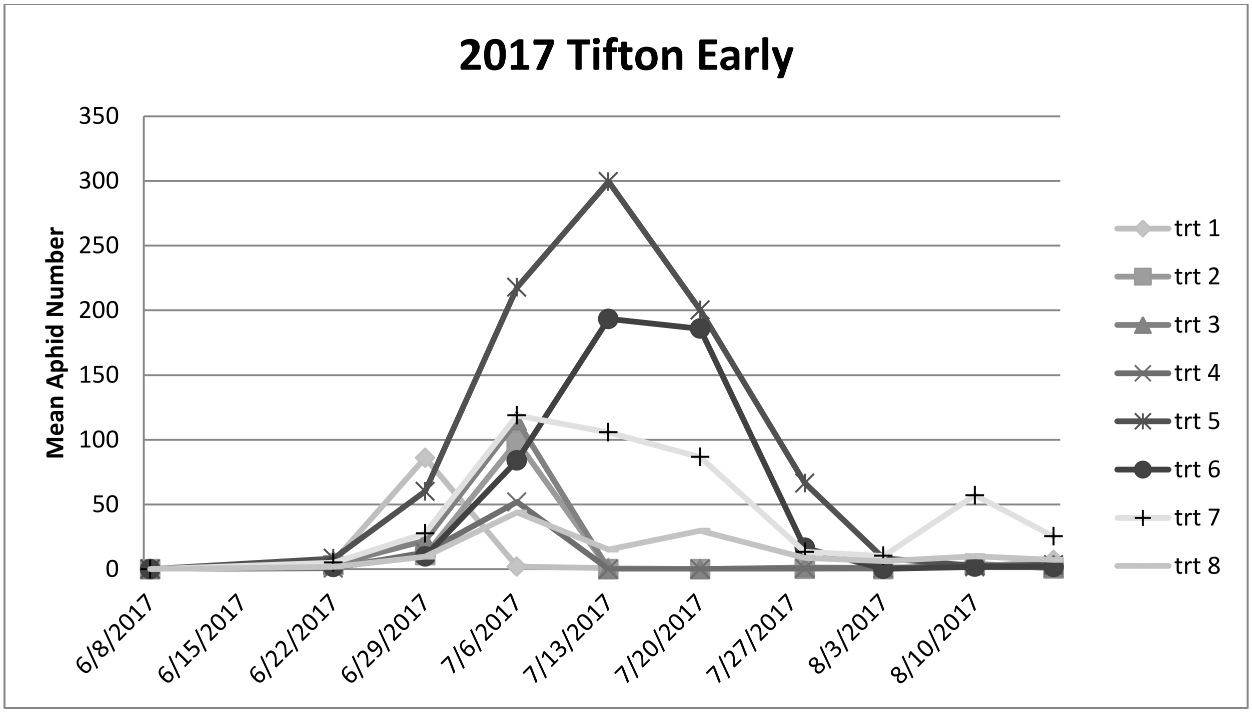


Figure 3.2: 2017 Griffin early and late planting mean aphid number by sampling date. Refer to Figure 3.1 for treatment assignment.



