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Evaluation of Management Strategies for the Headworm Complex in Grain Sorghum

Christopher Scott Dobbins

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Evaluation of management strategies for the headworm complex in grain sorghum

By

Christopher Scott Dobbins

A Thesis
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science
in Agricultural Life Sciences
in the Department of Biochemistry, Molecular Biology, Entomology and Plant Pathology

Mississippi State, Mississippi

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Evaluation of management strategies for the headworm complex in grain sorghum

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During 2013 and 2014, studies were conducted to determine the effects of
Helicoverpa zea and *Spodoptera frugiperda* on both damage and yield of *Sorghum
bicolor*. Results from damage ratings suggest that the amount of damage per single larva
decreases as population density increases. Also, yield results suggest that one *H. zea* and
one *S. frugiperda* larva per panicle results in a 3.6 and 4 percent yield loss, respectively.
Additionally, a dynamic EIL was determined using crop value along with various yield
potentials and control costs. Other research studies were conducted to determine the
efficacy of diamide and pyrethroid insecticides on headworms when applied at midge
timing for different locations and planting dates. Results suggest that diamides provide
longer and better control of headworms than do pyrethroids. However, applying diamides
as a preventative application at midge timing may not be economically feasible when
grain prices are low.

DEDICATION

First, I would like to dedicate this research to my beautiful wife, Bethany, for her patience, support, and endless love throughout the duration of this project. All of the effort spent to complete this degree was made in effort to provide a better life for us in the near future. Thanks for your encouragement and love along the way.

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A LITERATURE REVIEW OF GRAIN SORGHUM AND THE HEADWORM

COMPLEX COMMONLY ENCOUNTERED IN GRAIN SORGHUM

PRODUCTION SYSTEMS

Grain Sorghum

Grain sorghum, *Sorghum bicolor* L. Moench (Poales: Poaceae), is ranked fifth in

cereal crop production worldwide behind wheat, rice, maize, and barley (Soper et al.

2013). Historically, grain sorghum has been cultivated by approximately thirteen percent

of the farmers in the United States and is usually consumed locally, meaning that it has

not been a large part of international trade (Anderson and Martin 1949). Grain sorghum is

a globally important crop because of its high content of dietary proteins, carbohydrates,

and other nutrients (Dillon et al. 2007). In foreign continents, such as Africa and Asia,

grain sorghum is an important staple food, serving as a key source of energy, protein,

minerals, and vitamins (Satyaprasad and Udayini 2011). In the United States, grain

sorghum primarily serves as feed for cattle and poultry (Tuinstra et al. 1997). Grain

sorghum is adaptive to a wide range of environments and can grow under diverse

environmental conditions. It is typically a dryland crop with high yield potential,

expressing many mechanisms of drought tolerance (Kebede et al. 2001, Satyaprasad and

Udayini 2011). In spite of its adaptability, high yield potential, and excellent mechanism

of drought tolerance, grain sorghum is susceptible to numerous disease and insect pests

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(Satyaprasad and Udayini 2011). Disease and insect pests are both limiting factors that can cause plant stress, effectively reducing overall yield potential. Because each developmental stage is dependent on the previous stage, appropriate management procedures must be implemented in order to minimize plant stress during the growth and reproductive phases (Stichler et al. 1997). Management practices throughout the year will help determine the overall health and survival of the plant. Yield limitations may be addressed or avoided, by following guidelines developed by university research and extension agencies. The following review is a synopsis of grain sorghum including its history and common production practices used today. Additionally, a review of the headworm complex with current thresholds and management recommendations used in Mississippi along with goals and objectives of this research project are included.

Importance and Uses of Grain Sorghum

The United States led the world in grain sorghum production in 2014 at just over 10.9 million tonnes being produced (FAOSTAT 2015). Grain sorghum is the third-largest cereal grain produced in the United States (http://www.grains.org/buyingselling/sorghum, accessed March 3, 2016). In 2013, there were approximately 3.3 million hectares of grain sorghum planted in the United States, yielding ca. 9.9 billion kilograms of grain (USCP 2013). Of those 9.9 billion kilograms, 31% were consumed for ethanol production, 27% were fed to livestock, and 2% were used for human food. The remaining 40% of grain sorghum produced was exported. In 2013, U.S. grain sorghum was shipped to China in the first-ever bulk shipment of sorghum from the United States to China. This shipment was initiated by joint efforts of the United Sorghum Checkoff Program and the United States Grain Council (USCP 2013). Grain sorghum has gained momentum in new

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emerging markets including building products, foods, packing materials, and biofuel production (USCP 2013).

Sorghum has been used for molasses production, but it has also been commercially used as a sweetener in food products and liquid medications for humans (Sweet Sorghum Ethanol Association 2014). Sorghum has also been consumed by animals as a forage or silage crop for many years (Nuessly et al. 2013). More importantly, sorghum has become a suitable biofuel feedstock. The juice from harvested sweet sorghum stalks is being converted into ethanol using conventional fermentation technology (Nuessly et al. 2013). This type of ethanol is referred to as cellulosic ethanol, which is ethanol made from cellulose. Cellulose is a non-grain material or feedstock that provides the cellular structure for all plants (POET 2013). The Sorghum Checkoff Program is working with ethanol companies to help increase the number of sorghum acres planted in the United States and also add value of sorghum to the grower. The Sorghum Checkoff has also began work with POET (a refinery in Scotland, South Dakota) as an extensive effort to increase sorghum production. In 2013, $866,000,000 were generated by ethanol plants and twenty-four ethanol plants consumed sorghum at some level (USCP 2013). According to the Renewable Fuels Standard, an annual goal of 136.3 billion liters of renewable fuels has been set by 2022. Of these 136.3 billion liters produced, 60.6 billion will be produced from cellulosic ethanol (POET 2013).

Sorghum Growth and Development

The goal of domesticating grain sorghum was to change the small-seeded, shattering open panicles to larger, non-shattering seed with more compact panicles. This process involved several key factors including: an increase in number of branches within

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inflorescences, decrease of internode length of the rachis, and increase in seed size where it extended out of the glume. All of these modifications contributed to an increase in yield potential of sorghum varieties (Dillon et al. 2007). Plant growth and development of grain sorghum is mostly determined by temperature. However, growth and development may be impacted by cultural practices including fertility, row spacing and plant spacing as well as environmental conditions, insect pest management, and disease control. These management strategies may be implemented to minimize potential losses in yield.

Grain sorghum is primarily grown in low-rainfall environments because it is less prone to drought stress. Even though it can withstand stressful conditions, stress during certain stages of development may result in yield reductions (Stichler et al. 1997). 'Pre-anthesis' and 'post-anthesis' are two particular timings during development in which stress may negatively affect grain sorghum development. 'Pre- anthesis' is when plants are stressed during panicle differentiation prior to flowering and 'post-anthesis' is when moisture stress occurs during the grain fill stage of development.

Undomesticated *Sorghum* species have adapted to soil and moisture conditions and developed resistance to a number of pests and diseases that influence grain development (Dillon et al. 2007). Close to 75% of planted seed are expected to survive and produce emerged seedlings (Stichler et al. 1997). Survival may be affected by cool, wet soil at planting, crusting of soil surface, and herbicide injury (Gerik et al. 2003). Seeding rates vary based on environmental conditions, and may range from approximately 49,000 to 270,000 plants per hectare (Stichler et al. 1997). The minimum soil temperature for germination and emergence is 15.5 °C (Vanderlip 1993).

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Emergence (GS0) usually occurs 3 to 10 days after planting and is dependent on environmental conditions, disease, and insect pressure (Vanderlip 1993). Vegetative development continues for about three weeks after emergence (GS1 and GS2) (Vanderlip 1993). Growing point differentiation (GS3) occurs about 30 days after emergence, when the growing point changes from vegetative to reproductive growth (Vanderlip 1993). Growth stage 4 refers to the time when the flag leaf first emerges from the whorl and boot (GS5) is the time when the flag leaf collar becomes visible (Gerik et al. 2003). Boot is the stage where panicle development is completed and primed for flowering (Gerik et al. 2003). Moisture stress and herbicide injury during boot may prevent panicle exertion from the flag-leaf sheath (Vanderlip 1993). Grain formation begins at half-bloom (GS6) and marks the time when plant size, leaf area, or plant numbers can no longer be corrected (Vanderlip 1993). The soft-dough (GS7) stage occurs fifteen to twenty-five days after flowering when approximately fifty percent of the grain weight has accumulated (Gerik et al. 2003). Moisture stress after half-bloom and right before or at soft-dough can result in blasting and poor head filling (Vanderlip 1993). Hard-dough (GS8) is when seventy-five percent of the grain dry weight has accumulated. Moisture stress before the grain matures will result in light, chaffy grain (Vanderlip 1993). The grain is said to be physiologically mature (GS9) when a black-layer appears above the point of kernel attachment in the floret near the kernel base (Gerik et al. 2003). The time period between physiological maturity and when grain moisture is suitable for harvest will vary based on hybrid selection and weather conditions (Vanderlip 1993).

Cultural and Agronomic Practices of Grain Sorghum Production

Sorghum needs a warm, moist soil that is well supplied with air and fine enough to provide good seed-soil contact for rapid germination (Shroyer et al. 1998). The minimum soil temperature for germination and emergence is 15°C (Gerik et al. 2003). Seeding rates used in grain sorghum production are determined based on environmental conditions. Environmental conditions used to determine a desired plant population include moisture availability in the soil, average day/night time temperatures, and available water supply for a given area. A higher seeding rate may be applied when conditions are less favorable and irrigation is available. However, a lower seeding rate may be applied when conditions are less favorable and irrigation is not available, causing the plant to undergo stress. Seeding depth in sorghum is usually between 2.5 to 5 centimeters, depending on soil texture and moisture availability. Historically, 76.2 cm. rows are used when planting grain sorghum because they are more productive than wider rows and should develop canopy closure quicker, improving weed control and reducing soil erosion (Shroyer et al. 1998).

Soil erosion can be reduced through the implementation of a conservation tillage system. However, there are various other tillage and planting systems used to prepare seedbeds in grain sorghum production. Examples of tillage systems include reduced tillage, mulch-till, ecofallow (period of collecting rainfall on open ground), strip-till, ridge-till, zero-till, and no-till (USDA 2000). An ideal seedbed should effectively control weeds, preserve soil moisture, improve soil tilth, and prevent erosion while also being suitable for planting and cultivating with available equipment (Shroyer et al. 1998). As a result of implementing a reduced tillage system, it has been determined that as much or

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more grain can be produced when compared to grain sorghum grown in a conventional tillage system (Matocha 1990).

Weed management in grain sorghum is best achieved through crop rotation, proper tillage management and proper use and timing of herbicide applications. Using crop rotation as a means to vary the time when tillage and herbicide applications are made, weed pressure can be reduced allowing more favorable growing conditions resulting in potentially greater crop yields (Regehr 1998). Rotating soybeans with grain sorghum can increase grain yields due to increased moisture and nutrient availability along with improved quality of the soil (Kaye et al. 2007). In a tilled seedbed, field cultivation before planting will control weeds that have already emerged. In no-till seedbeds herbicides are generally used to control emerged weed seedlings (USDA 2000). Pre-emergence herbicides and post-emergence herbicides are different for each crop which allows the herbicides to effectively reduce weed populations present in the field (Regehr 1998).

Grain sorghum plants require various nutrients during different stages of growth and development. Nitrogen is most important, but is frequently lacking in sorghum production. Nitrogen is needed for chlorophyll and protein production, along with the formation of new plant cells (Stichler et al.1997, Whitney 1998). By rotating sorghum with soybeans, residual soil nitrogen can be increased in the soil (Kaye et al. 2007). Phosphorous, potassium, zinc, and iron are also important nutrients needed for sorghum production. Phosphorous deficiency along with drought can reduce plant growth and alter metabolic processes such as N metabolism (Al-Karaki et al. 1996). Potassium improves overall health of the plant and affects stalk strength or standability. Alone, potassium will

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not protect against stalk lodging but it is necessary for strong stalks (McClure 2014). Zinc is a nutrient that is a component of a variety of enzymes and also plays an important role in DNA and RNA metabolism (Mirshekali et al. 2012). Iron functions in supplying enough chlorophyll to promote the growth of new leaf tissue (Livingston et al. 1996). Sorghum fertility amendments may largely be determined by performing soil tests in order to determine the quantity and type of amendment needed for good crop yields. All soil nutrient requirements, except for nitrogen can be determined from analysis of soil samples.

Grain sorghum is the most drought-tolerant grain crop planted in Mississippi (Lewis 2012). The significant advantage of being drought-tolerant is adaptation to the location where grain sorghum is generally grown. In the United States, grain sorghum is predominately grown in the mid-western states that frequently experience periods of little to no rainfall. Because of sorghum's drought-tolerant reputation, it has become a choice of producers with limited to no available water supply (Rogers and Alam 1998). Lack of water or stress early in the season can affect head size and delay maturity, while stress later in the season can result in reduced seed size (Stichler et al. 1997). Although a large supply of water is not needed for sorghum growth and development, water deficit stress during certain stages of development can impact yield.

Pre-harvest desiccants are typically applied once grain has reached physiological maturity and moisture levels are between 25 and 35 percent. Diquat, sodium chlorate, urea ammonium nitrate (28% nitrogen), and glyphosate are all common desiccants of sorghum before harvest (Regehr 1998). Pre-harvest desiccants may take several days to weeks before results are ultimately achieved and there may be a preharvest interval until

the grain can be harvested due to specific regulations. Sorghum is usually harvested with a combine, when grain moisture levels are between 16 and 18 percent moisture to minimize harvest losses and lower drying expenses (Olson et al. 1959). Attempts at harvesting sorghum at moisture levels higher than 25 percent may result in unthreshed heads or cracked grain (Sumner 2012). Drying in a grain bin, is usually an alternative to minimize damage caused by birds and seed boring insects. Drying and cooling sorghum takes 30 to 50 percent longer than corn (Harner 1998), resulting in more fuel and electrical expenses. The optimum moisture content is 12 percent moisture, for long term storage of grain sorghum (Sumner 2012).

Integrated Pest Management in Grain Sorghum

Integrated pest management is a combination of biological, chemical, cultural, mechanical, and regulatory control used to effectively maintain pest populations below economically damaging levels. In this management philosophy, pesticides are only used when natural mortality agents are inadequate and the pest reaches a population sufficient enough to cause crop loss above treatment and external costs (Stern et al. 1959). Pesticide applications are kept at a minimum due to the adverse effects of pesticides leading to resistance, resurgence, and replacement of the pest (Dutcher 2007). Other risks associated with pesticides include the adverse effects on non-target species including natural enemies, bees and other pollinators, fish and wildlife along with the toxic hazard risks to humans. Common pest management strategies used in sorghum include: tillage, rotation, seedbed preparation, hybrid selection and seed treatments, planting dates, weed maintenance, scouting, economic thresholds, and harvesting at the proper time (Buntin

2012, Harris 2001). Management strategies vary by pest allowing different strategies to be used for a specific pest of interest.

In grain sorghum production, reduced tillage systems are a common practice of seedbed preparation. However, in some instances when below ground insect pests are present, a more conventional form of tillage may be implemented to reduce pest numbers. Crop rotation allows available resources in the soil to be effectively utilized while also minimizing weed, disease, and insect pressure. By rotating sorghum with soybeans and cotton, there has been a noticed ten to twenty percent increase in yield (msucares.com). Rotating sorghum with cotton has also shown to reduce corn earworm numbers below economically damaging levels, in turn minimizing insecticide applications (Chilcutt and Matocha 2007).

Hybrid selection is an important decision in sorghum production. Hybrids have been bred to adapt to specific insects, diseases, and weather conditions. When selecting a hybrid to plant, decisions should be based on adaptation to the environment, plant vigor, disease and insect resistance along with standability and yield potential (Buntin 2012). Seed treatments applied to hybrids serve as effective control options by minimizing soil, leaf, and stem feeding insects allowing seedlings to properly emerge. Common insects controlled by seed treatments include wireworms (Coleoptera: Elateridae), cutworms *Agrotis ipsilon* (Hufnagel)*, Lacinipolia renigera* (Stephens)*, Feltia jaculifera* (Guenée)*, Peridroma saucia* (Hübner); chinch bugs, *Blissus leucopterus leucopterus* (Say); aphids, *Rhopalosiphum maidis* (Fitch)*, Rhopalosiphum padi* (Linnaeus); and greenbugs *Schizaphis graminum* (Rondani) (Catchot et al. 2014).

A commonly used strategy for insect control in grain sorghum production throughout Mississippi, is the effective use of planting dates. In order to escape major insect pressure, sorghum should be planted so it is able to mature before heavy infestations occur (Buntin 2012). Planting dates are also dependent on several other factors including soil and air temperature, soil moisture, and future weather forecasts (Cothren et al. 2000).

The emergence, growth, and competition of weed species infesting sorghum varies greatly with geographic region. In sorghum, weeds compete for light, nutrients, and water ultimately reducing grain quality and yield along with raising production costs. In order to maximize yield, weeds must be properly controlled soon after emergence (Stahlman and Wicks 2000). Not only do weeds compete with plants, but they also serve as a host reservoir of many insects (Teetes and Pendleton 2000).

Scouting fields often and using economic thresholds are important practices used to effectively manage insect pests while minimizing input costs. According to Stern et al. (1959), an economic injury level represents the level of pest density accountable for a discrete amount of crop loss in order to justify costs of control. The economic threshold is somewhat lower than the economic injury level, allowing time for control measures to be taken before yield loss occurs. Economic thresholds are generally based on the number of insects per preferred scouting method. There are several types of scouting methods available, depending on the insect causing damage. Scouting for sorghum midge is usually performed by visually examining the sorghum panicle for the presence of adult midge (Catchot et al. 2014), while scouting sorghum for larvae of the headworm complex usually involves the use of a beat-bucket (Merchant and Teetes 1992).

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Harvesting at the proper time reduces the chance of insect and bird damage (Buntin 2012). In some instances, grain sorghum may be harvested at moisture levels closer to twenty percent to reduce the risks of damage caused by birds, insects, and environmental conditions. In order to store grain harvested at a high moisture content, the grain must be dried to a moisture content level near twelve percent (Sumner 2012). Although drying can be costly, it serves as a safe alternative compared to the potential damage caused by birds and insect pests (Harner 1998).

All of the management practices discussed above serve to be the foundation of integrated pest management in sorghum production. The core of integrated pest management is the combination of entomology, plant pathology, and weed science (Harris 2001). By using control guidelines produced by local University Extension Services, crop losses can be minimized. The key to integrated pest management is to effectively use biological control, cultural control, and host plant resistance methods to minimize exposure to insect pests and subsequent crop damage. Therefore, when these methods fail or are inadequate, insecticidal control is justified (Teetes 1981).

Commonly Encountered Insect Pests of Grain Sorghum

The most common insect pests that infest grain sorghum in Mississippi include: the sorghum midge, *Contarinia sorghicola* (Coquillett), the sugarcane aphid, *Melanaphis sacchari* (Zehntner), the fall armyworm, *Spodoptera frugiperda* (J. E. Smith), the corn earworm, *Helicoverpa zea* (Boddie), and the sorghum webworm, *Nola sorghiella* (Riley). Sorghum midge can only cause damage during bloom (Catchot 2015). Once bloom begins, panicles are at risks of being damaged by sorghum midge for the next four to nine days (Catchot 2015). Adult sorghum midge do not cause damage to grain sorghum, and

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are only used to determine the presence of the pests within the field (Catchot et al. 2015). Flowering grain sorghum is a preferred oviposition site of sorghum midge (Catchot et al. 2015). During the flowering period, female sorghum midge lay individual eggs between the glumes of a floret (Bohart and Koerber 1972, Catchot et al. 2015). As the eggs begin hatching, newly emerged larvae begin destroying the developing seed, resulting in blank or shriveled seed coats that often appear discolored (Catchot et al. 2015).

The sugarcane aphid is a newly invasive pest of grain sorghum in Mississippi. In 2013, the sugarcane aphid was only found in one county throughout the state. During 2014, the sugarcane aphid infested every county in Mississippi that grew grain sorghum (Catchot et al. 2015). Sugarcane aphids can cause panicles to not fully emerge during panicle emergence due to the presence of large amounts of honeydew secretions (Catchot et al. 2015). Honeydew produced by the pest has also been a problem during harvest, causing combine throats to choke up as the sticky residue is trying to feed through (Catchot et al. 2015).

The fall armyworm acts both as a direct pest and an indirect pest. As an indirect pest, fall armyworm larvae feed in the whorl of sorghum plants. As a direct pest, larvae feed directly on developing grain causing a reduction in yield. The corn earworm larvae have predominantly become the major pest of sorghum over the last few years due to developed resistance to several key insecticides (McCaffery 1998, Stadelbacher et al. 1990). Corn earworm larvae can feed on sorghum in the whorl stage, but are seldom reported. They do act as direct pests of sorghum by feeding on developing grain, resulting in a reduction of yield. The sorghum webworm is also a direct pest of sorghum, appearing more so in years when there is a lot of precipitation and humidity levels are

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high. Control of these pests is usually achieved through insecticide applications. Planting an early maturing variety at an early planting date is an effective way to minimize the risk of encountering economically damaging levels of fall armyworm, corn earworm, and sorghum webworm. Appropriate thresholds and management recommendations can be found in the Insect Control Guide provided by the Mississippi State University Extension Service (Catchot et al. 2014).

