EVALUATION OF THE VALUE OF SORGHUM MIDGE RESISTANT HYBRIDS IN THE USA

A Thesis

by

JOAQUIM AMERICO MUTALIANO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2005

Major Subject: Plant Breeding

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Approved by:

Chair of Committee,	William L. Rooney
Committee Members,	Marvin Harris
	Gary C. Peterson
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ABSTRACT

Evaluation of the Value of Sorghum Midge Resistant Hybrids in the USA.

(December 2005)

Joaquim Americo Mutaliano, B.S., Eduardo Mondlane University, Mozambique

Chair of Advisory Committee: Dr. William L. Rooney

Sorghum (*Sorghum bicolor* [L.] Moench) production in many areas of the world is reduced due to damage caused by sorghum midge (*Stenodiplosis sorghicola)*. There are several methods of control to reduce losses due to sorghum midge, which include cultural practices, biological control, chemical control and resistant cultivars. The best long-term solution for sorghum midge control is the use of genetic resistance in cultivars and hybrids. Recently, sorghum midge resistant hybrids have been developed by several sorghum breeding programs, but there is limited information about agronomic performance relative to planting dates compared to susceptible standards. Thus, the objectives of this research project are: (1) to evaluate the value of sorghum midge resistant sorghum hybrids in the USA production system, (2) to confirm the presence of sorghum midge insect resistance in sorghum hybrids, and (3) to determine whether the resistance in eighteen sorghum hybrids is stable across two environments in Texas where sorghum midge is a damaging pest. Sorghum hybrids with different levels of resistance to sorghum midge were evaluated at College Station and Corpus Christi, Texas in 2003 and 2004, using two different planting dates and the presence or absence of an insecticide treatment. Agronomic data, sorghum midge incidence ratings and number of adult midges, were determined for all entries. All entries designated as resistant did have some resistance compared to susceptible checks. Across all hybrids, grain yield was higher in sorghum with normal planting dates compared to late planting. Under midge pressure resistant hybrids performed better than susceptible hybrids, but lacking midge pressure the susceptible hybrids were higher performing. The use of midge resistant hybrids in commercial production is only warranted when producers are reasonably sure that midge will be a problem. Otherwise, they should continue to plant early using traditional hybrids.

DEDICATION

This thesis is dedicated to my daughters, Sonia, Milena and Irene, for my absence in the course of their growth during the present training program.

To my mother, Florencia, for everything and sacrifice that she has done when she was alive.

To my father, Americo, for his support and patience.

To my sister, Maria dos Anjos, my brothers, Albino and Hilario.

To my wife, Teresa, for the patience and courage.

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INTRODUCTION

Sorghum (*Sorghum bicolor* [L.] Moench) ranks fifth among the world cereals, following wheat, maize, rice and barley in production area and total production (FAO 2001). The crop is important in many regions of the world where drought stress is common. Sorghum is produced for its grain, fiber, and stalks in Africa, South Asia and Central America. In the USA, Australia and other developed countries sorghum is used primarily for animal feed as either grain or forage (Rooney and Serena-Saldivar 2000). In Africa, the largest sorghum producing nations are Nigeria, Burkina Faso, Mali, and Niger (FAO 1992). In Mozambique, it is the second most important cereal after maize.

There are several methods to reduce losses to sorghum midge including (1) cultural control, (2) biological control, (3) chemical control and (4) resistant cultivars. Harris (1976) reported on the cultural control methods that include destruction of infested panicles (in crop residues, wild sorghums, and crop rotations) and early synchronized regional sowings using pure seed to obtain uniform flowering prior to the emergence of large populations of midge. Teetes et al., (1980) indicated that early and uniform planting of grain sorghum within short periods can prevent the build up of damaging sorghum midge densities. For biological control there are several parasites of sorghum midge and the effectiveness of control depends on the balance among the parasites and the sorghum midge. However, Harris (1976) indicated that there is little evidence that natural parasitism and predation can provide significant control of

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This thesis follows the style of Crop Science.

sorghum midge. Thus, the prospects of biological control are probably limited. In many developed countries chemical control is used as needed to control damaging population densities of sorghum midge. However, this method is not feasible in subsistence agriculture.

The best long-term solution for sorghum midge control is to use genetic resistance in sorghum cultivars and hybrids. Different mechanisms of genetic resistance are available in sorghum. Several sorghum breeding programs have selected for midge resistance in an array of environments and these have resulted in the production of several different and unique types of sorghum hybrids with varying levels of resistance to the sorghum midge.

Given these developments, there is now interest in these sorghum hybrids in U.S. production systems, but there is little to no information regarding their agronomic performance and the level of midge resistance that these hybrids possess. The goal of this research project is to characterize the level and suitability of resistance in a set of sorghum midge resistant hybrids that were derived from different sorghum breeding programs. The specific objectives of this research are to:

1. Evaluate the value of sorghum midge resistant sorghum hybrids in a U.S. production system.
2. Confirm the presence of midge insect resistance in eighteen sorghum hybrids developed by TAES and Pioneer Hi-Bred Seed Company.

3. Determine whether the resistance in eighteen sorghum hybrids is stable across two environments (College Station and Corpus Christi) in South Texas where sorghum midge plays an important role in the reduction of grain yield.

LITERATURE REVIEW

Origin and Distribution of Sorghum

Sorghum is a tropical cereal crop that grows in a wide range of environments and it plays an important role as a staple food for many people all over the world. The center of origin for the crop is Northeast Africa, as all evidence indicates that the original domestication of the species occurred in this region between 5,000 and 7,000 years ago (House, 1985; Kimber, 2000). From this center of origin it was distributed along trade and shipping routes throughout Africa and through the Middle East to India 3,000 years ago. Sorghum was first taken to America through the slave trade from West Africa. It was introduced in the USA in late 19th century for commercial cultivation. Sorghum is now widely found in the drier areas of Africa, Asia, Australia, North, Central and South America (ICRISAT, 2005).

Adaptation

Sorghum is adapted to a wide range of environmental conditions but among the five most widely grown cereal grains sorghum has the greatest tolerance to drought stress. This tolerance is based on a number of morphological and physiological characteristics including an extensive root system, waxy bloom on the leaves that reduces water loss, and the ability to stop growth in periods of drought and resume when conditions become favorable (ICRISAT Web, 2005). It is primarily a crop grown in hot, semi-arid tropical environments with 400 – 600 mm rainfall that are too dry for maize (*Zea maize L.*). While it can be grown under drought stress, it can also be grown in high rainfall areas. It is also grown in temperate regions and at altitudes of up to 2300 meters in the tropics.

Sorghum can be successfully grown on a wide range of soil types. It is well suited to heavy vertisols found commonly in the tropics, but is equally suited to light sandy soils. It tolerates a range of soil pH from 5.0 – 8.5 and is more tolerant to salinity than maize. It is adapted to poor soils and can produce grain on soils where many other crops would fail (Maqbool et al., 2001, Maunder, 2001, ICRISAT Web, 2005).

Temperature

Sorghum is adapted to sub-tropical and tropical climes and is not tolerant to cool temperatures. Temperatures below 15^0 C reduce germination and emergence in most sorghum genotypes and temperatures below 7 ^{0} C stop the germination process. Cool temperatures also inhibit photosynthesis (chlorophyll synthesis) and cause pollen abortion and/or sterility. When this occurs there is a significant reduction of seed set and yield (McWilliams et al., 1979).

Production

Worldwide annual sorghum production ranges from 40 to 45 million tons from approximately 40 million hectares (ICRISAT web, 2005). The largest producers are the United States of America with annual production of 17 million tons of grain from 4 million hectares; India (11 million tons from 12.5 million hectares); Nigeria (6 million tons from 5.7 million hectares); China (5.5 million tons from 1.5 million hectares);

Mexico (4.5 million tons from 1.3 million tons) and Sudan (3 million tons from 5 million hectares) (ICRISAT web, 2005). As is seen from the previous statistics, productivity of sorghum varies widely. Under optimal conditions, grain yield up to 15 MT/ha have been reported and consistent yields between 7 and 9 MT/ha can be produced in most environments when rainfall is not a limiting factor. However, because the crop is usually grown in such stressed environments, average sorghum yields are low, ranging from between 3 and 4 MT/ha in a good year to 0.3 to 1 MT/ha under drought conditions (House, 1985).

Crop Utilization

Sorghum grain can be used as an ingredient in malts (Nigeria), ready to cook breakfast food (South Africa), and noodles (South East Asia). It is also used to make bread, cakes, muffins, cookies, biscuits, flour grits, ethanol, fermented drinks, syrup, sugar and porridges (Rooney et al., 1980).

Biotic Stresses

Although grain sorghum can be cultivated over a wide range of environments, its productivity is drastically influenced by biotic (pests and diseases) and abiotic (drought and temperature) factors. Though there are several species of insect pests that attack sorghum at different stages of its development only a few are considered to be economically important. For example, greenbug, *Schizaphis graminum* (Rondani), sorghum midge, *Stenodiplosis sorghicola* (Coquillett), shoot fly, *Atherigona socata*

(Rondani), corn earworm, *Helicoverpa zea* (Boddie), stalk bores, family Pyralidae; and leaf- and panicle-feeding bugs, order Hemiptera, are considered the most important insect pest infesting sorghum (Teetes et al., 1980). Among all species mentioned previously the sorghum midge (*Stenodiplosis sorghicola* [Conquillet], Diptera: Cecidomyiidae) is the most widely distributed sorghum insect pest occurring in most sorghum producing regions of the world (Young and Teetes 1977).

Sorghum Midge - *Stenodiplosis sorghicola* (Coquillett*)*

Sorghum midge occurs in almost all regions of the world where sorghum is grown except Southeast Asia (Teetes and Pendleton, 1994, Teetes et al., 1999; Boyd and Bailey, 2000). The adult sorghum midge is a 1.3 mm long, fragile-looking, orange-red fly, with yellow head, brown antennae and legs, and gray membranous wings. Teetes et al., (1999), reported that during the single day of adult life each female lays about 50 yellowish eggs between the glumes of sorghum florets during anthesis. The cylindrical eggs are 0.1 to 0.4 mm long and hatch in two to three days. The larvae complete development in nine to eleven days and pupate between the glumes of the spikelet. From egg to adult the life cycle requires 14 to 16 days. Given the insect's rapid development multiple generations emerge during a season resulting in high infestation levels when sorghum flowering is extended by a range of planting dates or maturities.

In the spring, adult midge begin to emerge when the temperature reaches 68-80^{o}F (20-26.7^{0}c) and in the US, when the first host, Johnsongrass (*S. halepense*), is blooming. Sorghum midge begin emergence in early morning with males first to emerge when the temperature is between 10 to 16 ^{0}c, and later females when the minimum emergence threshold temperature is 22 to 26 ^{0}c. Fisher et al. (1982) confirmed that females require slightly higher temperatures for emergence than males. Furthermore, Fisher and Teetes (1982) found that temperature is the principal driving force for sorghum midge to emerge with the second factor being moisture (relative humidity). Rainfall also plays an important role in sorghum midge population dynamics.

Johnsongrass in the USA and India, wild sorghums in Africa (*Sorghum* sp.) and grain sorghum are the primary host plants of sorghum midge (Dogget, 1988). Although the midge has been reported on 14 other grasses, these hosts are not considered suitable for normal midge development. Sorghum midge that emerge during the spring infest Johnsongrass before flowering sorghum is available, and the insect increases in abundance during the season, especially if flowering sorghum continues to be available (Teetes et al., 1999; Sharma and Teetes, 1995).

