Biology and management of the sugarcane aphid, *Melanaphis sacchari* (Zehntner), a new pest of sorghum, *Sorghum bicolor* (L.), in Alabama

by

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A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
Dec. 10, 2016

Key words: Sugarcane aphid, *Melanaphis sacchari,* sorghum, integrated pest management

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Abstract

The sugarcane aphid, *Melanaphis sacchari* (Zehntner), emerged as a new pest of sorghum in Texas and Louisiana in 2013, and has since spread rapidly throughout the Southern United States. Management of sugarcane aphid is difficult due to its rapid reproductive rate, our lack of knowledge on the biology and ecology of this emerging pest, and limited data on management options. The overall objective of this research was to develop an integrated pest management program for sugarcane aphid. Small plot research trials were conducted at several locations throughout Alabama to: 1) evaluate the efficacy of foliar and seed applied insecticides, 2) assess commercially available sorghum varieties for resistance and/or tolerance to sugarcane aphid, and 3) determine the most effective combination of these tactics for sugarcane aphid management in Alabama. The addition of all seed treatments including Cruiser® 5FS, Gaucho® 600, NipsIt® Inside, and Poncho® 600 managed populations below treatment threshold for at least 47 days after planting. Foliar insecticides showed that both rates of Sivanto® 200SL maintained populations below treatment threshold for 27 and 34 days after treatment, while Centric® 40WG and both rates of Transform® WG provided efficacy for 20 days after treatment. Several sorghum varieties including DeKalb 37-07, DowAg 1G588, DowAg 1G851, and Pioneer 83P17 showed high levels of tolerance to sugarcane aphid, however these results varied upon location. The most effective treatment combinations tested that produced the highest yields were early-planted and used Pioneer 83P17 with

or without the addition of seed treatments. All early-planted treatments required one insecticide application, while only one of the late-planted treatments required one, however all late-planted treatments produced lower yields than early-planted treatments.

Acknowledgements

Without the encouragement and inspiration from various faculty mentors throughout my post-secondary education I would have never identified my passion for agriculture. Growing up in Northeast Ohio, I quickly learned about the effects of pollution in water systems (Cleveland, the mistake-on-the-lake). At Ohio Wesleyan University I would eventually learn through my professors' personal experiences about agriculture's contributions to the development of modern society as well as the potential for negative consequences on the ecosystem as a byproduct of mismanagement. This was apparent when learning about the effects of agricultural runoff on Grand Lake St. Mary in Northwest Ohio.

It was at Auburn University during my time with Dr. Alana Jacobson that I was able to learn first-hand about agricultural processes and the necessity of them. I would like to thank her for the constant support and guidance she has offered these past two years. Dr. Jacobson's hard work and determination has made a lasting impact on my interest for row crop integrated pest management, an aspect of ecology I had never even considered. However, I have learned how rewarding pest management can be when done properly and quickly developed a passion for row crop entomology. I owe many thanks to Dr. Scott Santos who consistently provided advice in regard to potential molecular studies which will have a large influence in regard to future research. I owe a debt of gratitude to Dr. Kathy Flanders who worked tirelessly in relaying sugarcane aphid information for the state of Alabama and ensuring farmers were kept up to date with the status of sugarcane aphid on sorghum. In addition, I would like to thank Dr. David Held for his constant support of the project and contributions to editing. I also want to acknowledge Dr. Held for his efforts in providing feedback and assistance with the entomology debate team. I would not have been able to accomplish this research without the assistance of several lab members and Dr. Jacobson, who spent many hours in the blazing Alabama sun to count aphids. Lastly, I would like to thank my family and friends from home who have provided endless support despite our distance apart.

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CHAPTER 1

Review of Literature

Identification

Melanaphis Van Der Goot (Hemiptera: Aphididae) is an old world genus comprised of 25 species that originated from East Asia and is closely related to *Rhopalosiphum* Koch (Blackman and Eastop 2015). The species *Melanaphis sacchari* Zehntner is synonymous with several previously identified species; *Melanaphis sorghi* Theobald (Remaudiere and Remaudiere 1997), *Aphis sacchari* Zehntner) and *Longiunguis sacchari* Zehntner (Singh et al. 2004). In 1974, both *Aphis sacchari* and *Longiunguis sacchari* were classified as synonymous with *M. sacchari* (RoyChaudhuri and Banerjee 1974, Singh et al. 2004) while Eastop and Hille Ris Lambers (1976) later synonymized the genera *Geoktapia* Mordovilko, *Longiunguis* Van der Goot, *Masraphis* Soliman, *Nesikia* Mordvilko, *Piraphis* Borner, *Schizaphideilla* Hille Ris Lambers, and *Yezabura* Mastumura with *Melanaphis* (Singh et al. 2004).

It has recently become disputed as to whether or not *M. sacchari* and *M. sorghi* are different species (Remaudiere and Remaudiere 1997, Blackman and Eastop 2006, 2015; Nibouche et al. 2015). Both species are morphologically similar and have a body length of 1.1-2.0 mm. *M. sacchari* is pale yellow, yellow brown, dark brown, purple, or even pinkish in color while *M. sorghi* shows less variation and is predominately white or yellow, and sometimes bears a variably-developed black dorsal patch on the abdomen (Blackman and Eastop 2015). In addition, there are differences among the rhinaria of these species (Blackman and Eastop 2015). Both species depend on Poaceae in order to complete their life cycles; *M. sacchari* is found predominately on *Saccharum* L. spp.

and *M. sorghi* on *Sorghum bicolor* L. (Blackman and Eastop 2015). Molecular evidence suggests that these are the same species (Nibouche et al. 2014), but the fidelity of host-plant associations among different populations of this species are still unclear (Nibouche et al. 2015). Given the sugarcane aphid's historic association with sugarcane in the United States, sugarcane aphid on sorghum is also referred to as *Melanaphis sacchari* (Nibouche et al. 2014, Ahrens et al. 2014a, b; Brewer 2014, Brewer and Bowling 2014, Bowling and Brewer 2014, Villanueva and Sekula 2014, Villanueva et al. 2014) and will be referred to as *M. sacchari* for the rest of this paper.

Worldwide distribution

The sugarcane aphid has a worldwide geographic distribution that closely follows sorghum and sugarcane production (Singh et al. 2004). It has been reported in Africa (Brain 1929, Le Pelley 1959, Bohlen 1973, Mead 1978, Flattery 1982, Megenasa 1982, Sithole et al. 1987), Asia (Wilbrink 1922, Wang et al. 1961, Young 1970, Setokuchi 1973, Mead 1978, Hamid 1983, Agarwala 1985), Australia (Passlow 1985), North America (Mead 1978, Denmark 1988, White et al. 2001, Villanueva et al. 2014, Rodriguez del Bosque and Teran 2015), South America (Mead 1978, Delfino 1985), and the Caribbean (Edward 1937, Mead 1978, Singh et al. 2004). *M. sacchari* has been classified as a 'superclone' in which a few asexual genotypes of one species are able to establish across a range of geographical and ecological scales (Vorburger et al. 2003, Llewellyn et al. 2003, Harrison and Mondor 2011, Chen et al. 2013). The sugarcane aphid is designated as an economic pest of sorghum in Botswana (Flattery 1982), South Africa (van Rensburg 1973), India (Young 1970), China (Wang et al. 1961), Taiwan (Chang 1981 a, b; Pi and Hsieh 1982), Japan (Setokuchi 1973), and most recently in the sorghum production regions of the United States (Villanueva et al. 2014, Bowling et al. 2016) and Mexico (Rodriguez del Bosque and Teran 2015).

In North America, *M. sacchari* was first reported on sugarcane in Hawaii in 1896 (Zimmerman 1948, Singh et al. 2004), and more recently on sugarcane in Florida in 1977 (Mead 1978) and on sugarcane in Louisiana in 1999 (White et al. 2001) (Singh et al. 2004). Sugarcane aphid was most likely brought to the continental United States from Hawaii by commercial trade (Mondor et al. 2007, Nibouche et al. 2014). Sugarcane aphid populations in Louisiana and Florida remained confined to sugarcane production until July 2013 when *M. sacchari* was reported heavily infesting sorghum in Texas and Louisiana for the first time (Villanueva et al. 2014). By late 2013 the sugarcane aphid had colonized sorghum in 38 counties across four states including Texas, Louisiana, Mississippi (one locale) and Oklahoma (one locale) (Bowling et al. 2016). At the conclusion of 2014, 12 states and 340 counties reported sugarcane aphid infestations reaching as far east as Florida, and north as South Carolina, Tennessee, Missouri and Kansas (Bowling et al. 2016). Alabama reported infestations in 31 counties as of 24 October 2014 with the first infestation occurring in July 2014 (Flanders 2014). *M. sacchari* would eventually spread to 17 states and 417 counties in the United States by 30 September 2015 (Bowling et al. 2016).

Biology and life history

Aphid lifecycles can be described as either holocyclic or anholocyclic. Holocyclic aphid lifecycles undergo seasonal facultative reproduction where sexual reproduction occurs during autumn on primary woody perennial host plants so eggs can overwinter.

Once the eggs complete diapause, apterous morphs hatch and eventually produce alate individuals that migrate to secondary annual host plants where asexual reproduction occurs. Females may be viviparous with reproduction involving a ‘telescoping of generations’ that ensures continuous reproduction; female adults carry the developing embryos of their first-granddaughters. Once several asexual generations are produced during the summer on the secondary host, alates migrate back to their primary host species and lay eggs to overwinter, completing the cycle (Williams and Dixon 2007). Conversely, anholocyclic populations are comprised entirely of females that reproduce parthenogenetically, and do not exhibit seasonal sexual reproduction. Aphid growth and development are influenced by several abiotic variables including precipitation and temperature (Walgenbach et al. 1988, McVean and Dixon 2001), diet as observed in English grain aphid (Watt and Dixon 1981, Gruber and Dixon 1988) and citrus aphid (Tsai and Wang 2001), and from crowding during establishment (Johnson 1965, Chambers 1982, Kidd and Tozer 1984, Michaud 2001).

Global sugarcane aphid populations are predominately anholocyclic (Bowling et al. 2016), and sugarcane aphid in the United States is only known to reproduce via asexual parthenogenesis. Females give birth to live offspring, and newborn aphids must undergo 4 instars before reaching sexual maturity. The combination of asexual reproduction and high reproductive rate result in exponential growth of sugarcane aphid populations; a population of approximately 50 female aphids could increase to about 500 females in approximately one week (Bowling et al. 2016). Populations have been observed to naturally decline about 3-4 weeks after initial infestation as populations reach very high densities, natural enemy pressure becomes more persistent (Singh et al. 2004), and alates are produced that disperse to new hosts. Sugarcane aphid populations in the United States do not undergo diapause and must overwinter on live herbaceous host plants including ratooned sorghum and Johnsongrass in warmer regions (Singh et al. 2004, Bowling et al. 2004). Although sugarcane aphid is predominately anholocyclic there have been reports of monoecious holocyclic sugarcane aphid populations with the presence of sexual morphs from China (Wang et al. 1961), Japan (Setokuchi 1975), India (David and Sandhu 1976), and Mexico (Pena-Martinez et al. 2016). Only in China has an overwintering host been identified; *Miscanthus sacchariflorus* (Wang et al. 1961). No oviparae have been reported in the United States.

The geographical ranges of herbivorous insect species depend on their host plant distributions. However, the number of hosts required for an aphid species to complete its life cycle varies among species. Monoecious aphid species complete their life cycle on one or few annual host(s) throughout the year, while heteroecious species require alternation between an annual host in the summer and a woody perennial host plants for overwintering. The multiple host plants required by heteroecious aphids can include several or more species which cover a much larger geographical range, ultimately facilitating the potential for wide scale infestations (Moran 1992). Most species like *M. sacchari* are highly selective and only feed on one or a few hosts, while some species like the green peach aphid (*Myzus persicae*) and can feed on over one hundred host plant species in more than 40 families (Capinera 2005).

Sugarcane aphid populations in the United States have been reported on several host species. Alternate hosts of sugarcane aphid include grain and sweet sorghum, Johnsongrass, sorghum-sudan hybrids, and various millets (Denmark 1988, Bowling et al. 2016). Johnsongrass is an introduced invasive grass in the United States originally used for forage. Since its introduction in the 1800's Johnsongrass has naturalized throughout most of the country and is widespread (Cardina et al. 2015). When sugarcane aphid was first reported in Florida (Mead 1978, Denmark 1988), it was also found on sorghum, and 16 other Graminaceous species including plants of the genera *Oryza* L., *Panicum* L., *Pennisetum* Richard, *Setaria* Beauvoir, and *Paspalum* L., however, it is largely unknown whether sugarcane aphid can survive and reproduce on these hosts. Johnsongrass is the only alternate host that has been identified for sugarcane aphid in Alabama to date (Flanders 2016). Sugarcane aphid on sorghum was observed feeding on *Zea mays* (maize) in Bee County, Texas, but failed to reproduce (Brewer 2014). Another study determined sugarcane aphid was unable to survive on *Zea mays* L., *Eragrostis tef* Zuccagni, *Hordeum vulgare* L., *Panicum miliaceum* L., or *Secale cereale* L. (Armstrong et al. 2015). More information is needed in regard to sugarcane aphid's host range in the United States.

The host plant species utilized by sugarcane aphid can have varying outcomes on development and reproduction. Although little information is currently available for sugarcane aphid development on sorghum and sugarcane in the United States, sugarcane aphid growth and development have been studied in Asia under screenhouse and field conditions. In screenhouse studies, sugarcane aphid completed its four nymphal instars within 4.3-12.4 days (Chang et al. 1982, Singh et al. 2004) and was observed to reproduce 7-10 days after birth (Dixon 1998, Awmack and Leather 2007). Adults survived for 10-37 days (van Rensburg 1973, Chang et al. 1982, Meksongsee and Chawanapong 1985) and produced as many as 96 nymphs per aphid (van Rensburg 1973, Chang et al.

1982) with an average of 34 nymphs during their lifespan (Meksongsee and Chawanapong 1985). Anywhere from 51-61 generations were produced annually in screenhouse conditions with the shortest generation times occurring during the warmest temperatures in Taiwan (mean temp=93.7 degrees Fahrenheit) (Chang et al. 1982). Field studies performed in the Liaoning Province of China (Guo et al. 2011) reported longer development and reproduction times relative to screenhouse populations. Sugarcane aphid completed its four nymphal instars in about 1 week with reproduction occurring in 1-2 weeks after birth. Adults survived for 21-28 days and produced an average of 50-80 nymphs per female. Over 10 generations were produced annually, and more specifically 19-20 in Lianing Province, China. *M. sacchari* reared on sorghum in a screenhouse study exhibited lower fitness relative to those reared on sugarcane, yielding longer instar durations, shortened lifespans, and decreased reproduction (Kawada 1995). *M. sacchari* reared on sorghum was able to feed on both sugarcane and sorghum, whereas those reared on sugarcane are only able to feed on sugarcane (Setokuchi 1988). Host associations of sugarcane aphid in the United States and developmental rates on different hosts have not been studied.

Population genetics

Nibouche et al. (2014) analyzed mitochondrial cytochrome oxidase subunit I (mtCOI) sequence data from sugarcane aphid populations sampled from Southeast Asia, Australia, Africa, South America, the Caribbean, and North America, and yielded three specific haplotypes. Each haplotype was comprised of 1-3 multilocus lineages (MLLs), or parthenogenetic lineages, and a total of 5 MLLs were identified worldwide (MLLs-A through E). The first mtCOI haplotype consisted of individuals from MLL-A collected from sorghum in Benin, Cameroon, Kenya, and Nigeria, and from sugarcane in Benin and Kenya; from MLL-B collected from sugarcane in Australia; and from MLL-E collected from sorghum in China. The second and third mtCOI haplotypes were specific to MLL-C and MLL-D, respectively. MLL-C was collected from sugarcane in Brazil, Columbia, Guadeloupe, Kenya, Maritius, and Martinique, and from wild Sudan grass in Reunion, while MLL-D was comprised of United States populations collected from sugarcane in Louisiana and Hawaii, and from Johnsongrass in Louisiana. Two additional mtCOI haplotypes were identified from Indian sequences but not included in the MLL analyses (Nibouche et al. 2014). Each MLL showed noticeable geographic structuring and was composed of a distinct set of unique multilocus genotypes (MLG). MLGs were based on pairwise genetic distances for ten microsatellite loci that were grouped into similar genotypes varying by one to four alleles (Arnaud-Haond et al. 2007, Nibouche et al. 2014). Interestingly, comparisons of *M. sacchari*'s global host range (Singh et al. 2004, Villanueva and Sekula 2014) and the distribution of the three haplotypes suggest no global association between haplotype and host plant (Nibouche et al. 2014). More recent evidence provides support that populations of different genotypes within the same MLL have host plant associations at local scales as genotypes of MLL-C collected from different hosts on Reunion Island were shown to be associated with specific host plants (Nibouche et al. 2015).

The genetic markers developed in these studies provide methods for investigating movement or introductions of this species into new areas. In Nibouche et al. (2014), individuals from MLL-D were the only genetic group present in Louisiana (Johnsongrass and sugarcane) and Hawaii (sugarcane) in 2007. Populations were sampled prior to sugarcane aphid being identified on sorghum, so the origins of these populations are largely unknown. Since MLL-D was the only haplotype identified in and restricted to North American sugarcane and Johnsongrass populations, it is possible to identify whether or not sugarcane aphid on sorghum emerged from populations in the United States, or was introduced from elsewhere, solely on mtCOI DNA (Nibouche et al. 2014). Preliminary data is being generated that suggests a new clonal group associated with sorghum was introduced to the United States (unpublished data: Pekarcik and Jacobson, Holt and Villanueva).

Aphid migration and dispersal

Production of apterous and alate adults results from cyclical events that occur in aphid lifecylces. Apterous adults are produced during periods of population growth on good quality hosts. Aphid alate development is stimulated throughout the year by several cues (Dixon 1987, Ciss et al. 2013) including seasonal changes like thermoperiod (Johnson 1966b, Lees 1967, Schaefers and Judge 1971, Harrison 1980) and photoperiod (Johnson 1966b, Schaefers and Judge 1971, Harrison 1980), overcrowding (Lees 1967, Sutherland 1969a, Harrison 1980), and decreased resource availability (Johnson 1966a, Dadd 1968, Sutherland 1969b, Dixon 1972, Mittler 1973, Harrison 1980). Alate development is initiated in response to deteriorating host plant conditions so that the next generation can disperse to new hosts. Alate production occurs throughout the year in sugarcane aphid populations, allowing dispersal and migration to new areas in search of host plants throughout the year. Factors including temperature, climate change and host plant phenotypes all impact aphid dispersal success (Ciss et al. 2013).

Two types of dispersal behaviors are associated with aphids: diffusion and advection. Diffusion, or active flight, is a process in which aphids actively fly in search of a host in the local environment during a null or weak wind. Aphids are estimated to fly 0.9 m/s, or 3.24 km/hr, (Compton 2002) with an average flight period lasting over a minute (Kennedy and Booth 1963, Ciss et al. 2013). The second flight pattern used by aphids is advection, or passive flight. Advection requires strong wind currents which guide aphids allowing for a much longer dispersal relative to diffusion (Loxdale et al. 1985, Hardie 1993, Simon et al. 1999, Ciss et al. 2013). Wind-mediated dispersal has been studied for aphid species *Schizaphis graminum* and *Rhopalosiphum maidis* as reviewed in Irwin et al. 1988. It is believed that wind mediated dispersal allowed the sugarcane aphid to spread across 17 states in 2 growing seasons in the United States (Bowling et al. 2016), however, future studies are needed to better understand local and long-range dispersal of this species.

Aphid landing behavior is ultimately thought to rely on two mechanisms; phototactism and optomotor reflex (Ciss et al. 2013). Phototactism attracts aphids to crops from the reflection of long-wave energy coming off the vegetation. The second mechanism, the optomotor reflex (Kennedy and Booth 1963) allows aphids to detect color contrasts and distinguish plants from the soil or other vegetation (Ciss et al. 2013). These processes are argued to be either separate and antagonistic (Kennedy and Booth 1963) or consecutive and coordinated (Ciss et al. 2013). Manipulating visual cues by decreasing the contrast between crop plants and soil with mulches has been utilized as a cultural control tactic to deter colonization of crop plants by the sugarcane aphid (Singh et al. 2004).