Corn Earworm, *Helicoverpa zea* (Boddie)

Corn earworm is in the order Lepidoptera and the family Noctuidae (ESA 2014 http://www.entsoc.org). Corn earworm was previously described in the genus *Heliothis*. In 1965, it was placed into a new genus, *Helicoverpa* because they lacked morphological similarity to that of *Heliothis dispacea* (Hardwick 1965). *H. zea* has a polyphagous feeding nature, meaning that it feeds on many different hosts (Fitt 1989). Due to its polyphagous nature, *H. zea* has several common names based on the crop that is infested. These include cotton, *Gossypium hirsutum* (L.)*,* corn, *Zea mays* (L.)*,* grain sorghum, *Sorghum bicolor* (L.)*,* soybeans, *Glycine max* (L.)*,* tomatoes, *Solanum lycopersicum* (L.). In order to control the corn earworm, the biology and ecology of the pest must be understood. Understanding how the corn earworm interacts with its environment is a necessity for developing control strategies.

Biology and Development

The corn earworm undergoes a holometabolous life cycle (egg > larva > pupa > adult) and may produce as many as six generations per year depending on host availability and weather conditions (Barber 1937). Eggs are deposited singly (Drees and

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Jackman 1999), most commonly on the leaves and fruiting structures of cultivated crops such as corn, cotton, and grain sorghum along with many other wild hosts including crimson clover (Stadelbacher 1981). Eggs are translucent white to yellowish-white when first deposited with a reddish band developing during incubation (Neunzig 1964), progressively turning yellow then grey in color (Capinera 2000). The eggs vary in shape from a dome shape to a flattened spherical shape. They range from 0.5 mm to 1.2 mm in diameter, and 0.5 mm in height. Fecundity ranges from 350 to 3000 eggs laid per female and it usually takes three to four days for the eggs to hatch (Capinera 2000, Teetes and Pendleton 2000).

Larvae vary both in size and color. Early instar larvae are a translucent, yellowish-white color (Neunzig 1964), while mature larvae may be pink, green, or yellow to almost black with conspicuous stripes running lengthwise of the body. A pale stripe is usually edged by a dark stripe (Teetes and Pendleton 2000). Corn earworm larvae are also easy to distinguish from other larval pests, due to their easily noticed orange head capsule (Capinera 2000). *H. zea* undergo six larval instars. From instar 1 to 6, head capsule widths typically range from 0.29 mm to 3.10 mm and lengths range from 1.5 mm to 24.8 mm (Capinera 2000). Fully grown larvae can be up to 55 mm in length under optimal conditions (Teetes and Pendleton 2000). Developmental times from the first instar stage to the sixth instar stage depend mainly on temperature and the host on which the larva is feeding, with an average developmental time of about 18 days before pupating in the soil (Drees and Jackman 1999).

Corn earworm larvae are known to be cannibalistic. The young larvae do not possess cannibalistic qualities, and are often found feeding together. On the other hand,

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larvae in the latter instar stages of development between the fourth and sixth instar are highly cannibalistic and become very aggressive feeders (Capinera 2000, Teetes et al. 1992). Because early instar larvae are not cannibalistic, it is not uncommon to see many feeding on a single sorghum panicle. As the larvae mature, the more aggressive behavior results in fewer larvae per individual panicle.

Pupae are mahogany brown in color, and are about 17 to 26 mm in length and 6 mm wide (Neunzig 1960, Capinera 2000). Pupation begins as mature larvae drop to the ground and burrow into the soil after leaving their feeding site and remain there for about 8-25 days before emergence (Capinera 2000, Drees and Jackman 1999).

The forewings of adults are yellowish brown in color with a small dark spot in the center and a distal transverse band. The hind wings are white at the base and black at the distal edges. Moths have a wingspan about 32 to 45 mm in width. On average, adult lifespan ranges from 5 to 15 days, with some moths surviving as long as 30 days under optimal conditions. Moths are mostly nocturnal, usually mating during the night (Capinera 2000). Females are able to mate several times during their life cycle, but only once each night (Raina et al. 1986). Only about 50-60% of females mate in nature (Callahan 1958). Females usually begin depositing eggs three days after emergence and continue for 8 to 10 days thereafter (Capinera 2000, Fitt 1989). Oviposition sites are selected to allow a nutritious food source for newly developing larvae (Stadelbacher 1980). Fecundity per female moth averages around 350 eggs (Capinera 2000), with as many as 35 eggs per day (Capinera 2000).

Host Range

The corn earworm has a wide geographic distribution, attacking many cultivated crops and wild hosts resulting in significant amounts of economic damage each year (Stadelbacher and Pfrimmer 1973). When infesting cotton, *H. zea* is referred to as the bollworm because of its feeding activity on developing cotton bolls. As a pest of corn and grain sorghum, *H. zea* is most commonly referred to as the corn earworm, but can also be labeled as the sorghum headworm when feeding on grain sorghum. Whereas, *H. zea* is referred to as the soybean podworm when infesting soybeans and the tomato fruit worm when infesting tomatoes (ESA 2014 http://www.entsoc.org).

The host range of the corn earworm, reflects a balance of offspring fitness and rapid host finding and oviposition by female adults, which may be favorable of a broader diet (Jaenike 1990). Because corn earworm overwinters as diapausing pupae in Mississippi, adult activity begins approximately 1.5 months before any cultivated crop host is available (Stadelbacher and Pfrimmer 1972). Therefore the overwintering adults and the F_1 larval progeny are dependent on the availability of wild hosts on which they fed (Stadelbacher 1980). Early spring and fall populations of the corn earworm are dependent on only a few major plant species (Roach 1975). Stadelbacher (1980), compiled a list of favorable early season hosts of the corn earworm in the Delta of Mississippi, including: *Trifolium incarnatum* L. (crimson clover), *Geranium disectum* L. (cut-leaved cranesbill), *G. carolinianum* L. (Carolina cranes's-bill), *Medicago lupulina* L. (black medic), and *Zea mays* (early tasseling field corn). Crimson clover is a preferred host of the corn earworm during mid-March (Stadelbacher 1980). Crimson clover is commonly included in seed mixtures planted alongside road right-of-ways and is

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believed to have a major role in the buildup of corn earworm populations (Fernald 1970). Both *Geranium disectum* and *carolinianum* become more attractive during early May, but large numbers of eggs are still deposited on nearly mature crimson clover. Black medic is most attractive during June, after the senescence of previously favored hosts and before corn becomes attractive (Stadelbacher 1980). Although large populations of corn earworms are present in corn, research suggests that sorghum can be responsible for development through mid-June, dependent on availability. As both corn and sorghum mature, the corn earworm moves into other crops such as cotton (Graham et al. 1972).

Oviposition

Host preference is limited to the available host population. Weather conditions in the spring accompanied by very cold temperatures may limit the emergence of wild host plants available for the buildup of the corn earworm populations. Wild hosts serve as an insecticide-free niche for the development of early season corn earworm populations (Neunzig 1963). Stadelbacher (1980) suggests that female corn earworm moths have the ability to select oviposition sites that are favorable for their progeny. As flowering crops begin to senesce, they become less favorable sites for oviposition (Johnson et al. 1975). Crimson clover has been found to be a primary wild host selected for oviposition before cultivated crops begin flowering. Grain sorghum and corn are both suitable hosts responsible for generation turnover of developing corn earworm larvae. Flowering grain sorghum is a preferred oviposition site of the corn earworm where larvae develop throughout the soft dough stage (Teetes et al. 1992). As corn begins silking, it becomes the most preferred host site selected by female moths. Archer and Bynum (1994) suggest oviposition is not limited to the period when silks are fresh as previously believed, but

continues throughout the late dough stage. After maturity of corn and sorghum, cotton becomes the primary host site for oviposition.

Corn Earworm as a Pest of Grain Sorghum

Corn earworm has been reported infesting sorghum as early as 1893, and has become a major pest of sorghum throughout the sorghum producing regions of the United States (Kring et al. 1989, Mally 1893, Steward et al. 1990, Young and Teetes 1977). Infestation level can vary by location and season depending on environmental conditions. Corn earworm is both a direct and indirect pest of grain sorghum and has become the most damaging lepidopteran pest in Mississippi due to control failures with pyrethroids over the past several years (Stadelbacher et al. 1990, McCaffery 1998).

Although known to feed on foliage during the whorl stage, the corn earworm predominately infests sorghum heads during the flowering period (Steward et al. 1990). Female moths oviposit just before and during the flowering period. This allows subsequent larval populations to begin feeding on developed kernels (Teetes et al. 1992). Early instar larvae usually hollow out the developing kernels, while late instar larvae completely consume seed during the milk and soft dough stages (Burkhardt 1957, Teetes et al. 1992). Feeding habits of corn earworm larvae on grain sorghum results in decreased germination of the seed and losses in weight or yield (Burkhardt 1957). Burkhardt (1955), found that heavy corn earworm infestations can result in 30 to 50 percent of the grain being destroyed.

Level of infestation can be a result of hybrid selection. Buckley and Burkhardt (1962), determined that the compactness of grain sorghum panicles influenced the severity of corn earworm infestation. They found that tight panicle hybrids had higher

populations of corn earworm larvae present along with more damaged kernels than open panicle hybrids (Buckley and Burkhardt 1962). In 1992, prior results were validated by Teetes et al. (1992) where higher numbers of eggs were found in the more compact panicle hybrids. They suggest that egg parasitism may be the reason that fewer eggs were found in the open type panicles. Most of the egg parasites found were of the genus *Trichogramma*, with a few being of the *Telenomus* (Teetes et al. 1992).

Diseases and cannibalism can also impact corn earworm larval densities. The *Heliothis* nuclear polyhedrosis virus is the predominant pathogenic disease among corn earworm on grain sorghum and it can reduce densities by eighty percent (Teetes et al. 1992). When higher populations of corn earworm larvae are present, cannibalism can be an important factor in regulating larval densities. Early instar larvae are not cannibalistic, allowing for large larval populations to develop. As larvae develop in size, cannibalism rates increase, resulting in fewer large larvae present per individual sorghum panicle (Teetes et al. 1992).

Fall Armyworm, *Spodoptera frugiperda* (J. E. Smith)

The fall armyworm, *Spodoptera frugiperda* (J. E. Smith), is a major pest of the Poaceae family throughout the eastern United States ranging as far west as the Rocky Mountains and as far north as southern Canada (Capinera 1999, Sparks 1979, Ashley et al. 1989). Early records show the presence of the fall armyworm as early as 1797 in Georgia (Smith and Abbott 1797). With over sixty host plants recognized, the fall armyworm prefers to feed on members of the grass family (Poaceae), if readily available. Members of the grass family that are most preferred include: bermudagrass, *Cynodon*

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dactylon (L.)*,* corn, *Zea mays* (L.), crabgrass, *Digitaria spp.* and grain sorghum, *Sorghum bicolor* (L.) (Luginbill 1928).

The fall armyworm lacks a diapause mechanism, and only survives the winter in tropical and subtropical regions where temperatures are rarely below 10°C (Sparks 1979). These regions include the southern tips of Florida and Texas in the U.S., extending as far south as Argentina in South America (Ashley et al. 1989). Because fall armyworms are strong fliers (Capinera 1999), they have the ability to reinvade the eastern United States rather quickly, with some flights covering as much as 482 km in a single generation (Ashley et al. 1989). The fall armyworm usually reaches the northern part of Mississippi during late-May to June, depending on temperature and weather conditions (Sparks 1979).

Biology and Development

The fall armyworm undergoes a holometabolous life cycle (egg > larvae > pupa > adult) with the number of generations per year being dependent on environmental conditions. Eggs are laid in masses, with a dense covering of grayish scales for protection (Sparks 1979). The eggs are dome shaped, up to 0.4 mm in diameter and 0.3 mm in height. Females usually deposit between 100 to 200 eggs per mass, averaging between 1500 to 2000 eggs per lifetime (Capinera 1999). Eclosion usually occurs in two to three days during optimal conditions (Capinera 1999, Sparks 1979). There are usually six instars with first instar larvae being approximately 1.7 mm in length and sixth instar larvae reaching 34.2 mm. Young larvae are usually green with a black head, and mature larvae are usually brown to black in color with white lines running lengthwise the body. Fall armyworm larvae lack microspines, and are most noted by the inverted white Y on

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the head capsule. The larval stage takes approximately two weeks to complete under optimal conditions, and a month during cooler weather conditions (Capinera 1999).

Pupation begins as the sixth instar larvae burrow into the soil. They usually dig about 1 to 3 inches deep depending on soil moisture, texture, and temperature (Sparks 1979). Pupae are reddish to brown in color, reaching as wide as 4.5 mm and as long as 18 mm. Pupae are not tolerant to lengthy periods of cold weather, and emergence is dependent on temperature (Capinera 1999). Pupal duration ranges from 7 to 37 days at soil temperatures ranging from 15 to 28.9°C (Vickery 1929).

The forewing of male moths is usually a shaded grayish, brown color with triangular white spots near the center and tips of the wing. Female's forewings are grayish brown and less distinctly marked than males. The hindwings of both sexes are characterized by a narrow dark border along the outer edge (Capinera 1999). Adults are nocturnal, and mating takes place shortly after sunset with specified times depending on age (Sparks 1979). Virgin female moths begin mating shortly after dark and can mate multiple times (Sparks 1979).

Host Range and Oviposition

The fall armyworm is a polyphagous feeder that attacks 50 non-economically and 30 economically important plants (Ashley 1979). Due to the wide range of hosts that fall armyworm larvae feed on, there are a great number of oviposition sites. Female moths are known to oviposit on a number of crop and non-crop hosts, including all plant parts, window panes, flags, and cars (Sparks 1979, Pitre et al. 1983). Because of their ability to select hosts for oviposition, more eggs are laid on corn and sorghum plants than any other plant species. More oviposition occurs on corn than sorghum, even when these crops are

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intercropped (Sifuentes 1967, Van Huis 1981). Although corn is the most preferred site of oviposition, fecundity is often reduced for females that fed on corn compared to those that fed on sorghum (Castro and Pitre 1988).

Fall Armyworm as a Pest of Grain Sorghum

In Mississippi, the fall armyworm is an occasional pest of later planted grain sorghum (Henderson et al. 1966, Wiseman et al. 1986). Fall armyworm larvae cause damage to grain sorghum during three different stages of development. During the first stage, fall armyworm larvae feed on newly emerged seedlings. The growing point is still below ground at this time and economic damage seldom occurs. The second stage when damage occurs is during the whorl-stage. In the whorl, fall armyworm larvae feed on the foliage, reducing the surface area of the leaf that is absorbing light. They also act by destroying the growing point, which prevents the plant from further growth. Heavy infestations during the whorl stage can increase tillering, decrease plant heights and reduce grain yields (Henderson et al. 1966, McMillian and Starks 1967, Starks and Burton 1979). The third stage that fall armyworm larvae can cause damage is during grain development. During grain development, larvae consume developing kernels of individual sorghum heads, resulting in a reduction in yield (Martin et al. 1980).

Fall armyworm larvae are not as cannibalistic as corn earworm larvae, therefore more larvae per individual sorghum panicle can be found (Teetes and Pendleton 2000). Because they are not as cannibalistic, large populations of large larvae are able to develop, resulting in severe yield loss if left untreated (Teetes and Pendleton 2000). Approximately 80 percent of the damage to the grain is usually by fifth and sixth-instar larvae (Teetes and Pendleton 2000). There are many parasitoids, pathogens, and fungi

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that can parasitize or reduce fall armyworm larval numbers. There are over fifty parasitoids attacking fall armyworm larvae including several wasps, flies, beetles, and bugs (Ashley 1979, Teetes and Pendleton 2000). The most abundant parasitoids observed on larvae from corn and sorghum include: *Anomalon marmoratus* (Townsend)*, Campoletis sonorensis* (Cameron)*, Chelonus insularis* Cresson*, Cotesia marginiventris* (Cresson), *Ophion flavidus* Brulle, and *Rogas laphyhmae* Viereck (Pair et al. 1986).

Sorghum Webworm, *Nola sorghiella* (Riley)

The sorghum webworm*, Nola sorghiella* (Riley), is an occasional pest of sorghum, usually during the late season in the southern United States and Central America (Teetes et al. 1983). Occurrence is more common during cooler, wet years (Flanders and Smith 2008). The sorghum webworm mainly feeds on members of the grass family, including sorghum, corn, rye, timothy-grass, Sudan grass, and Johnson grass (Reinhard 1937). The number of generations per year, along with the number of larval instars varies considerably with environmental conditions.

Biology and Development

The sorghum webworm undergoes a holometabolous life cycle (egg > larva > pupae > adult), and completes a generation in about a month, depending on weather conditions (Teetes et al. 1983). Unlike many other lepidopteron insects, sorghum webworms undergo diapause as fully grown larvae, rather than pupae, in plant stubble and debris (Flanders and Smith 2008). In the spring, the overwintering larvae pupate, emerge as adults, and begin a new life cycle (Teetes et al. 1983). Sorghum webworm eggs are white with a pale green tint when first deposited, becoming more of a yellowish

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brown color as embryonic development continues. Eggs are roundish to oval in shape becoming flattened dorsoventrally over time. Eggs are approximately 0.46 mm in diameter and 0.26 mm in height (Reinhard 1937, Teetes et al. 1983). Eclosion generally occurs in three to four days when temperatures are 26.7°C and above, taking up to five and six days at lower temperatures (Reinhard 1937).

The number of larval instar stages can vary depending on weather conditions and available nutrient supply. Most larvae are fully grown by the end of the fifth instar, but some are capable of seven total instars. Newly hatched larvae average 0.7 mm in length (Carter 1982).Later instar larvae range from 9 to 14 mm in length and up to 4 mm wide. Mature larvae appear flattened (Teetes et al. 1983). They are usually a greenish-tan color with four red to black longitudinal stripes running lengthwise the body (Reinhard 1937), and covered with spines and hairs (Teetes et al. 1983). Most larvae enter the prepupal stage during the fifth instar, when the larvae begin spinning a white silken cocoon (Reinhard 1937). They begin overwintering by leaving sorghum panicles and moving down the plant, where they pupate behind leaves and other structures (Reinhard 1937). They remain on these structures throughout the winter and early spring until the pupation process begins.

Pupation begins when daily temperatures average between 58 and 60°F. The time required for pupae to transform into adults varies considerably and is highly dependent on temperature and weather conditions (Reinhard 1937). Sorghum webworm pupae are reddish to brown in color with an average length of 8.5 mm and a width of 2 mm (Reinhard 1937). The average pupal duration is approximately 6 days (Teetes et al.

1983), ranging from 4.7 to 9.2 days during periods of extreme weather conditions (Reinhard 1937).

Adult moths are usually small and whitish in color with a wingspan of 12 to 16 mm (Teetes et al. 1983). The forewings are usually yellowish to brown in color, while the hind wings are mostly white (Reinhard 1937). Eggs are deposited singly on flowering parts or seeds of sorghum plants (Teetes et al. 1983). Laboratory experiments suggest that most female's lay approximately 170 eggs per lifetime, but field experiments suggest a greater number of eggs being laid per individual. The adult lifespan is about five days (Teetes et al. 1983), but under optimum conditions can be as long as twenty-three days (Reinhard 1937).

Host Range and Oviposition

The sorghum webworm is generally found feeding on hosts of the grass family. The most preferred hosts found in Mississippi are corn, sorghum, and Johnson-grass. Oviposition usually occurs at night and takes place within the first twenty-four hours after adult eclosion (Reinhard 1937).

Sorghum Webworm as a Pest of Grain Sorghum

Sorghum webworm larvae are more prevalent pests of grain sorghum during cool, wet growing seasons (Doering and Randolph 1960), with higher larval densities found in later planted grain sorghum (Kinzer and Henderson 1967, Hobbs et al. 1979). Young larvae begin feeding on developing floral parts, and continue feeding on the inside portion of developing seed throughout the hard dough stage of development (Reinhard 1937, Teetes et al. 1983). Mature sorghum webworm larvae are usually observed on

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sorghum during the milk and soft dough stages, where large infestations can result in up to 70 percent yield loss (Reinhard 1937).

Planting date and maturity are not the only factors that contribute to high populations of sorghum webworm larvae. Hobbs et al. (1979) determined that sorghum webworm larvae prefer more compact-panicle hybrids. Open-panicle hybrids are rarely damaged to the extent of the more compact-panicle hybrids (Young and Teetes 1977). Panicle architecture may play a key role in the survival of the sorghum webworm, as with corn earworm. In the open panicle types, there are larger populations of egg parasites (Teetes et al. 1992) and other parasitoids, which can ultimately reduce the number of larvae present. Sorghum webworms are less vulnerable than the corn earworm to predators (Kinzer and Henderson 1967), resulting in large infestations if not properly managed. The sorghum webworm has proven to be a destructive pest, but due to the limitations of its geographical ranges, there was little if any economic literature present prior to 1932 (Reinhard 1937).

Current Thresholds and Management Recommendations

In Mississippi, the sorghum headworm complex refers to the complex of the corn earworm, fall armyworm, and sorghum webworm (Catchot et al. 2014). These lepidopteron pests may occur alone or simultaneously. The corn earworm and the fall armyworm can be considered both direct and indirect pest. As indirect pests, corn earworm and fall armyworm larvae may be found feeding on sorghum in the whorl stage of development (Catchot et al. 2014). Of the two pests, the fall armyworm is more likely to be found during this time. As direct pests of sorghum, the corn earworm and fall armyworm larvae feed on developing kernels (Catchot et al. 2014). The sorghum

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webworm only acts as a direct pest by consuming the inner contents of developing kernels (Reinhard 1937, Teetes et al. 1983).