Adult midge rarely live more than one days. After the female has mated, she lays eggs singly (30-100) within the flowering spikelets of the host plant. The larvae hatch within 2-3 days and feed on the developing kernel for another 9-11 days before reaching maturity and emerging from the floret. As mentioned previously, a generation is completed in 14 to 16 days. This rapid cycle allows for 9-12 generations during a season and permits a rapid increase in sorghum midge population density. This is especially important when the time of sorghum flowering in the region is extended by a wide range of planting dates and maturities. Typically, the first two generations occur on

Johnsongrass before sorghum midge adults migrate to flowering grain sorghum (Teetes et al., 1980, Doggett 1988, Boyd and Baily 2000).

Symptoms and Damage

Sorghum midge larvae feed on the newly fertilized ovary preventing kernel development and causing direct grain loss. Usually a sorghum panicle infested by sorghum midge will have, depending on the degree of damage, various proportions of normal kernels scattered among non-kernel-bearing spikelets. Glumes of affected sorghum florets fit tightly together because normal seed development was disrupted (Boyd and Bailey, 2000; Teetes et al., 1999). The damaged heads (panicles), also appear blasted and pinkish.

The feeding by sorghum midge larvae typically prevents normal grain development with total destruction of the grain. Thus, damage caused by sorghum midge in terms of yield loss is a direct function of the number of sorghum midge present during flowering. For example, if ten percent of the spikelets are damaged then grain yield will be reduced approximately 10%. In Africa, grain yield lost due to midge damage was estimated to be 91,000 tons in Nigeria in 1958, and yield losses as high as 25% have been reported to occur in Sudan (Cowland, 1935; Harris 1961a, b; Young and Teetes 1977).

Harris (1980), emphasized that damaging sorghum midge population levels are best attained by delayed planting, multiple planting of the same test materials, or the use of earlier planting of susceptible sorghums in which midge populations reach high levels by the time the test material are blooming. Sharma and Teetes (1995), reported that landrace varieties most often flower later and not uniformly, while high yielding early flowering cultivars often are uniform; though, sorghum sown and flowering later than normal is exposed to sorghum midge for a long period of time and can suffer severe damage.

Economic Impact

Sorghum midge is estimated to destroy between 10 to 15% of the annual crop in the world (Sharma and Teetes, 1995). In Texas, losses due to midge vary from year to year, but economic loss commonly exceeds $US 28 million per year. In 1990, nearly 30% of sorghum grain valued $US 7 million was damaged by the midge in Western Kenya. In Southern Africa, midge damages almost 25% of the sorghum grain production.

The economic threshold for midge is quite low and only one sorghum midge per panicle cause significant negative economic impacts. Boyd and Bailey (2000) concluded that if genetic resistance were available economic threshold levels for resistant varieties could be increased to five adult midges per panicle in anthesis. This higher threshold is due to the midge’s lower egg-laying capacity on resistant varieties. Teetes et al., (1999) reported that a $10 insecticide application is justified when there is about one sorghum midge per panicle of susceptible sorghum and about five sorghum midges per panicle of resistant sorghum.

Mechanisms of Control

There are several control mechanisms to suppress damage due to sorghum midge. These include cultural, biological, chemical controls as well as genetic resistance. Cultural control methods are important and effective at minimizing sorghum midge damage. These include avoidance by uniform and early planting of sorghum which minimizes exposure to higher sorghum midge population densities (Harris, 1980; Teetes and Pendleton 1994, and Dogget 1988). Another cultural method is through control of alternate hosts such as Johnsongrass. Alternate hosts enable sorghum midge populations to build up between emergence from diapause or hibernation and then be available for infestation on the main crop. Mott et al., (1996) reported that deep plowed sorghum residues reduce the population abundance and damaging infestation levels.

For biological control there are several natural enemies but the level of midge control depends upon the balance between these parasites (Dogget, 1988). For this reason biological control has not been widely used for sorghum midge control in any sorghum production area.

In the US, chemical control has been an important and necessary mechanism of sorghum midge control when no other effective alternatives were available. Chemical control is highly effective, reducing sorghum midge populations by 90% (Sharma et al., 1997). However, the effect is short term and multiple treatments are required to maintain control. These applications are expensive and are seen as ecologically unfriendly because chemicals can reduce natural occurring enemies and are environmentally dangerous because of safety and residue buildup concerns (Sharma et al., 1997, and Dogget, 1988).

From an environmental and efficiency standpoint the use of genetic resistance to sorghum midge is the most logical and effective means to control the pest. Sharma et al., (1997) reported that the use of resistant sorghum cultivars can slow down the rate of the insect pest increase and areas planted with midge resistant cultivars will reduce midge infestation pressure by over a 1,000 times compared to areas planted with susceptible varieties (Sharma et al., 1997). Genetic resistance has been applied in some production systems with great effectiveness; in others its success has been much less effective. There are several reasons for these different results, including agronomic adaptations, sorghum midge population cycles and the types of genetic resistance used in breeding. All of these factors must be considered when genetic resistance to sorghum midge is to be used as the primary means of control.

Sources of Midge Resistance

For many years sorghum breeders have screened for resistance to sorghum midge in exotic sorghum germplasm. Systematic field-based screenings for sorghum midge resistance were conducted in the early 1960's (Harris, 1980; Dogget, 1988). From these evaluations, more than 120 sources of resistance were identified, and among these sources were lines that have been important in the development of sorghum cultivars with sorghum midge resistance. These include AF28, AF117, SGIRL-MR-1, SC52-14E, SC63-14E, SC175-14E, SC239-14E, SC319-14E, SC414-14E and SC574-14E. The SC lines were developed from zera-zera sorghums in the sorghum conversion program from the Ethiopia-Sudan region (Stephens et al., 1967). Peterson et al., (1995) listed thirty-one sources of resistance to midge developed from conversion program in Texas and Australia. He reported that TAM 2566 has been the major source of resistance used in the sorghum midge resistance breeding program at Texas A&M University. The Texas A&M University sorghum breeding program has released and registered fifteen sorghum germplasm lines resistant to sorghum midge in 1985 and others such as CS24: 389-390, CS31: 498-499, CS22: 1273, CS22: 1271, and CS22: 1271-1272 (Peterson et al., 1985).

Mechanism of Midge Resistance

Sorghum researchers have identified many different sources of genetic resistance to sorghum midge and these sources can be grouped into one of three basic mechanisms of resistance: tolerance, antixenosis and antibiosis (Franzmann, 1993 and Sharma et al., 1997).

Tolerance refers to resistance in which a plant is able to withstand or recover from damage caused by insect abundance that would cause damage on a susceptible type of plant. Numerous studies have been conducted to confirm tolerance and it was found that there was no weight compensation between resistant and susceptible genotypes following sorghum midge damage (Hallman et al., 1984; Franzmann and Bulter, 1993; and Waquil and Teetes, 1990). However, Sharma et al., (1997) pointed out that midge resistant genotypes have a better capacity for compensation in grain mass than the sorghum midge susceptible cultivars. Since the studies were not conclusive it seems that this type of resistance is not important to sorghum midge resistant genotypes.

A second mechanism of resistance to midge is antixenosis, which means that the midge have a non-preference for oviposition on these genotypes. Genotypes of sorghum that possess this level of resistance may have several different morphological characteristics that facilitate this resistance. Some resistant sorghum genotypes such as TAM2566, Tx2782, released in 1981 (Peterson et al., 1983), AF-28, DJ 6514 and IS 3461 begin anthesis very early in the morning prior to the emergence of the female midge. In addition, many of these types have short, tight glumes making it difficult for the female midge to oviposite in the floret; thus fewer eggs are laid in these genotypes compared with susceptible genotypes (Wiseman and McMillian 1968; Harris, 1980; Sharma 1985; Jimenez, 1992, Diariso et al., 1995, and Diariso et al., 1998). However, these tight short glumes are often tightly adhered to the grain at maturity making it difficult to thresh the grain cleanly (Rossetto et al., 1984, and Rooney, 2004).

The third resistance mechanism is antibiosis. Antibiosis resistance affects the biology of the insect. It may result from lack of a necessary food material or the presence of a substance deleterious to the insect (Painter, 1951), so pest abundance and subsequent damage is reduced compared to that which would have occurred if the insect was on a susceptible genotype. It often results in increasing mortality or reduced longevity and reproduction of the insect. For example, genotypes TAM 2556, DJ 6514, ICSV 745, and the hybrid ATx2755/Tx2767 were found to show antibiosis to sorghum midge larvae. In several reports the post-embryonic developmental period (egg to adult) is prolonged by 5 - 8 days when the sorghum midges are reared on midge resistant genotypes with an antiobiosis mechanism (Melton and Teetes, 1984; Waquil et al., 1986; Sharma et al., 1993). In addition, adult emergence was delayed by 4 – 8 days on resistance genotypes resulting in a 10-14 day increase in the life cycle, which is highly significant in reducing midge populations. Antibiosis to sorghum midge is also expressed in terms of smaller size of larvae, reduced fecundity, and/or low larval survival. They concluded that non-preference (antixenosis) and antibiosis were the major mechanisms of resistance.

Genetics of Resistance

In a review of breeding for midge resistance, Henzell et al., (1997) summarized that the inheritance of midge resistance is usually complex and in many cases conflicting. Given that there are several different mechanisms of resistance to the pest and that they involve both morphological and biological factors this observation is not unexpected. In most reports midge resistance is reported as quantitative with multiple loci contributing to resistance (Henzell et al., 1997). The gene action in these reports ranges from completely recessive to partially dominant with both general and specific combining ability gene effects being significant (Henzell et al., 1997).

Boozaya-Angoon et al., (1984) evaluated sorghum genotypes resistant to the sorghum midge. Resistant genotypes such as SC175-14E, SC423-14E, MB-10 and SGIRL-MR-1 were crossed with susceptible genotypes Wheatland, OK94, and Caprock. The parents, F1, F2, F3, and back cross populations were visually rated for midge damage after natural midge infestation. They found that resistance to sorghum midge was controlled by recessive genes at two or more loci. The genotype SGIRL-MR-1 was observed to behave differently in crosses from the other three sources of resistance and the genotype Caprock gave a higher number of susceptible plants than the other susceptible parents. Based on these results they concluded that it is difficult to transfer genes for sorghum midge resistance into good agronomic B-lines by simple hybridization and the character of small glumes carried by resistant genotypes was seen as a useful genetic marker.

Widstrom et al., (1984); Agrawal et al., (1988); Singh (1997); and Sharma et al., (2002) conducted similar research to study the inheritance of resistance to sorghum midge. They used resistant parents crossed to susceptible genotypes and their reciprocals crosses and found that resistant x resistant parental crosses result in highly resistant progeny, while those involving resistant x susceptible and susceptible x resistant parents showed to be moderately susceptible with susceptible x susceptible parent crosses the F1 hybrids were susceptible, and that result led to the conclusion that resistance to sorghum midge is inherited quantitatively, with additive genes and some cytoplasm effects controlling resistance. On the other hand, susceptibility to sorghum midge is complete or incompletely dominant in some parents. Reddy et al., (1995) reported that at least two pairs of recessive genes determine the resistance in genotype AF28 and genes with minor effects are also present.

Sharma (1993) speculated that resistance to sorghum midge is associated with the genetic inheritance of floral morphology. Specific traits included the degree of opposition of glumes, closed spikelets, and short and tight glumes that hinder oviposition and limit the space between glumes and ovary for the development of sorghum midge larvae. If the mechanism of resistance was antixenosis, it is logical to expect that the inheritance of these traits would also be associated with midge resistance. Similar relationships of morphological traits with resistance to a pathogen have been reported previously (Klein et al., 2001).