Damage and crop losses in North America

The sugarcane aphid damages plants directly during feeding events. Sugarcane aphid feeds from the phloem and xylem interrupting the flow of water and nutrients in the plants (Brewer et al. 2016). In response to feeding, crops exhibit purple discoloration, signs of necrosis, chlorosis, stunting, delayed maturity, and yield loss (Singh et al. 2004, Bowling et al. 2016). Aphids indirectly damage plants by exuding honeydew, a byproduct of feeding that covers lower leaves in a sticky film that can clog harvesting equipment, and promotes black sooty mold (Narayana 1975). Sugarcane aphid is also known to vector three viruses of sorghum (Singh et al. 2004) including millet red leaf virus (Blackman and Eastop 1984), sugarcane yellow leaf virus (Schenck 2000), and sugarcane mosaic virus (Bhargava et al. 1971, Kondaiah and Nayudu 1984, Setokuchi and Muta 1993). In the United States, sugarcane yellow leaf virus (Luteoviridae*: Polerovirus*), a disease historically associated with sugarcane, and was recently detected in 41% of sorghum plants tested in Florida between September and December 2015 (Wei et al. 2016). The occurrence of this virus outside of Florida is unknown. Sugarcane aphid is not known to vector millet red leaf virus or sugarcane mosaic virus to sorghum in the United States (Bowling et al. 2016).

Sugarcane aphids heavily infest sorghum fields over a wide geographic area of the United States (Bowling et al. 2016). During the 2014 growing season sugarcane aphid expanded its geographic range to 12 states and was present in 100% of sorghum fields in Alabama, Louisiana, Mississippi, and South Texas, and 90% of fields in Georgia and Arkansas (Brewer 2015). Sorghum yield production losses averaged about 15% for all sorghum producing states and 20% in Alabama (Brewer 2015). Monetary yield losses due to sugarcane aphid infestation ranged from $0.88 million in Alabama to $34.8 million in Texas during 2014 and required treatment costs are estimated at $0.20 million in Alabama to $10.5 million in Texas (Brewer 2015). During 2015 sugarcane aphid posed risk to all sorghum production in Mexico and approximately 98% (15,687,084 tons) of production from 17 states in the United States (USDA NASS 2016, Bowling et al. 2016). Currently, sugarcane aphid populations above 250 aphids per leaf during warm and dry conditions can cause monetary losses ranging from $25 to $175 per acre (Bowling et al. 2016).

Integrated pest management

The sugarcane aphid currently threatens sorghum production in the United States. Sorghum is grown for sugar, forage, food, fiber, and ethanol (Li and Gu 2004, Liu et al. 2009, Guo et al. 2011) and in 2015 the United States was the world's largest producer yielding about 15 million metric tonnes (Sorghum Checkoff 2016). In 2015 approximately 24,281 hectares of grain sorghum and 16,187 hectares of forage sorghum were planted in Alabama (personal communication with Kathy Flanders 2015). Although not a major crop in Alabama, farmers commonly plant sorghum as a rotation crop as sorghum grows well under drought conditions and can tolerate variable soil types (Mask et al 1988). It is crucial that an Integrated Pest Management (IPM) program be established for sugarcane aphid so that sorghum remains an economically viable rotation crop for Alabama farmers.

The main principles of IPM originated from Stern et al.'s (1959) Integrated Control Concept (IC) which was originally intended for the management of spotted alfalfa aphid (*Therioaphis maculata,* Buckton) on alfalfa (*Medicago sativa,* L.) in response to the undisciplined overuse of broad-spectrum insecticides in agriculture. Overreliance on insecticides and unnecessary spraying subjects insect populations to Darwinian selection, and leads to the development of populations resistant to one or multiple classes of insecticides (Rider et al. 1998, Casida and Quistad 1998, Herzfeld and Sargent 2011). In addition, many studies have attributed insecticide use with natural enemy mortality and population decline (Nicholson 1939, Ripper 1944, 1956; Strickland 1948, Pickett 1949, Croft and Brown 1975, van Emden and Service 2004). The integrated control concept aims to conserve the services provisioned by biological control with restricted use of chemical control based on predetermined economic injury levels and economic thresholds that minimize the use of pesticides, and by using more selective chemistries (Stern et al 1959).

The integrated control concept would later evolve into integrated pest management (IPM) in the 1970's (Beirne 1970, Apple and Smith 1976) and would extend emphasis to all pest species. IPM programs are designed to adequately predict pest outbreaks and prevent any possible damage from reaching and exceeding economically damaging levels. Similar to the IC, the major components of IPM include pest identification, management, and evaluation to monitor treatment efficacy (Kogan 1998, Schellhorn et al. 2009, Zalucki et al. 2009, 2015; Herzfeld and Sargent 2011, Schellhorn et al. 2015). Scouting for and identifying pests are critical aspects of IPM to ensure proper pest management. This is important as not all species cause damage, and identification of different life stages can be difficult. Feeding patterns, discoloration, diseases, and interruptions of plant growth can also be used for identification of some species. Once the pest has been identified and population size has been estimated then a management plan can be developed and implemented.

When implementing IPM, it is important to avoid mismanagement. Some examples of pest mismanagement include overusing pesticides which promotes resistance in populations, using non-selective pesticides that have deleterious effects on biological control, or neglecting cultural control measures (van Emden 2007). Mismanagement of chemical control was observed to increase natural enemy mortality and subsequent natural enemy population decline (Nicholson 1939, Ripper 1944, 1956; Strickland 1948, Pickett 1949, Croft and Brown 1975, van Emden and Service 2004) and facilitate insecticide resistance (Rider et al. 1998) to one or even multiple classes of products (Casida and Quistad 1998, Herzfeld and Sargent 2011). Selective insecticides, however, do not prevent resistance or guarantee greater efficacy relative to nonselective insecticides.

Under IPM, chemical control is implemented to avoid economic damage (i.e. when the cost of pest induced crop injury exceeds management costs) and is administered according to predetermined economic injury levels (EIL) and economic threshold levels (ETL) for economically important pest populations (Herzfeld and Sargent 2011). The EIL is the lowest pest population size at which economic losses will occur. The ETL is the population size at which pest management must occur in order to prevent the insect populations from reaching the EIL and causing economic loss (Stern et al. 1959). ETLs are determined based on the economic value of the crop, the amount of damage an insect causes, damage per unit of injury, proportion reduction of injury by the control tactic, and cost of control measures. The ETL for the sugarcane aphid determined by Ahrens et al.

(2014b) in Texas, is to make an application of insecticide to plants when sugarcane aphid densities are approximately 50-125 per plant for 25% of all plants. The current threshold used in Mississippi is to scout for aphids twice weekly and spray once populations are detected on 20-30% of plants (Catchot et al. 2015), while in Louisiana this level was conservative at about 50 aphids per leaf for 20% of plants (Brown et al. 2015).

Chemical control

Under the IPM and IC paradigms, populations are managed with insecticides once they reach a specified ETL in order to prevent sugarcane aphid related yield losses. Chemical control with insecticides can quickly reduce aphid populations. Insecticides used for sugarcane aphid management can be applied directly to the soil as an in-furrow treatment, as a foliar spray to the plants, or directly to seeds prior to planting (Singh et al. 2004). Current sugarcane aphid management practices in the southeast United States use seed-treatments to manage early-season infestations, and rely heavily on foliar applied insecticides for mid- to late-season management (Bowling et al. 2016). At the beginning of this study foliar insecticides had not been evaluated for sugarcane aphid management in Alabama. In 2014, insecticide efficacy field trials performed in Corpus Christi and Beaumont, TX (Ahrens et al. 2014a), in Belle Glade, FL (Larsen et al. 2016), near Moultie and McDonough, GA and in Marion County, GA (Bunton and Roberts 2016), and in Alexandria, LA (VanWeelden et al. 2016) determined newer chemistries like Centric® 40WG (thiamethoxam), Endigo® ZC (lambda-cyhalothrin + thiamethoxam) (not assessed in Bunton and Roberts 2016, VanWeelden et al. 2016), Sivanto® 200SL (flupyradifurone), and Transform® WG (sulfoxaflor) were the most effective against sugarcane aphid. None of these materials appeared to decrease parasitoid populations

(Ahrens et al. 2014a). These newer more selective insecticide chemistries including flupyradifurone, sulfoxaflor and thiamethoxam are agonists of the nicotine acetylcholine receptor (nAChR) and target specific pathways and have been shown to minimize indirect damage toward natural enemies (Naranjo and Ellsworth 2009, Naranjo an Ellsworth 2010). Although these chemistries are all classified as Group 4 by IRAC, they each belong to different subgroups; thiamethoxam is a neonicotinoid, flupyradifurone is a butenolide, and sulfoxaflor is a sulfoximine. According to IRAC (2016), subgroup chemical classes have the same target site, but vary in chemical structure and mode of interaction at that target site. This reduces the potential for cross resistance in regards to metabolic or target-sites as subgroups may bind target sites differently or vary in target selectivity (IRAC 2016)

Another product evaluated in Texas (Ahrens et al. 2014a), Fulfill® (pymetrozine; 5 oz/A), was shown to perform similar to Centric® 40WG, Endigo® ZC, Sivanto® SL and Transform® WG 16 days after treatment, however such a delayed response would require a different ETL and reduce response time. Insecticides that failed to decrease aphid populations were older broad-spectrum chemistries previously used for Hemipteran pests and included Lorsban® Advanced (chlorpyrifos), Nufos® 4E (chlorpyrifos), Dimethoate 4EC (dimethoate) and pyrethroids. In Mississippi, populations were observed to increase exponentially in response to pyrethroids (Flanders 2014).

Neonicotinoid seed treatments are among the most important insecticides currently used against sap sucking pests. They are often applied to seeds before planting and are systemically taken up by the developing plant, eventually translocating throughout the plant. They provide broad spectrum control over many early-season pests including aphids, thrips, whiteflies, planthoppers and leafhoppers, and several coleopterans and micro lepidoptera (Jeschke and Nauen 2005). There are currently seven commercially available neonicotinoid chemistries; acetamiprid, clothianidin, dinotefuran, imidacloprid, nitenpyram, thiacloprid, and thiamethoxam. Initial studies on the neonicotinoid seed treatments Cruiser® 5FS (thiamethoxam), Poncho® 600 and NipsIt® Inside (clothianidin) and Gaucho® 600 (imidacloprid) showed these treatments to be effective for early-season management of sugarcane aphid in Louisiana (Jones et al. 2015).

Overreliance on chemical control for aphids is a concern due to the propensity of aphid populations to develop insecticide resistance (Rider et al. 1998). When populations are placed under selection pressure from insecticides, the susceptible individuals will be eliminated leaving resistant individuals in the population. Resistance can occur through several mechanisms including metabolic resistance, target-site resistance, and behavioral resistance (IRAC 2015). Metabolic resistance occurs when detoxification enzymes are overproduced allowing for a more efficient breakdown of toxins. Target site resistance stems from modifications of the target sites in which an insecticide acts on, consequentially reducing sensitivity (Nauen and Denholm 2005). Behavioral resistance arises when insects exhibit avoidance behaviors that reduce or eliminate their exposure to an insecticide.

Early resistance is initially met by applying higher insecticide rates, however, over time the insecticide can become ineffective altogether. Resistance can develop within a short time frame to individual pesticides, entire pesticide classes consisting of the same mode of action, and even multiple modes of action across all pesticides (Herzfeld and

Sargent 2011). Guidelines for delaying development of insecticide resistant insect populations include spraying at appropriate time intervals using recommended rates with the proper equipment as stated on the label, insecticide rotation, using insecticide mixtures, identifying generations present in infestation, and avoiding use of pesticides that pests begin to show resistance to, all in combination with cultural practices, biological control and routine scouting and monitoring (IRAC 2015).

Cultural control

Cultural control practices are manipulations of the agroecosystem implemented to reduce pest populations, and include practices such as vegetation management, crop rotation, planting date, planting density and growing resistant varieties. One early-season cultural practice used against aphid species is to minimize and eliminate the amount of suitable overwintering habitats (Wratten et al. 2007). Since the sugarcane aphid must overwinter on live plant tissue and has a narrow host range, eliminating ratooned sorghum and Johnsongrass refuges would eliminate sources of local populations (Singh et al. 2004). Management of non-crop habitat features including variability (species poor or rich), complexity (species composition) and quality (native or non-native), have been shown to influence natural enemy recruitment to noncrop habitats adjacent to crops (Elliott et al. 1999, Thies et al. 2003, Schmidt and Tscharntke 2005, Gardiner et al. 2009). Several studies showed that the establishment of noncrop habitats increased natural enemy abundance (Bianchi et al. 2006, Chaplin-Kramer et al. 2011, Veres et al 2013) and species richness (Bugg et al. 2009, Walton and Isaacs 2011, Marko et al. 2013, Schellhorn et al. 2015) by allocating additional species protection and food sources. When plant diversity was increased in Kansas, naturally enemies showed higher predation rates on *M. sacchari* populations in sorghum (Colares et al. 2015b). In addition, natural enemy movement into infested crops can be mechanically stimulated through more active practices like strategic mowing of noncrop areas (Bishop et al. 1991, Hossain et al. 2001, Samu 2003, Schellhorn et al. 2008).

Planting time and planting density are two variables that may be manipulated to decrease aphid populations. In Alabama, the recommended planting date for grain sorghum varies by region; 1 April to 15 July for South Alabama, 1 April to 30 June for Central Alabama, and 1 May to 30 June for North Alabama (Mask et al. 1988). Planting earlier in the season may allow sorghum plants to establish before initial infestation by sugarcane aphid (van Rensburg 1974), and early-planted sorghum was shown to suffer less injury and produce higher yields than late-planted sorghum (Mask et al. 1988). However, infestations of sugarcane aphid are not predictable and the impact of other pests such as whorlworms, headworms, and sorghum midge also need to be considered. Planting density has also been shown to influence aphid densities on various crops (Flattery 1982, van Rensburg 1979, Setokuchi 1975, Singh et al. 2004, Michels and Burd 2007, Parajulee et al. 1999, Karungi et al. 2000), but has not been evaluated for sorghum in the United States. Adjustments in seeding rate will be restricted by agronomic conditions of a field that include soil type and annual rainfall/irrigation (Mask et al. 1988).

One common cultural control practice is host plant resistance. Host plant resistance is one of the most reliable and stable forms of pest management (Starks and Schuster 1976). For example, it has been observed among *Erisoma lanigerum* (Hausmann) populations for over 100 years (Painter 1958). There are three mechanisms of host plant resistance which include antixenosis, antibiosis, and tolerance (Painter 1951, Horber 1980, Smith 1989, Smith et al. 1994, Singh et al. 2004). Antixenosis is referred to as non-preference and results from host plant characteristics that render the plant inadmissible to an insect (Teetes 1996). Plant characteristics that illicit antixenosis include plant volatiles (Gibson and Pickett 1983) and allelochemicals (van Emden 2007), pubescence, texture, and color of the plant surface (Powell et al. 2006), and the presence of non-glandular trichomes (Lapointe and Tingey 1984). Antibiosis is a type of resistance that does not deter pests like antixenosis, but causes direct deleterious physiological effects as a result of feeding. Various biochemical, morphological, and/or physiological mechanisms of the host plant influence insect physiology and ultimately cause decreased development, survival and fecundity (van Emden 2007). Unlike antixenosis and antibiosis which influence insect behavior, tolerance is a plant response to insect feeding (Teetes 1996). Tolerance occurs when plants are able to withstand population sizes relative to susceptible plants without sacrificing yield and/or injury (Teetes 1996). Several mechanisms of tolerance include compensatory growth (Castro et al. 2001, van Emden 2007), increased photosynthetic rates (Trumble et al. 1993, Strauss and Agrawal 1999), phenological changes such as faster seed production (Tiffin 2000), and the allocation of stored nutrients to compensate depletion (Trumble et al. 1993, Irwin et al. 2008).

Insects are able to overcome antibiosis through the introduction of genetic mutations that give rise to new biotypes as seen in *Schizaphis graminum* (Rodani) (Wood 1961, Harvey and Hackerott 1969, Wood and Starks 1972, Starks and Schuster 1976). Host plant resistance to aphids has been shown to decrease fecundity (van Emden and Wearing 1965), lengthen developmental time (Sotherton and Lee 1988), and decrease body size (Hassell et al. 1977). In addition, host plant resistance can target multiple pests, as observed in the sorghum variety RTx2783 which was shown to be resistant to both greenbug and sugarcane aphid (Armstrong et al. 2015). Although host plant resistance is compatible with other IP tactics, there have been instances of resistant varieties having deleterious effects on natural enemies (van Emden 1978, Rice and Wilde 1989), largely caused from allelochemicals (van Emden 1978). Host plant resistance can indirectly impact natural enemies due to reduced pest density and prey availability.

Biological control

Natural enemies are often over-looked when implementing IPM programs (Thomas 1999, Ehler 2006, Horne et al. 2008, Zalucki et al. 2009, Macfadyen et al. 2015), yet their ability to suppress pest infestations is largely known (Cardinale et al. 2012, Holland et al. 2012, Macfadyen et al. 2015). Approximately 47 species of natural enemies of the sugarcane aphid have been observed worldwide as of 2004 (Singh et al. 2004) and consist of a single pathogen (*Verticillium lecanii* Zimmerman), many predator species, and three parasitoid species. There have been no fungal pathogens reported infecting sugarcane aphid on sorghum in the southeast United States (Bowling et al. 2016).

Predators are free-living natural enemies that are constantly searching for sources of prey. Coccinellids (Coleoptera: Coccinellidae) are the most commonly observed predators of sugarcane aphid in the United States and nine species have been identified in Texas (Bowling et al. 2016); *Coleomegilla maculata* Degeer, *Cycloneda sanguinea* Casey, *Harmonia axyridis* Pallas, *Hippodamia convergens* Guerin-Meneville, *Olla v-nigrum* Mulsant, and three dusky lady beetle morphospecies (Coccinellidae: Scymnidae). Three dipteran (Diptera: Syrphidae) predators were reported in Texas (Bowling et al. 2016) including *Allograpta obliqua* Say, *Pseudodoros clavatus* Fabricius, and *Eupeodes* *americanus* Wiedemann. Neuropteran predators of sugarcane aphid in Texas (Bowling et al. 2016) include brown lacewing *Hemerobius* spp. L. (Neuroptera: Hemerobiidae) and five green lacewing species (Neuroptera: Chrysopidae); *Ceraeochrysa valida* Banks, *Chrysopa quadripunctata* Burmeister, *Chrysoperla externa* Hagen, *Chrysoperla rufilabris* Burmeister, and *Chrysoperla plorabunda* Fitch. The Minute pirate bug, *Orius insidiosus* Say is the only known Hemipteran predator of sugarcane aphid observed in Kansas (Colares et al. 2015a) and Texas (Bowling et al. 2016).

Parasitoids are often specific to an insect host and require that insect's body to complete their lifecycle. For aphids, parasitoids oviposit eggs directly into the aphid allowing their offspring to feed and develop within that host until they reach maturity. Parasitized aphids are referred to as mummies and can generally be recognized among different parasitoid species by color. Once the parasitoid reaches maturity it emerges from its host in search of mates and subsequent hosts for its offspring (Macfadyen et al. 2015). Three parasitoid species of sugarcane aphid have been identified in North America: two *Aphelinus* species including *Aphelinus* sp. *varipes* group (Hymenoptera: Aphelinidae) in the southeastern United States and *Lysiphlebus testaceipes* Cresson (Hymenoptera: Braconidae) (Bowling et al. 2016). *Syrphophagus aphidivorus* Mayr (Hymenoptera: Encyrtidae) was identified as a hyperparasitoid of *Aphelinus* sp. (Bowling et al. 2016).

The research presented in this thesis was initiated in 2015, the first summer after the sugarcane aphid was initially found infesting sorghum fields in Alabama. At that time limited information was available regarding the efficacy of different management tactics for sugarcane aphid populations. The overall objectives of this research were to first evaluate management tools for sugarcane aphid management individually, then to develop an integrated pest management program from the best performing treatments for each tactic. Small plot research trials were conducted to: 1) evaluate the efficacy of foliar and seed applied insecticides, 2) assess commercially available sorghum varieties for resistance and/or tolerance to sugarcane aphid, and 3) determine the most effective combination of these tactics for the development of an integrated pest management program for sugarcane aphid management in Alabama.

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CHAPTER 2

EVALUATION OF INSECTICIDE EFFICACY FOR MANAGEMENT OF *Melanaphis sacchari* (Zehntner) ON *Sorghum bicolor* (L.), IN ALABAMA

Abstract

Following the emergence of the sugarcane aphid, *Melanaphis sacchari* (Zehntner), as a new pest of sorghum in the United States, research was conducted to identify tools and tactics successful at reducing populations and preventing economic losses caused by this pest. This study was conducted to evaluate the efficacies of seed- and foliar-applied insecticide treatments for management of sugarcane aphid. Trials were conducted at the E.V. Smith Plant Breeding Unit in Tallassee, AL, and the Gulf Coast Research and Extension Center in Fairhope, AL, to evaluate the residual activity of four neonicotinoid seed treatments. In addition, trials at the Brewton Agricultural Research Unit in Brewton, AL and the Wiregrass Research and Extension Center in Headland, AL were conducted to assess the efficacy of nine foliar insecticides for sugarcane aphid management on sorghum in Alabama. The addition of Cruiser® 5FS, Gaucho® 600, NipsIt® Inside, and Poncho® 600 seed treatments suppressed sugarcane aphid populations for 42-47 days after planting. The foliar insecticide Sivanto® 200SL provided the longest suppression of aphid populations at both locations for 27-35 days after application, followed by Centric® 40WG and Transform® WG which suppressed populations for approximately 20 days. Lorsban® Advanced suppressed populations for less than 10 days, while Lorsban® Advanced + Dimethoate 4EC, Dimethoate 4EC, and Baythroid® XL did not reduce populations below threshold 5 or 10 days post treatment. All plots with insecticide seed treatments and plots sprayed with Sivanto® 200SL,

Centric® 40WG and Transform® WG produced significantly higher yields than control plots at all locations.