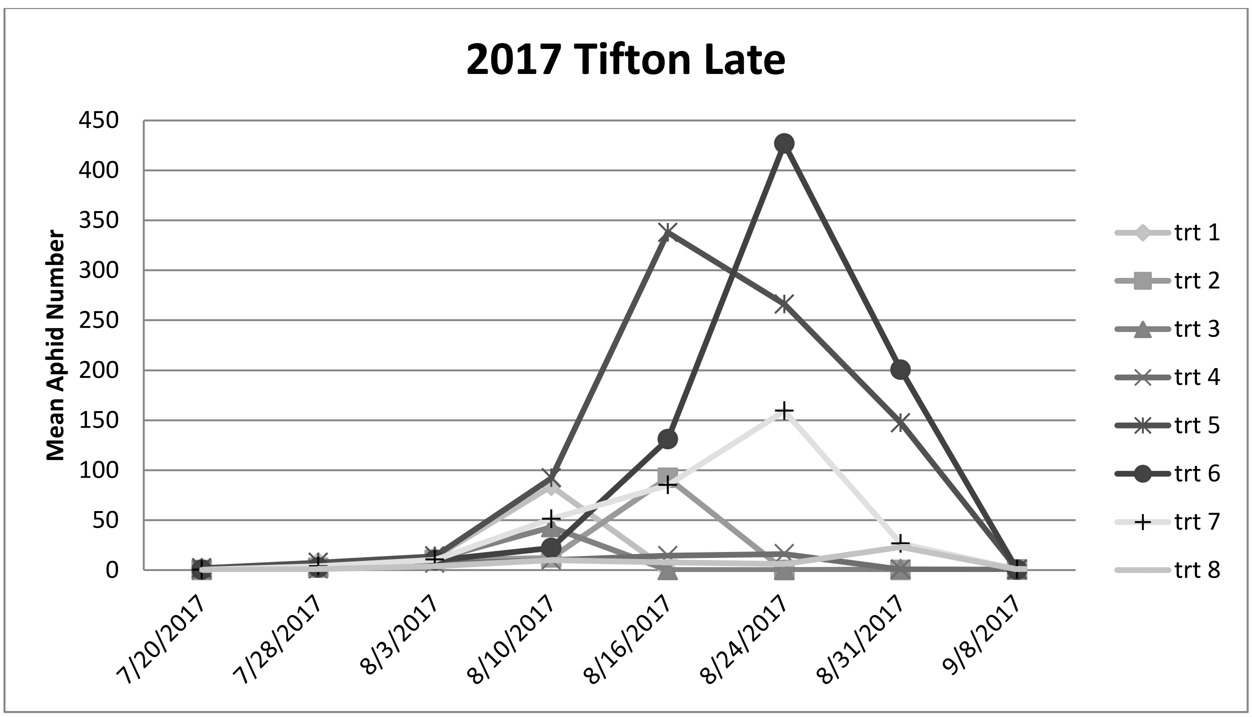
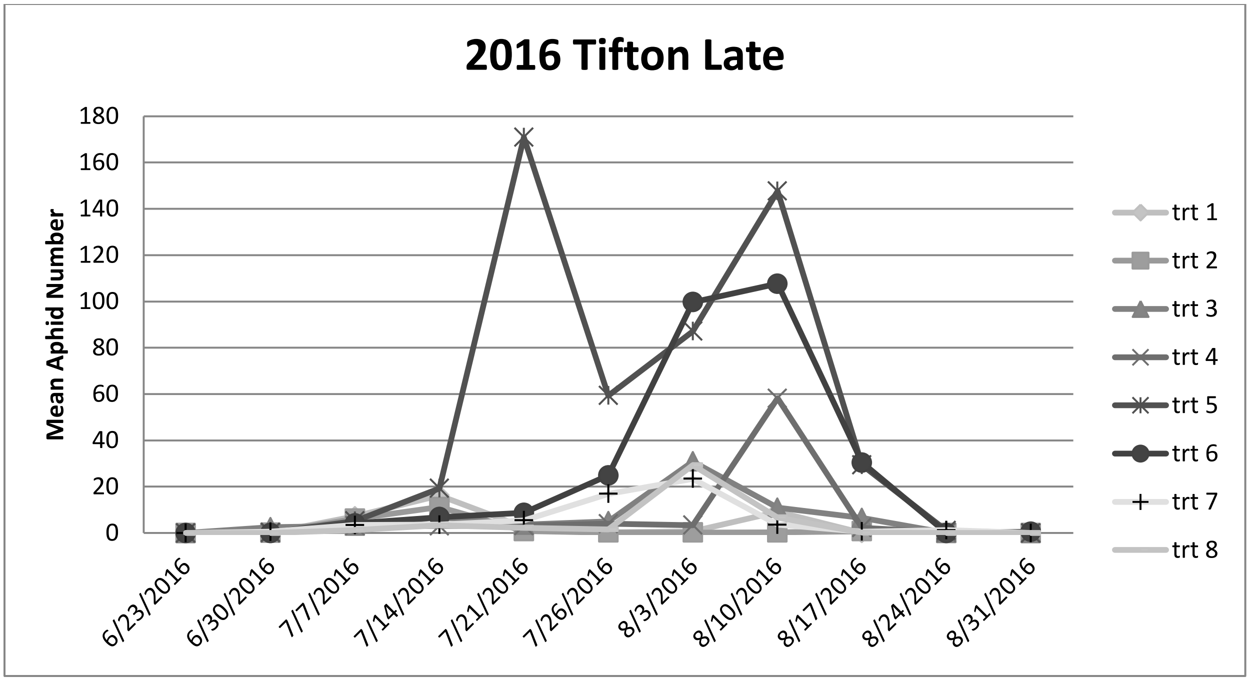