Santos and Carmo (1974) reported that tannin content of sorghum grain was one of the factors imparting sorghum midge resistance. Tannin and protein content were found to be greater in some midge resistant lines than in susceptible while soluble sugar content was lower in midge resistant lines. The composition of sorghum grain varies over the season, and these changes have been linked with the variation in expression of resistance to sorghum midge (Sharma, 1993).

In summary, inheritance studies clearly indicate that midge resistance is a heritable trait and that selection will result in enhanced midge resistance. However, since the inheritance of midge resistance seems to be complex and given that gene action ranges from recessive to partially dominant, the production of resistant hybrids will most likely require similar midge resistance sources in both parents of the hybrid.

Breeding for Midge Resistance

The main objective of breeding for sorghum midge resistance is to develop lines, varieties and hybrids with sorghum midge resistance. Over the past 50 years, several different improvement programs worldwide have emphasized selection for midge resistance as a major breeding objective. These programs have utilized an array of approaches, from traditional breeding methods such as pedigree and population approaches to more recent attempts to integrate marker-assisted selection into the midge resistance breeding effort.

Breeding for midge resistance is often difficult. To date, it has not been possible to maintain and rear midge in a greenhouse or laboratory setting. Consequently, all midge screening and evaluation must be done in a field setting with natural populations of the pest. While the results should be applicable to production systems, this approach is somewhat limited because screening can only be completed when there are consistent and reliable midge levels present to ensure uniform pressure on all germplasm being evaluated. If midge levels are uniform throughout a growing season then this is not a problem, but if midge populations are highly variable during the season the program must evaluate only during the time of high and more importantly consistent pressure. This simple biological fact has influenced the approach and results of many different midge resistance breeding programs.

In the USA, breeding for sorghum midge resistance was initiated at Texas A&M University soon after usable resistance was found, and hybrids that combine high levels of resistance to sorghum midge and good agronomic types are available in both the public and private sectors (Peterson et al., 1995). The primary focus for some programs was the development of highly resistant female and male lines, primarily utilizing antixenosis as the mechanism of resistance. Selection for midge resistance in the US cannot be successfully completed in a normal planting window because midge populations will not be high enough to produce consistent ratings of susceptibility, if any rating can be made at all. Consequently, midge breeding programs have had to utilize late planting dates. These late planting dates ensure that these nurseries will flower after the main production areas have completed anthesis and thus high levels of midge will be present to provide consistent pressure on the nursery. This approach was extremely effective at identifying lines with very high levels of midge resistance (Peterson, 2003), but there is significant concern that the agronomic adaptation of these lines and hybrids will also be different than normal planting dates because they have developed in an environment that is typically hotter, drier and a shorter growing season. This likely may have an effect on agronomic potential when compared with traditional sorghum hybrids.

The Department of Primary Industries (DPI) in Queensland has had an active midge resistance breeding program for over thirty years. While the breeding approaches and sources of resistance utilized are similar to those used in the US systems, the environmental and biological conditions for midge screening are quite different. In Queensland midge pressure is moderate and consistent regardless of the time. Evidently, suitable alternate hosts and a milder climate insure the continual presence of the pest. Therefore, it is possible to screen effectively for midge susceptibility in normal planting times. Consequently, the DPI program has been able to both select for agronomic adaptation and midge resistance concurrently. This has been extremely effective and all hybrids grown in Australian must have some level of midge resistance as producers expect to control or minimize damage with genetic resistance; they do not use chemical control. The levels of resistance in DPI germplasm vary; hybrids such as A23277/40386 lose no grain under sorghum midge pressure, whereas AQL39/QL36 (similar resistance to ATx2755/Tx2767) loses 40 – 50% of its grain, but susceptible hybrids such as RS610 have virtually no seed set (Henzell et al., 2001). The use of molecular markers, linked with sorghum midge resistance is another research tool that the Australian breeding program relies on and marker assisted selection is being used to pyramid the regions for ovipositional antixenosis and antibiosis to get higher levels of more durable resistance for sorghum midge (Dillon et al., 2001, Henzell et al., 2001).

These two extremes, both based on environmental conditions and their relative effect on the pest dictate the approaches used in breeding for resistance. The goal of this project is to utilize germplasm from both programs to determine if either provides suitable resistance to midge and if so, does it come at a cost in adaptation when grown in Texas.

MATERIAL AND METHODS

Plant Material and Experimental Design

A total of 18 hybrids were obtained for use in this study. The hybrids were selected based on their relative level of midge resistance and agronomic adaptability. Based on midge resistance these hybrids were broadly classified as susceptible, moderately resistant or highly resistant (Table 1). They were obtained from Dr. Gary C. Peterson, TAES – Lubbock; Ms. Lisa Blakely, Garst-AgriPro, Hereford, Texas; Dr. W. L. Rooney, TAMU – College Station; and Mr. John Jaster, Pioneer Hi-Bred, Taft, Texas. Due to availability, some hybrids were included in only a single year.

Field Trials

The experimental design used for this experiment was a factorial design with variables including resistance classification, hybrids, and treatments (planting dates and insecticide application). The trial was planted in a randomized complete block design with three replications and tow rows per plot with 21 feet each, in Corpus Christi, Texas in 2003 and 2004 and in College Station, Texas in 2003. In both locations were planted 4 grams of seed per row, and seed stand of 70,000 seeds/acre. Fertilizer N P K (60-40-40) lbs/acre was applied on pre-plant and 100 lbs of Nitrogen (N2)/acre were applied as side dressed in College Station 2003. At Corpus Christi, 319 lbs/acre of N P K (32-0-0) and 0.6 lbs/acre of Zinc (Zn) was applied on pre-plant. Treatments were a combination of planting dates and insecticide applications. Treatment 1 was planted March 10, 2003 and March 9, 2004 in Corpus Christi, Texas when sorghum is normally planted and midge pressure during anthesis is minimal. The remaining two treatments were planted March 27, 2003, and April 1, 2004 and sorghum midge infestation during anthesis is expected. One of the treatments was treated twice on June 4, 2003 and June 9, 2003 with 1.9 oz of Karate respectively at anthesis to reduce midge damage and the other was left untreated. In 2004 it was treated four times June 4, June 7, June 10, and June 14, with 1.5 oz of Karate in each treatment.

In College Station, Texas 2003 the treatment 1 was planted March 10th, and the two late planting treatments were planted on April 4, 2003. The late treatment with insecticide application was sprayed on June 1, 2003 with 6.4 oz of Asana excel. It was irrigated twice April 17 and June 3, 2003 with 6 inches of water each time of irrigation.

All environments were grown using standard agronomic practices at each location and herbicide (Roundup) was applied to control weed infestation. The trials in Corpus Christi were rainfed while the trial in College Station was irrigated twice to insure good production potential. In each location, data were collected on days to anthesis, plant height, panicle exsertion, grain and plant color, desirability, lodging, midge damage, grain yield and test weight. These traits are defined and measured as follows:

Days to anthesis – days from planting until the majority of the panicles are at 50% flowering.

Plant height – measure of average height in inches of plants from ground to tip of the panicle.

Panicle exsertion – measure in inches from the collar of the flag leaf to the first seed of the panicle. At least four panicles in a plot were measured to get a data point.

Grain color – classified as red, yellow and or white.

Plant color – is either purple (P), tan (T) or red (R).

Desirability rating – the overall desirability, adaptation or breeding potential ratings made near or at maturity. Rated on a scale of 1 to 9, with 1 being the best and 9 the poorest.

Lodging rating – lodging due to weak neck, stalk breakage, or high wind. Scored as a visual estimate of percent lodging. Rated on a scale 1 to 9, with 1 no lodging and 9 severe lodging.

Stand – number of plants in the plot were visually rated on a scale 1 to 5, with 1 equal to good stand up to 5 with no plants, plot is empty.

Sorghum midge damage rating – damage rating based on percentage of undeveloped kernels (blasted florets). Rated on a scale of 1 to 9; with 1 less than 5% kernel loss up to 9 = 81-100% kernel loss.

Test Weight – weight of a quart container filled with grain expressed in pounds per bushel (lb/bu).

Grain yield – weight of harvested grain expressed in pounds per acre (lb/acre) with moisture content of 13%.

Table1: Hybrids selected for the midge resistance study, their origin and reported resistance level.

Entry	Pedigree	Source	Midge Resistance Rating †
1	PM435	Pioneer Hi- Bred	MS
2	PM682	Pioneer Hi- Bred	MR
3	PM 090	Pioneer Hi- Bred	R
4	PM429	Pioneer Hi- Bred	R
5	Garst 5515	Garst Seed Co.	MR
6	Garst 5616	Garst Seed Co.	MS
7	A8PR1013*Tx2882	TAES	R
8	ATx640*Tx2880	TAES	R
9	ATx640*Tx2882	TAES	R
10	ATx399*TX2737	TAES	S
11	ATx378*RTx430	TAES	S
12	ATx2752*RTx430	TAES	S
13	ATx2752*Tx2783	TAES	S
14	ATx631*RTx436	TAES	S
15	84G62	Pioneer Hi- Bred	S
16	82G63	Pioneer Hi- Bred	S
17	DKS54-00	Monsanto	S
18	DK52	Monsanto	S

† Midge ratings are as follows and were provided by the supplier of the seed; MS = moderately susceptible, MR = moderately resistant, R = resistant, S = susceptible

Insect Evaluation

Sorghum midge populations were measured daily from the onset of and until the completion of anthesis. Sorghum midge populations were measured as the average number of midge present in 20 randomly selected flowering panicles within the test. Sorghum midges present in the two row plots were recorded up to the end of flowering stage by visual observation of insects attempting oviposition on the flowering florets. The sorghum midge damage rating was measured at physiological maturity and ratings were based on the percentage of spikelets in the panicles that fail to set seeds using the scale described by Harris (1980) and Reddy et al., (1995). The scale for midge damage is described as follows:

1 - Indicates less than 5% midge damage

2 - Indicates more than 5% and less than 10% midge damage

3 - Indicates more than 10% and less than 20 % midge damage

4 - Indicates more than 20% and less than 30 % midge damage

5 - Indicates more than 30 % and less than 60% midge damage

6 - Indicates more than 60% and less than 70% midge damage

7 - Indicates more than 70% and less than 80% midge damage

8 - Indicates more than 80% and less than 90% midge damage

9 - Indicates more than 90% midge damage.

Statistical Analyses

Analysis of the distribution of data was normal for all data, except for sorghum midge incidence. For this variable, transformation using the $\sqrt{(x+0.5)}$ formula successfully normalized the data prior to analysis. All other variables were analyzed using untransformed data. Prior to a combined analysis, data from the three environments were checked for homogeneity of error variances using Bartlett's test for homogeneity (Steel and Torrie, (1980)). From this test no evidence of heterogeneous error was detected and the data were combined among treatments and across environments. All statistical analyses were completed using PROC ANOVA and GLM (General Linear Model) procedures using SAS® (SAS Institute 1999) and SPSS® Software.

Individual analyses were performed for days to flowering, plant height, midge incidence and score, test weight and yield in each treatment (Appendix 1). Analysis within treatments assumes that genotypes were a random effect using the following model (Table 2). Tests of significance were based on expected mean squares (Table 2). Means among genotypes were compared using the least significance difference (LSD) procedure, with a level of significance of 0.05 (Steel and Torrie (1980).

Table 2: Degrees of freedom, mean squares, and expected mean squares for individual analysis of variance for each treatment.