Introduction

The sugarcane aphid, *Melanaphis sacchari* (Zehntner) (Hemiptera: Aphididae), is a worldwide pest of sorghum and sugarcane whose distribution closely follows these crops worldwide (Singh et al. 2004). The sugarcane aphid was first introduced to the continental United States in Florida in 1977 where it was identified on sugarcane (Mead 1978), and later it was found in Louisiana on sugarcane in 1999 (White et al. 2001). These populations remained confined to sugarcane until July 2013 when sugarcane aphid was detected for the first time in high numbers damaging sorghum (*Sorghum bicolor*) (L.) in Texas and Louisiana (Villanueva et al. 2014). It expanded its geographic range to 17 states and 417 counties throughout the southern U.S. by 30 September 2015 (Bowling et al. 2016).

In the United States sugarcane aphid reproduces by parthenogenesis and populations can increase rapidly under favorable environmental conditions (i.e. warm and dry) (Bowling et al. 2016). Subsequent overcrowding and poor host plant quality triggers development of alates (Harrison 1980) that disperse to new hosts throughout the growing season (Bowling et al. 2016). Alates can actively fly to new hosts in the local environment, or migrate long distances on wind currents (Ciss et al. 2013). Once a crop field is colonized, sugarcane aphid feeding damages plants directly by removing plant sap which causes physiological stress, chlorosis, leaf curl/wilt, and necrosis (Singh et al. 2004). Plants are indirectly damaged from exuded honeydew which is quickly colonized by black sooty mold (Narayana 1975). In addition, sugarcane aphid was identified as a vector of sugarcane yellow leaf virus in sorghum for the first time in Florida (Wei et al. 2016).

Management tactics need to be identified to suppress sugarcane aphid populations and minimize economic losses to crop hosts.

Limited information was available on management options for sugarcane aphid when it arrived in Alabama in 2014. Chemical control options that can be used to manage sugarcane aphid populations include seed- and foliar-applied products. Seed treatments are used to provide early-season systemic protection against pests, and could potentially postpone additional foliar treatments. Limited data from trials conducted in Louisiana in 2014 indicated Cruiser® 5FS, Gaucho® 600, NipsIt® Inside, and Poncho® 600 seed treatments significantly suppressed aphid populations (Jones et al. 2015). While seed treatments are used as a preventative measure for early-season infestations, foliar insecticides may be required to manage mid- to late-season infestations. Foliar insecticides including carbamates, organophosphates and pyrethroids have historically been used for Hemipteran management (Dewar 2007), however, these products provided inconsistent results for sugarcane aphid (Bowling et al. 2016). Several newer, more Hemipteran-specific chemistries have shown to be promising against sugarcane aphid and appear to have low toxicity to biological control (Ahrens et al. 2014a, Michaud et al. 2001, Bowling et al. 2016). Insecticide efficacy trials for management of sugarcane aphid on sorghum performed in Texas in 2014 identified several products that provided efficacy for at least 16 days after application including Centric® 40WG, Endigo® ZC, Sivanto® 200SL, and Transform® WG (Ahrens et al. 2014a). This study was conducted as part of a regional effort to investigate the efficacy of seed- and foliar-applied insecticides for sugarcane aphid management in sorghum production systems. The objectives of this study were to determine the efficacy of four neonicotinoid seed treatments and nine foliar applied insecticide treatments for the management of sugarcane aphid on sorghum in Alabama.

Materials and Methods

Seed treatment residual activity

Small grain sorghum research plots (Table 2.1) were established on 17 June 2015 at both the E.V. Smith Research and Extension Center Plant Breeding Unit (Tallassee) in Tallassee, AL and the Gulf Coast Research and Extension Center (Fairhope) in Fairhope, AL. Chromatin K73-J6, a known susceptible sorghum variety treated with Syngenta® Concep® III safener was used for all five treatments tested at both sites (Table 2.2). Experiments were conducted using a randomized complete block design with four replicates per treatment. Each research plot was 4 rows wide by 6.1 m long with rows spaced 0.91 m apart. The sorghum was seeded at approximately 148,263 seeds per hectare. Weeds were managed according to commercial recommendations, and one application of DuPont™ Prevathon® (1.462 L/ha) was made on 23 July for whorl worms at Fairhope. No other insecticide applications for non-aphid pests were applied.

Plant stand counts were recorded from 4 m of the interior rows for each plot 14 days post emergence. Plant heights (cm) and plant growth stage (i.e. number of fully developed true leaves) were recorded simultaneously from 10 random plants per plot of the interior rows at 7, 14, and 28 days post emergence. Plots were scouted for sugarcane aphid weekly and were first observed on 7 July at Tallassee and on 14 July at Fairhope. Once infested, the total number of aphids per plant was counted from 10 random whole plants in the exterior rows of each plot via destructive sampling on 7 July and 13 July at

Tallassee, and on 14 July and 22 July at Fairhope. Once the V8 growth stage was reached, aphid counts were taken from a single leaf (either the fourth, fifth or sixth whole leaf from the bottom of the plant) for 10 random plants per plot on 21 July, 27 July, 3 August, and 12 August at Tallassee, and on 28 July at Fairhope. Aphids were counted weekly until populations exceeded the treatment threshold of 75 aphids per plant for 30% of all plants (Brewer and Bowling 2014, Ahrens et al. 2014b), after which they were oversprayed with Transform® WG (0.105 kg/ha) and maintained aphid free until harvest.

Each plot was rated for injury once all treatments reached threshold using a 1-9 injury rating scale adapted from Webster et al. (1991), Burd et al. (2006), and Armstrong et al. (2015); 1 = healthy, 2 = 1-5% injury and spotted, 3 = 5-20%, 4 = 21-35%, 5 = 36-50%, 6 = 51-65%, 7 = 66-80%, 8 = 81-95%, and 9 = 95-100% or dead. Maturity ratings were conducted by recording when 50% of plants from each plot had fully exerted panicles. Ratings were made on the interior rows of each plot during weekly aphid counts, and these rows were harvested for yield (tonnes/ha) when grain moisture reached approximately 14%.

Insecticide efficacy

Small grain sorghum research plots (Table 2.1) were established on 15 June at the Wiregrass Research and Extension Center (Headland) in Headland, AL and on 17 June at the Brewton Agricultural Research Unit (Brewton) in Brewton, AL. Pioneer 84P80, a known susceptible sorghum variety pretreated with Apron XL®, Maxim®, and Dynasty® was used for all treatments tested at each site (Table 2.3). Experiments were conducted using a randomized complete block design with four replicates per treatment. Each research plot was 4 rows wide by 6.1 m long with rows spaced 0.91 m apart. The sorghum was seeded at approximately 148,263 seeds per hectare. Insecticide treatments were applied once sugarcane aphid populations reached the designated treatment threshold of 75 aphids per plant for 30% of all plants (Brewer and Bowling 2014, Ahrens et al. 2014b).

Plant stand counts were recorded from 1 m of the interior rows for each plot 14 days post emergence. Plots were scouted for sugarcane aphid weekly and were first observed in plots on 8 July at Brewton and on 9 July at Headland. Once infested, the total number of aphids was counted from an upper fully expanded leaf (below flag leaf) and lower leaf (second from the bottom, or lowest healthy leaf) for 10 random plants in the interior rows for each plot. When populations exceeded about 500 aphids per leaf, estimations were conducted using an Omnigrid Quilter's Square; the total number of aphids per leaf was extrapolated from the number of aphids present in a square area of average density on the grid. Aphids were evaluated before insecticide applications were made, 5 and 10 days post treatment, and then weekly; populations in all treatments were counted until they rebounded to treatment threshold. After populations rebounded in all plots, they were oversprayed with Transform® WG (0.105 kg/ha) and maintained below threshold until harvest.

The average final plant growth stage of each plot, as determined by the number of fully developed true leaves, was recorded once plants reached flag-leaf stage. Once aphid populations in all plots resurged to the treatment threshold after insecticide applications, a 1-9 injury rating for each plot was determined as described previously (Webster et al. 1991, Burd et al. 2006, Armstrong et al. 2015). Maturity ratings were conducted by recording when 50% of plants from each plot had fully exerted panicles.

Ratings were made on the interior rows of each plot during weekly aphid evaluations, and these two rows were harvested for yield (tonnes/ha) when grain moisture reached approximately 14%.

Statistical analysis

Prior to statistical analyses, the number of aphid-days per treatment for each evaluation period was calculated from the total number of aphids per sample for each plant following the equation developed by Ruppel (1983):

$$\textbf{Aphid-days} = (X_{i+1} - X_i)\,[(Y_i + Y_{i+1}) / 2]$$

in which X_i and X_{i+1} are two adjacent observation periods and Y_i and Y_{i+1} are the number of aphids present at each respective observation period. The aphid-days measurement is indicative of the severity of an insect attack and it takes into consideration the number of surviving insects between time periods. Cumulative aphid-days were then calculated by summing the number of aphid-days from each prior data collection period. In order to calculate aphid-days for the transition between whole-plant samples and single-leaf samples in the seed treatment trials, X_i was designated as the final observation period using whole-plant samples, while X_{i+1} was the first observation period using single-leaf samples.

Data was analyzed by location and evaluation date to compare the average number of aphid-days per sample, cumulative aphid-days per sample, the average plant stand counts, plant heights (cm), injury ratings, maturity ratings, and sorghum yields among treatments. Analyses were conducted using PROC GLIMMIX (SAS 9.4, SAS Institute 2013) with treatment as a main effect, and block, residuals, and plant (only for aphid-days analyses) as random effects. Mean comparisons were conducted using LS means at a $P \leq 0.05$ level

Results

Seed treatment residual activity

Gulf Coast Research and Extension Center. Sugarcane aphid was first detected 27 days after planting at Fairhope on 14 July (Table 2.4). During this time, populations on control plants were above treatment threshold, while all treated plants had significantly fewer aphid-days per whole plant both 27 days ($F=15.86$, $df=4,183$, $P<0.0001$) and 35 days after planting ($F=27.61$, $df=4,183$, $P<0.0001$). At 41 days post-planting treated plants had significantly fewer aphid-days per leaf sample than control plants ($F=19.69$, $df=4,183$, $P<0.0001$). During this evaluation period plants treated with Poncho® 600 had accumulated the fewest aphid-days per leaf followed by Cruiser® 5FS, NipsIt® Inside, and Gaucho® 600, all of which had significantly fewer aphids per leaf than control plants ($F=30.13$, $df=4,183$, $P<0.0001$). Due to inclement weather aphid counts were not made 48 days post-planting, however, all plots were scouted and determined to be well above threshold. Throughout the entire study plants treated with all seed treatments accumulated significantly fewer aphid-days than control plants.

The plant stand count per 4 row m at Fairhope ranged from 51-61 plants and did not significantly vary at 1 week ($F=0.87$, $df=4,12$, $P=0.5071$) or 2 weeks ($F=0.64$, $df=4,12$, $P=0.6422$) post emergence. The mean height (cm) per plant (Table 2.5) significantly differed among seed treated plants 27 days ($F=3.43$, $df=4,183$, $P=0.0098$) and 41 days post-planting ($F=3.47$, $df=4,183$, $P=0.0093$). At 27 days post-planting plants treated with

Poncho® 600, and NipsIt® Inside were the tallest, followed by Cruiser® 5FS, control plants, and those treated with Gaucho® 600. Plants treated with Poncho® 600 and NipsIt® Inside significantly differed from Gaucho® 600. Plants treated with Gaucho® 600 were the tallest 41 days post-planting, followed by NipsIt® Inside, Poncho® 600, and Cruiser® 5FS. Plants treated with Gaucho 600 were significantly taller than Cruiser® 5FS and non-treated plants, while plants treated with NipsIt® Inside and Poncho® 600 did not significantly vary from any treatment. Plant growth stage (Table 2.5) did not significantly differ among treatments at 21 days (F=0.06, df=4,12, P=0.9916), 27 days (F=0.01, df=4,12, P=0.9996), 35 days (F=0.00, df=4,12, P=1.0000), or 41 days post-planting (F=0.01, df=4,12, P=0.9996); due to insignificant differences among treatments for all evaluation periods, only values 41 days post-planting were reported (Table 2.5). Overall plant injury did not significantly differ among plots (Table 2.5) (F=0.40, df=4,12, P=0.8047). Maturation time (Table 2.5) (F=5.91, df=4,12, P=0.0073) significantly differed among treatments, with Cruiser® 5FS, NipsIt® Inside and Poncho® 600 reaching maturity fastest in 55 days, followed by Gaucho® 600 in 67 days and non-treated plants in 72 days. Due to an undetected sorghum midge infestation yield data was not available for this location.

E.V. Smith Plant Breeding Unit. Sugarcane aphid was first observed 20 days after planting in Tallassee on 7 July (Table 2.6). Initial aphid populations from control plots exceeded the treatment threshold at this time and had significantly more aphid-days than all treatments (F=69.59, df=4,183, P<0.0001). The number of aphid-days per whole plant treated with Cruiser® 5FS, Poncho® 600, and NipsIt® Inside was not significantly different from one another, but was significantly less than control and Gaucho® 600 treated plots. Plants treated with all four seed treatments had significantly smaller aphid populations than control plants, did not vary among one another, and suppressed aphid populations below threshold 26 days (F=28.18, df=4,98 P<0.0001), 34 days (F=73.59, df=4,183, P<0.0001), 40 days (F=86.34, df=4,183, P<0.0001), and 47 days post-planting (F=67.19, df=4,183, P<0.0001). At 56 days post-planting (36 days after initial infestation) sugarcane aphid populations on plants treated with Cruiser® 5FS were significantly lower than all other treatments and remained below threshold, while aphid populations in plots receiving the other seed treatments exceeded threshold (F=28.65, df=4,183, P<0.0001). During the course of this experiment plants treated with Cruiser® 5FS accumulated the fewest number of aphid-days per plant followed by Poncho® 600, NipsIt® Inside and Gaucho® 600, all of which had significantly fewer than control plants (F=146.04, df=4,183, P<0.0001).

The plant stand count per 4 row m at Tallassee ranged from 63 to 75 plants, but did not significantly vary among plots 14 days post emergence (F=1.94, df=4,12, P=0.1679). The mean height (cm) per plant (Table 2.7) significantly differed among seed treatments 20 days (F=6.63, df=4,192, P<0.0001), 26 days (F=1.28, df=4,192, P<0.0001) and 40 days post-planting (20 days post infestation) (F=3.00, df=4,192, P=0.0197). The tallest plants 40 days post-planting were treated with Cruiser® 5FS, followed by NipsIt® Inside, Gaucho® 600, and Poncho® 600, all of which were taller than control plants. Cruiser® 5FS was the only treatment to have significantly taller plants than control plants, but did not differ from other treatments. Plant growth stage (Table 2.7) did not significantly vary among treatments at 20 days (F=0.11, df=4,12, P=0.9783), 26 days (F=0.05, df=4,12 P=0.9944), 34 days (F=0.21, df=4,12, P=0.9276), 40 days (F=0.16, df=4,12, P=0.9543), or 63 days post-planting (F=0.01, df=4,12, P=0.9999), nor did plant injury (Table 2.7) (F=2.11, df=4,12, P=0.1426), or maturation time (Table 2.7) (F=0.79, df=4,12, P=0.5527). Sorghum grain yield significantly differed among treatments (Table 2.7) (F=67.31, df=4,12, P<0.0001). Plants treated with all seed treatments produced significantly greater yields than control plants, but yields from plots treated with Poncho® 600, Cruiser® 5FS, NipsIt® Inside, and Gaucho® 600 were not significantly different from one another.

Insecticide efficacy

Brewton Agricultural Research Unit. Sugarcane aphid was first detected in plots on 8 July with populations widespread throughout all plots and approaching treatment threshold (Tables 2.8, 2.9) (F=7.68, df=9,378, P=0.0834). At 5 days after infestation the number of aphid-days did not significantly differ among plots and was above threshold (F=1.75, df=9,114, P=0.0846). Insecticide treatments were applied on 16 July, and there were significant differences in the number of aphid-days per two-leaf sample among treatments 5 days (F=6.73, df=9,374, P<0.0001), 10 days (F=57.18, df=9,378, P<0.0001), 13 days (F=310.83, df=5,192, P<0.0001), 19 days (F=59.42, df=5,192, P<0.0001), and 25 days post-application (F=52.98, df=4,123, P<0.0001). Both rates of Sivanto® 200SL and Centric® 40WG suppressed populations below treatment threshold for 25 days after application, both rates of Transform® WG for 13 days, and Lorsban® Advanced for under 10 days. The addition of Lorsban® Advanced + Dimethoate 4EC, Dimethoate 4EC, or Baythroid® XL did not maintain populations below treatment threshold 5 or 10 days post application.

Plant stand counts per 1 row m ranged from 13 to 20 plants for all plots and did not significantly vary among treatments at Brewton (F=0.08, df=9,27, P=0.9998). The use of foliar insecticide applications on sorghum did not significantly affect plant growth stage (Table 2.10) 21 days (F=0.06, df=9,27 P=0.9916), 27 days (F=0.01, df=9,27 P=0.9996), 35 days (F=0.00, df=9,27 P=1.0000), or 41 days post-planting (F=0.22, df=9,27 P=0.9996). Plant injury ratings (Table 2.10) significantly differed among plots receiving different insecticide treatments (F=101.65, df=9,27, P<0.0001). Plants sprayed with either rate of Sivanto® 200SL had the lowest injury ratings, while plants receiving applications of Lorsban® Advanced, Dimethoate 4EC, Baythroid® XL, and Lorsban® Advanced + Dimethoate 4EC showed injury levels similar to control plants. Maturation time (Table 2.10) (F=0.21, df=9,27, P=0.9765) did not significantly differ among plots receiving different treatments. Sorghum grain yield (Table 2.10) significantly differed among plots sprayed with different insecticides (F=49.62, df=9,27, P<0.0001). Plants sprayed with Sivanto® 200SL, and Centric® 40WG produced significantly greater yields than all other treatments.

Wiregrass Research and Extension Center. Sugarcane aphid was first detected in plots on 9 July with populations well above treatment threshold for all plots, however, some plots were more heavily infested than others (Tables 2.11, 2.12) (F=4.18, df=9,127, P<0.0001). Insecticides were applied on 10 July and there were significant differences in the number of aphid-days per two-leaf sample among treatments 5 days (F=14.10, df=9,208, P<0.0001), 10 days (F=42.71, df=6,250, P<0.0001), 14 days (F=86.29, df=5,218, P<0.0001), 20 days (F=127.53, df=5,218, P<0.0001), 27 days (F=77.42, df=5,191, P<0.0001) and 34 days post treatment (F=47.23, df=4,122, P<0.0001). Applications of the high rate of Sivanto® 200SL suppressed populations below treatment threshold for at least 34 days after application, while the low rate was effective for 27 days. Both rates of Transform® WG and Centric® 40WG provided efficacy for 20 days. The application of Lorsban® Advanced, Lorsban® Advanced + Dimethoate 4EC, Dimethoate 4EC, or Baythroid® XL did not maintain populations below treatment threshold 5 or 10 days post application.

Plant stand counts per 1 row m ranged from 13 to 20 plants for all plots and did not significantly vary among treatments ($F=0.70$, $df=9,27$, $P=0.6815$). The use of foliar insecticide applications for management of sugarcane aphid on sorghum did not significantly affect final plant growth stage (Table 2.13) ($F=0.02$, $df=9,27$, $P=1.0000$). Plant injury ratings (Table 2.13) ($F=15.64$, $df=9,27$, $P<0.0001$) significantly varied across all treatments. Plants sprayed with Sivanto® 200SL had the lowest injury rating, followed by Centric® 40WG, and Transform® WG. The remaining treatments including Baythroid® XL, Lorsban® Advanced, Dimethoate 4EC, Lorsban® Advanced + Dimethoate 4EC and did not differ from control plots. Maturation time (Table 2.13) significantly varied among plants sprayed with different insecticides ($F=28.56$, $df=9,27$, $P<0.0001$). Plots sprayed with Transform® WG and Sivanto® 200SL, and Centric® 40WG reached maturity in significantly fewer days than control plots and those treated with Lorsban® Advanced, Lorsban® Advanced + Dimethoate 4EC, Dimethoate 4EC, or Baythroid® XL.