The threshold for the corn earworm and the fall armyworm during the whorl stage is 75 to 100 percent infestation of either species (Catchot et al. 2014). The threshold for the corn earworm and the fall armyworm found infesting panicles is 1 larva per panicle either alone or in combination (Catchot et al. 2014). The threshold is the same for both species because the economic impact of both species is similar (Teetes and Pendleton 2000). The economic impact of the sorghum webworm is much less than that of corn earworm and fall armyworm resulting in a threshold of 5 to 6 larvae per panicle (Catchot et al. 2014).

Insecticides labeled for control of the headworm complex include several pyrethroids, carbamates, diamides, insect growth regulators, and spinosyns (Catchot et al. 2014). Due to established resistance of the corn earworm to pyrethroids (Stadelbacher et al. 1990, Kanga et al. 1996), the diamide class of insecticides has become a more preferred option of control.

Preliminary efficacy studies conducted by the Mississippi State University Extension Service during 2012 indicated that yield loss occurred with corn earworm infestation levels below the current recommended threshold. Control also varied with some of the insecticides used. Therefore, the first two objectives of this project were to refine / validate the thresholds for both the corn earworm and fall armyworm larvae infesting reproductive stage grain sorghum. The third objective was to evaluate the impact of preventative insecticide applications made at early flowering against headworms. This timing coincides with insecticide applications for sorghum midge.

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CHAPTER II

THE EVALUATION OF THE CORN EARWORM (LEPIDOPTERA: NOCTUIDAE)

THRESHOLD ON REPRODUCTIVE STAGE GRAIN SORGHUM

Abstract

Research studies were conducted during 2013 and 2014 at Stoneville, MS to determine the impact of corn earworm on damage and yield of grain sorghum. Corn earworm larvae were infested at two plant densities and eight larval densities. Both damage ratings and yield data were collected. Data were analyzed using analysis of variance and regression analysis. Plant density had a significant effect on damage, but not on yield. One corn earworm larva per panicle caused an average of 6.05 and 7.05% damage, based on results from damage ratings for each plant density. Yield results suggested that one corn earworm larva per panicle consumed an average of 2.24 grams of grain, equivalent to a 3.6% yield loss. EIL's ranged from 0.41 to 1.54 larvae per panicle depending on control costs, crop value, and yield potential. ET's were set at 70% of each EIL, ranging from 0.29 to 1.08 larvae per panicle.

Introduction

The corn earworm, *Helicoverpa zea* (Boddie), is a common pest of grain sorghum, *Sorghum bicolor* L. Moench, ranging from an occasional pest to an annual pest depending on region (Buckley 1962, Young and Teetes 1977). In Mississippi, the corn earworm infests grain sorghum annually. Adults emerge from overwintering pupae and

become active approximately 1.5 months before any crop host is readily available (Stadelbacher 1972). Because of early emergence, adults and their progeny are dependent on wild hosts such as crimson clover, *Trifolium incarnatum* L., (Stadelbacher 1980). Crimson clover is often planted along roadside right-of-ways and plays a key role in the buildup of corn earworm populations before crop hosts become attractive (Fernald 1970). Not long after crimson clover senesces and other wild hosts become less attractive, corn begins silking and serves as the preferred host. As corn matures and grain sorghum begins flowering, grain sorghum becomes a preferred host for oviposition (Graham et al. 1972).

During the vegetative stages of grain sorghum, larvae feed in the whorl prior to emergence of the panicle and is thought to cause little to no yield loss (Kirk 1959). The greatest yield losses occur with infestations during the reproductive stage of development. First and second instar larvae consume the contents of developing kernels, while third through sixth instar larvae may completely consume the entire seed (Burkhardt 1957a). Larval feeding can result in reduced seed germination and can also lead to the development of mold throughout the grain sorghum panicle due to the accumulation of frass (Burkhardt 1957, Kirk 1959). Mold growth from frass accumulation can reduce grain quality and decrease the storage life of the grain.

Mally (1893) was one of the first to report corn earworm as a pest of grain sorghum. In the early 1900's, other researchers reported as many as eight to ten corn earworm larvae feeding together on a single panicle (Hayes 1922, Quaintance and Brues 1905). Yield reductions were not reported until 1942, when up to seventy-five percent yield loss from heavy corn earworm infestations was observed (Quinby and Gaines

1942). Literature discussing the economic impact of corn earworm larvae on grain sorghum was scarce until the mid to late 1950's. In 1955, researchers reported that twenty-five to thirty percent of grain sorghum kernels were damaged or destroyed by as many as sixteen corn earworms per panicle (Burkhardt and Breithaupt 1955). Additional research reported ten to twenty-five percent of grain being damaged or destroyed when panicles averaged one to two larvae per panicle. In the same studies, economically damaging levels of infestation were reached at two to three larvae per panicle (Burkhardt 1957a, 1957b).

Artificially infesting individual grain sorghum panicles with corn earworm larvae is a method of correlating pest damage with insect density (Buckley and Burkhardt 1962). Screen cages are used to isolate the larvae to a single panicle, reducing mortality caused by insect predators (Quinby and Gaines 1942) and to also protect grain sorghum panicles from potential bird damage (Buckley and Burkhardt 1962). Due to their cannibalistic nature, questions often arise when caging more than one corn earworm per individual grain sorghum panicle. Much of the literature on cannibalism is in reference to the corn earworm serving as a pest of corn. Young corn earworm larvae are not known to be cannibalistic and can be found feeding together at high densities (Capinera 2000). Larger larvae become more aggressive feeders and cannibalism is more common resulting in fewer larvae feeding within the same area (Capinera 2007). In grain sorghum cage studies, cannibalism by corn earworm has been reported as minimal, except for some sixth instar larvae congregated at the bottom of cages in an attempt to leave the panicle (Kinzer 1968).

While artificially infesting corn earworm larvae on different maturity levels of developing grain, Kinzer (1968) was able to establish feeding preferences of the corn earworm on grain sorghum. Results showed that most first and second instar larvae prefer feeding on flowering sorghum, while instars three through six prefer to feed on sorghum in the milk stage. Natural infestations of instars four through six fed on developing grain in the soft-dough stage and continued feeding throughout the hard-dough stage of development (Kinzer 1968). More precise data were collected by artificially infesting grain sorghum panicles with varying populations of corn earworm larvae. Results concluded that one corn earworm larva per panicle resulted in six percent damaged or destroyed kernels and that the number of kernels consumed by one corn earworm larva decreased as larval population increased (Buckley and Burkhardt 1962). Other artificial infestation trials showed that one corn earworm larva consumed 3.89 and 3.91 grams of grain resulting in yield losses of 3.22 and 4.25 percent, respectively (Kinzer 1968).

As a pest of grain sorghum, there is little to no information regarding the impact of corn earworm on grain sorghum yield in Mississippi. The current action threshold for the corn earworm feeding on grain sorghum panicles in Mississippi is one larva per panicle either alone or in combination with the fall armyworm, *Spodoptera frugiperda*, J.E. Smith (Catchot et al. 2014). Field efficacy trials with corn earworm larvae infesting reproductive stage grain sorghum were performed during 2012. Results indicated that significant yield losses occurred at pest densities approximately one half of the current recommended threshold (Catchot unpublished data). Those results suggest that further examination is needed to determine the economic impact of corn earworm larvae on grain

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sorghum yields. The objective of this research project was to refine or validate the threshold of corn earworm larvae feeding on reproductive stage grain sorghum.

Materials and Methods

Field Research

During 2013 and 2014, field cage experiments investigating the impact of corn earworm infestation density on damage and yield of grain sorghum were conducted at the Delta Research and Extension Center in Stoneville, MS. The hybrid DKS54-00 (semi-compact panicle) was planted at two plant populations on May 9, 2013 and May 2, 2014. All crop management practices were based on recommendations from the Mississippi State University Extension Service. Plots consisted of four rows (101.6-cm centers) in a randomized complete block design. Plots were 3.05 meters in length and separated by a 1.52 meter alley. Treatments were arranged as a split-plot with three replications in 2013 and four replications in 2014. Plant density was the main-plot factor and included densities of 123,500 or 197,600 plants/hectare. Level of infestation was the sub-plot factor. Eight levels of infestation ranging from zero larvae per panicle up to six larvae per panicle (0, 0.167, 0.25, 0.5, 1, 2, 4, and 6 larvae/panicle) were included. Treatments were assigned to plots according to randomly generated numbers produced using ARM 9 software (Gyling Data Management, Inc., Brookings, SD).

Larvae were infested on individual grain sorghum panicles during the late flowering to early milk stage of plant development. Because high mortality rates have been reported when using first instar larvae and because feeding by first instar larvae is minor (Kinzer 1968), second instar larvae were used to maximize survival. Larvae were placed on panicle branches and a 20 x 25 cm sleeve cage was carefully placed over the

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entire panicle and sealed at the bottom. Additionally, non-infested panicles were caged to serve as the control. Beginning at the time of infestation and continuing through the hard-dough stage of development, the outer rows of each plot were sampled several times each week to ensure no natural infestations of corn earworm larvae were present.

Grain sorghum panicles were hand harvested at maturity, using hand held garden shears. Panicles from each plot were cut 5 cm below the first panicle branch, placed in properly labeled paper bags, and transported to the laboratory for analysis. In the laboratory, infested panicles were visually examined and rated based on damage and presence of corn earworm frass. The damage rating scale ranged from 0 to 5, with 0 being no damage and 5 being greater than twenty percent damage (Table 2.1). Once all sorghum panicles were rated, the entire panicle (including the main stem and panicle branches) was weighed and recorded. After panicle weights were recorded, the seed were removed from the panicle branches. After all seed had been removed from each panicle, weights of grain and stems were determined. Because of variation in panicle sizes, the data were corrected by standardizing grain weights based on average panicle size. For each panicle, grain weight was divided by the stem weight which resulted in grams of grain per gram of stem. The grams of grain per gram of stem were averaged for each infestation level to develop the mean number of grams of grain per gram of stem for each level of infestation. Mean grain weight per weight of stem for each plot was multiplied by the average stem weight of all panicles within the study to obtain the corrected yield (g) of each panicle for each level of infestation (plot).

Source Colony

Corn earworm larvae used in the artificial infestations were F_1 or F_2 progeny of larvae collected on senescing crimson clover located south of Vicksburg, MS on U.S. Highway 61 or from larvae collected from early planted sweet corn, *Zea mays* at the Delta Research and Extension Center (DREC) in Stoneville, MS. Larvae collected from crimson clover were collected along roadside right-of-ways using a 38-cm sweep net (BioQuip Products, Rancho Dominguez, CA). To minimize larval injury, sweeps were reduced to 10 sweeps per sample. Larvae collected from each sample were placed in individual 29.6 ml cups filled with meridic diet (Heliothis Premix, Ward's Natural Science Company). Larvae collected from sweet corn were collected by gently pulling the corn husk back and removing larvae using forceps and carefully placing them in individual 29.6 ml cups filled with meridic diet. Immediately after collection, larvae were placed in a chilled cooler to avoid exposure to heat and sunlight, and transported to the insectary located at the Delta Research and Extension Center. All collections were held in the laboratory for a minimum of one generation to eliminate parasitoids and pathogens and to generate sufficient larval numbers of the proper growth stage needed for the artificial infestations. In the laboratory, larvae were fed meridic diet in individual 29.6 ml plastic cups with matching lids and maintained at 27±2°C with a relative humidity of 80% and a 14:10 hour (day: night) cycle until pupation. Pupae were placed into 3.79 L cylindrical cardboard containers (50 pupae/container) with vermiculite and maintained at 27±2°C. Once adult eclosion occurred, adults were fed a 10% sugar water solution in 29.6 ml plastic cups with absorbent wadding (cotton balls). Rearing containers were covered with a single layer of cotton gauze along the top, providing a substrate for oviposition.

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Egg sheets were changed daily and placed into a 3.79 L plastic bag and maintained in a growth chamber at 27±2ºC. Upon eclosion, neonate larvae were placed on meridic diet until they reached second instar.

Data Analysis

Damage ratings and yield data were analyzed with a general linear mixed model analysis of variance (PROC GLIMMIX, Little et al. 1996). Plant density, infestation level, and their interactions were considered fixed effects in the model. Random effects consisted of year, replication nested within year, and replication by plant density nested within year. Degrees of freedom were estimated using the Kenward-Roger method. Based on the overall analysis of variance, regression analyses (PROC GLIMMIX, Little et al. 1996) were conducted on fixed effects that were significant. Both linear and quadratic relationships were tested to determine the best fit of the model. Estimates from the regression analysis on yield and other economic factors were used in a mathematical model to calculate an economic injury level for corn earworm in grain sorghum. The mathematical model, EIL = C/VIDK developed by Pedigo et al. (1986) was used to determine the economic injury level. In this model, C = management costs per unit of production, V = current market value per unit of production, I = injury per pest equivalent, D = damage per unit injury, and K = proportionate reduction in pest density with the management tactic applied (Pedigo et al. 1986). Pest densities calculated using this model are important in determining the economic impact of a single corn earworm larva on grain sorghum yield. Economic injury levels of corn earworm larvae on grain sorghum panicles were calculated for a range of control costs (C = $15, $25, $35, $40 /

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ha) and yield potentials (5000, 6000, 7000 kg/ha). Values describing V ($0.16 per kg.), I (1 larva), D (3.6%), and K (90% control) all remained constant in these calculations.

Results and Discussion

Larvae were successfully established in these experiments and differences in damage ratings and grain weights were observed among infestation levels. For damage ratings, the interaction between plant density and infestation level was significant ($F = 2.25$; df = 7, 133; $P = 0.03$). Because there was a significant interaction between plant density and infestation level, the relationships between infestation level and damage rating were analyzed separately with regression analysis based on plant density. There was a significant quadratic relationship between level of infestation and damage ratings at the 123,500 plants per hectare level of plant density [$F = 9.1$; df = 1, 70.2; $P < 0.01$; $y = -0.08 (\pm 0.03)x^2 + 0.97 (\pm 0.16)x + 0.32 (\pm 0.17)$] (Fig 2.1). There was also a significant quadratic relationship between level of infestation and damage ratings at 197,600 plants per hectare level of plant density [$F = 43.3$; df = 1, 72.1; $P < 0.01$; $y = -0.14 (\pm 0.14)x^2 + 1.33 (\pm 0.13)x + 0.22 (\pm 0.19)$] (Fig 2.2). Where x is the number of larvae per panicle and y is the damage rating per panicle, one corn earworm larva per panicle caused an average of 6.05 and 7.05 percent damage at plant densities of 123,500 and 197,600 plants per hectare, respectively. Because the relationship was quadratic, these data suggests that the amount of damage caused by an individual larva decreased as infestation level increased. This is similar to what was observed by Buckley and Burkhardt (1962), where more grain was consumed per larva at lower larval densities and is probably a result of cannibalism at the higher densities (Capinera 2007).

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For corrected grain weight, the interaction between plant density and infestation level was not significant ($F = 0.51$; df = 7, 128.9; $P = 0.83$). There was a significant main effect for plant density ($F = 11.64$; df = 1, 5.026; $P = 0.02$) and infestation level ($F = 5.10$; df = 7, 128.9; $P < 0.01$). Mean grain weights of plants harvested from plots of higher plant densities averaged less than those of plants harvested from plots of lower plant densities (data not shown). Differences in mean grain weights per plant for the two plant densities were most likely a result of plants competing for available resources. Although there were differences in grain weights between the two plant densities, yield loss from larval feeding appeared to be similar. Because there was no interaction between level of infestation and plant density, data were combined across plant densities to increase the number of replications in the regression analysis. There was a significant linear relationship between infestation level and grain weight per panicle ($F = 16.60$; df = 1, 149.7; $P < 0.01$). Based on the regression equation [$y = -2.24 (\pm0.55)x + 62.61 (\pm3.78)$], as level of infestation increased by one larva per panicle, grain yield decreased by 2.24 grams (Fig. 2.3). This equates to a 3.6% decrease in yield for each increase of one corn earworm larva per grain sorghum panicle, which is similar to that observed in previous studies (Kinzer 1968). However, the amount of grain consumed by one larva was lower than that previously observed (Kinzer 1968).

Results from the regression analysis for yield were used to determine the economic injury levels for corn earworm larvae infesting grain sorghum panicles for a range of control costs and yield potentials. Economic injury levels are difficult to accurately define because commodity prices fluctuate regularly, costs of control change based on management decisions, and yield potential often changes. In a high value (7000

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kg/ha) and low cost ($15/ha) situation the economic injury level is 0.41 larva per panicle (Table 2.2). In a low value (5000 kg/ha) and high cost ($35/ha) situation the economic injury level is 1.35 larvae per panicle (Table 2.2). When a low value (5000 kg/ha) and low cost ($15/ha) situation is expected the economic injury level is 0.58 larva per panicle (Table 2.2). Economic thresholds were developed for management purposes. Economic thresholds are usually set somewhere below the economic injury level to allow enough time to make an application before pest densities reach the economic injury level (Stern et al. 1959). In this study, economic thresholds were set at seventy percent of the economic injury level to provide a sufficient amount of time for an insecticide application before corn earworm densities reach the economic injury level.

In Mississippi, pyrethroid resistance has led to an increase in control costs (Stadelbacher 1990, McCaffery 1998). Current control costs for corn earworm in grain sorghum are approximately $40/ha (Falconer et al. 2015). Also, average yields have ranged from 5000 to 6000 kg/ha during the years of this study. With insect control costs at $40/ha and yield potential at 5000 kg/ha, the economic injury level for corn earworm is 1.54 larvae per panicle with an economic threshold of 1.08 (Table 2.2). Using the same control costs and a yield potential of 6000 kg/ha, the economic injury level is 1.29 larvae per panicle with an economic threshold of 0.90 (Table 2.2). These demonstrate that using a more comprehensive economic threshold for corn earworm that incorporates crop value, yield potential, and costs of control included in grain sorghum production would provide an economic advantage to producers.

Table 2.1   Damage rating scale used to determine the amount of damage caused by corn earworm larvae to grain sorghum panicles.

Rating	Percent Damage
0	No damage
1	0 – 5 % damage
2	6 – 10 % damage
3	11 – 15 % damage
4	16 – 20 % damage
5	> 20 % damage

Table 2.2   Economic injury levels (EIL = C / VIDK) for corn earworm larva infesting reproductive stage grain sorghum. (V = $0.16 * Yield Potential, I = 1 larva, D = 3.6%, K = 90%)

Cost of Control ($/ha)	Yield Potential (kg / ha)		
	5000	**6000**	**7000**
	Larvae / Panicle		
$15.00	0.58	0.48	0.41
$25.00	0.96	0.80	0.69
$35.00	1.35	1.13	0.96
$40.00	1.54	1.29	1.10

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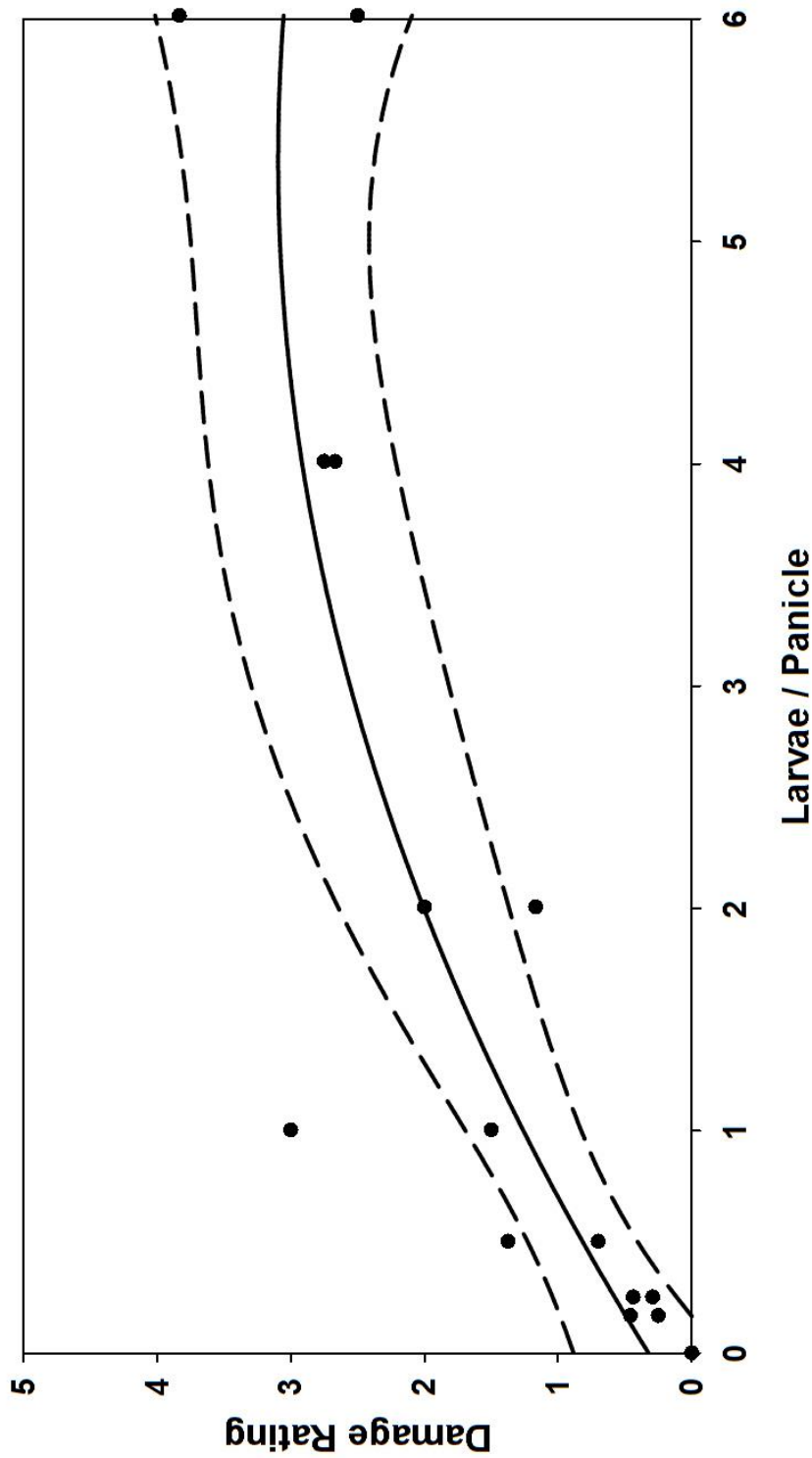
Figure 2.1   Relationship between *H. zea* level of infestation and damage ratings for individual grain sorghum panicles at 123,500 plants per hectare averaged across 2013 and 2014 in Stoneville, MS.