Source	df†	Mean Squares	Expected Mean Squares
Replications	r-1	MSr	$\sigma^2e + g\sigma^2r$
Genotypes	g-1	MSg	$\sigma^2e + r\sigma^2g$
Error	(r-1)(g-1)	MSe	σ^2e
Total	rg-1		

† Based on type III sum of squares.

Combined analyses for all treatments in each environment were completed with replication and genotypes as random effects and classes and treatments as fixed effects. Tests of significance are based on expected mean squares (Table 3). Means of genotypes within classes were compared among three treatments using the least significance difference with a probability level of 0.05.

Table 3: Degree of freedom, mean squares and expected mean squares for combine analysis among treatments in each location per year.

Source	df†	Mean Squares	Expected Mean Squares
Replications	r-1	MSr	$\sigma^2e + rtg\sigma^2r$
Class	c-1	MSc	$\sigma^2e + rt\,\sigma^2g(c) + rtg\,\sigma^2c$
Genotypes(Classes)	(g-1)c	MSg(c)	$\sigma^2e + rt\,\sigma^2\,g(c)$
Treatments	t-1	MSt	$\sigma^2e + r\sigma^2g(c)t + rgc\sigma^2t$
Class x Treat	(c-1)(t-1)	MSct	$\sigma^2e + r\sigma^2g(c)t + rg\sigma^2ct$
Genotype (class) x Treatment	(g-1)(t-1)c	MSg(t)c	$\sigma^2e + r\sigma^2g(c)t$
Error	gct(r-1)	MSe	σ^2e
Total	rcgt-1		

† Based on type III sum of squares.

The combined analyses across environments was performed to test stability of genotypes within classes across environments assuming environments, replications and genotypes as random factors and classes and treatments as fixed factors. Means were compared using the least significance difference with a probability level of 0.05 and the appropriate mean squares were reported based on the component under analysis (table 4). The numbers of sorghum midge adults recorded in College Station in 2003 were not combined with sorghum midge rating score recorded in Corpus Christi, and analyses were performed for each specific environment.

Table 4: Degree of freedom, mean squares, and expected mean squares to combined analysis of variance for across locations and environments.

Source	df†	Mean Squares	Expected Mean Squares
Environment	e-1	MSE	$\sigma^2e + \sigma^2g(c)E + \sigma^2r(E) + \sigma^2E$
Treat	t-1	MST	$\sigma^2e + \sigma^2g(c)ET + \sigma^2g(c)T + \sigma^2ET + \sigma^2T$
Treat x Environment	(t-1)(e-1)	MSET	$\sigma^2e + \sigma^2g(c)ET + \sigma^2ET$
Rep(Environment)	(r-1)e	MSr(E)	$\sigma^2e + \sigma^2r(E)$
Class	c-1	MSC	$\sigma^2e + \sigma^2g(c)ET + \sigma^2g(c)E + \sigma^2g(c) + \sigma^2CE + \sigma^2C$
Class x Environment	(c-1)(e-1)	MSCE	$\sigma^2e + \sigma^2g(c)E + \sigma^2CE$
Class x Treatment	(c-1)(t-1)	MSCT	$\sigma^2e + \sigma^2g(c)ET + \sigma^2g(c)T + \sigma^2CT$
Genotype (Class)	(g-1)c	MSg(c)	$\sigma^2e + \sigma^2g(c)e + \sigma^2g(c)$
Genotype (Class) x Environment	(g-1)(e-1)c	MSg(c)E	$\sigma^2e + \sigma^2g(c)E$
Genotype (Class) x Treatment	(g-1)(t-1)c	MSg(c)T	$\sigma^2e + \sigma^2g(c)et + \sigma^2g(c)T$
Genotype (Class) x Treatment x Environment	(g-1)(t-1)(e-1)c	MSg(c)ET	$\sigma^2e + \sigma^2g(c)ET$
Pooled Error	(gcet-1)(r-1)	MSe	σ^2e
Total	gcet-1		

† Based on type III sum of squares.

RESULTS AND DISCUSSION

College Station 2003

In College Station, significant variation among genotypes, classes, and treatments was detected for days to anthesis, plant height, average number of adult midges; test weight and grain yield (Table 5). The interaction class by treatment was significant for days to anthesis and grain yield, but not for plant height, midge average adults, and test weight (Table 5). The interaction genotypes by treatments were significant for plant height, average number of adult midges and grain yield, but not for days to anthesis and test weight (Table 5).

Table 5: Mean squares from the analysis of variance of data collected on agronomic parameters in College Station, Texas in 2003.

Source	Df†	Days to anthesis	Plant height (inches)	Average number of adult midges	Test Weight(lb/bu)	Yield (lb/acre)
Replications	2	18.7 *	5.6	1.8 *	8.0	3748152.0 *
Class	3	91.7	398.9	1.8	44.5 *	5492550.6
Genotypes(Classes)	14	32.8 *	138.5 *	0.9 *	6.6	3085425.2 *
Treatments	2	21570.2 *	217.6 *	4.1 *	138.6 *	5829908.6 *
Class x Treat	6	22.8 *	12.3	0.4	7.7	4487639.1 *
Genotype (class) x Treatment	28	5.1	14.8 *	0.3 *	3.5	2171441.2 *
Error	106	4.1	5.5	0.1	4.9	1072307.2
Total	161					

† Based on type III sum of squares.
* Significantly different from zero at the 0.05 probability level

Differences in days to anthesis, plant height, average number of adult midges, test weight, and grain yield were detected between early and late planting, but the only traits that were different across all treatments was the number of adult midges and test weight (Table 6).

As expected, sorghum midge incidence was higher in the late planting treatment without insecticide application. Consequently yields and test weight in this treatment were severely reduced (Table 6). These results confirm that early planting is an effective means of avoiding sorghum midge damage.

Table 6: Comparison of means among treatments in College Station 2003 for five agronomic measurements. Days-to-anthesis, plant height, average number of adult midges, test weight, and grain yield were measured as described in the materials and methods.

Treatments	Days to anthesis	Plant height (inches)	Average number of adult midges	Test weight (lb/bu)	Grain yield (lb/acre)
Early planting	92 a	51 b	3.0 c	59.3 a	5959.0 a
Late planting (without insecticide)	90 b	55 a	7.0 a	55.5 c	4954.0 b
Late planting (with insecticide)	90 b	54 a	5.0 b	57.5 b	5350.8 b
LSD (5%)	1.3	1.1	0.6	0.8	395.1
CV	3.7	2.7	14.5	3.8	19.1

As expected, significant variation was detected among classes, and among genotypes within the classes. The genotypes PM435 and ATx378*RTx430, classified as moderately susceptible and susceptible, respectively, were the earliest average days to anthesis of 87 days, respectively. The sorghum midge incidence were highest on genotypes DKS54-00 (susceptible), ATx631*RTx436 (susceptible), PM429 (resistant) and ATx2752*Tx2783 (susceptible) with average mean number of sorghum adult midges of 8.0, 7.0, 7.0, 6.0 respectively. The lowest sorghum midge incidence was observed on genotype PM435 known as moderately susceptible with average number of adult midges of 2.0 (Table 7). Based on this data resistance and incidence of the pest appear unrelated.

Across all treatments, grain yield and test weight were higher in susceptible genotypes with a few exceptions, presumably due to their extreme susceptibility in late treatments (Table 7). Unfortunately hybrids with a very high level of resistance were generally the lowest yielding.

Table 7: Average means across treatments in College Station 2003 for five agronomic measurements, days to anthesis, plant height, average midge adults, test weight and grain yield.

Hybrids	Source	Class	Days to anthesis	Plant Height (inches)	Average midge adults	Test weight (lbs/bu)	Grain yield (lbs/acre)
PM435	Pioneer Hi- Bred	MS	87	48	2.0	57.2	5612.3
PM682	Pioneer Hi- Bred	MR	91	53	5.0	57.2	5748.9
PM 090	Pioneer Hi- Bred	R	94	47	3.0	55.0	5434.1
PM429	Pioneer Hi- Bred	R	92	48	7.0	57.5	5580.4
Garst 5515	Garst Seed Co.	MR	89	50	3.0	57.0	6185.5
Garst 5616	Garst Seed Co.	MS	89	54	4.0	58.9	5774.1
A8PR1013*Tx2882	TAES	R	92	53	5.0	55.3	4148.6
ATx640*Tx2880	TAES	R	94	53	4.0	56.8	5259.8
ATx640*Tx2882	TAES	R	95	50	5.0	55.4	4402.2
ATx399*TX2737	TAES	S	89	48	4.0	57.6	4669.6
ATx378*RTx430	TAES	S	87	61	4.0	58.1	6127.9
ATx2752*RTx430	TAES	S	88	56	6.0	57.0	5346.6
ATx2752*Tx2783	TAES	S	89	59	7.0	58.0	5792.3
ATx631*RTx436	TAES	S	91	59	7.0	58.1	5086.8
84G62	Pioneer Hi- Bred	S	90	51	4.0	59.1	6503.4
82G63	Pioneer Hi- Bred	S	91	57	7.0	58.9	5616.7
DKS54-00	Monsanto	S	94	60	8.0	57.3	4705.5
DK52	Monsanto	S	89	54	5.0	58.4	5587.2
Means			91	53	5.0	57.4	5421.2
LSD (5%)			0.7	0.5	0.4	0.5	228.1
CV (5%)			3.7	4.4	14.5	3.8	19.1

The genotype A8PR1013*Tx2882 known as resistant showed the lowest grain yield performance among genotypes with 4148.6 lbs/acre, whereas the highest yield performance was observed for genotype 84G62 known as susceptible with grain yield performance of 6503.4 lbs/acre.

When mean of the different classes were compared clear trends were detected. In early plantings, susceptible hybrids were consistently highest yielding while the midge resistant hybrids were significantly lower. In late plantings with insecticide control, susceptible hybrids were slightly lower yielding than resistant, moderately susceptible and moderately resistant hybrids (Table 8). This fact suggests that in presence of midge populations the resistant material will produce more grain than susceptible materials. In late planting without insecticide control the moderately resistant and moderately susceptible hybrids showed higher yield than susceptible and resistant hybrids. Across all classes, hybrids with some levels of resistance yields better than susceptible and resistant hybrids (Table 8).

Table 8: Means of midge resistance classes for five agronomic traits in College Station, Texas in 2003.

Trait	Class	Resistant	Moderate Resistance	Moderate Susceptible	Susceptible
Days to anthesis	Early Planting	95	92	88	91
	Late Planting, No Insecticide	93	89	88	89
	Late Planting, Insecticide	93	89	88	89
	Mean	94	90	88	90
	L.S.D.	0.9	0.9	0.9	0.9
Plant height	Early Planting	47	51	48	54
	Late Planting, No Insecticide	52	52	53	58
	Late Planting, Insecticide	52	52	52	57
	Mean	50	52	51	56
	L.S.D.	1.1	1.1	1.1	1.1
Midge adults	Early Planting	3.0	3.2	3.0	3.0
	Late Planting, No Insecticide	7.5	5.8	3.2	7.0
	Late Planting, Insecticide	5.0	3.5	4.0	6.0
	Mean	5.0	4.0	3.4	5.0
	L.S.D.	0.8	0.8	0.8	0.8
Test Weight	Early Planting	57.7	59.0	59.2	60.0
	Late Planting, No Insecticide	54.4	53.8	57.7	55.9
	Late Planting, Insecticide	55.8	58.4	57.3	58.2
	Mean	55.9	57.1	58.1	58.0
	L.S.D.	1.0	1.0	1.0	1.0
Yield	Early Planting	4771.1	6362.5	5749.0	6575.9
	Late Planting, No Insecticide	4764.8	5518.6	5576.1	4795.4
	Late Planting, Insecticide	5359.2	6020.6	5754.5	5107.4
	Mean	4965.0	5967.2	5693.2	5492.9
	L.S.D.	483.9	483.9	483.9	483.9

Corpus Christi 2003

In Corpus Christi, significant variation was detected among genotypes, classes, and treatments for days to anthesis, plant height, and grain yield; midge damage rating score was determined to be significant for genotypes (Table 9). Test weight was significant for genotypes. Significant interaction class by treatment was not detected for all traits under study, but significant interaction genotypes by treatment were detected for midge damage rating, test weight and grain yield (Table 9). The results suggest that there was a great variability among genotypes within classes of sorghum midge resistance for all agronomic traits in study.