Sorghum grain yield (Table 2.13) significantly differed among plots receiving different treatments ($F=51.32$, $df=9,25$, $P<0.0001$). Plots sprayed with Sivanto® 200SL, and Centric® 40WG produced significantly larger yields than all others. Plots sprayed with Transform® WG produced a significantly greater yield than those receiving applications of Lorsban® Advanced, Baythroid® XL, Dimethoate 4EC, Lorsban®

Advanced + Dimethoate and control plots, which did not significantly differ from one another.

Discussion

The results of the seed treatment trials show that Cruiser® 5FS, Gaucho® 600, NipsIt® Inside, and Poncho® 600 seed treatments suppress aphid population growth for up to 6 weeks after planting, slightly reduce plant injury, and shorten maturation time. The aphid pressure experienced at each location varied; over 5,000 more aphid-days were accumulated at Tallassee than Fairhope in a 3-4-week time period. At Tallassee, Cruiser® 5FS provided longer efficacy (about 1 week) than Gaucho® 600, NipsIt® Inside or Poncho® 600, while at Fairhope all treatments suppressed sugarcane aphid populations for the same amount of time. While seed treatments did not completely kill aphids after colonization 20-27 days after planting, they were effective at suppressing populations below treatment threshold (75 aphids per plant sample for 30% of the plants) for 2-3 weeks.

Neonicotinoids are among some of the most important insecticides currently used against early-season sap sucking pests like aphids (Jeschke and Nauen 2005) due to their high efficacy and residual activity (Elbert et al. 2008). Early-season population suppression is important for sugarcane aphid management (Elbert et al. 2008, Gore et al. 2010) as it increases the amount of time farmers have to assess their fields to avoid unnecessary insecticide applications and optimize the timing of foliar sprays, (Nault et al. 2004). In addition, seed treatments require lower application rates relative to older foliar products (Elbert and Nauen 2004, Elbert et al. 2008), reduce exposure to humans and the environment during application (Taylor et al. 2001, Tomizawa and Casida 2003, Elbert et al. 2008), reduce exposure to natural enemies (Albajes et al. 2003), and suppress virus transmission by targeting early-season insect vectors (Bradshaw et al. 2008, Strausbaugh et al. 2010). Despite these benefits, there may be instances where sugarcane aphid populations arrive 6 weeks after planting at a time when residual activity of seed treatments has worn off and foliar insecticides will be required. Our limited knowledge on the overwintering range of sugarcane aphid in the United States, and the current inability to predict when this pest will arrive, prevents growers from being able to decide whether or not a seed treatment is needed before the growing season. Previous studies (Smith and Krischik 1999, Rogers et al. 2007, Henry et al. 2012, Schneider et al. 2012) have raised concerns about the safety of neonicotinoid seed treatments on non-target organisms. In this study predators and parasitoids were present throughout all plots on all observation periods and increased in abundance over time (A.J.P., personal observation). Future studies are needed to deduce whether or not these treatments have any negative impacts on beneficial insects present in sorghum agroecosystems, or are compatible with promoting the presence and abundance of biological control agents.

In situations where biological and cultural control methods are not able to suppress sugarcane aphid populations below the economic threshold, foliar insecticides are necessary to prevent economic loss. In this study we have identified three foliar insecticide products that provide high efficacy for sugarcane aphid management including Sivanto® 200SL (flupyradifurone), Transform® WG (sulfoxaflor) and Centric® 40WG (thiamethoxam). These treatments caused high aphid mortality and suppressed populations from resurging to threshold level for 2-3 weeks after application during heavy infestations at Brewton and Headland. As a result of reduced aphid populations, plants that received these three treatments had reduced chlorosis and necrosis, faster maturation times, and the highest yields at both locations. Only Sivanto® 200SL is currently available for commercial use while a Section 18 Emergency Exemption was obtained for the use of Transform® WG for Alabama in 2015 and 2016; Centric® 40WG is not currently labeled for use in sorghum.

In light of the fact that we have not identified other products that effectively manage sugarcane aphid, overreliance on Transform® WG and Sivanto® 200SL could lead to resistance (Rider et al. 1998, Herzfeld and Sargent 2011). Both of these products have slightly different modes of action and should be rotated to reduce selection pressure on these populations until alternative chemistries for sugarcane aphid management are developed. To reduce management costs, prevent insecticide resistance, and lessen harm to natural enemies and pollinators, other economical and environmentally safe IPM components should be evaluated including cultural control tactics like planting time and sorghum varieties for host plant resistance.

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Table 2.1. Information for locations where experiments were conducted.

Site	Location	Coordinates	Experiments	Planting date	Day of first infestation	Foliar treatment date
Summer 2015						
Gulf Coast Research and Extension Center	Fairhope, AL	(30.545540, -87.869477)	Seed Treatment[1]	17 June	14 July	7 August (overspray)
E.V. Smith Research Center Plant Breeding Unit	Tallassee, AL	(32.492629, -85.889075)	Seed Treatment[1]	17 June	7 July	14 August (overspray)
Brewton Agricultural Research Unit	Brewton, AL	(31.146054, -87.053819)	Insecticide[2], Variety[3]	17 June	8 July	16 July (treatment)
Wiregrass Research and Extension Center	Headland, AL	(31.355163, -85.326111)	Insecticide[2,] Variety[3]	15 June	9 July	10 July (treatment)
Prattville Agricultural Research Unit	Prattville, AL	(32.423873, -86.449504)	Variety[3]	17 June	7 July	N/A
Summer 2016						
E.V. Smith Research Center	Shorter, AL	(32.423049, -85.886371)	IPM[4]	Early – 10 June Late – 30 June	26 July	4, 5 - 10 August 1, 2, 7 – 18 August

[1]See Chapter 2 for seed treatment residual activity experiment
[2]See Chapter 2 for foliar-insecticide efficacy experiment
[3]See Chapter 3 for sorghum variety experiments
[4]See Chapter 4 for IPM experiment

Table 2.2. List of five seed treatments evaluated for population suppression of sugarcane aphid at the Gulf Coast Research and Extension Center in Fairhope, AL and the E.V. Smith Research and Extension Center Plant Breeding Unit in Tallasee, AL.

Trade Name	Treatment	Amount (kg ai/45 kg seed)	Rate formulated product (L/45 kg seed)	Distributor
Control	N/A	N/A	N/A	N/A
Cruiser® 5FS	thiamethoxam	0.135	0.225	Syngenta®
Gaucho® 600	imidacloprid	0.113	0.189	Bayer© CropScience
NipsIt® Inside	clothianidin	0.113	0.189	Bayer© CropScience
Poncho® 600	clothianidin	0.113	0.189	Valent® USA

Table 2.3. List of insecticides tested for management of sugarcane aphid on sorghum at the Brewton Agricultural Research Unit in Brewton, AL., and at the Wiregrass Research and Extension Center in Headland, AL are listed below along with their corresponding trade names, formulations, and the rates at which they were applied.

Trade Name	Common Name	Amount (kg ai/ha)	Rate formulated product	Distributor
Control	Control	N/A	N/A	N/A
Lorsban® Advanced	chlorpyrifos	1.053	2.338 L/ha	Dow® AgroSciences
Dimethoate 4EC	dimethoate	0.561	1.169 L/ha	Cheminova
Lorsban® Advanced + Dimethoate 4EC	chlorpyrifos + dimethoate	0.526, 0.561	1.169 L/ha, 1.169 L/ha	Dow® AgroSciences, Cheminova
Sivanto™ 200SL	flupyradifurone	0.0585	0.292 L/ha	Bayer© CropScience
Sivanto™ 200SL	flupyradifurone	0.102	0.512 L/ha	Bayer© CropScience
Baythroid® XL	beta-cyfluthrin	0.0275	0.205 L/ha	Bayer© CropScience
Transform® WG	sulfoxaflor	0.0351	0.0701 kg/ha	Dow® AgroSciences
Transform® WG	sulfoxaflor	0.0527	0.105 kg/ha	Dow® AgroSciences
Centric® 40WG	thiamethoxam	0.0561	0.140 kg/ha	Syngenta®

Table 2.4. Mean number of aphid-days accumulated from the previous evaluation date per plant/leaf and cumulative aphid-days per plant/leaf with corresponding LS means comparisons for all treatments tested during the seed treatment efficacy trial at Gulf Coast Research and Extension Center in Fairhope, AL.

Treatment	Aphid-days per plant[1]		Aphid-days per leaf[2]
	14 Jul	**22 Jul**	**28 Jul**
	27 DAP	**35 DAP**	**41 DAP**
Cruiser® 5FS	30.36b	67.80b	106.23b
Gaucho® 600	83.04b	140.90b	472.88b
NipsIt® Inside	64.05b	97.70b	131.70b
Poncho® 600	46.81b	59.40b	56.70b
Control	198.80a	364.50a	1907.63a
F-statistic	15.86	27.61	19.69
df	4, 183	4, 183	4, 183
P-value	<0.0001	<0.0001	<0.0001
Treatment	**Cumulative aphid-days per plant[1]**		**Cumulative aphid-days per leaf[2]**
	14 Jul	**22 Jul**	**28 Jul**
	27 DAP	**35 DAP**	**41 DAP**
Cruiser® 5FS	30.36b	98.16b	204.44b
Gaucho® 600	83.04b	223.94b	696.81b
NipsIt® Inside	64.05b	161.75b	293.45b
Poncho® 600	46.81b	106.21b	162.91b
Control	198.80a	563.30a	2470.93a
F-statistic	15.86	25.89	30.13
df	4, 183	4, 183	4, 183
P-value	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

[1] aphid counts were conducted on whole plants up to the V8 growth stage

[2] aphid counts on a single leaf were conducted after the V8 growth stage

Table 2.5. Mean injury rating, maturation rate, plant growth stages per plot and plant height (cm) per plant with LS means comparisons for all treatments tested during the seed treatment efficacy trial at Gulf Coast Research and Extension Center in Fairhope, AL.

Seed treatment	Mean injury[1]	Maturation time (days)[2]	Growth stage[3]	Plant height (cm)	
	4 Aug		11 Aug	14 July	28 July
	48 DAP		56 DAP	27 DAP	41 DAP
Cruiser® 5FS	4.50	54.97b	12.09	21.36ab	38.63b
Gaucho® 600	5.25	66.46ab	12.16	20.38b	41.90a
NipsIt® Inside	5.25	54.97b	12.00	22.10a	40.35ab
Poncho® 600	4.50	54.97b	11.80	22.18a	39.43ab
Control	6.25	72.21a	11.93	21.10ab	38.31b
F-statistic	0.40	5.91	0.01	3.43	3.47
df	4, 12	4, 12	4, 12	4, 192	4, 192
P-value	0.8047	0.0073	0.9996	0.0098	0.0093

Column means followed by the same letter are not significantly different (LS means, $p \leq 0.05$)

[1]Damage rating on a scale of 1-9, healthy-dead plants.

[2]Days from planting until 50% of plants per plot had exerted panicles.

[3]Number of fully developed true-leaves.

Table 2.6. Mean number of aphid-days accumulated from the previous evaluation date per plant/leaf and cumulative aphid-days per plant/leaf with LS means comparisons for all treatments tested during the seed treatment efficacy trial at the E.V. Smith Plant Breeding Unit in Tallassee, AL.

Treatment	Aphid-days per plant[1]		Aphid-days per leaf[2]			
	7 Jul	13 Jul	21 Jul	27 Jul	3 Aug	12 Aug
	20 DAP	26 DAP	34 DAP	40 DAP	47 DAP	56 DAP
Cruiser® 5FS	95.33c	199.83b	114.10b	47.78b	39.38b	468.90c
Gaucho® 600	208.50b	488.00b	521.40b	622.05b	1181.16b	2937.60b
NipsIt® Inside	75.38c	337.54b	201.40b	84.08b	411.69b	1333.95bc
Poncho® 600	94.35c	266.37b	151.70b	62.25b	32.11b	937.80bc
Control	470.03a	3714.98a	7244.90a	8094.75a	8714.74a	7537.65a
F-statistic	69.59	28.18	73.59	86.34	67.19	28.65
df	4, 183	4, 98	4, 183	4, 183	4, 183	4, 183
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment	**Cumulative aphid-days per plant[1]**		**Cumulative aphid-days per leaf[2]**			
	7 Jul	**13 Jul**	**21 Jul**	**27 Jul**	**3 Aug**	**12 Aug**
	20 DAP	**26 DAP**	**34 DAP**	**40 DAP**	**47 DAP**	**56 DAP**
Cruiser® 5FS	95.33c	306.20b	401.33b	449.10b	488.48b	957.38c
Gaucho® 600	208.50b	716.50b	1212.30b	1834.35b	3015.51b	5953.11b
NipsIt® Inside	75.38c	398.17b	538.45b	622.53b	1034.21b	2368.16cb
Poncho® 600	94.35c	316.34b	525.53b	587.78b	619.89b	1557.69cb
Control	470.03a	4144.03a	12172.83a	20267.58a	28982.31a	36519.96a
F-statistic	69.59	31.99	104.29	140.8	158.36	146.04
df	4, 183	4, 98	4, 183	4, 183	4, 183	4, 183
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

[1] aphid counts were conducted on whole plants up to the V8 growth stage

[2] aphid counts on a single leaf were conducted after the V8 growth stage

Table 2.7. Mean injury rating, maturation rate, plant growth stages, and yield per plot and mean plant height (cm) per plant with LS means comparisons for all treatments tested during the seed treatment efficacy trial at the E.V. Smith Plant Breeding Unit in Tallassee, AL.

Treatment	Mean injury[1]	Maturation time (days)[2]	Growth stage[3]	Plant height (cm)			Yield (tonnes/ha)
	19 Aug		19 Aug	7 July	13 July	27 July	12 Oct
	63 DAP		63 DAP	20 DAP	26 DAP	40 DAP	117 DAP
Cruiser® 5FS	2.75	63.00	16.00	17.63a	26.10ab	62.46a	5.40a
Gaucho® 600	3.25	63.00	16.00	16.77ab	24.81b	52.68ab	4.52a
NipsIt® Inside	3.75	63.00	16.25	17.62a	27.36a	54.85ab	5.24a
Poncho® 600	3.50	63.00	16.75	16.05b	25.75b	49.26ab	5.40a
Control	6.50	71.00	16.00	17.22a	26.12ab	38.76b	1.08b
F-statistic	2.11	0.79	0.01	6.63	1.28	3.00	67.31
df	4, 12	4, 12	4, 12	4, 192	4, 192	4, 192	4, 12
P-value	0.1426	0.5527	0.9999	<0.0001	<0.0001	0.0197	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

[1]Damage rating on a scale of 1-9, healthy-dead plants.

[2]Days from planting until 50% of plants per plot had exerted panicles.

[3]Number of fully developed true-leaves.

Table 2.8. Mean number of aphid-days accumulated from the previous evaluation date per two-leaf sample with LS means comparisons for all treatments tested during the insecticide efficacy trial at the Brewton Agricultural Research Unit in Brewton, AL. Treatments were applied on 16 July 2015.

Treatment	**Aphid-days per two-leaf sample**						
	8 Jul	**14 Jul**	**21 Jul**	**26 Jul**	**29 Jul**	**4 Aug**	**10 Aug**
	Check	**Check**	**5 DAT**	**10 DAT**	**13 DAT**	**19 DAT**	**25 DAT**
Control	63.53ab	339.07	2689.83a	6020.84a	4486.20a	7191.90a	4643.10a
Transform® WG (0.0701 kg/ha)	47.34bc	298.99	317.15bc	19.25e	83.10b	1559.10b	-
Transform® WG (0.105 kg/ha)	45.59bc	376.41	305.44bc	21.00e	63.04b	1604.81b	2888.33b
Sivanto® 200SL (0.292 L/ha)	77.09ab	250.00	466.08bc	6.00e	9.49b	23.10c	23.25c
Sivanto® 200SL (0.512 L/ha)	24.24c	129.64	213.60c	10.56e	11.51b	17.33c	16.05c
Centric® 40WG (0.140 kg/ha)	92.05a	353.06	528.51bc	8.56e	25.95b	159.53c	521.10c
Lorsban® Advanced (2.338 L/ha)	53.64bc	364.16	575.55bc	1828.94d	-	-	-
Dimethoate 4EC (1.169 L/ha)	45.06bc	318.59	1177.40bc	4352.75bc	-	-	-
Baythroid® XL (0.205 L/ha)	55.30bc	259.01	1569.08ab	2992.81cd	-	-	-
Lorsban® Advanced (1.169 L/ha) + Dimethoate 4EC (1.169 L/ha)	92.58a	206.92	1379.14abc	4425.44b	-	-	-
F-statistic	7.68	1.75	6.73	57.18	310.83	59.42	52.98
df	9, 378	9, 114	9, 374	9, 378	5, 192	5, 192	4, 123
P-value	<0.0001	0.0846	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

Table 2.9. Mean number of cumulative aphid-days per two-leaf sample with LS means comparisons for all treatments tested during the insecticide efficacy trial at the Brewton Agricultural Research Unit in Brewton, AL. Treatments were applied on 16 July 2015.

Treatment	Cumulative aphid-days per two-leaf sample						
	8 Jul	**14 Jul**	**21 Jul**	**26 Jul**	**29 Jul**	**4 Aug**	**10 Aug**
	Check	**Check**	**5 DAT**	**10 DAT**	**13 DAT**	**19 DAT**	**25 DAT**
Control	63.53ab	360.50	2843.98a	9119.15a	9583.57a	16769.15a	21412.25a
Transform® WG (0.0701 kg/ha)	47.34bc	352.07	446.14bc	341.83cd	424.93b	1984.03b	-
Transform® WG (0.105 kg/ha)	45.59bc	445.39	489.74bc	365.01cd	428.05b	2032.86b	4798.13b
Sivanto® 200SL (0.292 L/ha)	77.09ab	318.25	623.68bc	325.34cd	334.83b	357.93c	381.18c
Sivanto® 200SL (0.512 L/ha)	24.24c	158.81	289.13c	149.61d	161.13b	178.45c	194.50c
Centric® 40WG (0.140 kg/ha)	92.05a	423.44	730.59bc	495.68cd	521.63b	681.15c	1202.25c
Lorsban® Advanced (2.338 L/ha)	53.64bc	397.31	734.28bc	2443.21c	-	-	-
Dimethoate 4EC (1.169 L/ha)	45.06bc	379.01	1342.48bc	5808.65b	-	-	-
Baythroid® XL (0.205 L/ha)	55.30bc	297.10	1688.14ab	5093.01b	-	-	-
Lorsban® Advanced (1.169 L/ha) + Dimethoate 4EC (1.169 L/ha)	92.58a	310.75	1548.74abc	6480.60b	-	-	-
F-statistic	7.68	1.67	6.65	43.83	245.85	179.08	218.5
df	9, 378	9, 114	9, 374	9, 378	5, 192	5, 192	4, 123
P-value	<0.0001	0.104	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

Table 2.10. Mean injury rating, maturation rate, plant growth stage, and yield per plot with LS means comparisons for all treatments tested during the insecticide efficacy trial at the Brewton Agricultural Research Unit in Brewton, AL. Treatments were applied on 16 July 2015.

Insecticide	Mean injury[1]	Maturation time (days)[2]	Growth stage[3]	Yield (tonnes/ha)
	10 Aug		19 Aug	22 Oct
	25 DAT		34 DAT	98 DAT
Control	8.00a	78.00	12.00	0.26b
Transform® WG (0.0701 kg/ha)	3.50b	80.00	13.50	1.29b
Transform® WG (0.105 kg/ha)	3.25bc	80.00	13.25	1.33b
Sivanto® 200SL (0.292 L/ha)	2.00d	78.00	14.00	4.74a
Sivanto® 200SL (0.512 L/ha)	2.50cd	78.00	13.75	4.09a
Centric® 40WG (0.140 kg/ha)	2.75bcd	78.00	13.75	4.14a
Lorsban® Advanced (2.338 L/ha)	7.50a	78.00	13.25	0.47b
Dimethoate 4EC (1.169 L/ha)	7.50a	N/A	11.25	0.04b
Baythroid® XL (0.205 L/ha)	7.75a	N/A	13.25	0.19b
Lorsban® Advanced (1.169 L/ha) + Dimethoate 4EC (1.169 L/ha)	8.00a	86.00	13.25	0.66b
F-statistic	101.65	0.21	0.22	49.62
df	9, 27	9, 27	9, 27	9, 27
P-value	<0.0001	0.9765	0.9888	<0.0001

Column means followed by the same letter are not significantly different (LS means, $p \leq 0.05$)
[1]Damage rating on a scale of 1-9, healthy-dead plants.
[2]Days from planting until 50% of plants per plot had exerted panicles.
[3]Number of fully developed true-leaves.