For graphical purposes, the mean damage rating (across replications) for each year are plotted. Dashed lines represent upper and lower 95% confidence limits. [$y = -0.08(\pm0.03)x^2 + 0.97(\pm0.16)x + 0.32(\pm0.17)$]

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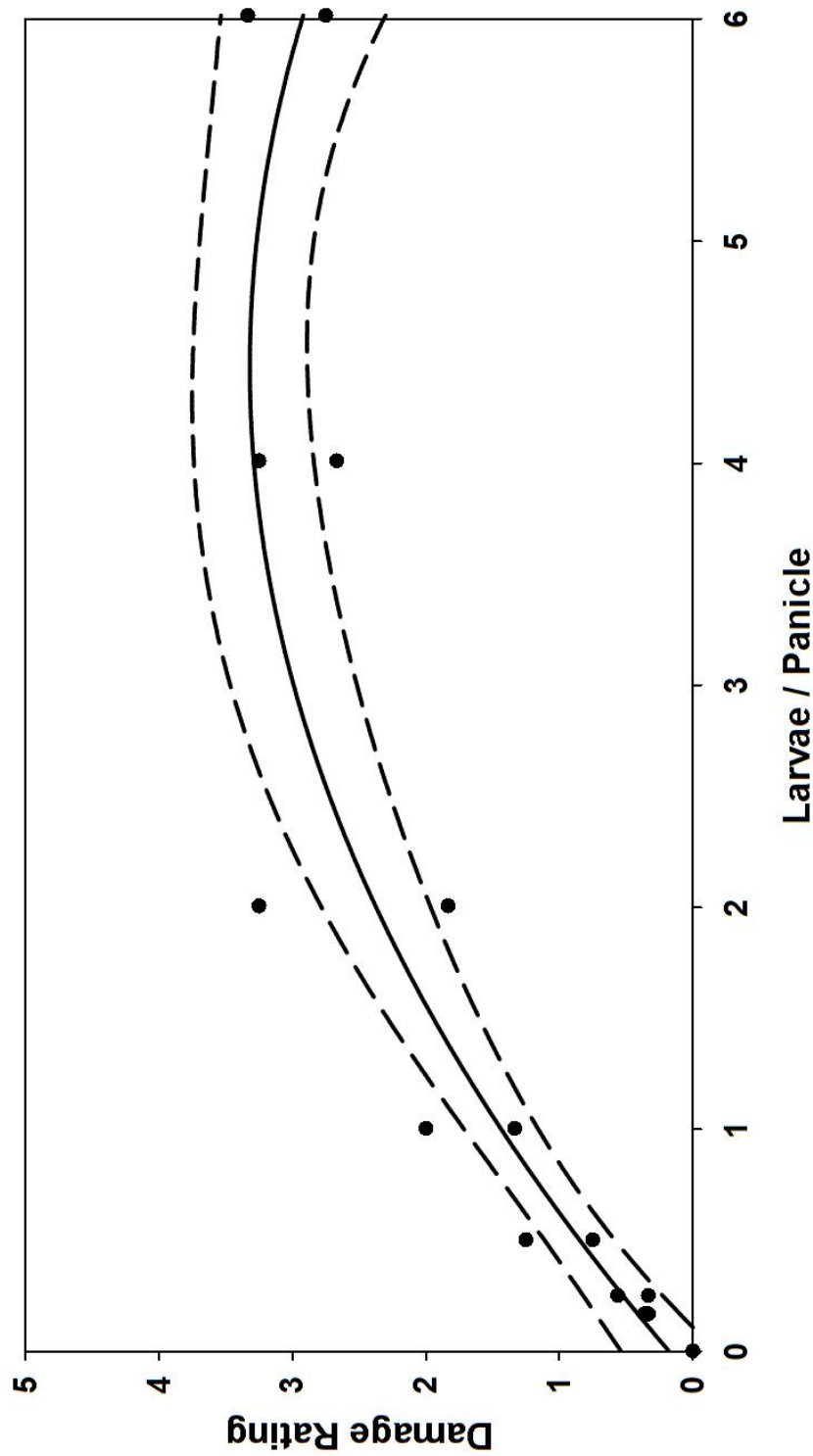
Figure 2.2   Relationship between *H. zea* level of infestation and damage ratings for individual grain sorghum panicles at 197, 600 plants per hectare averaged across 2013 and 2014 in Stoneville, MS.

For graphical purposes, the mean damage rating (across replications) for each year are plotted. Dashed lines represent upper and lower 95% confidence limits. [$y = -0.14(\pm0.14)x^2 + 1.33(\pm0.13)x + 0.22(\pm0.19)$]
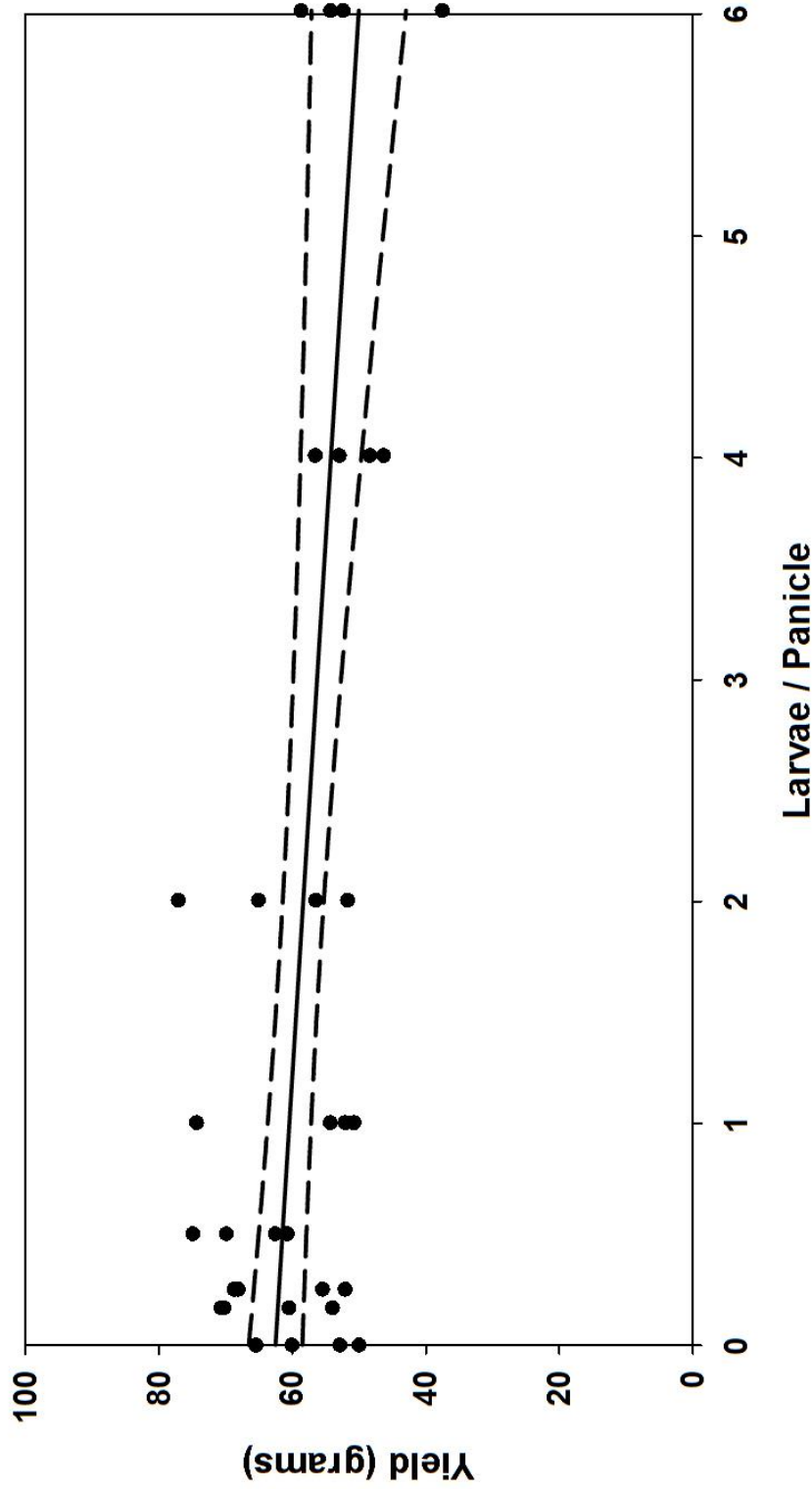
Figure 2.3   Relationship between *H.zea* level of infestation and corrected grain weights from cage studies on individual grain sorghum panicles averaged across 2013 and 2014 at Stoneville, MS.

For graphical purposes, the mean yield (across replications) for each level of plant density for each year is plotted. Dashed lines represent upper and lower 95% confidence limits. [$y = -2.24(\pm 0.55)x + 62.61(\pm 3.78)$]

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CHAPTER III

THE EVALUATION OF THE FALL ARMYWORM (LEPIDOPTERA: NOCTUIDAE)

THRESHOLD ON REPRODUCTIVE STAGE GRAIN SORGHUM

Abstract

Research studies were conducted during 2013 and 2014 at Stoneville, MS to determine the impact of fall armyworm on both damage and yield of grain sorghum. Fall armyworm larvae were infested at eight larval densities. Both damage ratings and yield data were collected. Data were analyzed using analysis of variance and regression analysis. One fall armyworm larva per individual grain sorghum panicle caused an average of 5.3% damage, based on results from damage ratings. Yield results suggested that one fall armyworm larva per individual grain sorghum panicle consumed an average of 2.37 grams of grain, equivalent to a 4% yield loss. Economic injury levels (EIL) ranged from 0.37 to 1.39 fall armyworm larvae per panicle depending on control costs, crop value, and yield potential. Economic thresholds (ET) were set at 70% of each EIL, ranging from 0.26 to 0.97 fall armyworm larvae per panicle.

Introduction

In Mississippi, the fall armyworm, *Spodoptera frugiperda* (J. E. Smith), is considered an economic pest of grain sorghum, especially at later planting dates (Wiseman et al. 1986, Henderson et al. 1966). Due to the lack of diapause mechanisms, fall armyworm can only survive winter in tropical and subtropical regions of the United

States where temperatures rarely fall below 10ºC (Starks an Burton 1979). These regions include the southern tips of Florida and Texas (Ashley et al. 1989). With no diapause mechanism, fall armyworm has to make lengthy flights each year to reinvade more northern environments, with flights covering as much as 480 km in a single generation (Ashley et al. 1989). The fall armyworm does not generally reach the northern part of Mississippi until late-May to June, with exact timings being dependent upon temperature and weather conditions (Starks and Burton 1979).

Fall armyworm larvae can cause damage to grain sorghum during three different stages of plant growth and development. These include the seedling, vegetative, and reproductive stages. Fall armyworm larvae cause damage to seedling plants by damaging or destroying meristematic tissue, resulting in reduced plant stand or a modified plant architecture (Buntin 1986). During the vegetative stage, fall armyworm larvae reduce the photosynthetic area of the plant by consuming portions of the leaf, indirectly affecting yield (Buntin 1986). Damage at this time can also increase tillering and decrease plant heights (Henderson et al. 1966, McMillian and Starks 1967, Starks and Burton 1979). However, during the reproductive stage, fall armyworm larvae cause direct damage to developing grain sorghum plants, by consuming varying portions of grain, resulting in reduced yield (Martin et al. 1980, Buntin 1986).

Cannibalism by fall armyworm is less prevalent than that of corn earworm (Teetes and Pendleton 2000). Cannibalism is low among younger larvae but increases as larvae become larger (Chapman et al. 1999). Cannibalism also increases with density, resulting in fewer larvae feeding within close proximity of one another (Raffa 1987). However, an increase in larval density per individual panicle can result in severe yield loss if treatment

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is not applied (Teetes and Pendleton 2000). As much as eighty percent of the total amount of damage to grain sorghum panicles is a result of direct feeding by fourth, fifth, and sixth instar larvae (Teetes and Pendleton 2000).

Fall armyworm larvae are also highly polyphagous, with greater than thirty economically important plant hosts (Ashley 1979). Despite their polyphagous feeding nature, fall armyworm larvae most often prefer to feed on members of the grass family (Luginbill 1928). Preference to grasses results in more oviposition on corn and grain sorghum in comparison to other crop hosts (Luginbill 1928, Pitre et al. 1983).

Two host strains of fall armyworm occur in the southern United States (Pashley 1986) and reproductive isolating mechanisms and incompatibility exist between the two strains (Pashley and Martin 1987 and Pashley et al. 1992). The host strains are identified according to host feeding preferences (Adamczyk et al. 1997). The "corn strain" larvae prefer feeding on corn, cotton, and sorghum, and the "rice strain" larvae are associated with rice and forage grasses (Meagher et al. 2011). Both strains are morphologically identical, but can be differentiated using molecular markers (Hardke et al. 2015, Nagoshi and Meagher 2008). Being able to identify the two strains is important from an insect management standpoint.

Initial research suggested that susceptibility to insecticides varied among larvae feeding on different host plants (Bishara et al. 1974, Refai et al. 1979, Wieb and Radcliffe 1973, and Wood et al. 1981). However, no differences in susceptibility to insecticides were observed when fall armyworm larvae fed on different hosts (Roberts 1965, Teotia and Gupta 1970, and Wood et al. 1981). More recently, researchers have found that insecticide susceptibility could be associated with host specific strains of fall

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armyworms (Adamczyk et al. 1997). Adamczyk et al. (1997) performed bioassay experiments to determine LD$_{50}$ values. Those findings suggest that the grass strain is up to 50 times more susceptible to pyrethroids than the corn strain. As a result, the consensus is that differences in insecticide susceptibility are due to the host specific strains.

Fall armyworm resistance to insecticides (carbamates) was first reported by Young and McMillian (1979). Wood et al. (1981) also suggested that fall armyworm showed the greatest amount of resistance to carbamates. These authors also reported resistance of up to 17-fold to pyrethroids when field strains were compared to laboratory strains. More recent studies conducted by Yu (1991) suggest that pyrethroid resistance ranges from 2- to 16-fold depending on the insecticide used. Established resistance to several key insecticides has resulted in control failures. Effective management strategies with insecticide applications are dependent on knowing which strain is present. Fall armyworm larvae of the rice (grass) strain are more susceptible to many key insecticides, than are fall armyworm larvae of the corn strain (Adamczyk et al. 1997).

Most of the research on fall armyworm infesting grain sorghum has focused on the vegetative stage (Luginbill 1928, Starks and Burton 1979). Literature relating to the economic impact of fall armyworm on reproductive stage grain sorghum is limited (Buntin 1986). Fall armyworm damage to reproductive stage grain sorghum is considered to be similar to that of corn earworm (Teetes and Pendleton 2000). As a result, thresholds for fall armyworm in reproductive stage grain sorghum are based on research with corn earworm.

Considerable research has been conducted on reproductive stage grain sorghum to determine the impact of corn earworm on grain sorghum yield (Quinby and Gaines 1942, Burkhardt and Breithaupt 1955, Burkhardt 1957a, 1957b, Buckley and Burkhardt 1962, Kinzer 1968). Results from artificial infestations in reproductive stage grain sorghum determined that one corn earworm larva causes as much as six percent damage and that the amount of grain consumed by one larva decreases as larval density increases (Buckley and Burkhardt 1962). Results from two similar studies determined that one corn earworm larva consumes 3.89 and 3.91 grams of grain, reducing yield by 3.22 and 4.25 percent, respectively (Kinzer 1968).

In Mississippi, the current action threshold for both the corn earworm and the fall armyworm is one larva per panicle, either alone or in combination. To address the lack of information on fall armyworm, artificial infestation trials were developed to refine and validate the threshold for fall armyworm infesting reproductive stage grain sorghum. The main objective of this research was to provide information on the economic impact of the fall armyworm as a pest of reproductive stage grain sorghum.

Materials and Methods

Field Research

During 2013 and 2014, field cage experiments were conducted to determine the impact of fall armyworm infestation density on damage and yields of grain sorghum. The hybrid DKS54-00 (semi-compact panicle) was planted at a seeding rate of 123,500 seed/ha on May 9, 2013 and May 2, 2014 at the Delta Research and Extension Center in Stoneville, MS. All crop management practices were based on recommendations from the Mississippi State University Extension Service. Plots consisted of four rows (101.6-cm

centers) that were 3.05 meters in length separated by a 1.52 meter alley. Treatments were assigned to plots according to randomly generated numbers produced using ARM 9 software (Gyling Data Management, Inc., Brookings, SD). Treatments consisted of eight levels of infestation ranging from zero larva per panicle up to six larvae per panicle (0, 0.167, 0.25, 0.5, 1, 2, 4, and 6 larvae/ panicle). Treatments were arranged in a randomized complete block design with five replications in 2013 and three replications in 2014. The number of replications were reduced in 2014 due to an insufficient number of fall armyworms.

Due to the lack of informative literature and similar feeding habits of fall armyworm larvae, infestations were conducted based on procedures used in corn earworm larval infestations. In order to maximize larval survival (Kinzer 1968), only second instar larvae were infested. Larvae were infested on individual grain sorghum panicles during the late flowering to early milk stage of development. During infestation, larvae were placed on panicle branches and a 20 x 25 cm sleeve cage was carefully placed over the entire panicle and sealed at the bottom. Additionally, non-infested panicles were caged to serve as the control. Beginning at the time of infestation and continuing through the hard-dough stage of development, the outer two rows were sampled bi-weekly to ensure that no natural infestations of fall armyworm larvae were present.

Grain sorghum panicles were hand harvested at maturity, using hand held garden shears. Panicles from each plot were cut 5-cm below the first panicle branch, placed in properly labeled paper bags, and transported to the laboratory for analysis. In the laboratory, infested panicles were visually examined and rated based on damage and

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presence of fall armyworm frass. The damage rating scale ranged from 0 to 5, with 0 being no damage and 5 being greater than twenty percent damage (Table 3.1). Once all sorghum panicles were rated, the entire panicle (including main stem and panicle branches) was weighed and recorded. After all panicle weights were recorded, the seed were removed from panicle branches. After all seed had been removed from each panicle, weights of grain and stems were determined. Because of variation in panicle sizes, the data were corrected by standardizing grain weights based on the average panicle size. For each panicle, grain weight was divided by the stem weight which resulted in grams of grain per gram of stem. The grams of grain per gram of stem were averaged for each infestation level to develop the mean number of grams of grain per gram of stem for each level of infestation. Mean grain weight per weight of stem for each plot was multiplied by the average stem weight of all panicles within the study to obtain the corrected yield (g) of each panicle for each level of infestation (plot).

Source Colony

Fall armyworm larvae used in the artificial infestations were F_1 or F_2 progeny of larvae collected on whorl-stage grain sorghum at the Delta Research and Extension Center (DREC) in Stoneville, MS. At the time of collection, larvae were placed in individual 29.6 ml plastic cups (with matching lids) that were filled with meridic diet (Heliothis Premix, Ward's Natural Science Company) and transported to the insectary located at the Delta Research and Extension Center. In the insectary, larvae were left in the plastic cups and maintained at 27±2ºC, 80% relative humidity, and a 14:10 hour (day: night) cycle until pupation. Pupae were placed in 3.79 L cylindrical cardboard containers (50 pupae/container) with vermiculite and maintained at 27±2ºC. Once adult eclosion

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occurred, moths were fed a 10% sugar water solution in 29.6 ml plastic cups with absorbent wadding (cotton balls). Rearing containers were covered with a single layer of cotton gauze along the top, providing a substrate for oviposition. Egg sheets were changed daily and placed into a 3.79 L plastic bag and maintained in a growth chamber at 27±2ºC. Upon eclosion, neonate larvae were placed on meridic diet until they reached second instar.

Data Analysis

The relationships between level of infestation and injury ratings, and level of infestation and yield were determined using regression analysis (PROC GLIMMIX, Little et al. 1996). Level of infestation was considered a fixed effect in the model. Year and replication nested within year were considered random effects in the model and served as the error term for level of infestation. Degrees of freedom were estimated using the Kenward-Roger method. Both linear and quadratic relationships were tested to determine the best fit of the model.