Table 9: Mean squares from the analysis of variance of data collected on agronomic parameters in Corpus Christi, Texas in 2003.

Source	Df†	Days to anthesis	Plant height (inches)	Midge damage rating (1- 9)	Test Weight (lb/bu)	Grain yield (lb/acre)
Replications	2	15.4	3.1	0.34	1.1	191448.0
Class	3	74.0	115.0 *	0.28	56.1	3104490.6
Genotypes(Classes)	14	33.8 *	22.6 *	0.52 *	16.8 *	2613405.1 *
Treatments	2	27.9 *	92.2 *	0.03	3.5	4102723.7 *
Class x Treat	6	2.7	9.4	0.21	1.4	355315.9
Genotype (class) x Treatment	28	4.5	5.2	0.27 *	7.0 *	675578.3 *
Error	106	5.1	4.2	0.13	2.1	197383.9
Total	161					

† Based on type III sum of squares.
* Significantly different from zero at the 0.05 probability level

As in College Station the early planting was different from the late planting treatments for days to anthesis, plant height and grain yield, but not for sorghum midge damage rating and test weight (Table10). The early planting and late planting without insecticide application showed no variation for grain yield performance (Table 10). The similarity observed in grain yield potential for early and late planting without insecticide application was probably due to water stress that occurred early in the growing season as the location received late season rains that eliminated the typical late season drought. Thus, genotypes in early planting could not express their genetic potential under water stress as well as in late planting without insecticide application.

Among hybrids days to anthesis ranged from 63 to 70 days while the range in height were quite narrow ranging from 39 to 45 (Table 11). The sorghum midge damage rating was highest on genotype DKS54-00 with an average mean score 5.0, whereas the lowest sorghum midge incidence was observed on ATx2752*T2783, PM 429 and PM435 known as susceptible, resistant, and moderately susceptible with average mean midge incidence of 1.0, 1.0, and 1.0 respectively (Table 11). Test weight was observed to be higher in susceptible genotypes that showed good grain yield performance, and the variation among genotypes was greater ranging from 56 to 61.2 lbs/bushels (Table 11). Grain yield performance was observed to be lower on the resistant hybrid A8PR1013*Tx2882 with average mean yield of 1582.3 lbs/acre and the highest yield performance was observed on hybrid ATx2752*Tx2783 classified as susceptible for sorghum midge (Table 11).

Table 10: Comparison of means by treatment in Corpus Christi, Texas 2003 for five agronomic measurements.

Treatments	Days to anthesis	Plant height (inches)	Midge damage rating (1- 9)	Test weight (lb/bu)	Grain yield (lb/acre)
Early	68 a	40 b	1.9 a	58.1 a	2524.7 b
Late (without insecticide)	66 c	42 a	2.3 a	58.5 a	2644.1 b
Late (with insecticide)	67 b	42 a	2.0 a	58.6 a	3039.6 a
LSD (5%)	0.8	0.7	2.1	0.6	169.5
CV	3.4	4.9	23.5	2.5	16.2

Table 11: Average means across treatments in Corpus Christi, Texas 2003 for five agronomic measurements, days to anthesis, plant height, midge damage rating, test weight and grain yield.

Hybrids	Source	Class	Days to anthesis	Plant height (inches)	Midge damage rating(1- 9)	Test weight (lbs/bu)	Grain yield (lbs/acre)
PM435	Pioneer Hi- Bred	MS	63	41	1.0	59.3	3057.6
PM682	Pioneer Hi- Bred	MR	69	41	3.0	58.9	2241.6
PM 090	Pioneer Hi- Bred	R	67	38	2.0	57.0	3262.1
PM429	Pioneer Hi- Bred	R	68	38	1.0	58.5	2774.4
Garst 5515	Garst Seed Co.	MR	66	40	3.0	56.6	2653.1
Garst 5616	Garst Seed Co.	MS	67	41	3.0	58.0	2661.6
A8PR1013*Tx2882	TAES	R	70	40	3.0	55.8	1582.3
ATx640*Tx2880	TAES	R	68	41	2.0	56.8	2528.6
ATx640*Tx2882	TAES	R	70	38	2.0	56.3	2018.3
ATx399*TX2737	TAES	S	64	39	2.0	57.2	2515.7
ATx378*RTx430	TAES	S	64	45	2.0	58.3	3039.3
ATx2752*RTx430	TAES	S	64	43	1.0	58.8	3024.7
ATx2752*Tx2783	TAES	S	66	43	1.0	61.2	3708.1
ATx631*RTx436	TAES	S	69	43	2.0	59.5	2707.0
84G62	Pioneer Hi- Bred	S	67	41	2.0	61.2	3253.9
82G63	Pioneer Hi- Bred	S	67	43	2.0	60.9	3540.4
DKS54-00	Monsanto	S	68	43	5.0	58.5	2044.8
DK52	Monsanto	S	69	41	2.0	57.8	2636.7
Means			67	41	2.0	58.4	2736.2
LSD (5%)			0.5	0.4	0.3	0.3	97.8
CV (5%)			3.4	4.9	23.5	2.5	16.2

As in College Station means of different classes were compared and trends were detected. In early plantings, susceptible hybrids were constantly the highest yielding while the sorghum midge resistant hybrids were significantly lower yielding. In late planting, with insecticide control the susceptible and moderate susceptible hybrids were higher yielding than resistant and moderately resistant hybrids (Table 12). The same pattern was detected in late planting with no insecticide control where the susceptible and moderate susceptible hybrids yield slightly higher than resistant and moderately resistant hybrids (Table 12). Across all classes the average mean yield was higher in susceptible and moderately susceptible hybrids than hybrids with some levels of midge resistance. The results suggest that water stress observed in early and late plantings, as well as biotic stress, had a greater influence on expression of genetic potential among classes of resistance.

Table 12: Means of midge resistance classes for five agronomic traits in Corpus Christi, Texas in 2003.

Trait	Class	Resistant	Moderate Resistance	Moderate Susceptible	Susceptible
Days to anthesis	Early Planting	70.0	68.0	66.0	68.0
	Late Planting, No Insecticide	68.0	68.0	65.0	66.0
	Late Planting, Insecticide	68.0	69.0	65.0	68.0
	Mean	69.0	68.0	65.0	67.0
	L.S.D.	1.2	1.2	1.2	1.2
Plant height	Early Planting	39.0	40.0	39.0	40.0
	Late Planting, No Insecticide	39.0	40.0	41.0	43.0
	Late Planting, Insecticide	39.0	42.0	44.0	44.0
	Mean	39.0	41.0	41.0	42.0
	L.S.D.	0.9	0.9	0.9	0.9
Midge damage rating	Early Planting	2.0	3.0	2.0	2.0
	Late Planting, No Insecticide	2.0	3.0	3.0	3.0
	Late Planting, Insecticide	2.0	2.0	2.0	2.0
	Mean	2.0	3.0	2.0	2.0
	L.S.D.	0.7	0.7	0.7	0.7
Test Weight	Early Planting	56.8	57.5	58.2	58.8
	Late Planting, No Insecticide	56.7	57.9	58.3	59.6
	Late Planting, Insecticide	57.1	57.9	59.4	59.3
	Mean	56.8	57.7	58.6	59.2
	L.S.D.	0.7	0.7	0.7	0.7
Yield	Early Planting	2114.9	2095.2	2392.7	2877.1
	Late Planting, No Insecticide	2465.9	2389.2	2904.2	2741.9
	Late Planting, Insecticide	2718.5	2857.6	3281.9	3204.6
	Mean	2433.1	2447.3	2859.6	2941.2
	L.S.D.	239.9	239.9	239.9	239.9

Corpus Christi 2004

Significant variation among classes, genotypes and treatments were detected for days to anthesis, plant height, midge damage rating score, and test weight (Table 13). For grain yield significant variation was detected only among classes. The interaction Class x Treatment was significant for midge damage rating score but not for days to anthesis, plant height, test weight and grain yield (Table 13). For the interaction Genotype x Treatment, significant variation was detected for days to anthesis, plant height, midge damage rating score and test weight but not for grain yield (Table 13).

Comparison of treatment means indicated that early planting were different from both late planted treatments for days to anthesis, plant height, midge damage rating score, test weight, and grain yield. However, the late planted treatments did not differ for all agronomic traits under study (Table 14). The results suggest that early planting reduces the risk of severe sorghum midge attack and yield performance could be improved in early planting treatments than late planting treatments, and in this case insecticide applications were not adequate to control the pest effectively (Table 14).

Table 13: Mean squares for five agronomic parameters (days to anthesis, plant height, sorghum midge damage rating score, test weight and grain yield) from the evaluation of hybrids with midge resistance in Corpus Christi, Texas 2004.

Source	Df†	Days to anthesis	Plant height (inches)	Midge damage rating (1- 9)	Test Weight (lbs/bu)	Grain yield (lbs/acre)
Replications	2	19.9 *	4.4	0.2	2.8	176.9 *
Class	3	66.5	124.9 *	1.6 *	25.8	29.4 *
Genotypes(Classes)	8	26.7 *	65.1 *	0.8 *	16.2 *	9.8
Treatments	2	333.1 *	27.5 *	4.3 *	64.9 *	3.8
Class x Treat	6	4.1	0.8	0.7 *	11.1	1.7
Genotype (class) x Treatment	16	5.3 *	9.3 *	0.2 *	4.5 *	10.7
Error	70	1.5	3.1	0.1	1.1	9.5
Total	107					

† Based on type III sum of squares.
* Significantly different from zero at the 0.05 probability level

Table 14. Comparison of means by treatment in Corpus Christi 2004 for five agronomic measurements.

Treatments	Days to anthesis	Plant height (inches)	Midge damage rating (1- 9)	Test weight (lbs/bu)	Grain yield (lbs/acre)
Early planting	69 a	48 b	1.0 b	51.4 a	6259.9 a
Late planting (w/o insecticide)	63 b	50 a	4.3 a	52.2 a	4900.5 b
Late planting (with insecticide)	63 b	49 a	4.5 a	52.2 a	4950.1 b
LSD (5%)	0.6	0.8	0.5	1.4	517.7
CV	1.9	3.5	13.5	5.9	20.5

w/o = without insecticide control

There were fewer entries in the 2004 test because hybrids that were submitted by Pioneer Hi-Bred were no longer available. Days to anthesis ranged from 62 to 68 d and plant height ranged from 45 to 55 (Table 15). The genotypes Garst 5515 and Garst 5616 were the earliest. The sorghum midge incidence was highest on ATx399*Tx2737 known as susceptible with average mean score 6.0, whereas the lowest sorghum midge incidence was on ATx640*Tx2882, A8PR1013*Tx2882 and DKS54-00 with average mean midge damage rating incidence of 1.0, 2.0 and 2.0 respectively (Table 15). Test weight was observed to be slightly lower on the hybrid A8PR1013*Tx2882 with an average mean of 49.5 lbs/bushels but in general there was no greater variation among classes of sorghum midge resistance (Table 15). Grain yield performance was lowest on ATx399*Tx2737 and highest on 82G63 (Table 15). The results suggest that susceptible genotypes perform better than some resistant genotypes in absence of sorghum midge pressure.