Table 2.11. Mean number of aphid-days accumulated from the previous evaluation date per two-leaf sample post-hoc multiple comparisons for all treatments tested during the insecticide efficacy trial at the Wiregrass Research and Extension Center in Headland, AL. Treatments were applied on 10 July 2015.

Treatment	Aphid-days per two-leaf sample						
	9 Jul	15 Jul	20 Jul	24 Jul	30 Jul	6 Aug	13 Aug
	Check	5 DAT	10 DAT	14 DAT	20 DAT	27 DAT	34 DAT
Control	769.30b	1410.53b	7403.40a	11438.57a	20800.50a	18830.09a	14413.97a
Transform® WG (0.0701 kg/ha)	1143.23ab	777.95b	656.23bc	451.42b	508.35b	5325.78b	7917.62b
Transform® WG (0.105 kg/ha)	1136.59ab	1135.32b	542.43bc	218.73b	204.98b	1683.77c	-
Sivanto® 200SL (0.292 L/ha)	1630.48a	744.60b	163.01c	57.96b	65.18b	158.47c	977.79cd
Sivanto® 200SL (0.512 L/ha)	926.59ab	676.70b	210.36c	124.43b	38.93b	113.33c	198.53d
Centric® 40WG (0.140 kg/ha)	1280.03ab	707.92b	335.13bc	244.07b	123.83b	841.93c	2530.74c
Lorsban® Advanced (2.338 L/ha)	1037.72ab	1057.45b	1802.94b	-	-	-	-
Dimethoate 4EC (1.169 L/ha)	1206.80ab	2649.29a	-	-	-	-	-
Baythroid® XL (0.205 L/ha)	352.21b	3699.50b	-	-	-	-	-
Lorsban® Advanced (1.169 L/ha) + Dimethoate 4EC (1.169 L/ha)	1024.67ab	2504.38a	-	-	-	-	-
F-value	4.18	14.1	42.71	86.29	127.53	77.42	47.23
df	9, 118	9, 208	6, 250	5, 218	5, 191	5, 191	4, 122
P-value	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

Table 2.12. Mean number of cumulative aphid-days per two-leaf sample post-hoc multiple comparisons for all treatments tested during the insecticide efficacy trial at the Wiregrass Research and Extension Center in Headland, AL. Treatments were applied on 10 July 2015.

Treatment	Cumulative aphid-days per two-leaf sample						
	9 Jul	**15 Jul**	**20 Jul**	**24 Jul**	**30 Jul**	**6 Aug**	**13 Aug**
	Check	**5 DAT**	**10 DAT**	**14 DAT**	**20 DAT**	**27 DAT**	**34 DAT**
Control	769.30b	2179.83bc	7403.40a	13589.81a	29985.00a	49098.03a	64028.80a
Transform® WG (0.0701 kg/ha)	1143.23ab	1364.69c	1284.29b	1707.12b	2250.09b	7559.71b	15673.30b
Transform® WG (0.105 kg/ha)	1136.59ab	1714.53bc	1236.28b	1440.35b	1675.80b	3343.41c	-
Sivanto® 200SL (0.292 L/ha)	1630.48a	1548.87c	1147.59b	1226.43b	1304.36b	1446.67c	2429.79c
Sivanto® 200SL (0.512 L/ha)	926.59ab	1150.96c	622.43b	723.60b	733.40b	747.74c	1076.66c
Centric® 40WG (0.140 kg/ha)	1280.03ab	1351.62c	1209.15b	1204.28b	1308.23b	2097.55c	4617.94c
Lorsban® Advanced (2.338 L/ha)	1037.72ab	1557.14bc	2156.51b	-	-	-	-
Dimethoate 4EC (1.169 L/ha)	1206.80ab	3285.20a	-	-	-	-	-
Baythroid® XL (0.205 L/ha)	352.21b	3864.53a	-	-	-	-	-
Lorsban® Advanced (1.169 L/ha) + Dimethoate 4EC (1.169 L/ha)	1024.67ab	3005.79ab	-	-	-	-	-
F-value	4.18	7.84	31.25	96.09	103.68	140.18	166.97
df	9, 118	9, 208	6, 250	5, 218	5, 191	5, 191	4, 122
P-value	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

Table 2.13. Mean injury rating, maturation rate, plant growth stage, and yield per plot with post-hoc multiple comparisons for all treatments tested during the insecticide efficacy trial at the Wiregrass Research and Extension Center in Headland, AL. Treatments were applied on 10 July 2015.

Insecticide	Mean injury[1]	Maturation time (days)[2]	Growth stage[3]	Yield (tonnes/ha)
	13 Aug		13 Aug	20 Oct
	34 DAT		34 DAT	102 DAT
Control	7.50a	88.00a	13.00	0.26c
Transform® WG (0.0701 kg/ha)	5.25ab	62.75b	13.25	1.34bc
Transform® WG (0.105 kg/ha)	4.25bc	59.00b	13.00	3.45b
Sivanto® 200SL (0.292 L/ha)	2.75c	59.00b	13.25	8.20a
Sivanto® 200SL (0.512 L/ha)	2.75c	59.00b	13.00	8.30a
Centric® 40WG (0.140 kg/ha)	4.00bc	59.00b	13.00	7.03a
Lorsban® Advanced (2.338 L/ha)	7.25a	109.00a	13.75	0.46c
Dimethoate 4EC (1.169 L/ha)	7.25a	109.00a	13.25	0.35c
Baythroid® XL (0.205 L/ha)	7.00a	109.00a	13.00	0.36c
Lorsban® Advanced (1.169 L/ha) + Dimethoate 4EC (1.169 L/ha)	7.50a	109.00a	12.75	0.33c
F-statistic	15.64	28.56	0.02	51.32
df	9, 27	9, 27	9, 27	9, 25
P-value	<0.0001	<0.0001	1	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

[1]Damage rating on a scale of 1-9, healthy-dead plants.

[2]Days from planting until 50% of plants per plot had exerted panicles.

[3]Number of fully developed true-leaves.

CHAPTER 3

EVALUATION OF COMMERCIALLY AVAILABLE SORGHUM VARIETIES FOR RESISTANCE AND TOLERANCE TO SUGARCANE APHID IN ALABAMA

Abstract

Host plant resistance offers a cost-effective, low-input, and environmentally sound option for the management of economically important agricultural pests. The sugarcane aphid emerged as a pest of grain sorghum in Alabama in July of 2014 and has caused significant yield losses, however, no information is available regarding levels of resistance to sugarcane aphid in commercially available sorghum varieties. The overall objective of this research was to evaluate locally available sorghum varieties for resistance to sugarcane aphid in small plot field studies at the Brewton Agricultural Research Unit in Brewton, AL, the Prattville Agricultural Research Unit in Prattville, AL and the Wiregrass Research and Extension Center in Headland, AL. Varieties that had the lowest aphid populations and injury ratings, and produced the greatest yields varied among different locations. Under dryland conditions and heavy initial infestation DeKalb 37-07 showed the highest levels of tolerance, while under irrigation Pioneer 83P17, DowAg 1G588 and DowAg 1G855 showed the highest tolerance. ATx2752RTx430, Chromatin KS585, Chromatin SP6929, and DowAg 1G741 performed similarly to Pioneer 84P80, a variety known to be susceptible to sugarcane aphid. Strong associations were identified between the number of aphid-days and yield, and the number of aphid-days and plant injury for all varieties under irrigation.

Introduction

Cultural control methods are important components of integrated pest management plans that modify agronomic practices in order to alter the natural relationship between a pest species and its host plant (Teetes 1996). Growing plant varieties with resistance to arthropods is one cultural control tactic that is an economically and environmentally friendly method for reducing yield loss. Host plant resistance is also compatible with control methods including other cultural control tactics, chemical control and biological control (Teetes 1996), and its effects have been shown to be stable over a long period of time (Painter 1951, 1958; Teetes 1996). The use of resistant varieties may be a valuable tool for reducing sugarcane aphid populations on sorghum.

There are three mechanisms of host plant resistance to insects including antixenosis, antibiosis, and tolerance (Painter 1951, Horber 1980, Smith 1989, Smith et al. 1994, Singh et al. 2004). Antixenosis, or non-preference, results from morphological (Teetes 1996) and physiological (Nottingham et al. 1991b, Hori 1999) characteristics of the host plant that render it inadmissible to the pest. Oftentimes when antixenosis is strong the insect will reject the host even when no alternate choices are available. Antibiosis is a type of host-plant resistance that does not deter pests, but causes direct deleterious effects to an insect's physiology leading to decreased growth, survival, and fecundity (Teetes 1996, van Emden 2007). Antibiosis is attributed to a combination of biochemical, morphological, and/or physiological components of the host plant that lead to reduced pest abundance and reduced injury levels relative to susceptible plants. The last resistance mechanism is tolerance, where the host plant is able to sustain levels of infestations relative to a susceptible host without economic yield losses. Antibiosis and tolerance are not mutually exclusive; both mechanisms often coexist (Mauricio et al. 1997).

Despite being a minor crop in Alabama, sorghum production has increased more than three-fold in the past several years with approximately 24,281 hectares of grain sorghum and 16,187 hectares of forage sorghum being planted for the 2015 growing season (Kathy Flanders, personal communication 2015). Sugarcane aphid feeding directly damages sorghum by reducing the sugar and nutrient content which can cause chlorosis, necrosis, delayed maturity, and yield loss (Singh et al. 2004). In addition, sugarcane aphid exudes honeydew on lower leaves which is rapidly colonized by black sooty mold, ultimately reducing photosynthetic activity (Singh et al. 2004). Increased costs resulting from multiple insecticide applications for sugarcane aphid management jeopardize the viability of sorghum as a rotation crop. It is important that resistant sorghum varieties adapted to growing conditions in Alabama be identified as sugarcane aphid was observed in 100% of sorghum fields during the 2014 growing season and reduced sorghum yields in Alabama by an average of 20% (Brewer 2015). The objective of this study was to evaluate commercially available sorghum varieties for resistance to sugarcane aphid in Alabama.

Materials and Methods

Small grain sorghum research plots (Table 2.1) were established on 15 June 2015 at the Wiregrass Research and Extension Center (Headland) in Headland, AL, and on 17 June at both the Brewton Agricultural Research Unit (Brewton) in Brewton, AL and the Prattville Agricultural Research Unit (Prattville) in Prattville, AL. Up to 11 varieties, including Pioneer 84P80 which is known to be susceptible to sugarcane aphid feeding damage, were tested at each site, and information regarding each variety and the addition of seed treatments is available in Table 3.1.

Experiments were conducted using a randomized complete block design with four replicates per treatment. At Brewton and Headland, each research plot was 4 rows wide by 6.1 meters long with rows spaced 0.91 meters apart. At Prattville a split plot design comprised of eight row plots that were 9.1 meters long with rows spaced 0.91 meters apart was used. Each split plot was divided in half; four rows were not treated with insecticides while the other four rows were maintained aphid free throughout the season in order to compare yield data for sorghum with and without sugarcane aphid infestations. Because yield data was not obtainable due to bird damage, and aphid counts were not made in insecticide-treated plots, this trial was analyzed as a randomized complete block design. The sorghum was seeded at approximately 148,263 seeds per hectare for all locations. Experiments at Brewton and Prattville were performed under dryland conditions while plots in Headland were irrigated.

Plant stand counts were taken from 1 m of one interior row for each plot 14 days post emergence. Plots at each site were scouted for sugarcane aphid weekly starting the week of 24 June and were detected at Prattville on 7 July, Brewton on 8 July, and Headland on 9 July. Once infested, the total number of aphids was estimated from an upper fully expanded leaf (below flag leaf) and lower leaf (second from the bottom, or lowest healthy leaf) for 10 random plants in the exterior rows of each plot. Aphid counts were taken weekly until populations for all varieties were naturally declining, at which time the plots were oversprayed with Transform® WG (0.105 kg/ha) and maintained aphid free through harvest

The final growth stage of each plant, as determined by the number of fully developed true leaves, was recorded once varieties reached flag-leaf stage. Each plot was rated for injury once populations naturally declined using the 1-9 injury rating adapted from Webster et al. (1991), Burd et al. (2006), and Armstrong et al. (2015). The injury rating scale is as follows; 1 = healthy, 2 = 1-5% injury and spotted, 3 = 5-20%, 4 = 21-35%, 5 = 36-50%, 6 = 51-65%, 7 = 66-80%, 8 = 81-95%, and 9 = 95-100% or dead. A rating of 1-3 indicates the variety is resistant/tolerant, 3-6 is moderately resistance/tolerant, and 6-9 is susceptible. Maturity ratings were conducted by recording when 50% of sorghum plants in each plot had fully exerted panicles. Ratings were made on the interior rows of each plot, and these two rows were harvested for yield (tonnes/ha) when grain moisture reached approximately 14%.

Statistical analysis

Prior to analyses, the number of aphid-days and cumulative aphid-days per two-leaf sample were calculated from the total number of aphids per two-leaf sample for each treatment following the equation developed by Ruppel (1983):

$$\textbf{Aphid-days} = (X_{i+1} - X_i)\,[(Y_i + Y_{i+1}) / 2]$$

in which X_i and X_{i+1} are two adjacent observation periods and Y_i and Y_{i+1} are the number of aphids present at each respective observation period. The aphid-day measurement is indicative of the severity of an infestation and it takes into consideration the number of surviving insects between time periods. Cumulative aphid-days were then calculated by summing the number of aphid-days from each prior data collection period.

Data were analyzed by location and evaluation date to compare the average number of aphid-days per two-leaf sample, cumulative aphid-days per two-leaf sample, the average plant stand counts, injury ratings, maturity ratings, and sorghum yields per treatments. Analyses were conducted using PROC GLIMMIX (SAS 9.4, SAS Institute 2010) with treatment as a main effect; block and residuals as random effects, and plant as an additional random effect for aphid-days analyses. Mean comparisons were conducted using LS means at a $p \leq 0.05$ level. Simple linear regression analyses and a multiple regression analysis were performed using the PROC REG function ANOVA (SAS9.4, SAS Institute 2010) to identify whether the mean accumulated number of aphid-days at peak infestation per plot, or the final 1-9 injury rating per plot, or both were correlated with the resulting yield. This was done for data collected from each location and across locations.

Results

Brewton Agricultural Research Unit

The initial infestation at Brewton was detected on 8 July 2015 (Tables 3.2) with sugarcane aphid populations abundant throughout all plots ($F=6.78$, $df=5,222$, $P<0.0001$). During this time DowAg 1G855, Pioneer 84P80, and DeKalb 37-07 had significantly fewer aphid-days per two-leaf sample than Pioneer 83P17 and Chromatin SP6929, while aphid-days on DowAg 1G588 were not significantly different from any other variety. Aphid populations rapidly increased and populations peaked on 29 July

(F=8.47, df=5,133, P<0.0001), 21 days after initial infestation. During this time DeKalb 37-07 and Chromatin SP6929 had accumulated significantly fewer aphid-days than Pioneer 83P17 and Pioneer 84P80. DowAg 1G588 and DowAg 1G855 had significantly fewer cumulative aphid-days than Pioneer 84P80, but did not differ from the other varieties. On the last evaluation period, 4 August, 6 days after populations peaked (F=9.41, df=5,212, P<0.0001), Chromatin SP6929 and DowAg 1G588 had accumulated the fewest aphid-days, followed by DeKalb 37-07, DowAg 1G855, Pioneer 83P17, and Pioneer 84P80. Pioneer 83P17 did not significantly differ from the known susceptible Pioneer 84P80.

Plant growth measurements (Table 3.3) that were not significantly different among varieties included plant stand count per row m (F=0.43, df=5,24, P=0.8923), maturation time (F=0.30, df=5,15, P=0.9078), and the mean injury ratings (F=1.25, df=5,15, P=0.3334). Mean injury ratings ranged from 4.5-8 for these varieties with Pioneer 83P17 and DowAg 1G588 exhibiting the least injury, followed by DeKalb 37-07 and DowAg 1G855, while Chromatin SP6929 and Pioneer 84P80 had the most injury. The final plant growth stage significantly differed among varieties (F=14.73, df=5,15, P<0.0001). DeKalb 37-07 and DowAg 1G855 had significantly more true-leaves than DowAg 1G588, Pioneer 84P80, and Chromatin SP6929, but did not differ from Pioneer 83P17. Sorghum grain yield (Table 3.3) also significantly differed among sorghum varieties (F=33.43, df=5,15, P<0.0001): DeKalb 37-07 produced significantly greater yields than the other varieties.

Simple linear regression analyses (Figure 3.1) showed strong negative relationships between overall injury rating per plot and corresponding grain yield per plot (R^2=0.49, F=19.92, df=1,21, P<0.0002) with injury rating accounting for 49 percent of yield variation among varieties. There was a moderate positive relationship between the growth stage per plot and yield (R^2=0.28, F=8.33, df=1,21, P=0.0088), with growth stage accounting for 28% of the variation in yield among varieties. There was weak negative association between the total number of cumulative aphid-days per plot and grain yield (R^2=0.039, F=0.84, df=1,21, P=0.3691), and for the accumulated number of aphid-days per plot and 1-9 injury rating (R^2=0.029, F=0.63, df=1,21, P=0.4361). There was no significant association between the total number of cumulative aphid-days per plot and growth stage per plot (R^2=0.007, F=0.15, df=1,21, P=0.7047).

Multiple regression analysis showed a significant strong negative relationship between the amount of plant injury, accumulated aphid-days and the resulting yield (R^2=0.49, F=9.72, df=1,21, P=0.0011). There was a significant correlation with injury rating (t=-4.23, df=22, P=0.0004) and resulting yield, however, the number of accumulated aphid-days and grain yield did not significantly influence yield (t=-0.49, df=22, P=0.6276).

Prattville Agricultural Research Unit

Initial infestation at Prattville was observed on 7 July 2015 (Tables 3.4, 3.5) and there were significant differences (F=13.01, df=9,378, P<0.0001) for the number of aphids per plant among varieties: DowAg 1G855 and Pioneer 83P17 had the fewest aphid-days per two-leaf sample, followed by ATx2752RTx2783, DeKalb 37-07, DowAg 1G588, DowAg 1G741, ATx2752RTx430, Chromatin SP6929, Pioneer 84P80, and Chromatin KS585. The number of cumulative aphid-days increased for all varieties on the 13 July (F=9.13, df=9,168, P<0.0001), and 20 July (F=2.33, df=9,168, P=0.0150). On the 27 July populations decreased (F=4.53, df=9,293, P<0.0001), but eventually rebounded and reached peak population size on the 24 August (F=7.56, df=9,378, P<0.0001). At peak population size the total number of cumulative aphid-days per two-leaf sample were the lowest on DowAg 1G588, followed by ATx2752RTx2783, Pioneer 83P17, DeKalb 37-07, DowAg 1G855, DowAg 1G741, Pioneer 84P80, Chromatin KS585, Chromatin SP6929, and ATx2752RTx430. Populations were monitored on 31 August and 7 September to ensure populations continued to decline. On 7 September (F=11.47, df=9,378, P<0.0001), 14 days after populations peaked, ATx2752RTx2783, DowAg 1G588, Pioneer 83P17, DeKalb 37-07, and DowAg 1G855 all had significantly fewer cumulative aphid-days per two-leaf sample than Pioneer 84P80, Chromatin KS585, Chromatin SP6929, and ATx2752RTx430. There were no significant differences between cumulative aphid-days on DowAg 1G741 and any other variety.

There were no significant differences in plant stand count per row meter (F=0.63, df=9,27, P=0.7583), injury rating recorded on 7 September (F=1.05, df=9,27, P=0.4268), or maturation time (F=0.87, df=9,27, P=0.5589) among varieties (Table 3.6). The final plant growth stage significantly varied among varieties (F=8.36, df=9,27, P<0.0001). DowAg 1G855 had the highest number of true-leaves, followed by ATx2752RTx2783, Chromatin SP6929, DowAg 1G588, Pioneer 83P17, Pioneer 84P80, DowAg 1G741, ATx2752RTx430, DeKalb 37-07, and Chromatin KS585. Sorghum yield was unobtainable due to extensive bird damage.

Simple linear regression analyses (Figure 3.2) showed a moderate positive relationship among cumulative aphid-days per plot and 1-9 injury rating (R^2=0.19, F=9.03, df=1,38, P=0.0047) with the number of aphid-days explaining 19% of variation in plant injury. There was no significant association between the cumulative number of aphid-days and the final growth stage per plot (R^2=0.046, F=1.84, df=1,38, P=0.1825).