Figure 3.3: 2017 Tifton early and late planting mean aphid number by sampling date. Refer to Figure 3.1 for treatment assignment.



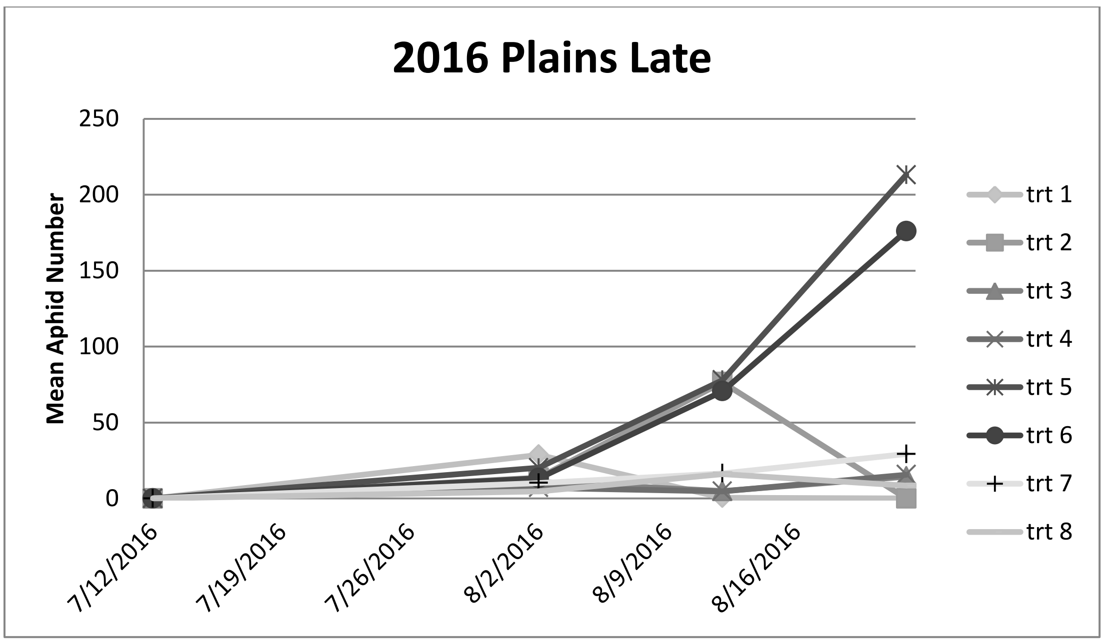


Figure 3.4: 2016 Tifton and Plains late planting mean aphid number by sampling date. Refer to Figure 3.1 for treatment assignment.