Table 15: Average means across treatments in Corpus Christi, Texas 2004 for five agronomic measurements, days to anthesis, plant height, midge rating, test weight, and grain yield.

Hybrids	Source	Class	Days to anthesis	Plant Height (inches)	Midge damage rating (1- 9)	Test weight (lbs/bu)	Grain yield (lbs/acre)
Garst 5515	Garst Seed Co.	MR	63	49	4.0	51.9	4774.5
Garst 5616	Garst Seed Co.	MS	64	49	4.0	52.6	5137.8
A8P1013*Tx2882	TAES	R	68	45	2.0	49.5	5012.5
ATx640*Tx2882	TAES	R	68	45	1.0	50.4	4777.3
ATx399*TX2737	TAES	S	62	47	6.0	51.5	4189.5
ATx2752*RTx430	TAES	S	64	48	4.0	52.6	5390.8
ATx2752*Tx2783	TAES	S	63	50	4.0	53.7	6055.8
ATx631*RTx436	TAES	S	67	54	2.0	53.2	5903.5
84G62	Pioneer Hi- Bred	S	64	47	5.0	50.6	5049.8
82G63	Pioneer Hi- Bred	S	65	50	4.0	52.4	6279.8
DKS54-00	Monsanto	S	67	55	2.0	53.2	5829.4
DK52	Monsanto	S	66	50	2.0	51.4	6041.2
Means			65	49	3.4	51.9	5370.2
LSD (5%)			0.3	0.4	0.3	0.8	298.8
CV (5%)			1.8	3.5	13.5	5.9	20.5

The comparison of class means indicated the existence of trends among classes of sorghum midge resistance. In early plantings, moderately susceptible and susceptible hybrids were the highest yielding while the sorghum midge resistant material was slightly lower. In late planting, with insecticide control, the susceptible hybrids were higher yielding than resistant, moderately resistant, and moderately susceptible hybrids (Table 16). The same pattern was detected in late planting with no insecticide control where the susceptible and moderately susceptible hybrids produced grain yield slightly higher than resistant, moderately resistant, and moderately susceptible hybrids (Table 16). The result implies that midge pressure was not particularly high in this environment. Across all classes, the average mean yield was observed to be higher in susceptible and moderately susceptible hybrids than hybrids with some levels of midge resistance. Although there was slight variation among classes the results suggest that hybrids with some levels of resistance performs better or similarly in presence of midge than hybrids with some levels of susceptibility. In early planting, all classes of resistance to sorghum midge were observed to yield better than late plantings (Table 16).

Table 16: Means of midge resistance classes for five agronomic traits in Corpus Christi, Texas in 2004.

Trait	Class	Resistant	Moderate Resistance	Moderate Susceptible	Susceptible
Days to anthesis	Early Planting	73.0	67.0	68.0	69.0
	Late Planting, No Insecticide	65.0	60.0	63.0	62.0
	Late Planting, Insecticide	65.0	62.0	61.0	63.0
	Mean	68.0	63.0	64.0	65.0
	L.S.D.	0.6	0.6	0.6	0.6
Plant height	Early Planting	44.0	48.0	47.0	49.0
	Late Planting, No Insecticide	46.0	50.0	50.0	51.0
	Late Planting, Insecticide	45.0	50.0	49.0	50.0
	Mean	45.0	49.0	49.0	50.0
	L.S.D.	0.8	0.8	0.8	0.8
Midge rating score	Early Planting	2.0	1.0	2.0	1.0
	Late Planting, No Insecticide	2.0	7.0	4.0	5.0
	Late Planting, Insecticide	2.0	5.0	7.0	5.0
	Mean	2.0	4.0	4.0	4.0
	L.S.D.	0.6	0.6	0.6	0.6
Test Weight	Early Planting	48.7	51.7	53.1	51.7
	Late Planting, No Insecticide	50.4	52.5	52.4	52.6
	Late Planting, Insecticide	50.6	51.6	52.4	52.7
	Mean	50.0	52.0	53.0	52.3
	L.S.D.	2.0	2.0	2.0	2.0
Yield	Early Planting	5633.1	5782.2	6864.4	6400.7
	Late Planting, No Insecticide	4560.3	3624.4	3974.9	5260.8
	Late Planting, Insecticide	4491.3	4917.1	4574.3	5115.8
	Mean	4894.9	4774.6	5137.8	5592.4
	L.S.D.	571.6	571.6	571.6	571.6

Combined Analysis across Environments

Significant variation among environments, treatments by environment interaction, and genotypes within classes by treatments interaction were detected for days to anthesis, plant height, test weight and grain yield at the 5% level of significance, but significant variation was not detected among class x environment and class x treatment interactions (Table 17). The classes were detected to be significant for days to anthesis, plant height and test weight, but not significant for gain yield. For genotypes within classes significance was detected for days to anthesis and plant height but no significance was detected for test weight and grain yield. The genotype by treatment interaction was significant only for plant height. Significant variation among genotypes by treatment by environments interaction were detected for plant height, test weight and grain yield performance but no significant variation was detected for days to anthesis across environments (Table 17). The different measurements for midge (rating score and number of midge adults) were not included in this analysis as mentioned in the materials and methods.

The results suggest that climatic, biotic and abiotic conditions vary across environments over years. Genotypes behave differently across environments within classes of resistance. The significant interaction detected in genotype x treatment x environment suggest that resistance for sorghum midge is not stable across environments over the years.

Table 17: Degree of freedom and mean squares to combined analysis of variance for five agronomic measurements across environments in College Station and Corpus Christi, Texas 2003/2004.

Source	Df†	Days to anthesis	Plant height (inches)	Test weight (bu/acre)	Grain yield (lb/acre)
Environment	2	186.5 *	4386.9 *	882.1 *	294120471.7 *
Treat	2	8637.9 *	216.9 *	21.7 *	9682012.1 *
Treat x Environment	4	7101.6 *	38.7 *	83.8 *	9356157.4 *
Rep(Environment)	6	18.0 *	4.4	62.0 *	2501860.0 *
Class	3	185.3 *	570.8 *	101.1 *	5228764.6
Class x Environment	6	7.2	42.5	3.3	3013529.1
Class x Treatment	6	14.0	7.7	1.8	2472490.9
Genotype (Class)	14	68.3 *	156.2 *	14.7	5399335.9
Genotype (Class) x Environment	22	8.6 *	26.8 *	9.1 *	15700183.4 *
Genotype (Class) x Treatment	28	6.1	14.1 *	4.2	1541984.4
Genotype (Class) x Treatment x Environment	56	4.8	7.3 *	7.3 *	1926878.4 *
Pooled Error	282	3.8	4.4	5.0	778301.0
Total	431				

† Based on type III sum of squares.
* Significantly different from zero at the 0.05 probability level

The comparison among treatments across environments for the combined analysis showed that early treatment was significantly different for the late planting treatments with and without insecticide control at LSD 5% for days to anthesis, plant height, test weight, and grain yield, but the late planting treatment with insecticide application did not differ from the early planting for test weight (Table 18). For plant height there was no significant difference detected between late planting treatments. The results suggest that early planting across all environments improves test weight as well as grain yield performance versus late planting without insecticide application. There was observed a slight improvement in yield performance for late planting with insecticide application versus late planting without insecticide control (Table 18). The results suggest that yield performance would be reduced in 14% when materials are late planted without insecticide control.

Table18: Comparison of means by treatments in combined analysis across environments for four agronomic measurements; days to anthesis, plant height, test weight, and grain yield.

Treatments	Days to Anthesis	Plant height (inches)	Test weight (lbs/bu)	Grain yield (lbs/acre)
Early planting	77 a	56 b	56.8 a	4746.4 a
Late planting (without insecticide)	74 b	49 a	55.7 b	4074.4 c
Late planting (with insecticide)	75 b	49 a	56.6 a	4383.9 b
LSD	0.6	0.5	0.5	204.6
CV (5%)	2.9	4.4	3.9	20.0

The average means among classes of sorghum resistance genotypes across environments were 66 days, 48 cm, 56.4 lbs/bushels and 4401.6 lbs/acre for days to anthesis, plant height; test weight and grain yield respectively (Table 19).

The genotypes ATx399*Tx2737, ATx2752*RTx430, Garst5515, Garst5616 and ATx2752*Tx2783 were the earliest. The genotypes A8PR1013*Tx2882 and ATx640*Tx2882 classified as resistant to sorghum midge showed lower test weight across all environments with average mean of 53.5 and 54.0 lbs/bushels respectively. The highest test weights were observed for hybrids PM429, PM682, ATx378*RTx430, and PM435 with an average mean of 58.0, 58.1, 58.2 and 58.3 lbs/bushels respectively (Table 19).

Grain yield performance was lower on resistant genotypes A8PR1013*Tx2882, ATx640*Tx2880 and ATx640*Tx2882 with average mean yield of 3581.2, 3894.3 and 3732.6 lbs/acre, but the genotypes PM090 and PM429 known as resistant to sorghum midge performed relatively better across environments with average mean yield of 4348.1 and 4177.4 lbs/ acre. The genotypes Garst 5515 and Garst 5616 with some level of resistance performed better than some susceptible genotypes (Table 19). In general the means of grain yield for susceptible genotypes were higher than some resistant genotypes in the absence of sorghum midge pressure.

Table 19: Average means of combined analysis for four agronomic measurements across environments in College Station and Corpus Christi, Texas 2003/2004.

Hybrids	Source	Class	Days to anthesis	Plant Height (inches)	Test weight (lbs/bu)	Grain yield (lb/acre)
PM435	Pioneer Hi- Bred	MS	75	44	58.3	4334.9
PM682	Pioneer Hi- Bred	MR	80	47	58.1	3995.3
PM 090	Pioneer Hi- Bred	R	81	42	56.0	4348.1
PM429	Pioneer Hi- Bred	R	81	43	58.0	4177.4
Garst 5515	Garst Seed Co.	MR	73	46	55.2	4537.7
Garst 5616	Garst Seed Co.	MS	73	48	56.5	4524.5
A8PR1013*Tx2882	TAES	R	76	46	53.5	3581.2
ATx640*Tx2880	TAES	R	81	47	56.8	3894.3
ATx640*Tx2882	TAES	R	78	44	54.0	3732.6
ATx399*TX2737	TAES	S	71	44	55.4	3791.6
ATx378*RTx430	TAES	S	76	53	58.2	4583.6
ATx2752*RTx430	TAES	S	72	49	56.2	4587.4
ATx2752*Tx2783	TAES	S	73	51	57.6	5185.4
ATx631*RTx436	TAES	S	76	52	56.9	4565.7
84G62	Pioneer Hi- Bred	S	74	46	57.0	4935.7
82G63	Pioneer Hi- Bred	S	74	50	57.4	5145.6
DKS54-00	Monsanto	S	76	52	56.3	4193.3
DK52	Monsanto	S	75	48	55.8	4755.0
Means			75	48	56.4	4401.6
LSD(5%)			3.1	1.7	1.0	467.3
CV (5%)			2.9	4.4	3.9	20.0

As was observed in specific environments, similar trends were detected in combined analysis among classes (Table 20). In early planting, susceptible and moderately susceptible hybrids yield better than resistant and moderately resistant hybrids. In late planting with insecticide control, the susceptible hybrids produced less yield than hybrids with some level of resistance. High grain yield performance was observed on moderately resistant and moderately susceptible across all environments (Table 20). In late planting without insecticide control, the susceptible and moderately susceptible hybrids yield slightly higher than resistant and moderately resistant hybrids. Across all environments, differences were detected in comparison between resistant – susceptible and resistant – moderate susceptible hybrids comparisons, but other paired comparison classes did not show to be different at the LSD 5% level of significance (Table 20).