Wiregrass Research and Extension Center

Sugarcane aphid was initially identified at very high levels (Table 3.7) on 9 July 2015. DowAg 1G855 had the fewest aphid-days per two-leaf sample followed by Pioneer 83P17, DowAg 1G588, Chromatin SP6929, DeKalb 37-07 and Pioneer 84P80 (F=8.08, df=5,222, P<0.0001). Populations continued to increase until 30 July when they reached peak levels for all varieties; the varieties with the fewest to the highest number of cumulative aphid-days per two-leaf sample are Pioneer 83P17, DowAg 1G855, DowAg 1G588, DeKalb 37-07, Chromatin SP6929 and Pioneer 84P80 (F=38.89, df=5,212, P<0.0001). On 6 August, aphid populations had declined on all sorghum varieties (F=49.55, df=5,222, P<0.0001).

The plant stand count per row meter did not significantly vary among plots (F=0.70, df=5,24, P=0.6892), nor did the overall injury ratings (Table 3.8) per plot recorded on 6 August (F=1.62, df=5,15, P=0.2155). The final growth stage (Table 3.8) significantly differed among varieties (F=0.48, df=5,15, P<0.0004) with DowAg 1G588 and Pioneer 83P17 having the most true-leaves, followed by DeKalb 37-07 and DowAg 1G855, Pioneer 84P80, and Chromatin SP6929. Maturation time (Table 3.8) significantly differed among varieties (F=6.27, df=5,15, P=0.0025); Pioneer 83P17 and DowAg 1G588 reached maturity the fastest, followed by DeKalb 37-07 and DowAg 1G855, Pioneer 84P80, and Chromatin SP6929. Sorghum grain yield (Table 3.8) did not significantly differ among sorghum varieties (F=0.91, df=5,15, P=0.5002): DowAg 1G855 and Pioneer

83P17 produced the highest yields followed by DowAg 1G588, DeKalb 37-07, Chromatin SP6929, and Pioneer 84P80.

Simple regression analyses (Figure 3.3) identified a significant and strong positive relationship between the cumulative number of aphid-days per plot and injury rating (R^2=0.54, F=26.24, df=1,22, P<0.0001), with the number of aphid-days accounting for 54% of variation in injury rating. There was a significant and strong negative relationship among injury rating per plot and corresponding yield (R^2=0.55, F=26.48, df=1,22, P<0.0001) with 55% of variation in yield being attributed to plant injury. The same trend was observed for cumulative aphid-days per plot and yield (R^2=0.49, F=21.27, df=1,22, P=0.0001). A significant and moderate positive relationship was identified among plant growth stage per plot and yield (R^2=0.18, F=4.98, df=1,22, P=0.0361) and for the total number of cumulative aphid-days per plot and growth stage per plot (R^2=0.19, F=5.22, df=1,22, P=0.0324).

Multiple regression analysis showed a significant strong negative relationship between the amount of plant injury and accumulated aphid-days and grain yield (R^2=0.60, F=15.723, df=2,21, P<0.0001). There was a significant correlation with injury rating (t=-2.38, df=22, P=0.0269) and resulting yield, but not with the number of accumulated aphid-days and grain yield (t=-1.67, df=22, P=0.1090).

Discussion

The sorghum varieties evaluated at all sites showed varying levels of aphid infestation, injury, and yield loss to sugarcane aphid. Based on our observations several sorghum varieties including DeKalb 37-07, DowAg 1G588, DowAg 1G855, and Pioneer

83P17 exhibited varying levels of tolerance to sugarcane aphid and showed lower levels of injury, matured the fastest, and produced the highest yields. Previous studies have observed tolerance to sugarcane aphid in DeKalb 37-07 and Pioneer 83P17 (Anonymous 2016, Brown and Kerns 2016), while studies in Louisiana also observed tolerance in DowAg 1G855 and Chromatin SP6929 (Brown and Kerns 2016). It does not appear that any of the varieties evaluated showed true antixenosis or antibiosis, however, throughout the duration of these studies several varieties had significantly fewer cumulative aphid-days and/or higher yields than the known susceptible varieties. This suggests that some varieties likely exhibit antibiosis and tolerance resistance mechanisms. Both mechanisms have been observed in other crops (Mauricio et al. 1997), but a better understanding on the characterization of these mechanisms in sorghum and their compatibility with other management tactics is still needed (Bowling et al. 2016).

Factors such as the timing and magnitude of infestations may have influenced differences among varietal performance across different locations. Varieties at all locations were infested about 2-3 weeks after planting with plants at approximately the same growth stage. Headland had the highest initial populations followed by Brewton and Prattville. Populations on all varieties at each location decreased to some extent after initial infestation, likely from insecticide seed treatments. At Headland and Brewton where initial infestation was high, populations resurged quickly and reached peak levels in approximately 3 weeks. Populations at Prattville were less than half that of Headland and reached peak levels in twice the amount of time. Regardless of initial aphid intensity, the total number of aphid-days accumulated differed among varieties. At Prattville ATx2752RTx2783, Pioneer 83P17, DeKalb 37-07, DowAg 1G588 and DowAg 1G855 accumulated the fewest cumulative aphid-days. At Brewton DeKalb 37-07, Chromatin SP6929, and DowAg 1G855 had the fewest cumulative aphid-days. At Headland, Pioneer 83P17, DowAg 1G588 and DowAg 1G855 accumulated the fewest aphid-days. These results suggest variables other than the timing and intensity of infestations may be contributing to varietal performance.

The presence or absence of irrigation and rain likely influenced differences in varietal performance among locations. Plots at Headland received 10.668 cm of rain in addition to 8.382 cm of irrigation, and sustained the largest aphid populations. Plots at Prattville and Brewton were grown under dryland conditions and received 19.406 cm and 8.382 cm of rain, respectively. At Headland aphid population size was shown to correlate significantly with injury and yield, however, this these trends were not observed at Brewton. Yields from Prattville are not available due to extensive bird damage, however, the cumulative aphid-days and injury rating were much lower compared to the other locations. Under high water stress at Brewton all varieties exhibited high injury levels, but DeKalb 37-07 produced at least 2.32 tonnes/ha grain more than all of the other varieties even though the cumulative number of aphid-days and injury did not significantly differ from DowAg 1G588, DowAg 1G855, Pioneer 83P17 or Chromatin SP6929. In general, varieties exhibited less injury at Headland than at Brewton and produced yields that were12-19 times greater, yet DeKalb 37-07 only produced 1.2 times more yield under irrigation. Water stress in other aphid-crop systems has been shown to reduce turgor pressure, making it more difficult to feed on plant sap (Huberty and Denno 2004), but has also been shown to increase nutrient concentrations in plant sap which can positively affect aphid populations (White 1969, 1984; Archer et al. 1995, Bale et al. 2007, Tariq et al. 2012). No previous studies have specifically examined the influence of sorghum water stress on sugarcane aphid population growth and damage to sorghum.

The results from this study identify several varieties that exhibit tolerance to the sugarcane aphid. The inclusion of resistant varieties for management of sugarcane aphid could increase the treatment threshold used for insecticide applications as these varieties are able to tolerate heavier infestations before yield is decreased. A higher threshold would give farmers a longer treatment window to make a foliar application of insecticides which could potentially reduce the number of insecticide sprays required for management of sugarcane aphid, and promote biological control. Future research investigating thresholds appropriate for these varieties, and the effects of rainfall and irrigation on varietal tolerance will generate better information about the effectiveness of these varieties for management of the sugarcane aphid. Host plant resistance is a cultural control method intended to be used in combination with other management tactics such as other cultural control methods, biological, and chemical control. The tolerant varieties identified in this study also need to be evaluated for impacts on biological control agents, and yield potential when insecticide applications are used to manage aphid populations.

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Table 3.1. Sorghum varieties tested for resistance/tolerance to sugarcane aphid injury in the sorghum variety trial. Test location abbreviations; BARU - Brewton Agricultural Research Unit in Brewton AL, PARU - Prattville Agricultural Research Unit in Prattville, AL, and WREC – Wiregrass Research and Extension Center in Headland, AL.

Sorghum hybrid	Distributor	Seed treatments	Test location(s)
ATx2752RTx2783	TAMU	N/A	PARU
ATx2752RTx430	TAMU	N/A	PARU
84P80	Pioneer	Apron® XL, Maxim®, Dynasty®, Cruiser® 5FS, Concep® III	BARU, PARU, WREC
83P17	Pioneer	Apron® XL, Maxim®, Dynasty®, Cruiser® 5FS, Concep® III	BARU, PARU, WREC
DKS37-07	DeKalb	Poncho® 600, Concep® III	BARU, PARU, WREC
KS585	Chromatin	Apron® XL, Maxim® 4FS, Storcide II™, Cruiser® 5FS	PARU
SP6929	Chromatin	Apron® XL, Maxim® 4FS, Storcide II™, Cruiser® 5FS	BARU, PARU, WREC
1G741	Mycogen	Maxim®, Apron® XL LS, Cruiser® 5FS	PARU
1G588	Mycogen	Maxim®, Apron® XL LS, Cruiser® 5FS	BARU, PARU, WREC
1G855	Mycogen	Maxim®, Apron® XL LS, Cruiser® 5FS	BARU, PARU, WREC

Table 3.2. Mean number of aphid-days and cumulative aphid-days per two-leaf sample with corresponding LS means comparisons for all sorghum varieties evaluated at the Brewton Agricultural Research Center in Brewton, AL.

Variety	**Aphid-days per two-leaf sample**		
	8 Jul	**29 Jul**	**4 Aug**
	21 DPP	**42 DPP**	**48 DPP**
Chromatin SP6929	256.90a	10407.95c	8707.07b
DeKalb 37-07	163.45b	12176.15c	11146.81ab
DowAg 1G588	196.96ab	16208.94bc	7740.10b
DowAg 1G855	136.41b	13141.89bc	12069.74ab
Pioneer 83P17	246.93a	23810.41ab	15661.24a
Pioneer 84P80	143.59b	27131.30a	13132.40ab
F-statistic	6.78	8.54	3.88
df	5, 222	5, 133	5, 212
P-value	<0.0001	<0.0001	0.0022
Variety	**Cumulative aphid-days per two-leaf sample**		
	8 Jul	**29 Jul**	**4 Aug**
	21 DPP	**42 DPP**	**48 DPP**
Chromatin SP6929	256.90a	10663.10c	14566.13c
DeKalb 37-07	163.45b	12338.32c	20442.38bc
DowAg 1G588	196.96ab	16288.77bc	17094.38c
DowAg 1G855	136.41b	13266.87bc	19829.94bc
Pioneer 83P17	246.93a	23976.17ab	28866.21ab
Pioneer 84P80	143.59b	27252.63a	33624.46a
F-statistic	6.78	8.47	9.41
df	5, 222	5, 133	5, 212
P-value	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

Table 3.3. Mean injury rating, maturation rate, plant growth stage, and yield per plot with LS means comparisons for all treatments tested during the sorghum variety trial at the Brewton Agriculture Research Unit in Brewton, AL.

Variety	Mean injury[1]	Maturation rate (days)[2]	Growth stage[3]	Yield (tonnes/ha)
	4 Aug		**4 Aug**	**22 Oct**
	48 DPP		**48 DPP**	**127 DPP**
Chromatin SP6929	8.00	84.00	10.25c	0.14b
DeKalb 37-07	6.75	78.00	13.75a	2.76a
DowAg 1G588	5.00	78.00	11.50bc	0.37b
DowAg 1G855	7.75	80.00	13.25a	0.37b
Pioneer 83P17	4.50	78.00	12.25ab	0.44b
Pioneer 84P80	8.00	82.00	11.00bc	0.10b
F-statistic	1.25	0.30	14.73	33.43
df	15	15	5, 15	15
P-value	0.3334	0.9078	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, $p \leq 0.05$)
[1]Damage rating on a scale of 1-9, healthy-dead plants.
[2]Days from planting until 50% of plants per plot had exerted panicles.
[3]Number of fully developed true-leaves.

Table 3.4. Mean number of aphid-days accumulated from the previous evaluation date, per two-leaf sample with corresponding LS means comparisons for all sorghum varieties evaluated at the Prattville Agricultural Research Unit in Prattville, AL.

Variety	Aphid-days per two-leaf sample								
	7 Jul	**13 Jul**	**20 Jul**	**27 Jul**	**7 Aug**	**12 Aug**	**24 Aug**	**31 Aug**	**7 Sep**
	20 DPP	**26 DPP**	**33 DPP**	**40 DPP**	**51 DPP**	**56 DPP**	**68 DPP**	**75 DPP**	**82 DPP**
ATx2752RTx2783	105.35cd	108.93c	175.35b	61.08b	152.08b	158.25c	359.40d	115.59d	69.04b
ATx2752RTx430	154.79bcd	200.25bc	317.89a	78.49b	926.34ab	1797.97a	7265.51a	2996.72abc	872.90b
Chromatin KS585	265.30a	341.39a	-	1494.94a	2004.06a	1542.28ab	4877.25abc	1898.62bcd	146.21b
Chromatin SP6929	161.53bc	255.85ab	276.68ab	116.11b	416.76b	432.50c	5280.90ab	4674.78a	2715.39a
DeKalb 37-07	116.73bcd	135.82c	193.73ab	106.75b	490.05b	224.13c	866.10cd	462.26d	50.93b
DowAg 1G588	121.63bcd	164.80bc	235.38ab	54.43b	178.34b	121.06c	344.85d	123.03d	25.64b
DowAg 1G741	133.53bcd	187.98bc	-	616.18b	752.26b	628.91bc	2666.78bcd	1724.63bcd	661.59b
DowAg 1G855	97.21d	125.75c	159.60b	67.29b	237.46b	464.81c	1838.93bcd	586.56cd	49.70b
Pioneer 83P17	91.18d	161.85bc	148.93b	72.98b	301.95b	165.75c	622.20d	304.24d	285.34b
Pioneer 84P80	173.51b	252.75ab	319.20a	71.14b	436.56b	450.84c	4859.33abc	3696.96ab	675.06b
F-statistic	13.01	9.20	5.12	7.93	4.00	8.44	7.56	8.55	8.57
df	9, 378	9, 168	7, 300	9, 378	9, 378	9, 378	9, 378	9, 378	9, 378
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, $p \leq 0.05$)

Table 3.5. Mean number of cumulative aphid-days per two-leaf sample with corresponding LS means comparisons for all sorghum varieties evaluated at the Prattville Agricultural Research Unit in Prattville, AL.

Variety	Cumulative aphid-days per two-leaf sample								
	7 Jul	**13 Jul**	**20 Jul**	**27 Jul**	**7 Aug**	**12 Aug**	**24 Aug**	**31 Aug**	**7 Sep**
	20 DPP	**26 DPP**	**33 DPP**	**40 DPP**	**51 DPP**	**56 DPP**	**68 DPP**	**75 DPP**	**82 DPP**
ATx2752RTx2783	105.35cd	135.94c	333.65ab	295.80b	447.88b	606.13c	965.53d	1081.11d	1150.15b
ATx2752RTx430	154.79bcd	241.95bc	420.08a	504.28b	1430.61b	3228.58ab	10494.09a	13490.80a	14240.85a
Chromatin KS585	265.30a	413.64a	262.17ab	1494.94a	3499.00a	5041.28a	9918.53a	11817.15ab	11963.36a
Chromatin SP6929	161.53bc	305.38ab	388.84ab	529.21b	945.98b	1378.48bc	6659.38ab	11334.15ab	13421.03a
DeKalb 37-07	116.73bcd	168.01c	281.77ab	380.65b	870.70b	1094.83bc	1960.93bcd	2423.19d	2474.11b
DowAg 1G588	121.63bcd	196.00bc	309.85ab	381.30b	559.64b	680.70c	1025.55d	1148.58d	1174.21b
DowAg 1G741	133.53bcd	228.95bc	201.86b	616.18b	1368.44b	1997.34bc	4664.12bcd	6388.74bcd	7050.33ab
DowAg 1G855	97.21d	152.18c	372.43ab	296.61b	534.08b	998.89c	2837.8bcd	3424.37cd	3479.41b
Pioneer 83P17	91.18d	191.90bc	279.16ab	317.85b	619.80b	785.55c	1407.75cd	1711.99d	1871.85b
Pioneer 84P80	173.51b	295.45ab	295.51ab	538.06b	974.63b	1425.47bc	6284.79abc	9981.76abc	11528.32a
F-statistic	13.01	9.13	2.33	4.53	6.58	8. 31	10.56	10.33	11.47
df	9, 378	9, 168	9, 293	9, 378	9, 378	9, 378	9, 378	9, 378	9, 378
P-value	<0.0001	<0.0001	0.0150	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

Table 3.6. Mean injury rating, maturation rate, and growth stage per plot with LS means comparisons for all treatments tested during the sorghum variety trial at the Prattville Agriculture Research Unit in Prattville, AL.

Variety	Mean injury[1]	Maturation rate (days)	Growth stage[2]
	31 Aug		24 Aug
	75 DPP		68 DPP
ATx2752RTx2783	2.00	56.00	14.25ab
ATx2752RTx430	3.50	51.00	12.75bcd
Chromatin KS585	3.75	51.00	11.75d
Chromatin SP6929	3.25	56.00	14.00ab
DeKalb 37-07	2.00	52.25	12.00cd
DowAg 1G588	2.25	51.00	14.00ab
DowAg 1G741	1.25	51.00	12.75bcd
DowAg 1G855	2.25	61.25	14.75a
Pioneer 83P17	2.75	53.50	14.00ab
Pioneer 84P80	3.75	51.00	13.50abc
F-statistic	1.05	0.87	8.36
df	9, 27	9, 27	9, 27
P-value	0.4268	0.5589	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)
[1]Damage rating on a scale of 1-9, healthy-dead plants.
[2]Number of true-leaves.

Table 3.7. Mean number of aphid-days per plant and cumulative aphid-days per plant with LS means comparisons for all treatments tested during the sorghum variety trial at Wiregrass Research and Extension Center in Headland, AL.

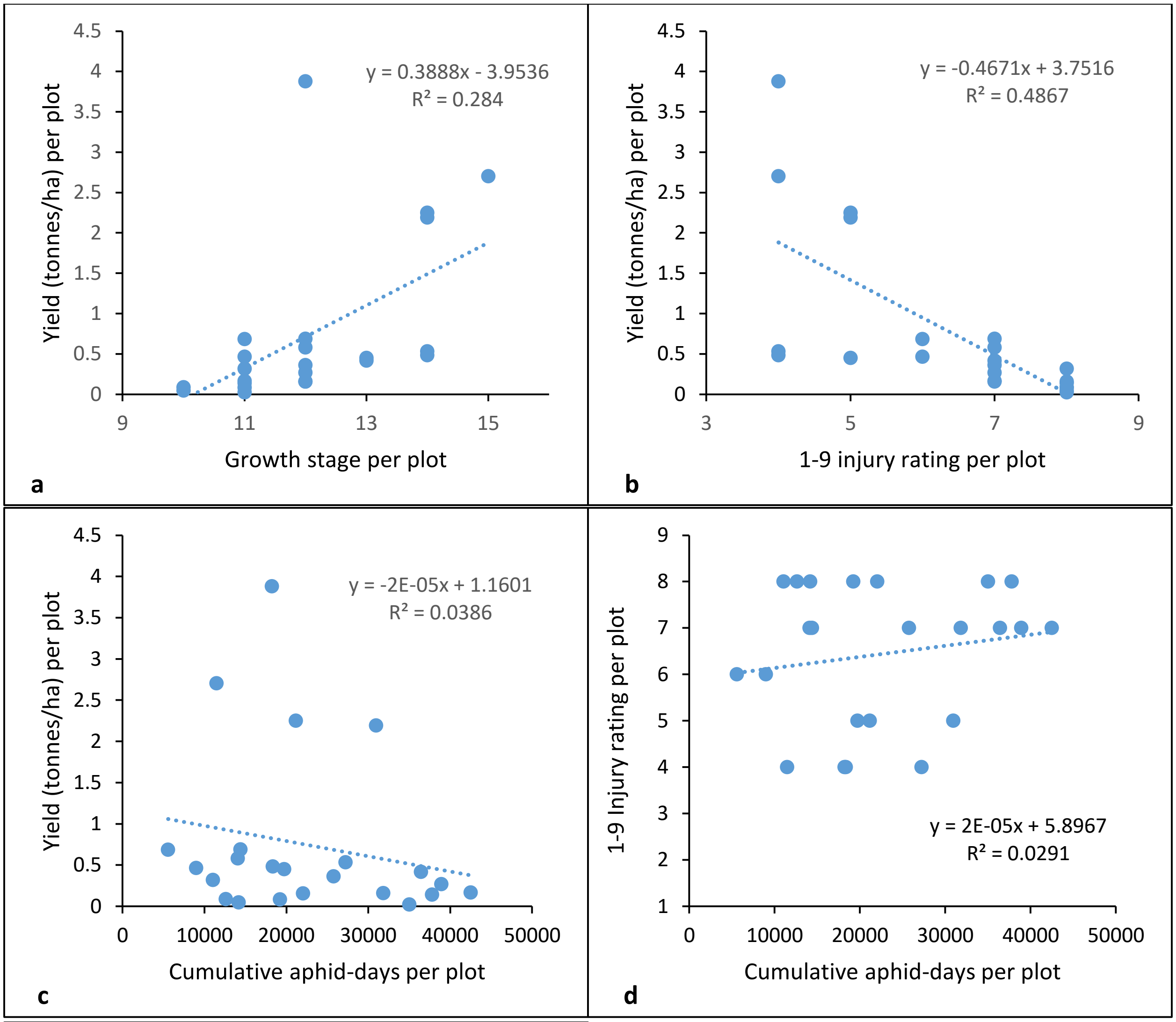
Variety	Aphid-days per two-leaf sample				
	9 Jul	15 Jul	24 Jul	30 Jul	6 Aug
	24 DPP	30 DPP	39 DPP	45 DPP	52 DPP
Chromatin SP6929	697.81ab	1364.88b	-	13065.07ab	7255.59b
DeKalb 37-07	721.00a	2283.40a	9365.35a	10924.29b	10073.70a
DowAg 1G588	615.83ab	1126.95b	4460.98b	4722.20c	4389.18c
DowAg 1G855	374.41c	1136.69b	3451.28b	3233.74c	2693.16cd
Pioneer 83P17	504.00bc	1177.59b	2256.55b	2288.30c	1786.05d
Pioneer 84P80	769.30a	1410.53b	11444.60a	16292.59a	9403.98ab
F-statistic	8.08	8.85	22.01	43.85	31.75
df	5, 222	5, 185	4, 183	5, 212	5, 222
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Variety	**Cumulative aphid-days per two-leaf sample**				
	9 Jul	**15 Jul**	**24 Jul**	**30 Jul**	**6 Aug**
	24 DPP	**30 DPP**	**39 DPP**	**45 DPP**	**52 DPP**
Chromatin SP6929	697.81ab	2055.55b	-	14588.80c	18743.03b
DeKalb 37-07	721.00a	3004.68a	11915.83a	22840.11b	32913.81a
DowAg 1G588	615.83ab	1622.64b	5952.20b	10674.40cd	15063.58bc
DowAg 1G855	374.41c	1530.56b	4600.59b	7834.33d	10527.49cd
Pioneer 83P17	504.00bc	1743.31b	3566.13b	5854.43d	7640.48d
Pioneer 84P80	769.30a	2179.83b	13624.43a	29917.01a	39320.99a
F-statistic	8.08	9.25	27.88	38.89	49.55
df	5, 222	5, 185	4, 183	5, 212	5, 222
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

Table 3.8. Mean injury rating, maturation rate, plant growth stage, and yield reported in metric tons per hectare per plot with LS means comparisons for all treatments tested during the sorghum variety trial at the Wiregrass Research and Extension Center in Headland, AL.