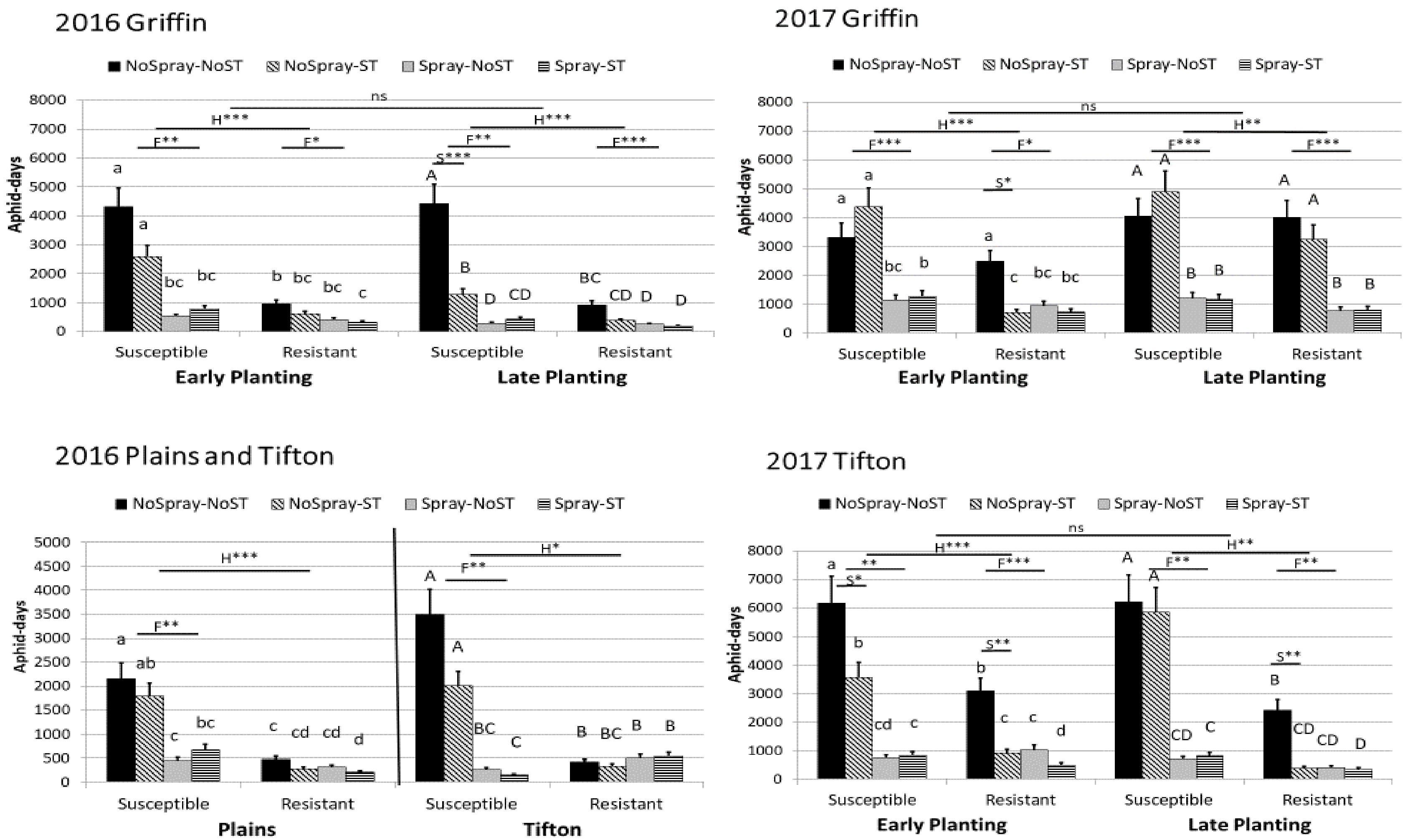


Figure 3.5 Aphid-days by date and location comparing early and late planting, resistant and susceptible hybrid, foliar spray and no spray, and seed treatment vs. no seed treatment. F = foliar spray, H = hybrid, S = seed treatment, ST = seed treatment.