Table 20: Means of combined midge resistance classes for five agronomic traits across environments, in Corpus Christi and College Station, Texas in 2003 and 2004.

Trait	Class	Resistant	Moderate Resistance	Moderate Susceptible	Susceptible
Days to anthesis	Early Planting	79	76	74	76
	Late Planting, No Insecticide	67	64	64	64
	Late Planting, Insecticide	67	63	63	66
	Mean	71	68	67	69
	L.S.D.	3.2	3.2	3.2	3.2
Plant height	Early Planting	44	46	45	48
	Late Planting, No Insecticide	46	47	48	51
	Late Planting, Insecticide	45	48	48	50
	Mean	45	47	47	49
	L.S.D.	2.0	2.0	2.0	2.0
Test Weight	Early Planting	54.4	56.1	56.8	56.8
	Late Planting, No Insecticide	53.8	54.7	56.1	56.0
	Late Planting, Insecticide	54.5	55.9	56.4	56.6
	Mean	55.4	56.4	57.2	56.7
	L.S.D.	1.0	1.0	1.0	1.0
Yield	Early Planting	4173.3	4746.6	5002.0	5284.6
	Late Planting, No Insecticide	3930.3	3844.1	4151.7	4266.0
	Late Planting, Insecticide	4189.6	4598.4	4536.8	4475.9
	Mean	3898.4	4320.7	4448.7	4640.3
	L.S.D.	467.3	467.3	467.3	467.3

The analysis for the difference between late planting with insecticide control and late planting without insecticide control was detected to be statistical significant for genotypes within classes across all environments, but no significance was detected for classes of resistance across environments (Table 21). The result suggests that the hybrids perform differently among classes of resistance.

Significant difference was detected in combined analysis for the difference between late planting with insecticide control and late planting without insecticide control to environment by genotype interaction, but there was not detected significance difference among environments, classes, genotypes within classes and environment by classes' interaction (Table 22).

Table 21: Mean of squares for differences between late planting with insecticide control and late planting without insecticide control for grain yield (lb/acre) in each environment.

		Environments		
Source of variation	Df†	College Station- 03	Corpus Christi- 03	Corpus Christi- 04††
Replications	2	577993 *	396397	37525
Classes	3	888692	154085	2111280
Genotype(classes)	14	2974013 *	507317 *	9798639 *
Error	34	13355192	213618	2660476
Total	53			

† Based on type III sum of squares.
* Significantly different from zero at the 0.05 probability level
†† Degree of freedom are different to College station -03 and Corpus Christi -03.

Table 22: Mean of squares for differences between late planting with insecticide control and late planting without insecticide control for grain yield (lb/acre) combined across environments.

Source of variation	Df†	Combined Mean Squares	
Environments	2	19979	
Replications (Env.)	6	2071305	
Classes	3	1564308	
Env.*Classes	6	1357033	
Gen(Classes)	14	3101740	
Env*Gen(classes)	22	3805850	*
Error	90	1235445	
Total	143		

† Based on type III sum of squares.
* Significantly different from zero at the 0.05 probability level

In each environment trend was detected among hybrids for the difference between late planting with insecticide control and late planting without insecticide control (Table 23).

The negative yield performances observed in some hybrids suggest that probably the insecticide control was not effective in College Station 2003. The genotype ATx2752*RTx2783 and DKS54-00 classified as susceptible performed better when insecticide control was applied, as well as some hybrids with some level of resistance.

In Corpus Christi 2003 negative yield performance was observed only for the hybrid ATx2752*RTx430 classified as susceptible (Table 23).

The same scenario was detected in Corpus Christi 2004 where hybrids such as ATx640*Tx2882, 84G62, 82G63, and DKS54-00 showed negative yield performance between treatments (Table23).

Across all environments, hybrids responded positively for insecticide control and yield was observed to improve with insecticide application in late planting, but hybrids, ATx640*Tx2882, ATx378*RTx430, 84G62, 84G62, and 82G63 performed poorly across environments (Table 23). The results suggest that late planting with insecticide control improve the yield performance when sorghum midge population density is higher.

Table 23: Average mean for the difference between late planting with insecticide control and late planting without insecticide control for grain yield (lbs/acre) in each environment, and across environments.

		Environments			
Hybrids	Classes	College Station 2003	Corpus Christi 2003	Corpus Christi 2004	Combined
PM435	MS	972.5	241.5	na	607.1
PM682	MR	683.6	557.8	na	620.7
PM 090	R	651.8	216.1	na	433.9
PM429	R	-3.50	234.4	na	115.6
Garst 5515	MR	320.5	379.1	1292.7	664.1
Garst 5616	MS	-549.0	513.7	599.3	188.0
A8PR1013*Tx2882	R	437.2	228.7	1274.2	646.7
ATx640*Tx2880	R	980.4	321.3	na	650.8
ATx640*Tx2882	R	905.7	262.2	-1412.3	-81.5
ATx399*TX2737	S	988.9	268.9	2727.8	1328.5
ATx378*RTx430	S	-1145.0	556.5	na	-294.2
ATx2752*RTx430	S	-522.1	-152.1	1579.2	301.6
ATx2752*Tx2783	S	1676.6	135.5	231.0	681.1
ATx631*RTx436	S	960.0	379.4	-633.1	307.8
84G62	S	-1095.3	547.6	-1924.5	-790.1
82G63	S	-1874.6	712.0	-2028.6	-1063.7
DKS54-00	S	1084.4	1690.8	-1974.3	266.9
DK52	S	743.2	25.2	779.5	515.9
Means		327.8	395.5	42.5	281.8
LSD (5%)		451.9	108.7	797.3	260.2

na = not available

CONCLUSIONS

Sorghum midge was prevalent in susceptible genotypes and the resistant genotypes showed less damage when planted later in the growing season facts that confirm the presence of levels of resistance. Thus, breeding for sorghum midge resistance has been effective and hybrids from these programs have been shown to possess some levels of resistance. Hybrids such as PM435, PM090, PM429, Garst 5515 and Garst 5616 were observed to express some level of resistance to sorghum midge across environments.

In normal plantings (no midge pressure) midge susceptible hybrids perform better than resistant hybrids. This fact has been demonstrated for the treatments planted earlier across environments. Thus, escape (antexinosis) and/or non–preference for oviposition is the mechanism of resistance to sorghum midge and it characterizes the value of resistance to sorghum midge.

In late plantings (midge pressure) yields of resistant hybrids are slightly higher. Overall, midge resistant hybrids are not competitive in yield with susceptible hybrids; therefore, producers will only consider a midge resistant hybrid when they know that sorghum midge will be present.

Sorghum midge adults were more sever in late planting without insecticide control in College Station 2003. A similar situation occurred in Corpus Christi in 2004 based on midge rating score. Sorghum midge population density was variable within a particular year across environments. The shifts of sorghum midge population density observed across environments over the year were due to climatic factors (humidity, drought, temperature and rain).

The significant interaction detected among genotypes across environments suggests that environments are different and resistance among genotypes is not stable across environments due to different climatic conditions within a particular year.

Among classes of resistance to sorghum midge the resistant hybrids showed slightly better yield performance when planted late than some susceptible hybrids. The insecticide control in late planting material minimizes the damage caused by midge infestation, and consequent yield improvement.

REFERENCES

Agrawal, B. L., C. V. Abraham, and L. R. House. 1988. Inheritance of resistance to midge, *Contarinia sorghicola* Coq. in sorghum, *Sorghum bicolor* (L.) Moench. Insect Science and Its Application 9(1): 43-45.

Boozaya-Angoon, D., K. J. Starks, D. E. Weibel, and G. L. Teetes. 1984. Inheritance of resistance in sorghum, *Sorghum bicolor*, to the sorghum midge, *Contarinia sorghicola* (Diptera: Cecidomyiidae). Environmental Entomology 13(6): 1531-1534.

Boyd, M.L., and W.C. Bailey. 2000. Sorghum Midge in Missouri. Insects and Diseases. Agricultural Department of University of Missouri-Colombia.

Cowland, J. W. 1935. The sorghum midge in the Anglo-Egyptian Sudan. Annals of Applied Biology 23 (1): 110-113.

Diarisso, N. Y., B.B. Pendleton, and G. Teetes. 1995. Sorghum spikelet morphology and flowering time as causes of resistance to sorghum midge, p. 92. *In* Nineteenth Biennial Sorghum Research and Utilization Conference, Lubbock, TX.., 5-7 March 1995.

Diariso, N.Y., B.B. Pendelton, G. Teetes, G.C. Peterson, and R.M. Anderson. 1998. Spikelet flowering time: Cause of sorghum resistance to sorghum midge (Diptera: Cecidomyiidae). J. Econ. Entomol. 91(6): 1464-1470.

Dillon, S., P. Lawrence and R. Henry. 2001. Genetic diversity of *Sorghum* genus. p. 1. *In* Proc. of the Fourth Australian Sorghum Conference, Biloela, Queensland. Australia. 5-8 February 2001.

Dogget, H. 1988. Sorghum insect pests. 2nd ed.. Sorghum. Tropical Agriculture Series. John Wiley & Sons, Inc., NY.

Food and Agriculture Organization of the United Nations (FAO). 1992. The world sorghum and millet economics: Facts, trends and outlook. FAO, Rome, Italy.

Food and Agriculture Organization of the United Nations (FAO). 2001. The world sorghum and millet economics: Facts, trends and outlook. FAO, Rome, Italy.

Fisher, R.W., and G.L. Teetes. 1982. Effect of moisture on sorghum midge (Diptera: Cecidomyiidae) emergence. Environmental Entomology 11(4): 946-948.

Fisher, R. W., G. L. Teetes, and F. P. Baxendale. 1982. Effects of time of day and temperature on sorghum midge emergence and oviposition. Texas Agricultural Experiment Station PR-4029.

Franzmann, B. A. 1993. Ovipositional antixenosis to *Contarinia sorghicola* (Coquillett) (Diptera: Cecidomyiidae) in grain sorghum. Journal of the Australian Entomological Society 32(1): 59-64.

Franzmann, B. A., and D. G. Butler. 1993. Compensation for reduction in seed set due to sorghum midge (*Contarinia sorghicola*) in midge-susceptible and midge-resistant sorghum (*Sorghum bicolor*). Australian Journal of Experimental Agriculture 33: 193-196.

Hallman, G. J., G. L. Teetes, and J. W. Johnson. 1984. Weight compensation of undamaged kernels in response to damage by sorghum midge (Diptera: Cecidomyiidae). Journal of Economic Entomology 77(4): 1033-1036.

Harris, K.M. 1961a. The sorghum midge, *Contarinia sorghicola* (Coquillett) in Nigeria, Bulletin of Entomological Research 52: 129-146.

Harris, K. M. 1961b. The sorghum midge, *Contarinia sorghicola* (Coquillett) in West Africa. Nature, 192: 187-188.

Harris, K. M. 1976. The sorghum midge. Annals of Applied Biology 84: 114-118.

Harris, M.K. (ed.). 1980. Biology and Breeding for resistance to Arthropods and Pathogens in Agricultural Plants.MP1451. Ag. Com. Texas A&M.