Variety	**Mean injury[1]**	**Maturation rate (days)**	**Growth stage[2]**	**Yield (tonnes/ha)**
	6 Aug		**6 Aug**	**20 Oct**
	52 DPP		**52 DPP**	**127 DPP**
Chromatin SP6929	5.75	81a	11.00b	2.58
DeKalb 37-07	6.00	67ab	12.50ab	3.18
DowAg 1G588	3.75	60b	14.00a	4.43
DowAg 1G855	4.00	67ab	12.75ab	8.30
Pioneer 83P17	3.25	60b	13.75a	7.43
Pioneer 84P80	6.75	74ab	11.50b	1.22
F-statistic	1.62	3.91	6.27	0.91
df	5, 15	5, 15	5, 15	5, 15
P-value	0.2155	0.0181	0.0025	0.5002

Column means followed by the same letter are not significantly different (LS means, $p \leq 0.05$)
[1]Damage rating on a scale of 1-9, healthy-dead plants.
[2]Number of true-leaves.



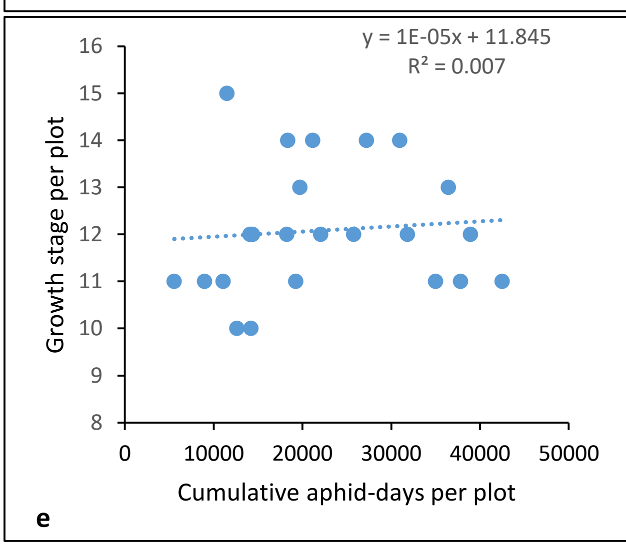


Figure 3.1. Scatterplots with regression lines showing the relationship between; (a) growth stage per plot and yield per plot, (b) 1-9 injury rating per plot and yield per plot, (c) cumulative aphid-days per plot and yield per plot, (d) cumulative aphid-days per plot and 1-9 injury rating per plot, and (e) cumulative aphid-days per plot and growth stage per plot. All varieties were included in these analyses and all variables used are from the final evaluation period on 4 August 2015 at the Brewton Agricultural Research Unit in Brewton, AL. Plots were under dryland conditions.

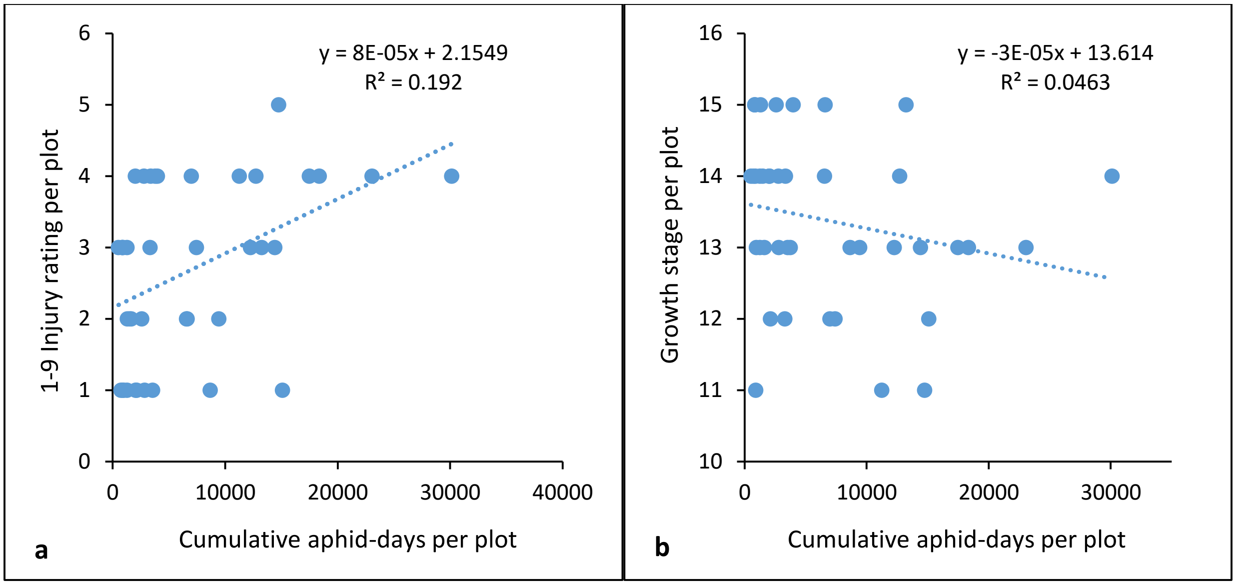
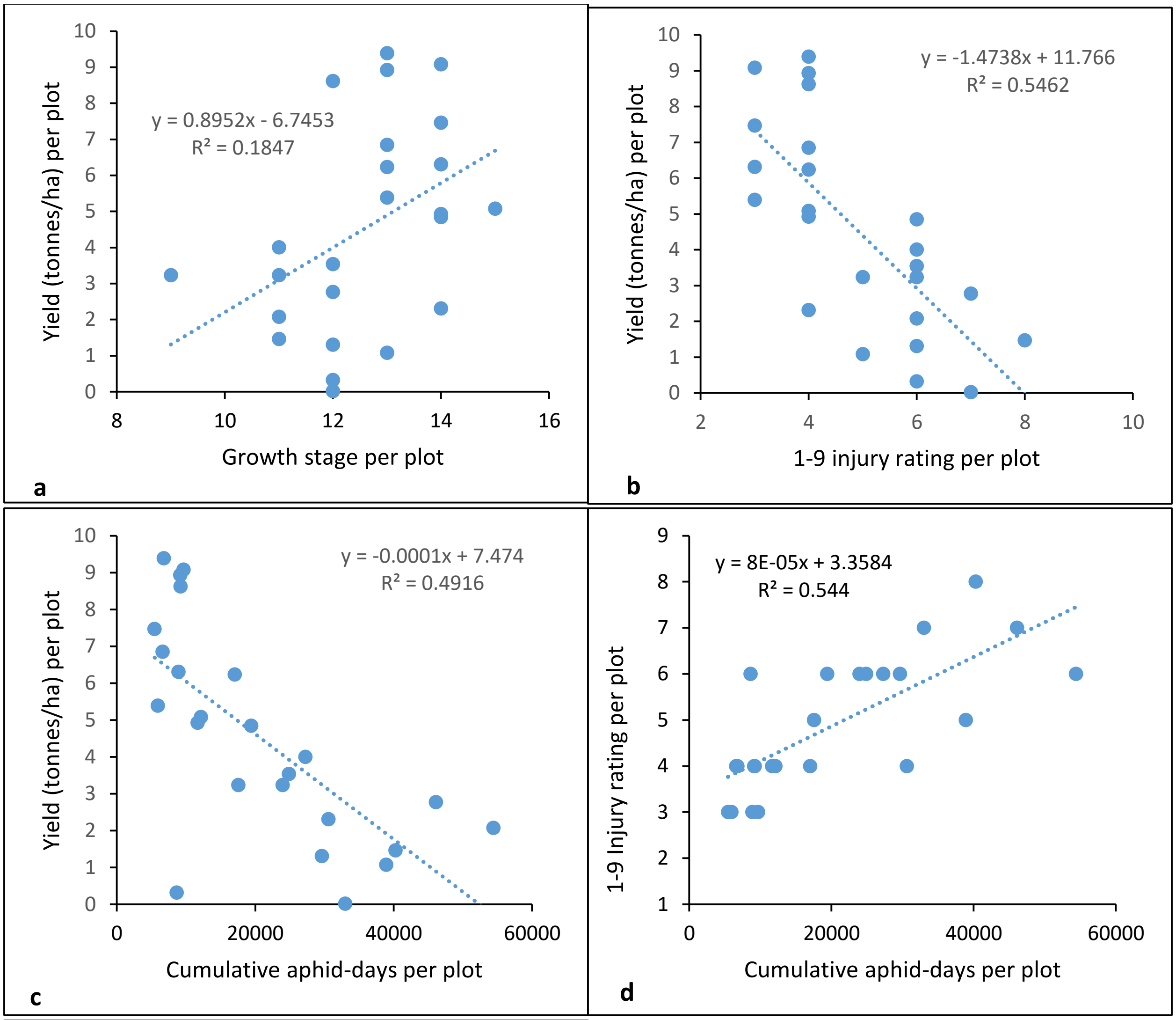


Figure 3.2. Scatterplots with regression lines showing the relationship between; (a) cumulative aphid-days per plot and 1-9 injury rating per plot, and (b) cumulative aphid-days per plot and final plant growth stage per plot. All varieties were included in these analyses and all variables used are from the final evaluation period on 7 September 2015 at the Prattville Agricultural Research Unit in Prattville, AL Plots were under dryland conditions.



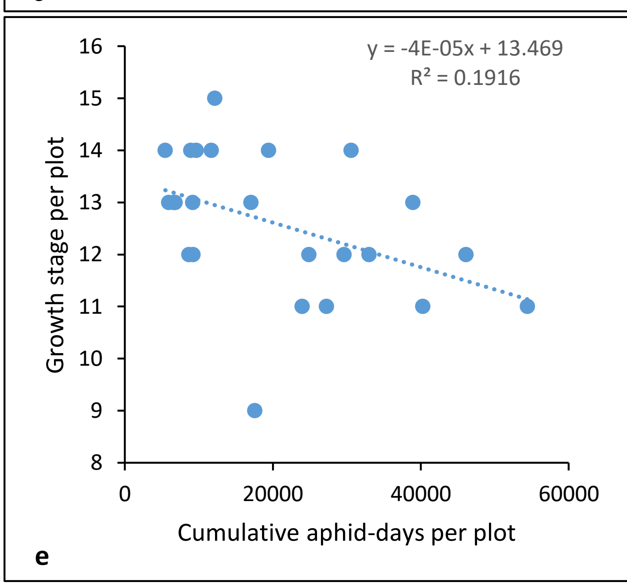


Figure 3.3. Scatterplots with regression lines showing the relationship between; (a) growth stage per plot and yield per plot, (b) 1-9 injury rating per plot and yield per plot, (c) cumulative aphid-days per plot and yield per plot, (d) cumulative aphid-days per plot and 1-9 injury rating per plot, and (e) cumulative aphid-days per plot and growth stage per plot. All varieties were included in these analyses and all variables used are from the final evaluation period on 6 August 2015 at the Wiregrass Research and Extension Center in Headland, AL. Plots were irrigated

CHAPTER 4

INTEGRATED PEST MANAGEMENT FOR SUGARCANE APHID, *Melanaphis sacchari* (Zehntner), ON SORGHUM (*Sorghum bicolor*) (L.) IN ALABAMA

Abstract

Integrated pest management programs are designed to minimize or eliminate pest outbreaks to prevent economic losses. This is often accomplished using a combination of tactics that have been assessed for efficacy. Preliminary small plot field studies performed in 2015 evaluated seed treatment residual activity, foliar insecticide efficacy, and tolerance levels of commercially available sorghum varieties, however, combinations of these treatments that may reduce insecticide applications have not been evaluated. The overall objective of this research was to develop an integrated pest management program for sugarcane aphid in sorghum. A small plot research trial was conducted at the E.V. Smith Research and Extension Center Field Crops Unit in Shorter, AL, in order to determine the most effective combination of planting date, sorghum variety, insecticide seed treatment, and foliar insecticide treatment for sugarcane aphid management in Alabama. The most effective treatment combination for sugarcane aphid management consisted of early-planted tolerant sorghum with a seed treatment and insecticide spray at treatment threshold. Sugarcane aphid populations only reached treatment threshold and required an insecticide spray for early-planted treatments and one late-planted treatment. Although aphid populations were much lower in late-planted treatments yields were higher in early-planted plots.

Introduction

For the past four decades, insect pests of agricultural crops have been managed using ‘the integrated control concept’ (IC) (Stern et al. 1959) and principles of integrated pest management (IPM) (Beirne 1970, Apple and Smith 1976) in order to reduce our overreliance on pesticides and minimize negative impacts on non-target organisms, the environment and human health (van Emden 2007). IPM programs are designed to succinctly predict, scout and identify pest outbreaks, manage the pest to prevent injury from exceeding economically damaging levels, and implement methods that have been evaluated for efficacy (Kogan 1998, Schellhorn et al. 2009, Zalucki et al. 2009, 2015; Herzfeld and Sargent 2015, Schellhorn et al. 2015). IPM utilizes multiple control tactics which can include cultural control techniques like host plant resistance and hybrid selection, natural enemies, and more selective insecticides.

Several tactics for the management of sugarcane aphid were identified in the previous chapters. The addition of Cruiser® 5FS, Gaucho® 600, NipsIt® Inside, and Poncho® 600 seed treatments maintained populations below treatment threshold for at least 47 days after planting. The foliar insecticide Sivanto® 200SL maintained populations below threshold for 27 to 34 days after treatment, while Centric® 40WG and Transform® WG provided efficacy for 20 days after treatment. In addition, several sorghum varieties including DeKalb 37-07, DowAg 1G588, DowAg 1G851, and Pioneer 83P17 exhibited tolerance to sugarcane aphid. These tactics were tested individually, and to date, no studies have been conducted to examine combinations of these tactics for sugarcane aphid management. The overall objective of this research was to develop an integrated approach for management of sugarcane aphid on sorghum to minimize chemical applications. To do this a small plot research trial was conducted to determine the most effective combination of previously tested insecticide seed treatment, foliar insecticide, resistant sorghum varieties, and planting date, for sugarcane aphid management.

Materials and Methods

Small grain sorghum research plots were established on 10 June 2016 and 30 June 2016 for the early- and late-planting dates, respectively, at the E.V. Smith Research and Extension Center Field Crops Unit in Shorter, AL (Table 2.1). The treatments tested in this study included combinations of early- and late-planted sorghum, a tolerant and susceptible variety, with and without an insecticide seed treatment, and with and without a threshold application of foliar insecticide (Table 4.1). Pioneer 84P80, a known susceptible sorghum variety, and Pioneer 83P17, a tolerant variety, were used in this study. Experiments included seed treated with Cruiser® 5FS (0.225L/45.359kg seed), and seed that did not have any insecticide. Some plots received a foliar application of Sivanto® 200SL (0.292 L/ha) when sugarcane aphid populations reached the treatment threshold of 100 aphids per plant for 30% of plants. The nomenclature used to label the treatments included in this trial are a list of planting date (Early/Late), followed by variety (84P80/83P17), while IST indicates use of a seed treatment and ISP indicates the plots were sprayed with insecticide when aphid populations reached threshold. The absence of ISP or IST is indicative of its absence in that treatment.

Experiments were conducted using a randomized complete block design with four replicates per treatment. Each research plot was 4 rows wide by 6.1 meters long with rows spaced 0.91 meters apart. The sorghum was seeded at approximately 148,263 seeds per hectare. All plots were treated for whorl worms with 0.365 L/ha Tundra® (WinField®) on 6 July and the late-planted plots were treated a second time with 0.511 L/ha Intrepid® (Dow® AgroSciences) on 5 August.

Plant stand counts were taken from 2 m of each interior row at approximately 14 to 21 days post-planting. Plots were scouted for sugarcane aphid weekly and were first observed on 2 August. Once infested, the total number of aphids was estimated from an upper fully expanded leaf (below flag leaf) and lower leaf (second from the bottom, or lowest healthy leaf) for 10 random plants in the interior rows of each plot. For the estimation; the total number of aphids was counted when under 30, then estimated by 10's when over 30, and by 100's when over 500. Plots were evaluated for sugarcane aphid weekly from 2 August to 30 August, and ISP plots were sprayed with Sivanto® 200SL (0.292 L/ha) when aphid populations reached the treatment threshold of 100 aphids per plant for 30% of plants.

The growth stage of each plant was determined weekly by counting the number of fully developed true leaves. A 1-9 injury rating for each plot was recorded weekly and was adapted from Webster et al. (1991), Burd et al. (2006), and Armstrong et al. (2015); 1 = healthy, 2 = 1-5% injury and spotted, 3 = 5-20%, 4 = 21-35%, 5 = 36-50%, 6 = 51-65%, 7 = 66-80%, 8 = 81-95%, and 9 = 95-100% or dead. Maturity ratings were conducted by recording when 50% of plants in each plot had exerted panicles. Ratings were made on the interior rows of each plot during weekly aphid counts, and these two rows were harvested for yield (tonnes/ha) on 12 October when grain moisture reached approximately 14%.

Statistical analysis

Prior to analyses, the number of aphid-days and cumulative aphid-days per two-leaf sample were calculated from the total number of aphids per two-leaf sample for each treatment following the equation developed by Ruppel (1983):

$$\textbf{Aphid-days} = (X_{i+1} - X_i)\ [(Y_i + Y_{i+1}) / 2]$$

in which X_i and X_{i+1} are two adjacent observation periods and Y_i and Y_{i+1} are the number of aphids present at each respective observation period. The aphid-days measurement is indicative of the severity of an insect attack and it takes into consideration the number of surviving insects between time periods. Cumulative aphid-days were then calculated by summing the number of aphid-days from each prior data collection period.

Data was analyzed by location and evaluation date to compare the average number of aphid-days per two-leaf sample, cumulative aphid-days per two-leaf sample, the average plant stand counts, injury ratings, maturity ratings, and sorghum yields per treatment. Analyses were conducted using PROC GLIMMIX (SAS 9.4, SAS Institute 2010) with treatment as a main effect; block and residuals as random effects, and plant as an additional random effect for aphid-days analyses. Mean comparisons were conducted using LS means at a $p \leq 0.05$ level. Simple linear regression analyses and a multiple regression analysis were performed using the PROC REG function ANOVA (SAS9.4, SAS Institute 2013) to identify whether the mean accumulated number of aphid-days at peak infestation per plot, or the 1-9 injury rating per plot, or both were correlated with the resulting yield.