Results from the regression analysis on yield along with other economic factors were combined and used in a mathematical model (Pedigo et al. 1986) to calculate the economic injury level for fall armyworm on grain sorghum panicles. . This model is set on the idea that economic injury level = C/VIDK. In this model, C = management costs per unit of production, V = the current market per unit of production, I = injury per pest equivalent, D = damage per unit injury, and K = proportionate reduction in pest density with management tactic applied (Pedigo et al. 1986). This estimates a pest density that has an economic impact on grain sorghum yield. Economic injury levels of fall armyworm larvae on grain sorghum panicles were calculated for a range of control costs

(C = \$15, \$25, \$35, \$40 / ha) and yield potentials (5000, 6000, 7000 kg/ha). Values describing V (\$0.16 per kg.), I (1 larva), D (4%) and K (90% control) all remained constant in the calculations. A few scenarios are presented to describe how the economic injury level changes under different circumstances.

Results and Discussion

A significant quadratic relationship was observed between level of infestation and damage rating [$F = 26.33$; df = 1, 59; $P < 0.01$; y = -0.08 (±0.02)x^2 + 0.97 (±0.10)x + 0.17 (±0.08)] (Fig. 3.1). Based on the regression equation, one fall armyworm larva per panicle caused an average of 5.3 percent damage. Results from the regression analysis suggest that the amount of damage per larva decreased as level of infestation increased. These results are similar to results observed for corn earworm in chapter 2 and also result from prior literature (Buckley and Burkhardt 1962).

There was a significant linear relationship between level of infestation and yield ($F = 13.76$; df = 1, 59; $P < 0.01$). Results from the regression equation [y = - 2.37 (±0.64) + 59.60 (±3.28)], demonstrated that as level of infestation (x) increased by one larva per panicle, yield (y) per panicle decreased by 2.37 grams (Fig. 3.2). This equates to a 4% decrease in yield for each increase in one fall armyworm larva per grain sorghum panicle. The percent yield loss determined in this experiment is similar to that reported by Kinzer (1968) for corn earworm (3.22 – 4.25%) and also that determined in chapter 2 (3.6%), but the amount of grain consumed by one larva (2.37 g) was lower than what Kinzer (1968) observed with corn earworm (3.89 – 3.91 g).

Results from the regression analysis for yield were used to determine the economic injury levels for fall armyworm larvae infesting grain sorghum panicles for a

range of control costs and yield potentials. Economic injury levels are difficult to adequately define because commodity prices fluctuate regularly, costs of control changes based on management decisions, and yield potential often changes. In a high value (7000 kg/ha) and low cost ($15/ha) situation the economic injury level is 0.37 larva per panicle (Table 3.2). In a low value (5000 kg/ha) and high cost ($35/ha) situation the economic injury level is 1.22 larvae per panicle (Table 3.2). When a low value (5000 kg/ha) and low cost ($15/ha) situation is expected, the economic injury level is 0.52 larva per panicle (Table 3.2).

Economic thresholds were developed for management purposes. Economic thresholds are usually set somewhere below the economic injury level to allow enough time to make an application before pest densities reach the economic injury level. In this study, economic thresholds were set at seventy percent of the economic injury level to provide a sufficient amount of time for an insecticide application before fall armyworm densities reach the economic injury level.

In Mississippi, resistance to several key insecticides has led to an increase in control costs (Stadelbacher 1990, McCaffery 1998). Because corn earworm and fall armyworm are treated one in the same, control costs are equal. Current control of these pests in grain sorghum is approximately $40/ha or more (Falconer et al. 2015). Average grain sorghum yields in Mississippi range anywhere from 5000 to 6000 kg/ha each year. With insect control costs at $40/ha and yield potential at 5000 kg/ha, the economic injury level of fall armyworm larvae is 1.39 larvae per panicle with an economic threshold of 0.97 (Table 3.2). When yield potential is 6000 kg/ha, the economic injury level is 1.16 larvae per panicle with an economic threshold of 0.81 (Table 3.2). As discussed in

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chapter 2, these data also demonstrate that using a more comprehensive economic

threshold for fall armyworm that incorporates crop value, yield potential, and costs of

control included in grain sorghum production would provide an economic advantage to

producers.

Table 3.1   Damage rating scale used to determine the amount of damage caused by
            fall armyworm larvae to grain sorghum panicles.

Rating	Percent Damage
0	No damage
1	0 – 5 % damage
2	6 – 10 % damage
3	11 – 15 % damage
4	16 – 20 % damage
5	> 20 % damage

Table 3.2   Economic injury levels (EIL = C / VIDK) for fall armyworm larva
            infesting reproductive stage grain sorghum. (V = $0.16 * Yield Potential, I
            = 1 larva, D = 4%, K = 90%)

Cost of Control	Yield Potential (kg / ha)		
	5000	6000	7000
($/ha)	Larvae / Panicle		
$15.00	0.52	0.43	0.37
$25.00	0.87	0.72	0.62
$35.00	1.22	1.01	0.87
$40.00	1.39	1.16	0.99

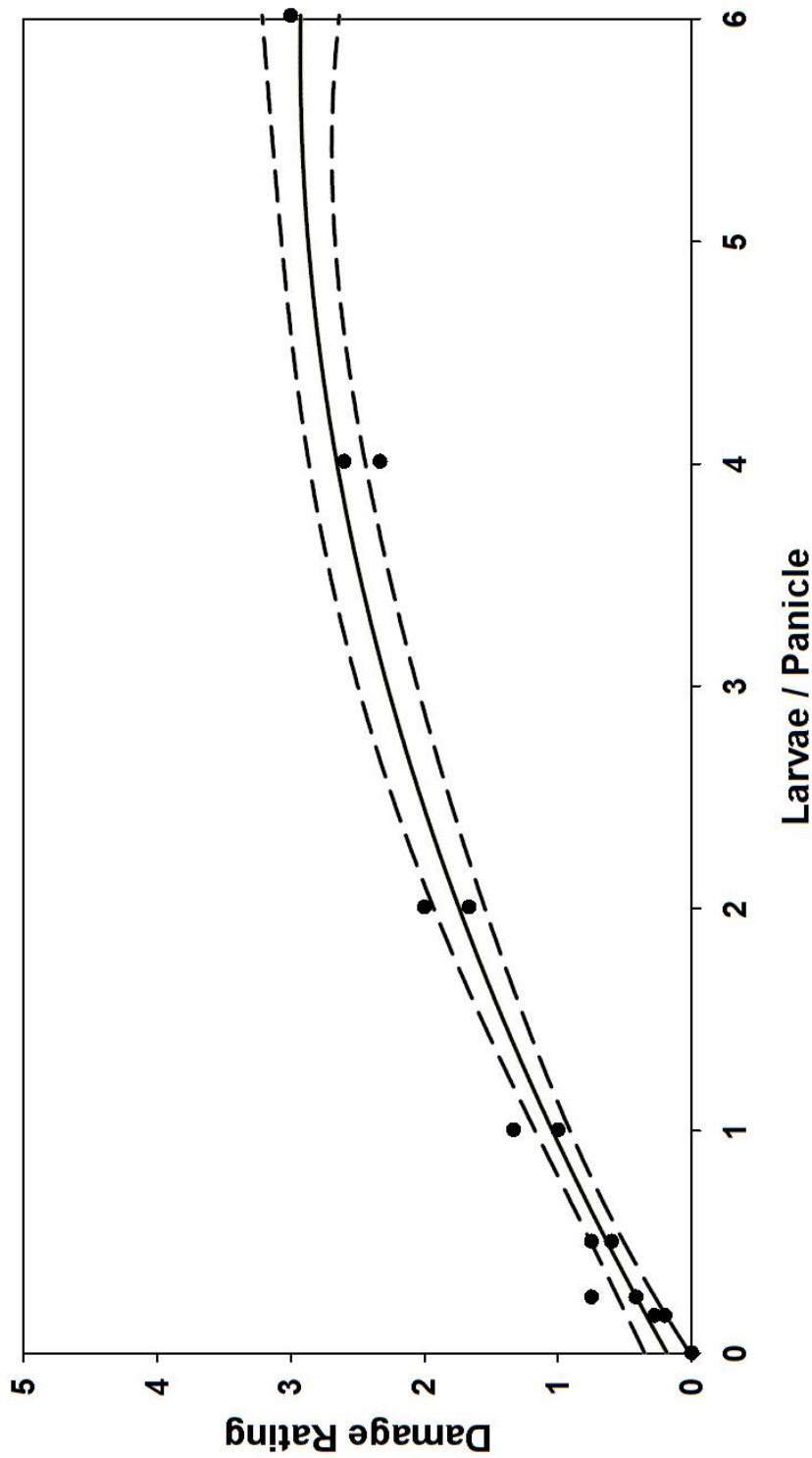Figure 3.1   Relationship between *S. frugiperda* level of infestation and damage ratings for individual grain sorghum panicles averaged across 2013 and 2014 in Stoneville, MS.

For graphical purposes, the mean damage rating (across replications) for each year are plotted. Dashed lines represent upper and lower 95% confidence limits. [$y = -0.08(\pm0.02)x^2 + 0.97(\pm0.10)x + 0.17(\pm0.08)$]

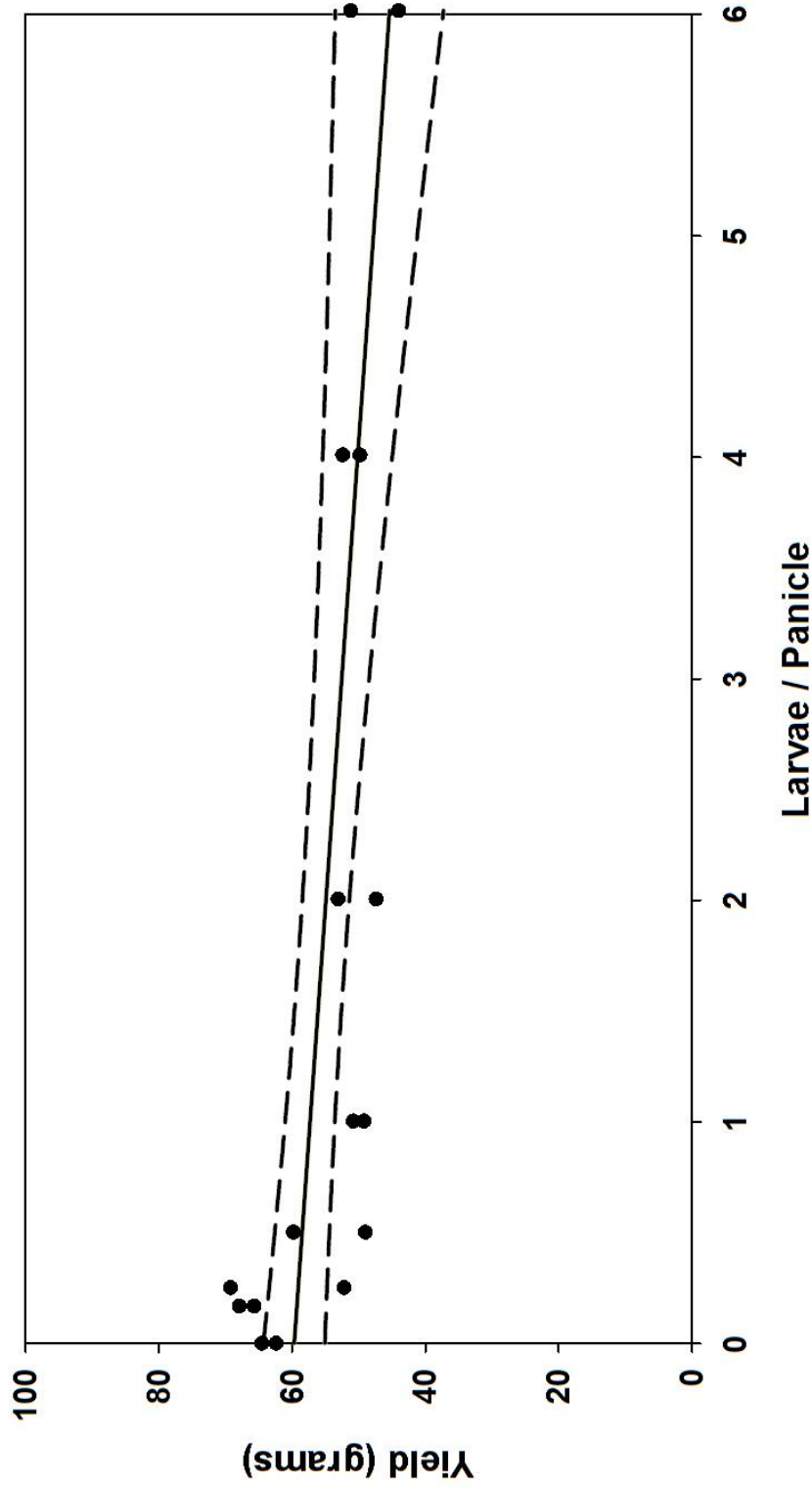Figure 3.2   Relationship between *S. frugiperda* level of infestation and corrected grain weights from cage studies on individual grain sorghum panicles averaged across 2013 and 2014 at Stoneville, MS.

For graphical purposes, the mean yield (across replications) for each year is plotted. Dashed lines represent upper and lower 95% confidence limits. [$y = -2.37(\pm0.64)x + 59.60(\pm3.28)$]

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CHAPTER IV

THE IMPACT OF PREVENTATIVE INSECTICIDE APPLICATIONS MADE AT

EARLY FLOWERING AGAINST HEADWORMS

Abstract

Research studies were conducted in the delta and hills regions of Mississippi during 2013 and 2014 to determine the impact of preventative insecticide applications made at early flowering on the headworm complex. Grain sorghum was planted early and late to determine the efficacy of insecticides when pest pressure is both low and high. Diamide and pyrethroid insecticides were evaluated based on headworm control. Diamides provided excellent control with long residual activity. However, results show that applying diamide insecticides as a preventative measure of control is not economically feasible when pest densities are low.

Introduction

Grain sorghum, *Sorghum bicolor* (L.) Moench, is a crop with high yield potential under suitable growing conditions (Satyaprasad and Udayini 2011). Yield reductions most often occur when proper management practices are not followed. Globally, grain sorghum production is affected each year by damage caused from insect pests (Dillon et al. 2007). In the U.S., producers spend an average of $80 million each year on insect control costs alone (Soper et al. 2013). Both direct and indirect damage from insect pests can negatively affect grain sorghum production. Indirect pests are a lesser problem in

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Mississippi production due to the efficacy and systemic activity of neonicotinoid insecticide seed treatments (Furlan and Kreutzweiser 2015). Direct pests that are routinely encountered include sorghum midge, *Contarinia sorghicola* (Coquillett), corn earworm, *Helicoverpa zea* (Boddie), fall armyworm, *Spodoptera frugiperda* (J. E. Smith), and sorghum webworm, *Nola sorghiella* (Riley). Corn earworm, fall armyworm, and sorghum webworm larvae are commonly referred to as the headworm complex because they usually occur simultaneously on grain sorghum panicles. Of the headworm complex, corn earworm larvae cause the most damage each year in the southern U.S. Their polyphagous feeding nature, wide geographic range, and ability to adapt to diverse cropping systems has led to them being one of the world's most significant crop pests (McCaffery 1998).

Control failures are a result of corn earworm having developed resistance to most of the insecticides that have been used for their control (McCaffery 1998). Pyrethroid insecticides were first introduced in the United States in 1978 and were widely used for control of lepidopteran insect pests in cotton (McCaffery 1998). Resistance of corn earworm to pyrethroid insecticides has been widely documented (Brown 1987, Stadelbacher et al. 1990, Kanga et al. 1996, Jacobson et al. 2009). Pyrethroid resistance has caused an increase in insect control and increased the cost of grain sorghum production. Pyrethroid insecticides were once a preferred option for insect control in grain sorghum (Catchot et al. 2015), with multiple applications typically being made throughout the growing season. The first application was made at flowering to control sorghum midge (Doering and Randolph 1963), and at least one follow-up application was made to control headworms. A single application was less than twelve dollars per hectare

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on average, leaving producers with low out of pocket expenses for insect control even in years of heavy worm infestations. Resistance to pyrethroid insecticides has resulted in fewer effective products and higher insect control costs.

Pyrethroid resistance has led to the registration and use of several novel insecticides for headworm control. Newer products used in grain sorghum include the diamides, insect growth regulators, and spinosyns. Chlorantraniliprole (Prevathon®, DuPont Crop Protection, Wilmington, DE) and flubendiamide are newly developed insecticides for use in a wide range of crops to control Lepidoptera, some Coleoptera, Diptera, and Isoptera species (Bassi et al. 2009). Chlorantraniliprole and flubendiamide belong to the diamide class of insecticides. Both of these insecticides have a similar, yet novel mode of action (Bassi et al. 2009, Tohnishi et al. 2010). They activate ryanodine receptors, stimulating the release and depletion of intracellular calcium stores from the sarcoplasmic reticulum of muscle cells. This results in impaired muscle regulation, paralysis, and eventually death of sensitive species (Bassi et al. 2009). The diamides provide consistent performance and long lasting crop protection (Bassi et al. 2009) and have been found to be 50-fold more active against *S. frugiperda* than the pyrethroid cypermethrin (Cordova et al. 2005).

The diamide insecticides provide effective control of numerous lepidopteran pests in soybean and vegetable crops such as tomato (Roditakis et al. 2015, Sridhar and Sharma 2015). They provide long residual activity at relatively low use rates compared with other classes of insecticides. The diamides are formulated either alone or as a pre-mix with a pyrethroid. Companies are recommending application of the pre-mixed formulation for both sorghum midge and headworm control. Both of these insecticides are marketed as

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preventative applications at flowering to provide enough residual control to protect grain from headworms until harvest. Producers have started using the pre-mix formulation to save money on overall application costs by eliminating a trip across the field. In years of heavy infestation, this can be a profitable management decision. In low pressure years, producers may actually spend more money on chemical application costs than needed.

Although, the diamide insecticides provide long residual control in other crops, little information exists about their effectiveness in grain sorghum. Using an application timing that coincides with treating sorghum midge, the objective of this research project was to determine the effects of a preventative insecticide application made at early flowering on the headworm complex.

Materials and Methods

Experiments were conducted in grain sorghum during the summers of 2013 and 2014 at two different regions in Mississippi. They included the delta region and the hills region of the state. Experiments in the delta region were conducted at the Delta Research and Extension Center located in Stoneville, MS. Experiments in the hills region were conducted at the R.R. Foil Plant Science Research Center in Starkville, MS and the Black Belt Branch Experiment Station located in Brooksville, MS. The DEKALB® grain sorghum hybrid DKS51-01 (Monsanto Company, St Louis, MO) was planted at an early and late timing in the delta and only an early timing in the hills. For timings, mid-May was considered early and mid-June was considered late. All plots were managed based on management recommendations provided by the Mississippi State University Extension Service. Experiments included six treatments that were arranged in a randomized complete block design. Treatments included beta-cyfluthrin (Baythroid® XL, Bayer

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CropScience, Research Triangle Park, NC) at 11.4 g ai per ha, flubendiamide (Belt®) at 70.1 g ai per ha, chlorantraniliprole + lambda cyhalothrin pre-mix (Besiege®, Syngenta Crop Protection, Greensboro, NC) at 51.2 g ai + 25.6 g ai per ha, lambda-cyhalothrin (Karate® Z, Syngenta Crop Protection, Greensboro, NC) at 25.9 g ai per ha, chlorantraniliprole (Prevathon®) at 52.7 g ai per ha, and an untreated control. Treatments were automatically applied at 25% bloom, the stage recommended for sorghum midge control. Treatments were applied using a John-Deere® 6000 high clearance sprayer at 8.05 km/hour with an application rate of 93.49 L per hectare (40 psi) using TXVS-10 hollow cone nozzles.

Plots were sampled using a beat-bucket at 6 to 10, 12 to 16, and 18 to 24 days after treatment. The center two rows of each plot were sampled by shaking 20 panicles per plot into the bucket. Corn earworm, fall armyworm, and sorghum webworm larval counts were recorded separately for each plot on each sampling date. Because larval numbers were low, counts from all three species were combined together and expressed as headworms. Because the economic injury level for sorghum webworm is five times higher than the economic threshold for corn earworm and fall armyworm (Catchot et al. 2014), the number of sorghum webworm larvae collected was divided by five to standardize larval counts for injury potential.

At the end of the season, the center two rows of each plot were harvested with a small-scale research combine (Kincaid® 8-XP; Kincaid Equipment Manufacturing, Haven, KS). The combine was equipped with a scale and moisture meter (Juniper® Systems & Harvestmaster, Logan, UT) to record grain weight and moisture content. Yields from each plot were converted to kg per ha and converted to 12% moisture.

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Data Analysis

Over the course of a two year period, ten total trials were conducted Six trials were planted in 2013 and four trials were planted in 2014. In 2013, two were planted early in the hills, three were planted early in the delta, and one was planted late in the delta. In 2014, one was planted early in the hills, one was planted early in the delta, and two were planted late in the delta. In the trials planted in the hills region, larval densities were measured for all three trials at 6 to 10 and 12 to 16 days after treatment. Larval densities were not measured at 18 to 24 days after treatment because larvae had pupated. Yields from all three trials in the hills region were measured.

In the trials planted early in the delta region, larval densities were measured at 6 to 10 and 12 to 16 days after treatment in four trials and 18 to 24 days after treatment in only two trials because larvae had pupated. Yield data were measured in all four trials planted early in the delta region. Yield data from one trial was not included in the statistical analysis because significant bird damage was observed.

In the trials planted late in the delta region, larval densities were measured for all three trials at 6 to 10, 12 to 16 days, and 18 to 24 days after treatment. Yield data were measured in all three trials planted late in the delta region. Two were removed from statistical analysis because significant bird damage was observed in one and mechanical harvesting errors occurred in the other.