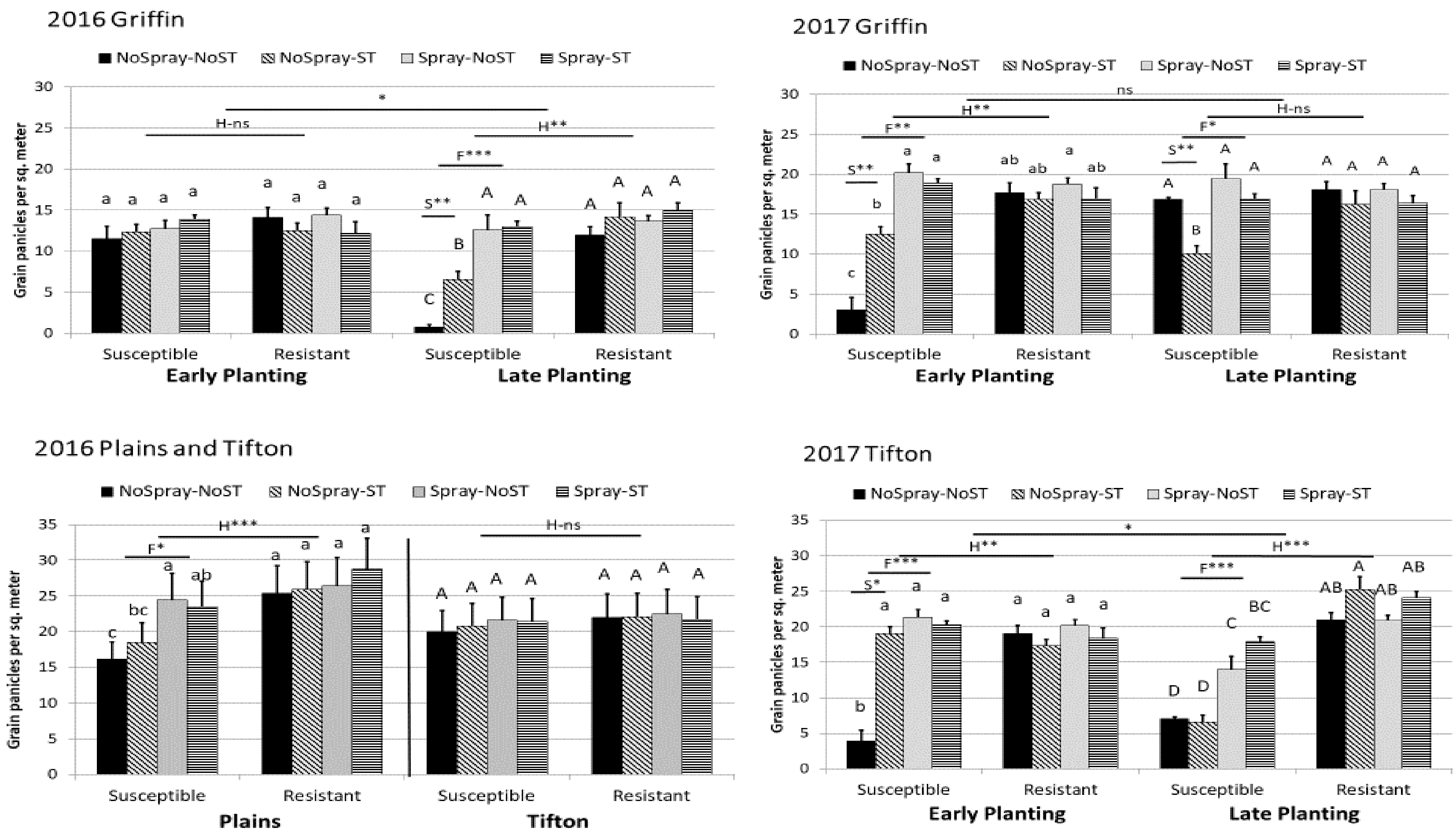


Figure 3.6 Grain panicles per square meter by date and location comparing early and late planting, resistant and susceptible hybrid, foliar spray and no spray, and seed treatment vs. no seed treatment. F = foliar spray, H = hybrid, S = seed treatment, ST = seed treatment.