Results

Sugarcane aphid was first observed in plots on 2 August 2016, 53 days after planting for early-planted sorghum and 33 days after planting for late-planted sorghum, and populations were below the treatment threshold (Table 4.2). During this time all treatments except Early|84P80|ISP had significantly fewer aphid-days than Early|84P80 ($F=3.90$, $df=11,456$, $P<0.0001$). On 9 August, 7 days after initial infestation, sugarcane aphid populations in Early|84P80|ISP and Early|84P80|IST|ISP plots exceeded the treatment threshold and were the only two treatments that did not significantly differ from Early|84P80 ($F=22.42$, $df=11,456$, $P<0.0001$). These treatments received an insecticide application on 10 August, 8 days after the initial infestation, which suppressed populations below treatment threshold for the remainder of the study. On 16 August ($F=30.50$, $df=11,456$, $P<0.0001$) aphid populations in Early|84P80 plots remained significantly higher than all other treatments, however, aphid populations in Early|83P17|ISP, Early|83P17|IST|ISP, and Late|84P80|ISP plots approached treatment threshold and were sprayed on 18 August. Populations had completely declined for all treatments on 30 August ($F=16.45$, $df=11,456$, $P<0.0001$). Treatments Late|84P80|IST|ISP, Late|83P17|ISP and Late|83P17|IST|ISP never exceeded the treatment threshold prior to populations declining and, therefore, never received a foliar insecticide application.

Overall, the mean number of cumulative aphid-days per two-leaf sample significantly differed among treatments, and the early-planted control plots accumulated significantly more aphid-days per two-leaf sample than all other treatments. The late-planted control, Late|84P80 did not significantly differ from other late-planted treatments, and accumulated fewer aphid-days per two-leaf sample than the late-planted resistant variety Late|83P17. Plants in the Early|83P17|IST|ISP had the fewest cumulative aphid-days per two-leaf sample of early-planted treatments, and Late|83P17|IST|ISP plots had the fewest cumulative aphid-days per two-leaf sample for late-planted treatments. All late-planted treatments and one early-planted treatment, Early|83P17|IST|ISP, accumulated significantly fewer aphid-days per two-leaf sample than the early-planted control Early|84P80. All of the late-planted treatments accumulated no more than 2838.68 aphid-days per two-leaf sample, however, no significant differences were observed among Pioneer 84P80 and Pioneer 83P17. Plants that received seed treatments in both early- and late-planted plots, Early|83P17|IST|ISP, Early|84P80|IST|ISP Late|83P17|IST|ISP, and Late|84P80|IST|ISP, yielded lower numbers of cumulative aphid-days than those without. Treatments that only received an insecticide spray, Early|83P17|ISP, Early|84P80|ISP, Late|83P17|ISP, and Late|84P80|ISP accumulated fewer aphid-days than controls for both planting dates on both varieties.

The final mean plant growth stage per plot (Table 4.3) did not significantly differ among any treatments on 23 August ($F=0.14$, $df=11,33$, $P=0.9994$); plants in all plots had 13-15 leaves. The mean sorghum injury rating per plot (Table 4.3) significantly differed among treatments on 2 August ($F=14.90$, $df=11,33$, $P<0.0001$), 9 August ($F=4.92$, $df=11,33$, $P=0.0002$), 16 August ($F=12.31$, $df=11,33$, $P<0.0001$), 23 August ($F=11.04$, $df=11,33$, $P<0.0001$), and 30 August ($F=11.04$, $df=11,33$, $P<0.0001$). During the final mean injury rating per plot all late-planted treatments had significantly less injury than Early|84P80. Early|83P17|IST|ISP was the only early-planted treatment that exhibited damage ratings significantly lower than Early|84P80. Maturity rating per plot (Table 4.3) did not significantly vary among treatments ($F=1.09$, $df=11,33$, $P=0.3991$). All early planted treatments reached maturity in 60 days and all late planted treatments matured in 68 days.

The percentage of plants covered in honeydew per plot (Table 4.4) significantly differed among treatments on 2 August (F=2.93, df=11,33, P=0.0083), 9 August (F=4.54, df=11,33, P=0.0003), 16 August (F=4.06, df=11,33, P=0.0008), but did not on 23 August (F=1.44, df=11,33, P=0.2034). There was no honeydew observed on 30 August after populations declined. The percentage of leaves per plot covered with honeydew was the most pronounced 16 August; Early|84P80 plots had an average of 91.25% leaves covered with honeydew, followed by Early|83P1|IST|ISP, Early|83P17, and Early|83P17|ISP. The late planted plots overall had numerically lower percentages of honeydew than the earlier planted treatments, however, they did not significantly differ among each other, and were statistically similar to all early-planted plots except Early|P84P80. After the addition of foliar insecticides for designated treatments, the presence of honeydew disappeared or remained below 5%. Linear regression analysis showed a weak, but significant positive relationship between the cumulative number of aphid-days and honeydew (R^2=0.05, F=12.22, df=1,237, P=0.0006). There was no black sooty mold present on plants during 2 August, however the percentage of plants covered in black sooty mold per plot (Table 4.4) significantly differed among treatments on 9 August (F=2.49, df=11,33, P=0.0210), 16 August (F=7.17, df=11,33, P<0.0001), 23 August (F=6.79, df=11,33, P<0.0001) and 30 August (F=6.79, df=11,33, P<0.0001). A very strong positive and significant relationship was identified between the cumulative number of aphid-days per two-leaf sample and black sooty mold (R^2=0.73, F=634.01, df=1,237, P<0.0001). There was a weak, but significant positive relationship between the percentage of honeydew per plot and the percentage of black sooty mold per plot (R^2=0.05, F=12.33, df=1,237, P=0.0005).

The average plant stand counts (Table 4.3) were significantly different among treatments (F=11.06, df=11,81, P<0.0001). Late-planted resistant sorghum treatments Late|83P17 and Late|83P17|ISP had significantly lower plant stands than all other treatments except Late|83P17|IST|ISP. Sorghum grain yield (Table 4.3) significantly differed among treatments (F=13.62, df=11,33, P<0.0001), but reductions in yield were not always consistent with treatments where reduced plant stands were observed. The Early|83P17|IST|ISP plots produced significantly greater yields than all-late-planted treatments, but did not differ from Early|84P80|IST|ISP, Early|83P17|ISP, Early|84P80|ISP, and Early|83P17. Late-planted treatments did not significantly differ from each other or Early|84P80. There were no significant differences among Early|83P17, Early|84P80|ISP, Early|84P80, Late|84P80|IST|ISP, or Late|84P80.

Discussion

In this experiment pest management programs that integrate planting date, seed treatment, and sorghum variety were identified that reduced insecticide spray applications in 2015 to manage sugarcane aphid populations. The most effective treatment combinations for suppressing populations included all late-planted sorghum treatments regardless of sorghum variety, and the three early-planted treatments that included variety Pioneer 83P17 treatments. However, all early-planted treatments produced larger yields than late-planted treatments. Previously, planting sorghum early in Alabama has been shown to reduce injury and produce higher yields than late-planted sorghum (Mask et al. 1988). Although planting date reduced sugarcane aphid damage in this trial, the risk of damage caused by other insects increased for late-planted sorghum; late-planted plots received two applications of insecticides to manage whorlworms, while headworms and sorghum midge can cause local problems mid- to late-season in some areas of the state. In addition, differences in growing conditions may impact yield potential of the crop. The effects of these are not entirely clear from this one year of data because significant differences among plant stand counts likely contributed to variation in yield among treatments and planting dates. The late-planted resistant variety treatments Late|83P17 and Late|83P17|ISP had the smallest plant stands of all treatments, with low plant stand counts being observed in majority of plots sampled. There was consistent variation in plant stand counts among other treatments.

Altering the planting date of crops to avoid insect injury is a successful pest management tactic when infestations are predictable, and yield is not compromised by other factors. Sugarcane aphid populations undergo rapid growth followed by alate development and subsequent dispersal (van Rensburg and van Hamburg 1975). Factors that influence timing and magnitude of infestations include overwintering range, quantity of host plants in the landscape, and migratory ability. Limited information exists on the sugarcane aphid's current overwintering and migration habits in the U.S., which complicates predicting the timing of infestations (Bowling et al. 2016). Sugarcane aphid has a limited host range and feeds on other *Sorghum* spp. including Johnsongrass, an introduced invasive grass that is now considered a weed pest in agricultural fields, pastures, and roadsides (Holm 1969). Johnsongrass and ratooned sorghum provide sugarcane aphid with alternate hosts for overwintering and early-season before sorghum is cultivated (Bowling et al. 2016). In 2016 sugarcane aphid was detected on Johnsongrass in Alabama on 3 May in Prattville and Milstead (Flanders 2016), although it is unknown whether these populations overwintered in Alabama. Despite this, sugarcane aphid was not detected in plots until 2 August 2016, whereas in 2015 initial infestations in Tallassee, AL occurred on 7 July. During the growing season there are a limited number of hectares of sorghum in the Alabama landscape relative to other crops; sorghum is a minor crop in Alabama with approximately 40,468 hectares planted in 2015 as a rotation crop. In 2016 across the southeast and mid-south, sorghum production decreased, which may have reduced populations and the number of migrants across this region. Future studies are needed to develop a better understanding of the sugarcane aphid's overwintering range and migration to improve our understanding of when infestations are likely to occur.

Host plant tolerance was observed to have a larger impact for early-planted treatments than late-planted treatments. For the early-planted sorghum, sugarcane aphid populations were twice the size on susceptible sorghum than on tolerant sorghum. The number of aphid-days on late-planted sorghum were generally lower than early-planted sorghum, and there were no statistical differences in aphid-days among late-planted treatments. Host-plant resistance is one of the most reliable and stable forms of pest management (Starks and Schuster 1978), although the mechanism of resistance (Chapter 3) can have varying effects on pest populations. From two years of studies it does not appear that host plant resistance alone is effective at maintaining populations below threshold, but does play a role in population suppression. Other crops that exhibit resistance to other aphid species have been reported to decrease aphid fecundity (van

Emden and Wearing 1965) and body size (Hassell et al. 1977), and increase the time it takes to develop (Sotherton and Lee 1988). These consequences have been shown to enhance the services provided by biological control (Gowling and van Emden 1994, Hassell et al. 1977), however, negative effects of host plant resistance on natural enemies have been reported (van Emden 1991). In this study predators and parasitoids were observed in all treatments regardless of sorghum variety or the presence of seed treatment, however, species richness and abundance appeared to increase as aphid population size increased, and the mummies of three parasitoid species were observed in all treatments before and after insecticide applications (A.J.P. personal observation). Future studies should examine whether or not these resistant sorghum varieties impact sugarcane aphid fitness or the fitness of natural enemies.

The addition of a seed treatment provided little to no benefit to early-planted sorghum. Initial infestation occurred 53 days after planting, so it is likely the insecticide seed treatment's residual activity was gone as Cruiser® 5FS was previously shown to provide efficacy for 4 to 6 weeks in the 2015 seed treatment trials (see Chapter 2). The use of foliar insecticides on early-planted sorghum resulted in the highest yields overall regardless of variety. Early-planted treatments required one application of Sivanto® 200SL which provided efficacy until populations naturally declined in all plots. In 2015 Sivanto® 200SL provided efficacy for about 27 days after treatment, however, plots were infested in early July and required a second application as populations resurged later in the growing season. Given that initial infestation was low for late-planted sorghum in 2016 and occurred 33 days after planting, it is likely the effects of the seed treatment were still present. Only one late-planted treatment exceeded treatment threshold and received an application of Sivanto® 200SL, yet populations naturally declined 5 days later, so the insecticide treatment likely could have been avoided.

Although IPM for sugarcane aphid on sorghum in Alabama is in the early stages of development, these results provide groundwork for the development of more comprehensive management plans. It is important that pest-mismanagement is avoided when implementing sugarcane aphid IPM. There are currently only two foliar insecticides available (Sivanto® 200SL and Transform® WG) that provide high efficacy against sugarcane aphid in Alabama. These products should be rotated to delay resistance development, and alternative insecticides that can be used for sugarcane aphid management should be identified. It is also critical to assess how environmental conditions influence different management tactics. Several sorghum varieties from the sorghum variety trial (see Chapter 3) showed moderate to high levels of tolerance to sugarcane aphid, but the effects of irrigation and soil type on varietal performance should be further investigated. Further studies should also be aimed at the impact of these management practices on other sorghum pests, along with studying other cultural control methods, and the impact natural enemies have on sugarcane aphid populations.

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Table 4.1. List of treatment combinations evaluated in the integrated pest management trial at the E.V. Smith Field Crops Unit in Shorter, AL.

Treatment	Planting time	Variety	Spray at threshold (ISP)	Seed treatment (IST)
Early|83P17|ISP	Early	Pioneer 83P17	Yes	No
Early|83P17|IST|ISP			Yes	Yes
Early|8317			No	No
Early|84P80|ISP		Pioneer 84P80	Yes	No
Early|84P80|IST|ISP			Yes	Yes
Early|84P80			No	No
Late|83P17|ISP	Late	Pioneer 83P17	Yes	No
Late|83P17|IST|ISP			Yes	Yes
Late|83P17			No	No
Late|84P80|ISP		Pioneer 84P80	Yes	No
Late|84P80|IST|ISP			Yes	Yes
Late|84P80			No	No

Table 4.2. Mean number of aphid-days and cumulative aphid-days per two-leaf sample with LS means comparisons for all treatments tested during the sorghum variety trial at the E.V. Smith Field Crops Unit in Shorter, AL. Treatments Early|84P80|ISP and Early|84P80|IST|ISP were treated on 10 August, and Early|83P17|ISP, Early|83P17|IST|ISP, and Late|84P80|ISP were treated on 18 August.

Treatment	Aphid-days per two-leaf sample				
	2 Aug	9 Aug	16 Aug	23 Aug	30 Aug
Early|83P17|ISP	34.91b	585.38b	2001.21bc	1450.84bc	0.09b
Early|83P17|IST|ISP	30.71b	275.01b	852.34c	608.30bc	0.26b
Early|83P17	17.41b	344.84b	1322.04c	1860.86b	866.25a
Early|84P80|ISP	533.66ab	4259.24a	3899.26b	256.38bc	82.69b
Early|84P80|IST|ISP	327.43b	4185.91a	3859.71b	3.06c	1.84b
Early|84P80	1241.54a	4521.30a	10293.76a	8189.48a	1175.48a
Late|83P17|ISP	19.25b	159.16b	524.04c	385.00bc	3.76b
Late|83P17|IST|ISP	21.96b	113.58b	165.03c	81.55bc	10.68b
Late|83P17	48.83b	193.99b	1360.28c	1223.43bc	12.16b
Late|84P80|ISP	5.16b	82.78b	194.60c	326.29bc	278.34b
Late|84P80|IST|ISP	13.39b	124.51b	306.08c	226.28bc	43.14b
Late|84P80	15.49b	64.31b	364.88c	399.09bc	97.13b
F-statistic	3.90	22.42	30.50	34.95	16.45
df	11, 456	11, 456	11, 456	11, 456	11, 456
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Treatment	**Cumulative aphid-days per two leaf sample**				
	2 Aug	**9 Aug**	**16 Aug**	**23 Aug**	**30 Aug**
Early|83P17|ISP	34.91b	620.29b	2621.50c	4072.34bcd	4072.43bc
Early|83P17|IST|ISP	30.71b	305.73b	1158.06c	1766.36d	1766.63c
Early|83P17	17.41b	362.25b	1684.29c	3545.15cd	4411.40bc
Early|84P80|ISP	533.66ab	4792.90a	8692.16b	8948.54b	9031.23b
Early|84P80|IST|ISP	327.43b	4513.34a	8373.05b	8376.11bc	8377.95b
Early|84P80	1241.54a	5762.84a	16056.60a	24246.08a	25421.55a
Late|83P17|ISP	19.25b	178.41b	702.45c	1087.45d	1091.21c
Late|83P17|IST|ISP	21.96b	135.54b	300.56c	382.11d	392.79c
Late|83P17	48.83b	242.81b	1603.09c	2826.51d	2838.68c
Late|84P80|ISP	5.16b	87.94b	282.54c	608.83d	887.16c
Late|84P80|IST|ISP	13.39b	137.90b	443.98c	670.25d	713.39c
Late|84P80	15.49b	79.80b	444.68c	843.76d	940.89c
F-statistic	3.90	18.65	31.87	38.65	40.76
df	11, 456	11, 456	11, 456	11, 456	11, 456
P-value	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, $p \leq 0.05$)

Table 4.3. The mean plant stand count, injury rating, maturation rate, plant growth stage, and yield per plot with LS means comparisons for all treatments tested during the sorghum variety trial at the E.V. Smith Field Crops Unit in Shorter, AL.

Treatment	Plant stand	Mean injury[1]	Maturation rate[2]	Growth stage[3]	Yield (tonnes/ha)
	2 Aug	30 Aug		30 Aug	10 Oct
Early|83P17|ISP	21.36abc	4.50abcd	60.00	14.25	5.34ab
Early|83P17|IST|ISP	25.61ab	4.00bcd	60.00	14.00	6.37a
Early|83P17	21.61abc	5.00abc	60.00	14.75	4.84abc
Early|84P80|ISP	29.61a	5.00abc	60.00	14.00	4.90abc
Early|84P80|IST|ISP	27.35ab	6.00ab	60.00	14.00	5.44ab
Early|84P80	27.86ab	7.25a	60.00	13.50	2.78cd
Late|83P17|ISP	11.74d	2.25d	68.00	13.25	1.69d
Late|83P17|IST|ISP	17.61cd	2.25d	68.00	13.00	2.66d
Late|83P17	12.99d	2.75cd	68.00	13.00	1.56d
Late|84P80|ISP	22.99abc	2.50d	68.00	12.50	2.35d
Late|84P80|IST|ISP	20.74bc	2.25d	68.00	13.25	2.82cd
Late|84P80	21.50abc	2.75cd	68.00	12.75	3.54bcd
F-statistic	11.06	11.04	1.09	0.14	13.62
df	11, 81	11, 33	11, 33	11, 33	11, 33
P-value	<0.0001	<0.0001	0.3991	0.9994	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)

[1]Damage rating on a scale of 1-9, healthy-dead plants.

[2]Days from planting until 50% of plants per plot had exerted panicles.

[3]Number of fully developed true-leaves.

Table 4.4. The mean percent of plants per plot covered in honeydew and percent black sooty mold with LS means comparisons for all treatments tested during the sorghum variety trial at the E.V. Smith Field Crops Unit in Shorter, AL.

Treatment	**Percent honeydew**				**Percent sooty mold**			
	2 Aug	**9 Aug**	**16 Aug**	**23 Aug**	**9 Aug**	**16 Aug**	**23 Aug**	**30 Aug**
Early|83P17|ISP	0.00b	8.75ab	37.50ab	2.50	0.00a	6.25cd	6.25bc	6.25bc
Early|83P17|IST|ISP	1.25ab	7.50b	60.00ab	0.00	2.50a	2.50cd	2.50c	2.50c
Early|83P17	0.00b	5.00b	40.00ab	35.00	0.00a	11.25bcd	17.50abc	17.50abc
Early|84P80|ISP	3.75ab	20.00ab	5.00b	1.25	10.00a	27.50abc	27.50abc	27.50abc
Early|84P80|IST|ISP	5.00a	32.50a	0.00b	0.00	7.50a	33.75ab	33.75ab	33.75ab
Early|84P80	1.25ab	18.75ab	91.25a	12.50	1.25a	38.75a	41.25a	41.25a
Late|83P17|ISP	0.00b	0.00b	15.00b	5.00	0.00a	0.00d	0.00c	0.00c
Late|83P17|IST|ISP	0.00b	0.00b	2.50b	5.00	0.00a	0.00d	0.00c	0.00c
Late|83P17	0.00b	0.00b	21.25b	12.50	0.00a	0.00d	2.50c	2.50c
Late|84P80|ISP	0.00b	1.25b	0.00b	7.50	0.00a	0.00d	0.00c	0.00c
Late|84P80|IST|ISP	0.00b	0.00b	16.25b	0.00	0.00a	0.00d	0.00c	0.00c
Late|84P80	0.00b	0.00b	27.50ab	6.25	0.00a	0.00d	0.00c	0.00c
F-statistic	2.93	4.54	4.06	1.44	2.49	7.17	6.79	6.79
df	11, 33	11, 33	11, 33	11, 33	11, 33	11, 33	11, 33	11, 33
P-value	0.0083	0.0003	0.0008	0.2034	0.0210	<0.0001	<0.0001	<0.0001

Column means followed by the same letter are not significantly different (LS means, p≤0.05)