Larval densities were log transformed prior to statistical analyses because of unequal variances among treatments. Larval densities and yield data were analyzed using a mixed model analysis of variance (Proc MIXED, Littell et al. 1996) by region and planting date. Data from each planting date within each region were analyzed separately

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because the data were unbalanced. Treatment was considered a fixed effect in the model. Sample timing was not included as a fixed effect in the model because some trials were not evaluated at all timings as described above. As a result, insect data were analyzed by sample timing. Year, year by trial, and replication nested within year by trial were considered random effects in the model. Degrees of freedom were estimated using the Kenward-Roger method. Mean separation was determined using least significant differences (Fisher's Protected LSD) of the mean with $P < 0.05$.

Results

Delta Region – Early Planting Date

Overall pest pressure was low throughout the duration of these experiments, with larval numbers nearing threshold in the untreated plots only on one occasion. Insecticide treatment had a significant effect on the number of larvae per panicle at 6 to 10 days ($F = 67.90$; df = 5, 135; $P < 0.01$), 12 to 16 days ($F = 7.87$; df = 5, 99.9; $P < 0.01$), and at 18 to 24 days ($F = 3.16$; df = 5, 35; $P = 0.02$) after treatment. All of the insecticides reduced the number of larvae per panicle compared to the untreated control at 6 to 10 days after treatment (Fig. 4.1). Plots treated with chlorantraniliprole + lambda-cyhalothrin (Besiege[®]) and chlorantraniliprole (Prevathon[®]) had fewer larvae than plots treated with lambda-cyhalothrin (Karate[®] Z). Plots sprayed with treatments that included chlorantraniliprole (Besiege[®] and Prevathon[®]) had fewer larvae than the untreated control at 12 to 16 days (Fig. 4.2) and 18 to 24 days (Fig 4.3) after treatment. Plots sprayed with flubendiamide (Belt[®]) had larval densities lower than the untreated control at 12 to 16 days after treatment (Fig. 4.2), but not at 18 to 24 days after treatment (Fig. 4.3).

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Insecticide treatment had a significant effect on grain sorghum yields ($F = 2.63$; df = 5, 60.7; $P = 0.03$). Plots treated with chlorantraniliprole only (Prevathon®) and flubendiamide (Belt®) resulted in grain yields greater than the untreated control (Fig. 4.4). No other treatment resulted in grain yields that were different than the untreated control and no differences were observed among treatments.

Delta Region – Late Planting Date

Overall pest pressure was higher in these experiments, with larval numbers ≥ 1.5 times the threshold in the untreated plots on one occasion. Insecticide treatment had a significant effect on the number of larvae per panicle at 6 to 10 days ($F = 11.53$; df = 5, 55; $P < 0.01$), 12 to 16 days ($F = 41.19$; df = 5, 55; $P < 0.01$), and at 18 to 24 days ($F = 4.66$; df = 5, 55; $P < 0.01$) after treatment. All of the insecticides reduced the number of larvae per panicle compared to the untreated control at 6 to 10 days after treatment (Fig. 4.5). No differences were observed among insecticides at 6 to 10 days after treatment. All treatments reduced larval densities relative to the untreated control at 12 to 16 days (Fig. 4.6). Differences were observed among treatments at 12 to 16 days after treatment with chlorantraniliprole (Prevathon®), chlorantraniliprole plus lambda-cyhalothrin (Besiege®), and flubendiamide (Belt®) resulting in lower larval densities than lambda-cyhalothrin and beta-cyfluthrin. Chlorantraniliprole (Prevathon®), chlorantraniliprole plus lambda-cyhalothrin (Besiege®), and flubendiamide (Belt®) treatments also reduced larval densities relative to the untreated control at 18 to 24 days after treatment (Fig. 4.7). Differences were observed among treatments at 18 to 24 days after treatment. Plots treated with chlorantraniliprole (Prevathon®) and chlorantraniliprole plus lambda-

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cyhalothrin (Besiege®) had lower larval densities than plots treated with lambda-cyhalothrin or beta-cyfluthrin.

Insecticide treatment had a significant effect on grain sorghum yields ($F = 7.95$; df = 5, 15; $P < 0.01$). All treatments resulted in grain yields greater than the untreated control (Fig. 4.8). Differences in yield were not observed among treatments.

Hills Region – Early Planting Date

Overall pest pressure in the hills was lower than that observed in the delta. Larval densities peaked at just over half the threshold of one per panicle. Insecticide treatment had a significant effect on the number of larvae per panicle at 6 to 10 days ($F = 16.66$; df = 5, 60.4; $P < 0.01$) and 12 to 16 days ($F = 6.04$; df = 5, 65; $P < 0.01$) after treatment. All of the insecticides reduced the number of larvae per panicle compared to the untreated control at 6 to 10 days after treatment (Fig. 4.9). Plots treated with chlorantraniliprole (Prevathon®) had significantly fewer larvae than plots treated with lambda-cyhalothrin (Karate® Z), however no differences were observed among other insecticides at 6 to 10 days after treatment. All treatments, except for lambda-cyhalothrin (Karate®), reduced larval densities relative to the untreated control at 12 to 16 days after treatment (Fig. 4.10). Plots treated with chlorantraniliprole (Prevathon®) resulted in grain yields greater than all others except those treated with lambda-cyhalothrin (Karate®). No significant differences in yield were observed among any other treatment ($F = 3.07$; df = 5, 55; $P = 0.02$) (Fig. 4.11).

Discussion

These data suggest that pyrethroid and diamide insecticides provided effective control of headworms up to ten days after treatment when applied at midge timing. As time progressed, the efficacy of pyrethroids declined to unacceptable levels. Chlorantraniliprole alone (Prevathon®), chlorantraniliprole combined with lambda-cyhalothrin (Besiege®), and flubendiamide (Belt®) all provided effective control in low pressure situations when they were applied at midge timing. As pest densities increased over time, chlorantraniliprole alone (Prevathon®) and chlorantraniliprole combined with lambda-cyhalothrin (Besiege®) provided the most complete control.

In the delta region, when trials were planted early, all insecticide treatments resulted in at least a 400 kilogram per hectare increase in grain yields. When trials were planted late in the delta region, use of any insecticide resulted in an average yield gain of 1306 kilograms per hectare. Insecticide treatments consisting of chlorantraniliprole (Prevathon®) resulted in significantly greater yields compared to all other treatments planted early in the hills region. Average yields ranged from 5545 to 6308 kilograms per hectare.

Pyrethroid insecticides used for sorghum midge control are generally applied as grain sorghum begins flowering (Doering and Randolph 1963). Historically, several follow-up applications were made through maturity to control headworms. Due to established resistance of corn earworm (Brown 1987, Jacobson et al. 2009, and Kanga et al. 1996), there have been inconsistencies in control when using pyrethroid insecticides in grain sorghum (McCaffery 1998). These results suggest that pyrethroid insecticides can provide effective control of the headworm complex up to ten days after an application for

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sorghum midge. As larvae mature, results suggest that diamide insecticides are a more efficient option for control, with residual control being measured up to twenty-four days after application. These results are supportive of the consistency and long lasting crop protection previously determined by other scientists (Bassi et al. 2009, Roditakis et al. 2015, Sridhar and Sharma 2015). In these trials, diamide insecticide use did not necessarily result in yields greater than where only a pyrethroid was used.

In Mississippi, insecticide costs in grain sorghum production for 2016 alone are estimated at ca. $97 per hectare. Estimated costs of lambda-cyhalothrin (Karate® Z) and chlorantraniliprole (Prevathon®) are $10.37 and $43.23 per hectare, respectively (Falconer et al. 2015). Estimated crop consultant costs are $17.29 per hectare in grain sorghum and custom spray application costs are estimated at $16.06 per hectare (Falconer et al. 2015). A single insecticide application at flowering targeting both sorghum midge and headworms costs $69.66 per hectare (Falconer et al. 2015). Control costs have risen even more over the past few years with the invasion of the sugarcane aphid, *Melanaphis sacchari* (Zehntner). Using the most effective labeled insecticide (flupyradifurone - Sivanto®, Bayer CropScience) for this pest costs $23.72 per hectare (Falconer et al. 2015). Budgeting two aphid applications ($47.44 per hectare) in addition to the application applied at midge timing ($69.66 per hectare), equates to $117.10 per hectare (Falconer et al. 2015). Under these conditions, control costs are greater than the estimated planning budget costs for 2016 (ca. $97 per hectare). The strategy of applying an insecticide preventatively at flowering for headworms was evaluated as a potential cost savings tool (primarily application costs). However, if infestations do not reach treatable levels, this would result in an economic loss of $43.23 per hectare. Based on results from

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the current study, preventative applications for head worms would not be economically viable in a low pest pressure situation. However, because larval densities were low throughout the duration of this study, the economic benefit of diamide insecticides in a high pest pressure situation was unable to be determined.
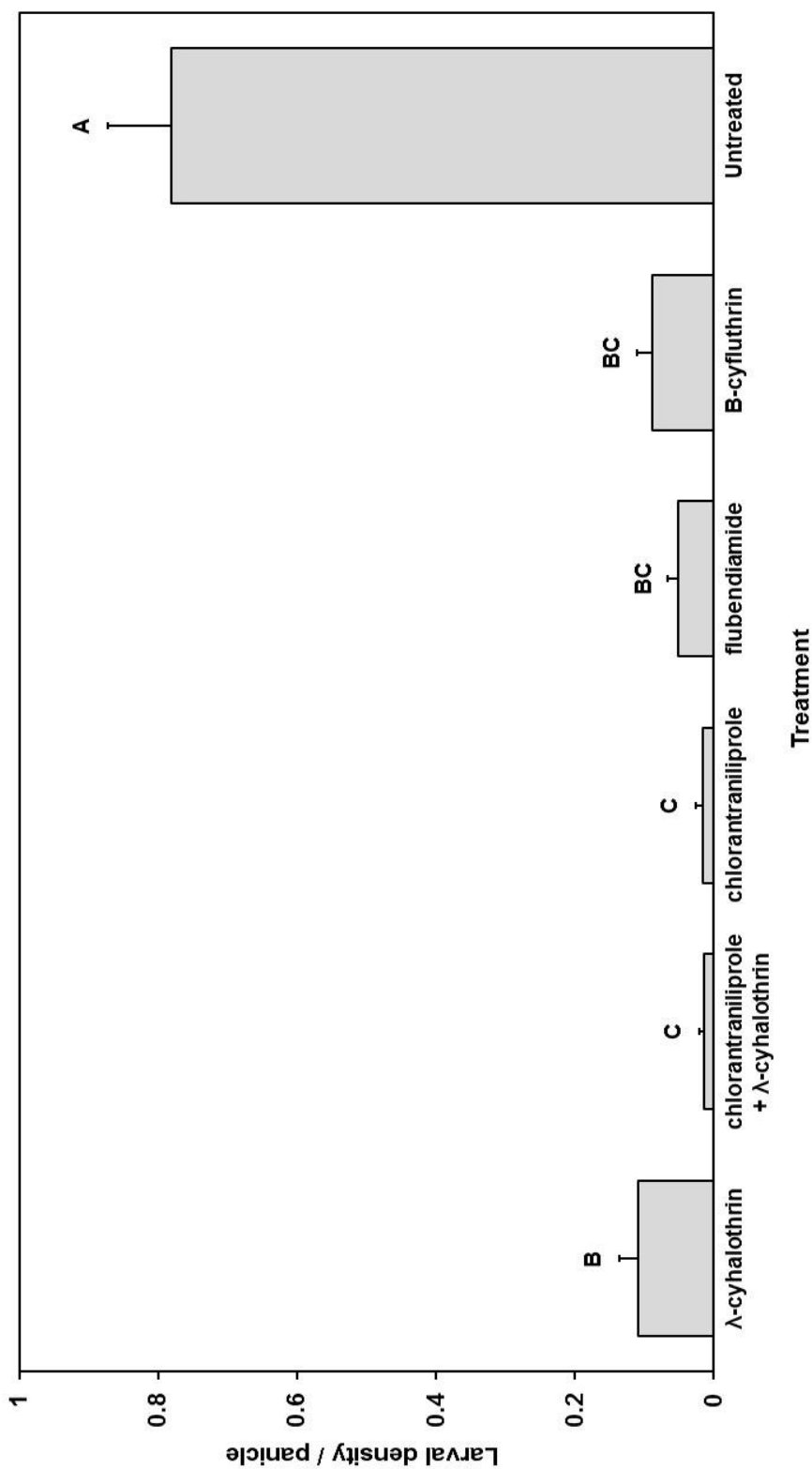
Figure 4.1   Mean (SEM) densities of headworms (*H. zea*, *S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the early planting date in the delta region of Mississippi at 6 – 10 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.
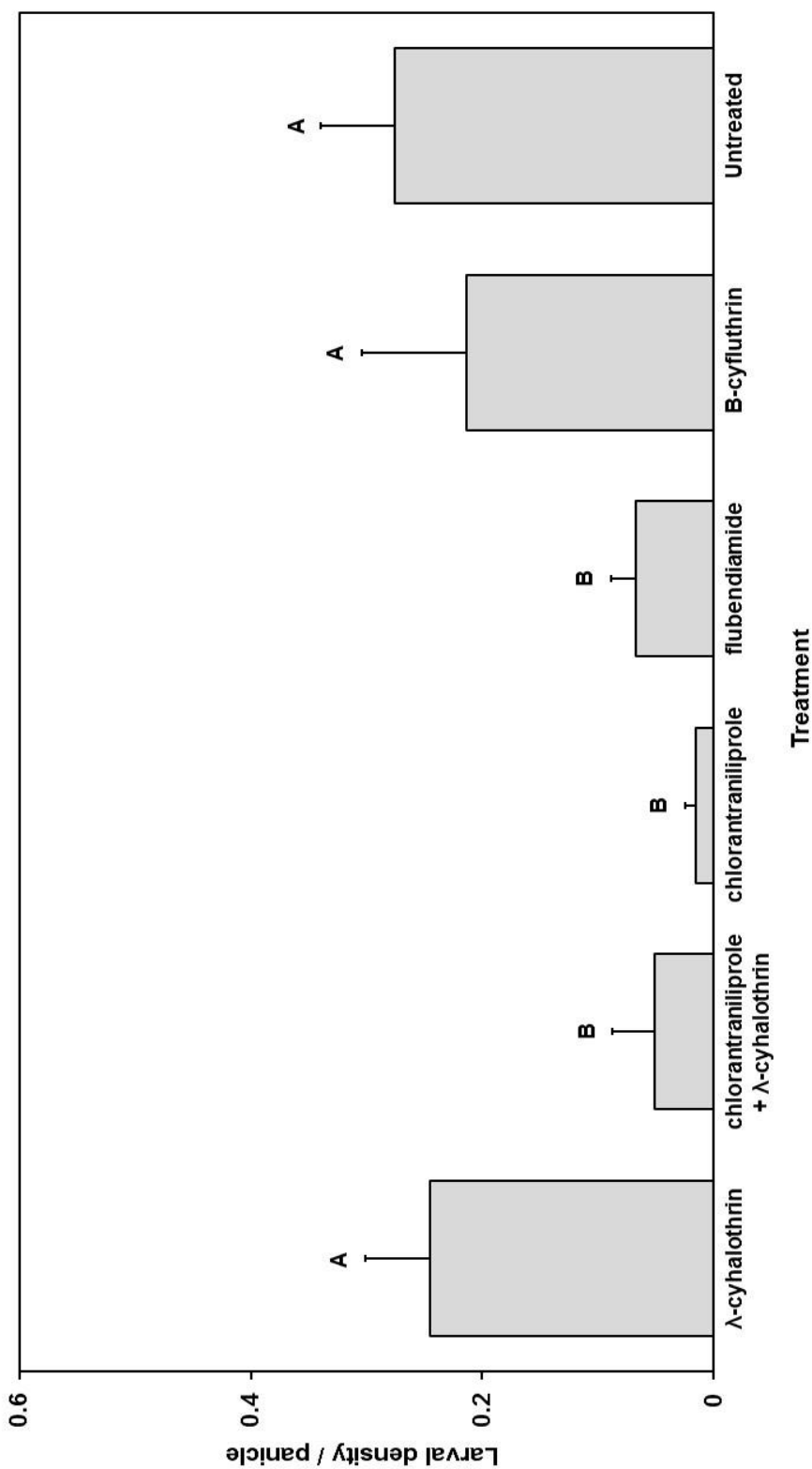
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Figure 4.2   Mean (SEM) densities of headworms (*H. zea, S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the early planting date in the delta region of Mississippi at 12 – 16 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.
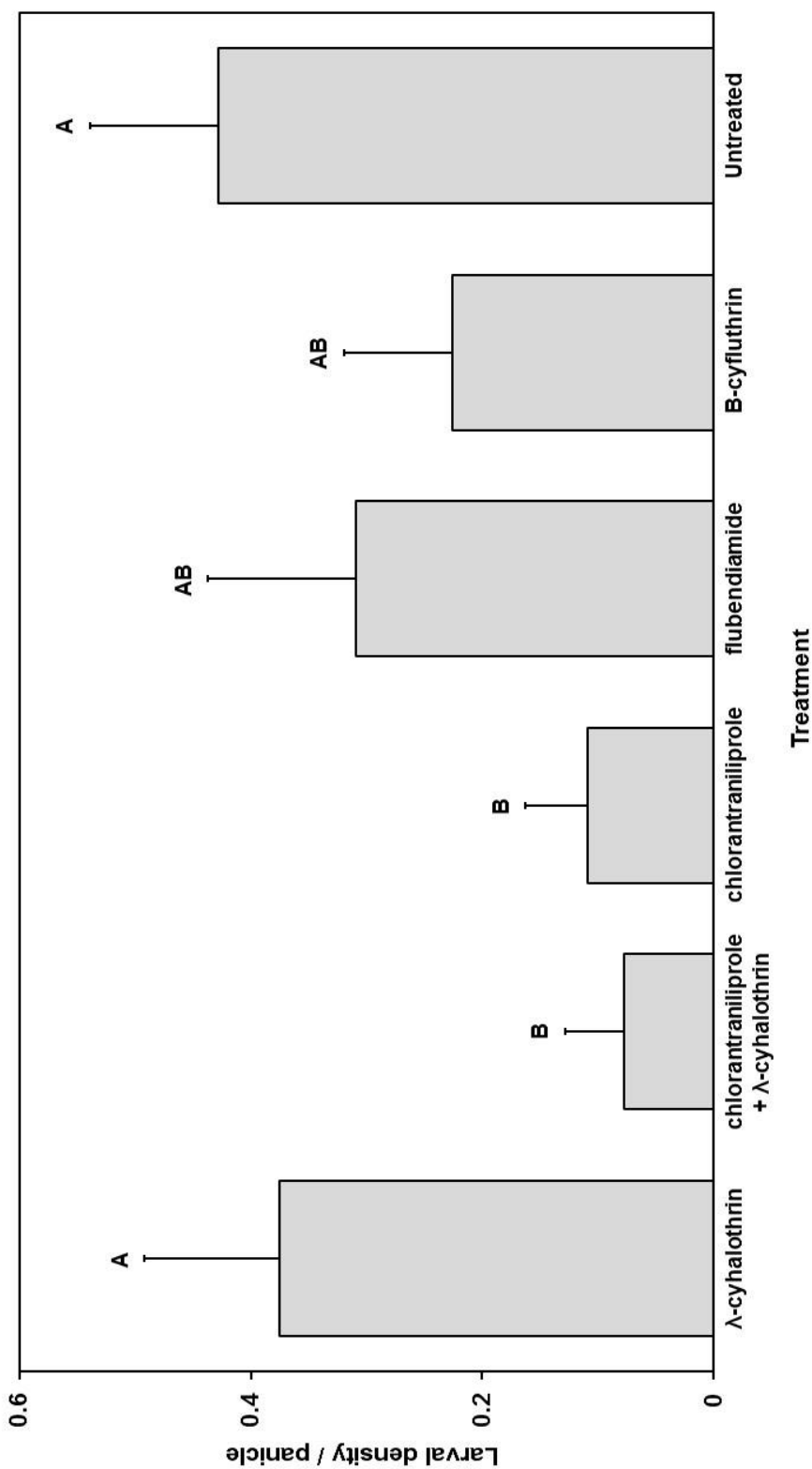
Figure 4.3   Mean (SEM) densities of headworms (*H. zea*, *S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the early planting date in the delta region of Mississippi at 18 – 24 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD (α = 0.05). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.
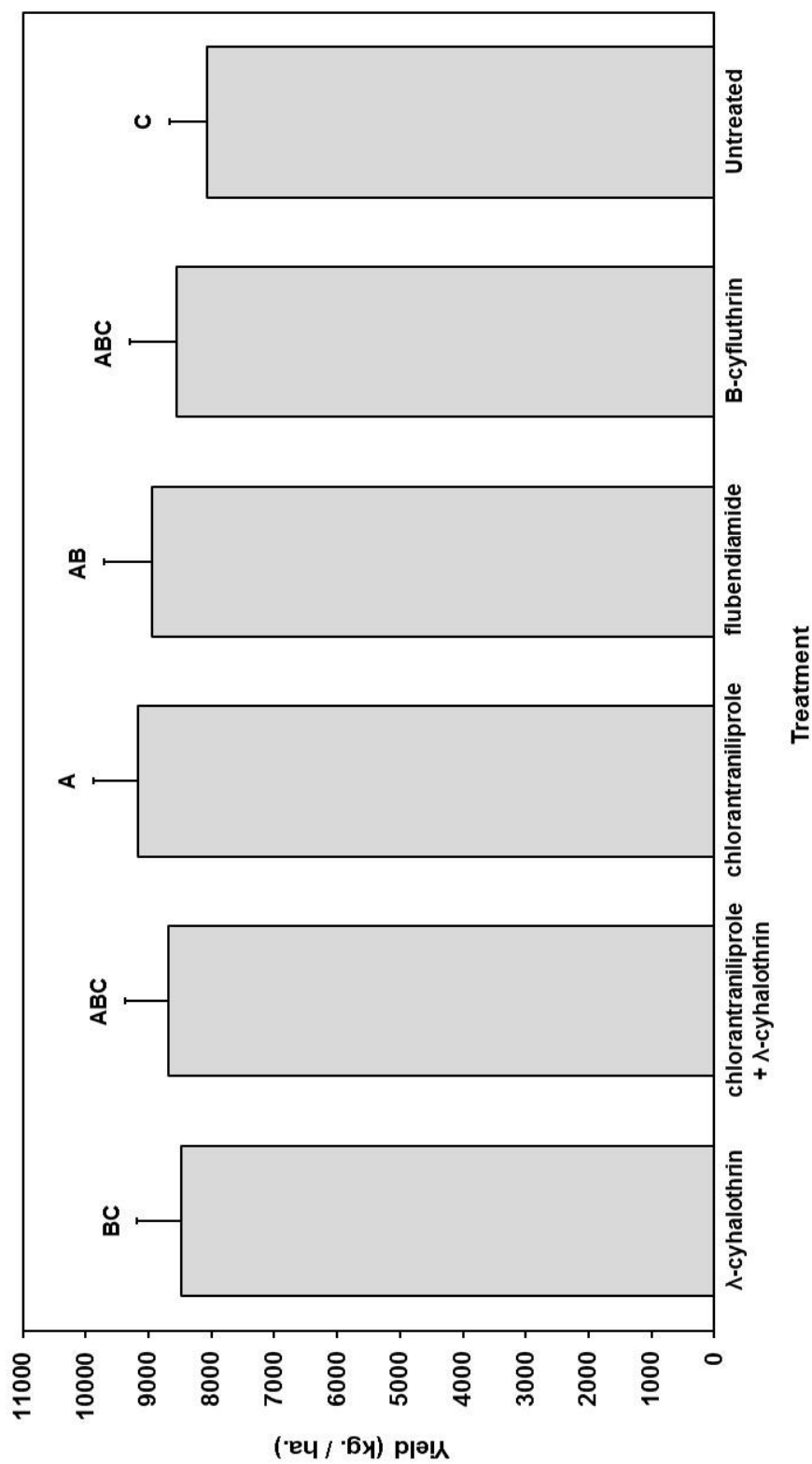
Figure 4.4   Mean (SEM) grain sorghum yields among insecticide treatments applied to grain sorghum at 25% bloom at the early planting date in the delta region of Mississippi.