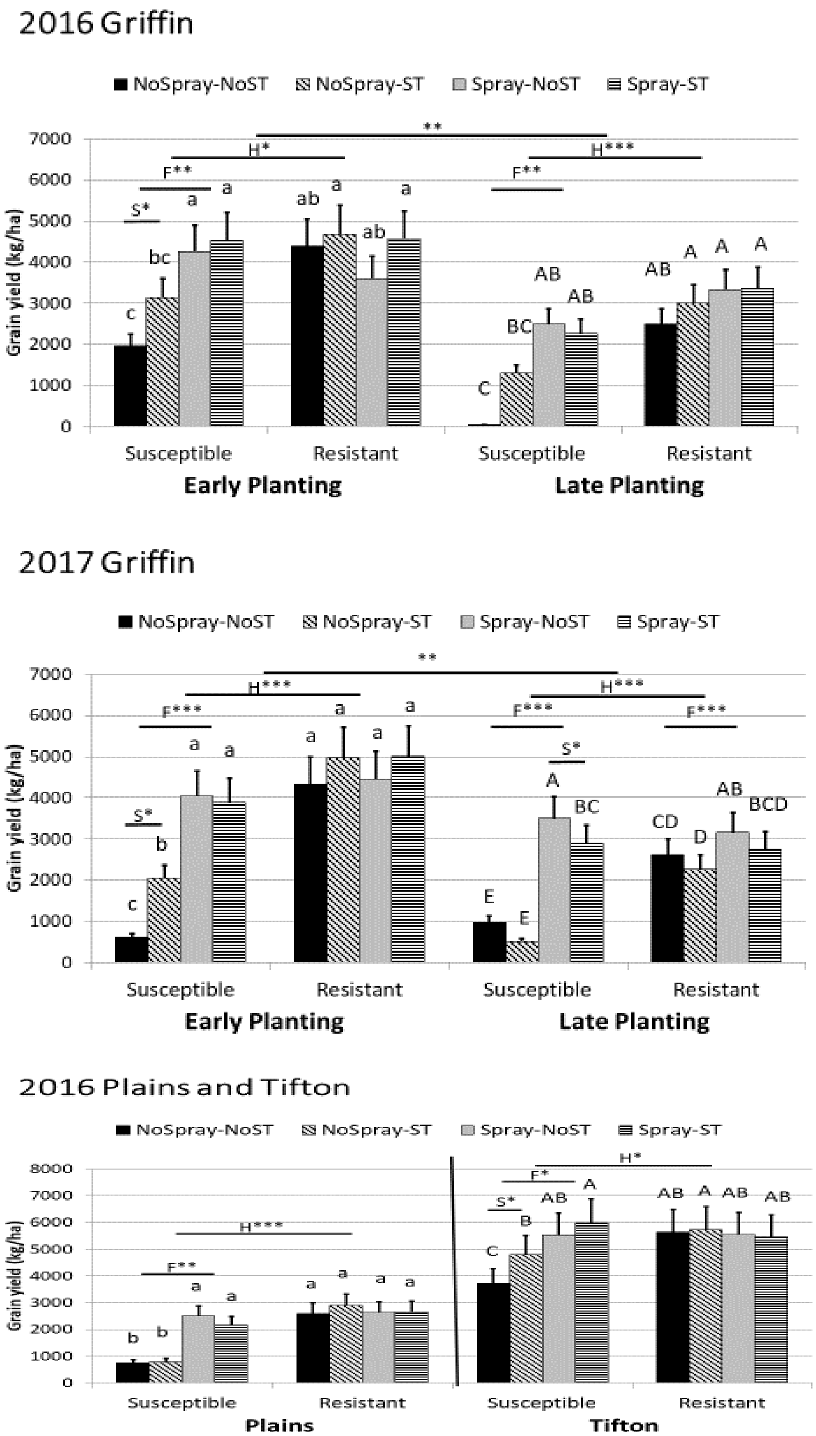


Figure 3.7 Grain yield by date and location comparing early and late planting, resistant and susceptible hybrid, foliar spray and no spray, and seed treatment vs. no seed treatment. F = foliar spray, H = hybrid, S = seed treatment, ST = seed treatment.