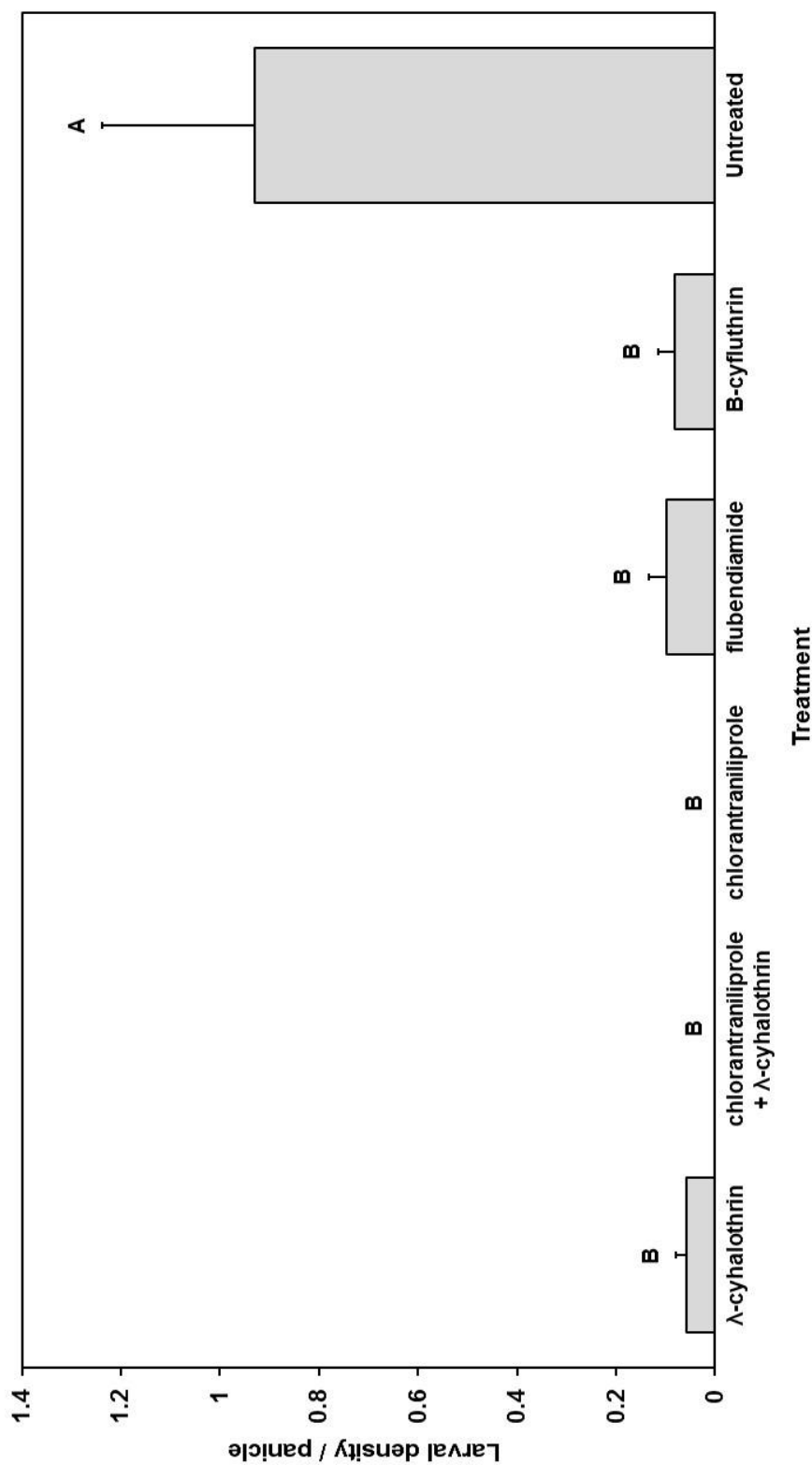Means with a common letter are not significantly different ($\alpha = 0.05$, Fisher's Protected LSD).

Figure 4.5   Mean (SEM) densities of headworms (*H. zea*, *S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the late planting date in the delta region of Mississippi at 6 – 10 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.

Figure 4.6   Mean (SEM) densities of headworms (*H. zea*, *S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the late planting date in the delta region of Mississippi at 12 – 16 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD (α = 0.05). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.
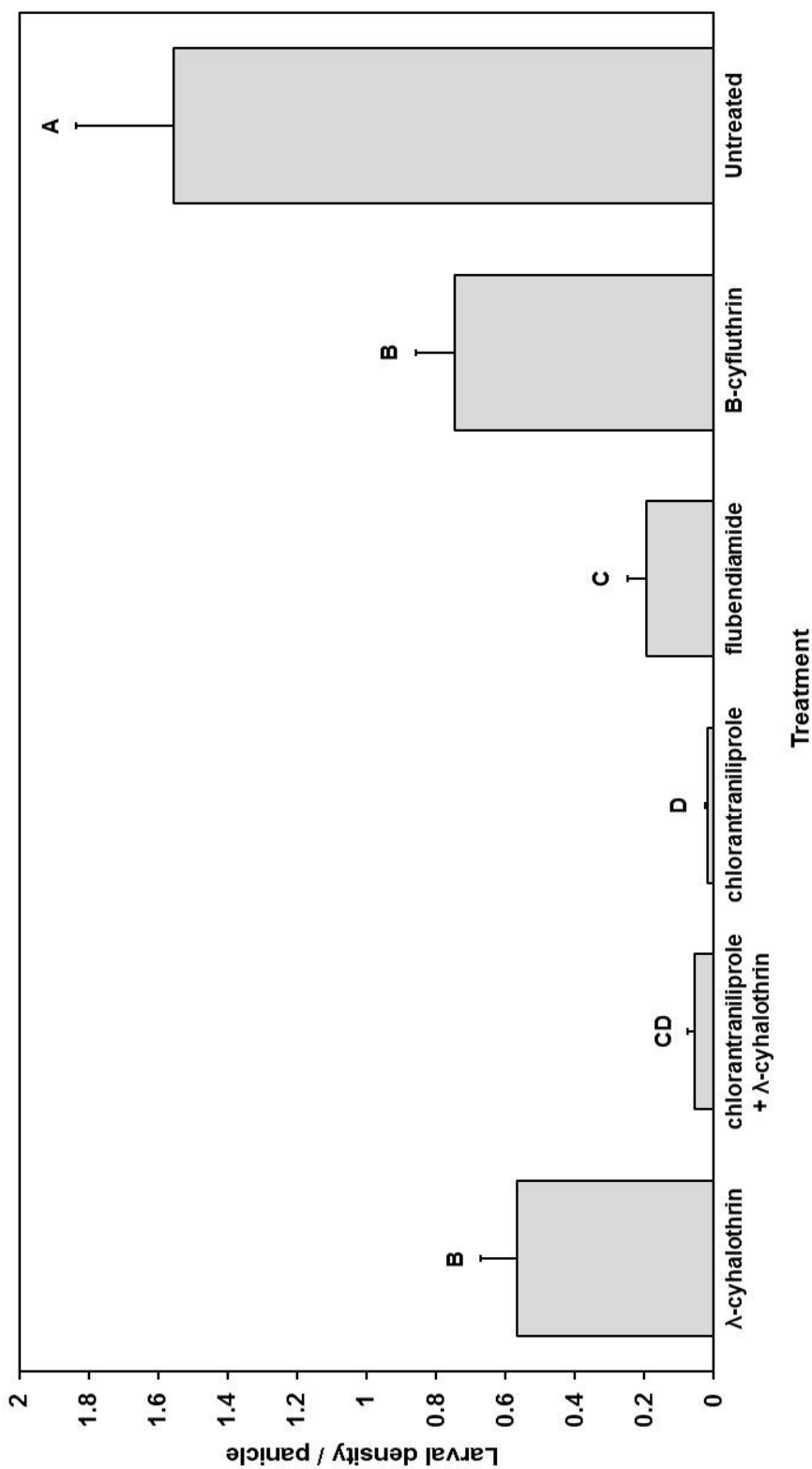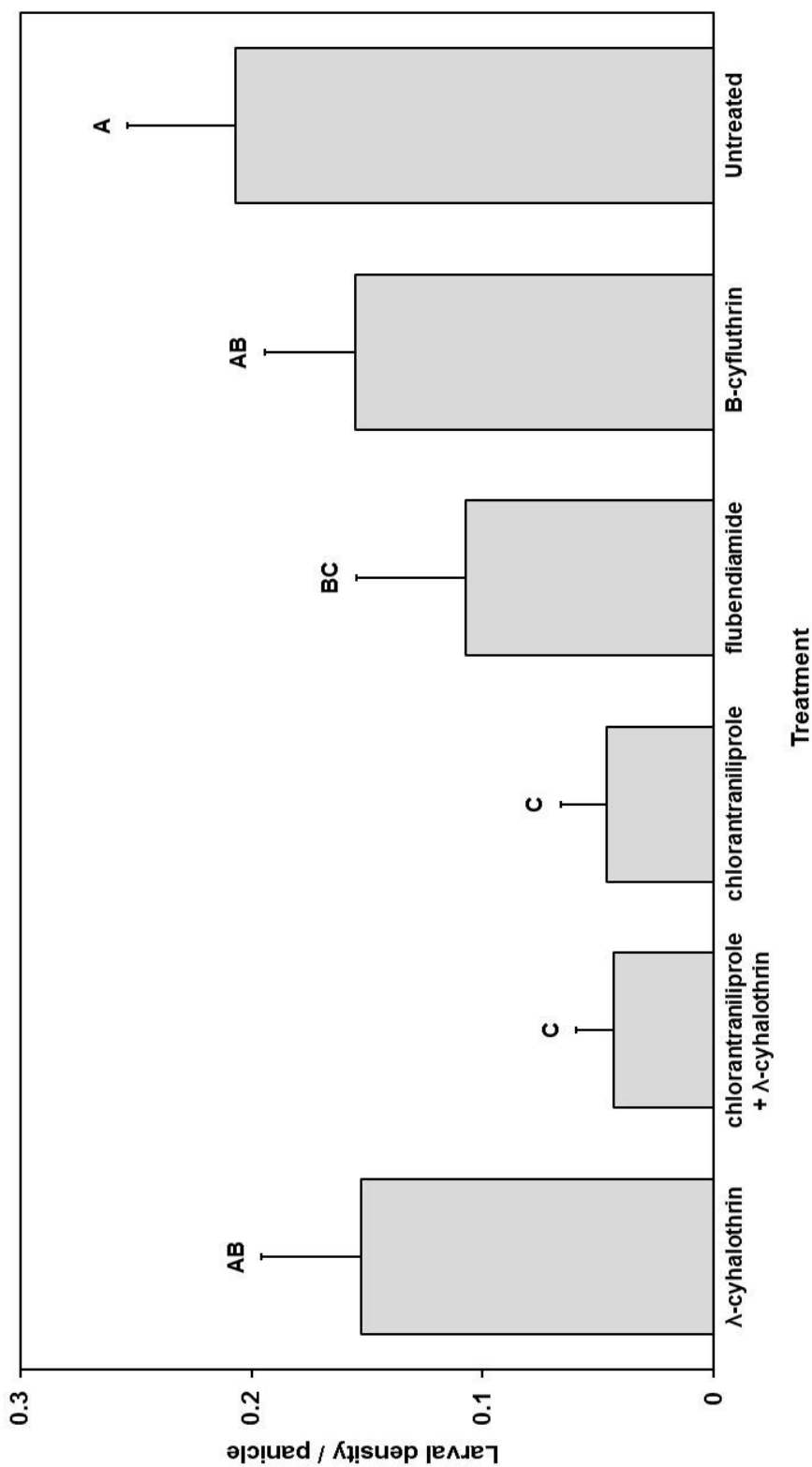
Figure 4.7   Mean (SEM) densities of headworms (*H. zea*, *S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the late planting date in the delta region of Mississippi at 18 – 24 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.
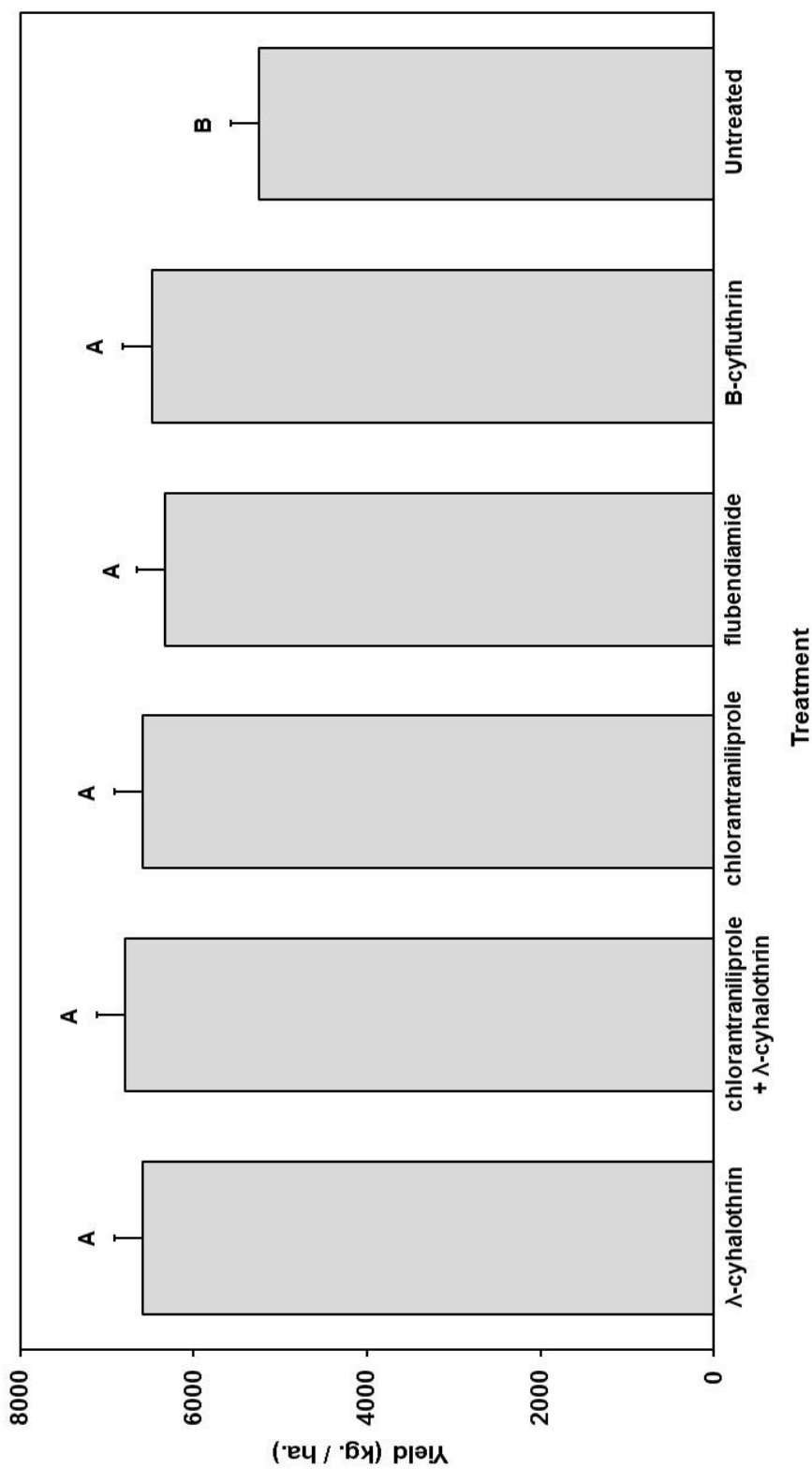
Figure 4.8   Mean (SEM) grain sorghum yields among insecticide treatments applied to grain sorghum at 25% bloom at the late planting date in the delta region of Mississippi.

Means with a common letter are not significantly different ($\alpha = 0.05$, Fisher's Protected LSD).

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Figure 4.9   Mean (SEM) densities of headworms (*H. zea*, *S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the early planting date in the hills region of Mississippi at 6 – 10 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD ($\alpha = 0.05$). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.
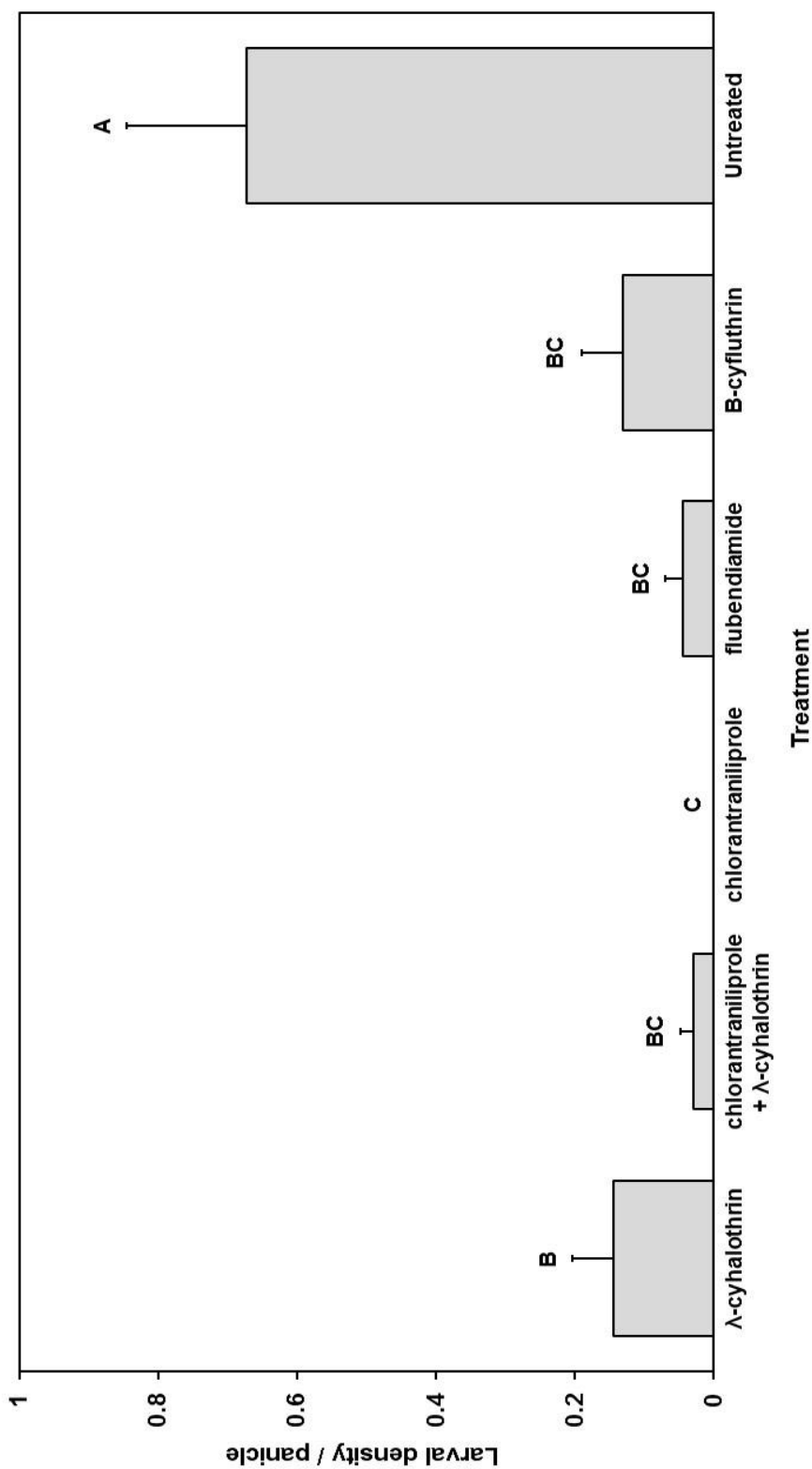
Figure 4.10   Mean (SEM) densities of headworms (*H. zea*, *S. frugiperda*, and *N. sorghiella*) among insecticide treatments applied at 25% bloom to grain sorghum at the early planting date in the hills region of Mississippi at 12 – 16 days after application.

Means with a common letter are not significantly different according to Fisher's Protected LSD (α = 0.05). Analyses were determined using log transformed data. Actual means and standard errors presented on graph.

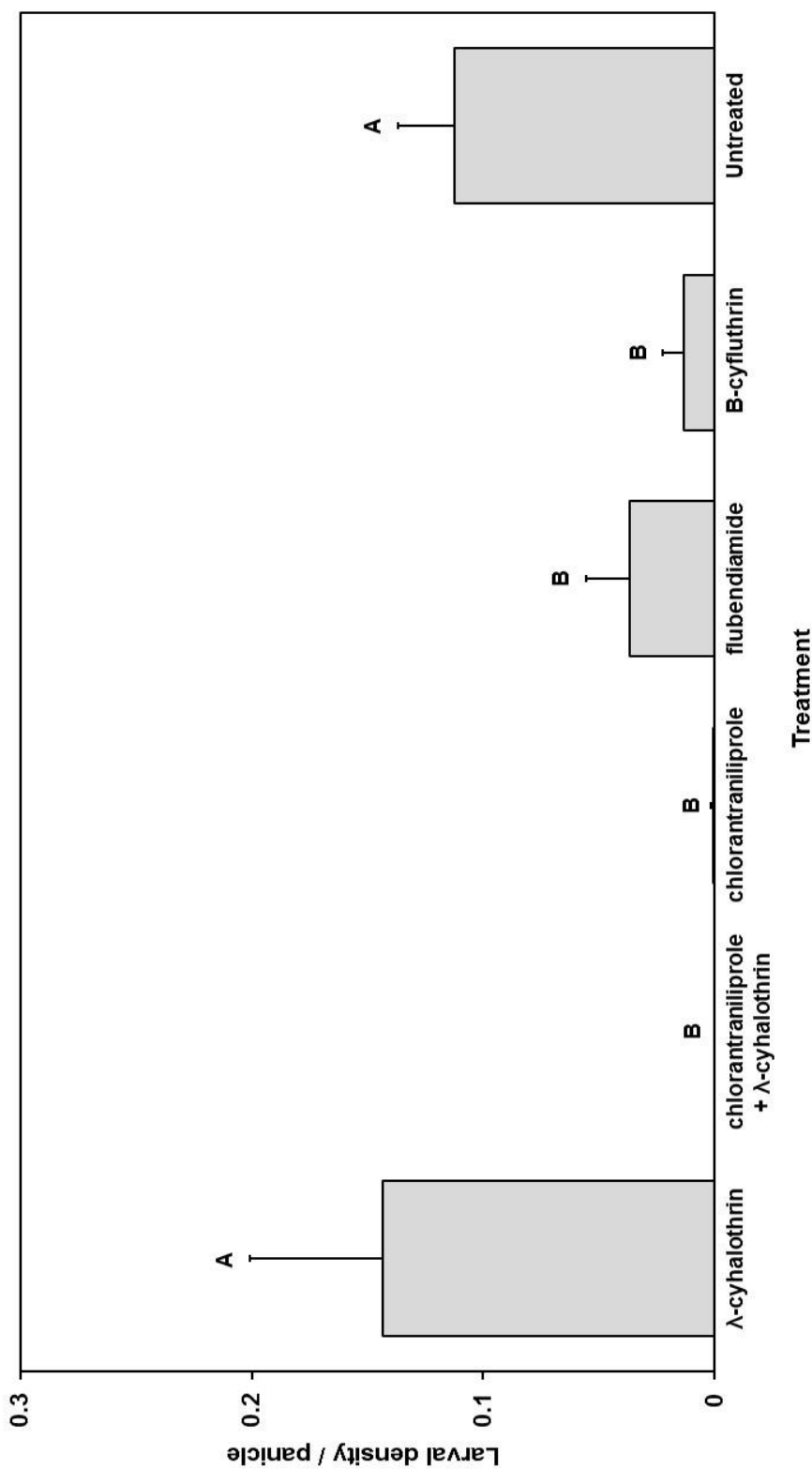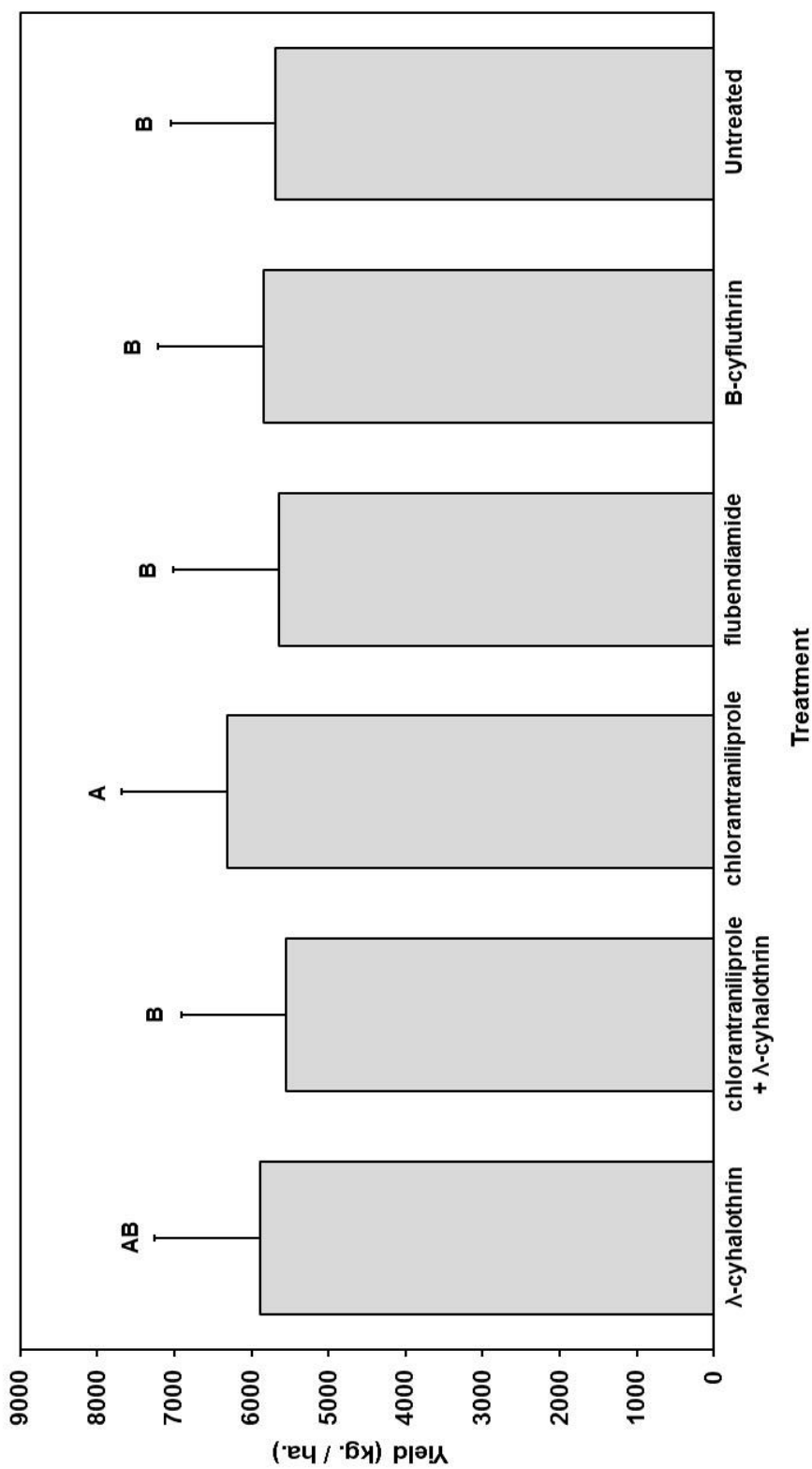Figure 4.11   Mean (SEM) grain sorghum yields among insecticide treatments applied to grain sorghum at 25% bloom at the early planting date in the hills region of Mississippi.

Means with a common letter are not significantly different ($\alpha = 0.05$, Fisher's Protected LSD).

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CHAPTER V

SUMMARY AND CONCLUSIONS

The headworm complex is a combination of pests that occasionally cause damage to reproductive stage grain sorghum. This pest complex consists of corn earworm, *Helicoverpa zea* (Boddie), fall armyworm, *Spodoptera frugiperda* (J.E. Smith), and sorghum webworm, *Nola sorghiella* (Riley). In Mississippi, the corn earworm is a regular pest of grain sorghum each year and the fall armyworm is an occasional pest. The current action threshold used to treat these pests on reproductive stage grain sorghum is one larva per panicle either alone or combined.

Crop production costs for grain sorghum are relatively high in relation to crop value. Producers sometimes apply a tank mixture or pre-mixture of pyrethroid and diamide insecticides at 20-30% bloom to manage both sorghum midge and headworms in an attempt to lower production costs. Pyrethroid insecticides provide excellent control of sorghum midge, but control of the headworm complex has become inconsistent. In contrast, the diamide insecticides are not known to provide control of sorghum midge, but provide excellent initial and residual control of caterpillar pests.

Experiments were conducted in Mississippi from 2013 to 2014 to determine the economic impact of corn earworm and fall armyworm on reproductive stage grain sorghum and to evaluate their control with automatic insecticide applications at 20-30% bloom. Those experiments concluded that one corn earworm per panicle resulted in a

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3.6% yield loss and one fall armyworm per panicle resulted in a 4.0% yield loss. Overall results suggest that diamide insecticides provided better control of headworms, compared to pyrethroid insecticides and chlorantraniliprole provided acceptable control until harvest.

Results from the previous experiments were used to develop pest and insecticide specific economic injury levels for reproductive stage grain sorghum. Economic injury levels reported in the tables were developed using the economic injury level formula determined by Pedigo et al. (1986). The costs of control used for each insecticide were determined by contacting local retailers to get an average price for each product (chlorantraniliprole - $43.23, chlorantraniliprole + λ-cyhalothrin - $30.88, flubendiamide - $32.11, λ-cyhalothrin - $10.37). Insecticide costs were combined with custom spray application costs ($16.06 per ha) to determine a total costs of insect control (C) per unit area of production (Falconer et al. 2015). The crop value (V) was determined by taking the reported value of grain sorghum in 2014 ($0.16 / kg; USDA-NASS) and multiplying it by the average yield potential for each experiment. Yield potential was calculated as the highest average yield among all insecticide treatments within each experiment. Injury per pest equivalent (I), was set at one larva per panicle. Damage (D) was set at 3.8% and was determined by averaging the percent damage obtained from the *H. zea* and *S. frugiperda* larval infestations. The proportionate control (K), was obtained by calculating the percent control for each insecticide in relation to the untreated control within each experiment. Values from economic injury levels were used to calculate individual economic thresholds for each product. Economic thresholds are difficult to accurately define because of the many factors that are involved. Economic thresholds are often set

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lower than the economic injury level, allowing enough time to make an application based on the amount of time between sampling and the development of the pest on that particular crop. In this case, the economic threshold was set at seventy percent of the economic injury level. This level was decided by comparing larval development of *H. zea* on grain sorghum and soybean. Mean larval development time on grain sorghum and soybean was 15.6 and 18.4 days, respectively (Gore et al. 2003). The dynamic threshold currently used for *H. zea* in Mississippi soybean production is set at seventy-five percent of the economic injury level. Due to differences in *H. zea* larval development between the two crops and the amount of time between sampling (5-7 days), the economic threshold is within close proximity of where it needs to be. Examples showing how the economic injury level fluctuates based on control costs, level of control, crop value, and yield potential are provided below.

In experiments from the Delta region at an early planting date where yield potential was high and pest pressure was low (Table 5.1), and level of control ranged from 44 to 83%. The economic injury level rose with increased control costs and decreased level of control. As an example, with expected yield of 8000 kg of grain sorghum and a larval density of 0.6 young larvae (1st – 3rd instar larvae) per panicle with less than a week until maturity and the producer wants to make an application, there would be two options of control. Option one would be a pyrethroid (λ-cyhalothrin – Karate$^{®}$ Z; B-cyfluthrin – Baythroid$^{®}$ XL) and option two would be a pre-mix of chlorantraniliprole and λ-cyhalothrin (Besiege$^{®}$). Although the pre-mix provides better control (82%) than the pyrethroid (44%), the lower cost of control with the pyrethroid would make up the difference. At 0.6 larvae per panicle there would be 182.4 kg of grain

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loss (0.6 larvae per panicle * 3.8% yield loss from one larva * 8000 kg). By using a

pyrethroid, the producer would break even at 165.2 kg (control costs / crop value per kg).

Using the pre-mix (chlorantraniliprole and λ-cyhalothrin) formulation, the producer

would break even if he saved 293.4 kg (control costs / crop value per kg) of grain.

Therefore, a pyrethroid application would likely be the best option of control to provide

the producer with the best economic return in this situation.

From a different standpoint, in the Delta region at a later planting date where crop

value was lower and pest pressure was higher (Table 5.2), the overall efficacy of each

product was better. Control levels ranged from 60 to 93 percent, with pyrethroids being

the weakest. Economic injury levels were similar to the ones shown in table 5.1. In this

instance, the expected yield would be 7000 kg of grain sorghum. Larval density is 1 per

panicle and the grain sorghum is at the soft dough stage, leaving it vulnerable to pests for

the next two to three weeks. There are three options of control to choose from at this time

that will carry the crop to harvest. Option one would be chlorantraniliprole (Prevathon®),

option two would be a pre-mix of chlorantraniliprole and λ-cyhalothrin (Besiege®), and

option three would be flubendiamide (Belt®). Option one and option two both provide

93% control. However, option three only provides 77% control. Because of differences in

price and level of control, option two (Besiege®) would be the best product to use. The

producer would break even if he saved 293.4 kg (control costs / crop value per kg) of

grain, which is 35.3 kg more than the amount of grain being lost at the infestation level of

one larva per panicle (258.1 kg). However, if he does not go ahead and take immediate

action, yield losses may become greater than expected.

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Looking at things from an angle where both crop value and larval density are both low in the Hill region (Table 5.3), the level of control from insecticide applications was similar to that reported in table 5.1 and 5.2. If larvae are averaging 0.9 larvae per panicle and the producer is only expecting to yield 5800 kg of grain sorghum, options for control are limited. At an infestation level of 0.9 larvae per panicle, the amount of grain that must be protected to pay for the application using diamide insecticides well exceeds the amount of grain actually being lost (198.4 kg). This leaves pyrethroids as the only other option for control. To equal costs of control using a pyrethroid, 165.2 kg (control costs / crop value per kg) of grain must be protected. Based on results from table 5.3, pyrethroids only provided 58 percent control. If 58 percent of the 0.9 larvae per panicle were controlled, only 115.05 kg of grain would be protected [(58% control*0.9 larvae per panicle)*(3.8% yield loss at one larva per panicle)*(5800 kg expected yield potential) = 115.05 kg], resulting in control costs greater than the return. This is a great example showing how level of control adversely affects a producers ability to use a particular insecticide when less favorable growing conditions are present.

Growing conditions often vary among fields making insecticide selection a more difficult challenge. However, one must consider level of control from each available insecticide before making a decision. A table (5.4) was developed to illustrate the influence of level of control on grain sorghum management decisions. This table includes averages of data obtained from all three of the experiments discussed in chapter 4. Control costs include insecticide and custom spray application costs for each product used. Percent control is the level of control that each product provided obtained by measuring larval densities. The calculated EIL = C/VIDK (economic injury level) was

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obtained using the formula determined by Pedigo et al. (1986). The percent yield loss was determined by multiplying the calculated EIL by 3.8% (average yield loss of one *H.zea* or *S. frugiperda* larva per panicle determined in chapters 2 and 3) * 100. Yield loss in kg/ ha was determined by multiplying the percent yield loss of the calculated EIL by the average yield potential (7013 kg) of all three experiments discussed in chapter 4. The gain threshold was determined by dividing the costs of control of each insecticide product by the crop value of $0.16 per kg of grain sorghum. The percentage of grain protected to equal the gain threshold was determined using the formula [(1)-(gain threshold/yield loss of the calculated EIL)]. Results from this table illustrate how level of control affects the EIL. When using a product that provides adequate control (chlorantraniliprole and chlorantraniliprole + λ-cyhalothrin), the calculated EIL and actual EIL are relatively close. However, when using a product such as flubendiamide that provides seventy-five percent control, the actual EIL is a bit lower than previously estimated. When using a pyrethroid insecticide that provides on average fifty-four percent control, the actual EIL is almost half of the calculated EIL. Data from this table are justification as to why a dynamic threshold would be a better fit in grain sorghum production than a set threshold for every situation.

Overall, these studies demonstrate that the economic impacts of *H.zea* and *S. frugiperda* are very similar and both should be treated equal. It was also demonstrated that diamide insecticides are a great option to achieve excellent control of both species. However, in some situations the diamide insecticides do not seem to be economically viable in grain sorghum production. These data also show how the economic injury level fluctuates based on changes in control costs, efficacy, and yield potential. In order to

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reduce production costs, applying a dynamic threshold that takes all of these variables

into account seems to be most sensible

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Table 5.1   Economic injury level (EIL) and economic threshold (ET) calculated for each insecticide applied during the early planting date in the delta region of Mississippi.

Product Applied at 25% Bloom	Control Costs	% Control	EIL	ET
Pyrethroid (λ-cyhalothrin – Karate® Z) or (B-cyfluthrin - Baythroid® XL)	$26.43	44	1.18	0.82
chlorantraniliprole + λ-cyhalothrin (Besiege®)	$46.94	82	1.12	0.79
chlorantraniliprole (Prevathon®)	$59.29	83	1.40	0.98
flubendiamide (Belt®)	$48.17	62	1.52	1.07

The value of grain sorghum was $0.16 / kg with an expected yield potential of 8388 kg / ha. Expected yield potential was determined as being the highest average yield among all treatments.

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Table 5.2   Economic injury level (EIL) and economic threshold (ET) calculated for each insecticide applied during the late planting date in the delta region of Mississippi.

Product Applied at 25% Bloom	Control Costs	% Control	EIL	ET
Pyrethroid (λ-cyhalothrin – Karate® Z) or (B-cyfluthrin - Baythroid® XL)	$26.43	60	1.07	0.75
chlorantraniliprole + λ-cyhalothrin (Besiege®)	$46.94	93	1.22	0.86
chlorantraniliprole (Prevathon®)	$59.29	93	1.54	1.08
flubendiamide (Belt®)	$48.17	77	1.51	1.06

The value of grain sorghum was $0.16 / kg with an expected yield potential of 6791 kg / ha. Expected yield potential was determined as being the highest average yield among all treatments.

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Table 5.3   Economic injury level (EIL) and economic threshold (ET) calculated for each insecticide applied during the early planting date in the hills region of Mississippi.

Product Applied at 25% Bloom	Control Costs	% Control	EIL	ET
Pyrethroid (λ-cyhalothrin – Karate® Z) or (B-cyfluthrin - Baythroid® XL)	$26.43	58	1.28	0.90
chlorantraniliprole + λ-cyhalothrin (Besiege®)	$46.94	100	1.32	0.92
chlorantraniliprole (Prevathon®)	$59.29	100	1.66	1.16
flubendiamide (Belt®)	$48.17	85	1.59	1.11

The value of grain sorghum was $0.16 / kg with an expected yield potential of 5860 kg / ha Expected yield potential was determined as being the highest average yield among all treatments.

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Table 5.4   Data collected from efficacy trials in Mississippi during 2013 and 2014 showing how level of control from different insecticides can have an adverse effect on EIL calculations.

Product Applied at 25% Bloom	Control Costs	% Control	EIL [% Yield Loss]	Yield Loss (kg / ha)	Gain Threshold [% Yield Protected = Gain Threshold]
Pyrethroid (λ-cyhalothrin – Karate® Z) or (B-cyfluthrin - Baythroid® XL)	$26.43	54	1.17 [4.46%]	313.01	165.19 [52.77%]
chlorantraniliprole + λ-cyhalothrin (Besiege®)	$46.94	92	1.22 [4.64%]	325.33	293.38 [90.18%]
chlorantraniliprole (Prevathon®)	$59.29	92	1.54 [5.84%]	409.41	370.56 [90.51%]
flubendiamide (Belt®)	$48.17	75	1.54 [5.86%]	411.21	301.06 [73.21%]

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