Henzell, R.G., G.C. Peterson, G.L. Teetes, B.A. Franzman, H.C. Sharma, O. Youm, A. Ratnadass, A. Toure, J. Raab, and O. Ajayi. 1997. Breeding for resistance to panicles pests of sorghum and pearl millet. p. 255-280. *In* Proc. of the International Conference on Genetic Improvement to Sorghum and Pearl Millet. Lubbock, Tx. September 23-27, 1996.

Henzell, R.G., B.R. Hare, D.R. Jordan, D.S. Fletcher, A.N. McCosker, G. Bunker and D.S. Persley. 2001. Sorghum breeding in Australian public and private endeavours. p. 3. *In* Proc. of the fourth Australian sorghum conference, Biloela, Queensland. Australia. 5-8 February 2001.

House, L. R. 1985. A guide to sorghum breeding. International Crops Research Institute For Semi-Arid Tropics. 2nd ed. Patancheru, A.P., India.

International Crops Research Institute of the Semi-arid Tropics (ICRISAT web). 2005. Sorghum Bicolor (L.) Moench. Accessed on March 2005. http://www.icrisat.org./text/coolstuff/crops/gcrops2.html

Jimenez Mass, N.C. 1992. Mixed planting sorghum midge (Diptera: Cecidomyiidae) resistant and susceptible sorghums to enhance and assess non-preference resistance. M.S. thesis, Texas A&M University, College Station.

Kimber, C.T. 2000. Origin, history, technology, and production. p. 3-99. *In* Smith, C.W., and R.A. Frederiksen (eds.). Sorghum. John Wiley & Sons, NY, 2000.

Klein, R.R., J.A. Rodriguez-Herrera, P.R. Scheulter, P.R Klein, Z.H. Yu, and W.L. Rooney. 2001. Identification of genomic regions that affects grain mold incidence and other traits of agronomic importance in sorghum. Theor. Appl. Genet. 102:307-319.

Maqbool, S.B., P. Davi, and M. B. Sticklen. 2001. Biotechnology: Genetic improvement of sorghum (*Sorghum Bicolor* (L.) Moench). In vitro Cell. Dev. Biol. Plant 37: 504- 515.

Maunder, A. B. 2001. Sorghum – The global grain of the future. p. 1-19. *In* Proc. of the fourth Australian sorghum conference, Biloela, Queensland. Australia. 5-8 February 2001.

McWilliams, J.R., W. Manokaran, and T. Kipnis. 1979. Adaptation to chilling stress in sorghum. p.491-505. *In* M. Lyons, D. Grahan, and J.R. Raison (eds.). Low temperature stress in crop plants. Academic Press, NY.

Melton, K. D., and G. L. Teetes. 1984. Effects of resistant sorghum hybrids on sorghum midge (Diptera: Cecidomyiidae) biology. Journal of Economic Entomology 77(3): 626-631.

Mott, D.A., G.L. Teetes, B.B. Pendleton, and R.M. Anderson. 1996. Effect of sorghum residue destruction on abundance of sorghum midges emerging from diapause. Southwestern Entomologist 21(3): 345-347.

Painter, R.H. 1951. Resistance to insects in sorghums, p. 326-356. *In* Insect resistance in crop plants. MacMillan, NY.

Peterson, G.C., J.W. Johson, G.L. Teetes, D.T. Rosenow, and R.E. Schaffert. 1983. Registration of Tx2782 midge resistant sorghum germplasm line. Crop. Sci. 24: 389-390.

Peterson, G.C., J.W. Johnson, G.L. Teetes, and D.T. Rosenow. 1985. Registration of midge resistant sorghum germplasm. Crop Science 25 : 372.

Peterson, G.C. 1995. Breeding for resistance to sorghum midge in the USA. p. 149-157. *In* K.F. Nwanze, and O. Youm (eds.). Panicle insect pests of sorghum and pearl millet: Proc. of an International Consultative Workshop, 4-7 Oct 1993, ICRISAT Sahelian Center, Niamey, Niger. International Crops Reseach Institute for Semi-Arid Tropics. Patancheru 502324, Andhra Pradesh, India.

Peterson, C.G.. 2003. Germplasm enhancement for resistance to insects and improved efficiency to sustainable agriculture systems. p.93-101. *In* Germplasm enhancement and conservation. Annual Report. INTSORMIL - Sorghum and Pearl Millet Collaborative Research Support Program (CRSP). University of Nebraska, Lincoln.

Reddy, B.V.S., H.C. Sharma, and J.W. Stenhouse. 1995. Breeding for resistance to sorghum midge at ICRISAT Asia Center. p. 159-169. *In* K.F. Nwanze and O. Youm (eds.). Panicle insect pests of sorghum and pearl millet: Proc. of an International Consultative Workshop, 4-7 Oct 1993, ICRISAT Sahelian Center, Niamey, Niger. International Crops Reseach Institute for Semi-Arid Tropics. Andhra Pradesh, India.

Rooney, L.W., M.N. Khan, and C.F. Earp. 1980. The technology of sorghum products. *In* E. Inglett and L. Munck (eds.) Cereals for food and beverages: Recent progress in cereal chemistry. Academic Press, New York.

Rooney, L.W. and S.O. Serena-Saldivar. 2000. Sorghum. p. 513-564 *In* Handbook of cereals and technology, 2nd ed. K. Kulp and , J.G. Ponte (eds). Marcel Dekker. NewYork.

Rooney, W.L. 2004. Sorghum improvement – integrating traditional and new technology to produce improved genotypes. Advances in Agronomy 83: 37- 109.

Rossetto, C. J., V. Nagai, and J. Overman. 1984. Mechanism of resistance in sorghum variety AF-28 to *Contarinia sorghicola* (Diptera: Cecidomyiidae). Journal of Economic Entomology 77(6): 1439-1440.

Santos, J.H.R., and C. Martins do Carmo. 1974. Evaluation of resistance to *Contarinia sorghicola* by sorghum lines from the Cameroon, Africa collection, in Ceara, Brazil. Sorghum Newsletter 17: 10-11.

SAS Institute. 1999. SAS user's guide: Statistics, release 8.01 edition. SAS Institute Inc., Cary, NC.

Sharma, H.C. 1985. Screening for sorghum midge resistance and resistance mechanisms. p275- 292. *In* proc. of the international Sorghum Entomology Workshop, 15- 21 July 1984, Texas A&M University, College Station.

Sharma, H.C. 1993. Host-plant resistance to insects in sorghum and its role in integrated pest management. Crop Prot 12: 11- 34.

Sharma, H.C., Vidyasagar, P., and Subramanian, V. 1993. Antibiosis component of resistance in sorghum to sorghum midge, *Contarinia sorghicola*. Annals of Applied Biology 123: 469 – 483.

Sharma, H.C., and Teetes, G.L. 1995. Yield loss assessment and economic injury levels for panicle-feeding insects of sorghum. p125-134. *In* K.F. Nwanze and O. Youm (eds.). Panicle insects pests of sorghum and pearl millet: proceedings of International Consultative Workshop, 4- 7 Oct 1993, ICRISAT Sahelian Center, Niamey, Niger.

Sharma, H.C., K.F. Nwanze and V. Subramanian. 1997. Mechanisms of resistance to insects and their usefulness in sorghum improvement. p. 81-100. *In* H.C. Sharma, Faujdar Singh, and K.F. Nwanze (eds.). Plant resistance to insects in the sorghum. International Crops Reseach Institute for Semi-Arid Tropics.

Sharma, H.C., C.V. Abraham, and J.W. Stenhouse. 2002. Compensation in grain weight and volume in sorghum is associated with expression of resistance to sorghum midge, *Stenodiplosis sorghicola*. Euphytica 125: 245– 254.

Singh, F. 1997. Inheritance of resistance to insect pests in sorghum. p. 101-111. *In* H.C Sharma., Faujdar Singh, and K.F. Nwanze (eds.). Plant resistance to insects in the sorghum. International Crops Reseach Institute for Semi-Arid Tropics.

Steel, R.G.D. and J.H. Torrie. 1980. Principles and procedures of statistics. A biometric approach. 2nd ed. McGraw Hill Book co. New York.

Stephens, J.C., F.R. Miller, and D.T. Rosenow. 1967. Conversion of alien sorghums to early combine genotypes. Crop Sci. 7: 396.

Teetes, G.L, W.R. Young, and M.G. Jotwani. 1980. Insect pests of sorghum, pp.17-40. Elements of integrated control of sorghum pests. FAO Plant Production and Protection Paper 19. F.A.O. Organization of the United Nations, Rome.

Teetes, G.L., and B.B. Pendleton. 1994. Sorghum midge dispersal from sorghum. Southwestern Entomologist 19(1): 1-9.

Teetes, G.L., G.C. Peterson, K.F. Nwanze, and B.B. Pendleton. 1999. Genetic diversity of sorghum: A source of insect-resistant germplasm, pp. 63-82. *In* Stephen L. Clement and Sharron S. Quisenberry [eds.], Globabl plant genetic resources for insect-resistant crops. CRC Press, Boca Raton, FL.

Waquil, J. M. and G.L. Teetes, 1990. Impacto do dona da mosca do sorgo, Contarinia sorghicola (Coquillett, 1898), no peso de cada grao remanescente a infestacao. Ann. Ent Soc Brasil 19: 201-209.

Waquil, J. M., G. L. Teetes, and G. C. Peterson. 1986. Adult sorghum midge (Diptera: Cecidomyiidae) nonpreference for a resistant hybrid sorghum. Journal of Economic Entomology 79(2): 455-458.

Widstrom, N. W., B. R. Wiseman, and W. W. McMillian. 1984. Patterns of resistance in sorghum to the sorghum midge. Crop Science 24(4): 791-793.

Wiseman, B. R., and W. W. McMillian. 1968. Resistance in sorgham to the sorghum midge, *Contarinia sorghicola* (Coquillett) (Diptera: Cecidomyiidae). Journal of the Georgia Entomological Society 3 (4): 147-153.

Young, W.R., and G.L Teetes. 1977. Sorghum entomology. Ann. Rev. of Entomology 22:193.

APPENDIX

Individual environment analysis by treatment.

Early planting college Station, Texas 2003

		Mean Squares				
Source	df†	Days to anthesis	Plant height (inches)	Midge adults	Test weight (lbs/bu)	grain yield (lbs/acre)
Rep	2	28.129 *	24.388 *	3.685 *	3.678	589763.42
Genotypes	17	35.377 *	66.196 *	0.871	4.644*	4569403.69 *
Error	34	7.012	5.859	0.489	1.243	1833708.60

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Late planting without insecticide College Station, Texas 2003

		Mean Squares				
Source	df†	Days to anthesis	Plant height (inches)	Midge adults	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	3.722	27.629 *	9.407	33.984 *	1036420.26
Genotypes	17	9.186 *	67.538 *	28.463 *	11.223	2828600.15 *
Error	34	2.095	4.865	3.035	9.805	585443.51

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Late planting with insecticide College Station, Texas 2003

Source	df†	Mean Squares Days to anthesis	Plant height (inches)	Midge adults	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	13.018 *	11.555 *	45.035 *	2.304	6404179.09 *
Genotypes	17	15.038 *	79.539 *	16.615 *	5.994 *	1272572.32
Error	34	2.038	3.124	4.756	2.448	672028.42

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Early planting Corpus Christi, Texas 2003

Source	df†	Mean Squares Days to anthesis	Plant height (inches)	Midge rating	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	1.685	1.167	14.518 *	5..512	1422454.34 *
Genotypes	17	12.845 *	6.480	2.645	6.835 *	663683.85 *
Error	34	0.606	5..304	3.675	1.777	329252.76

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Late planting without insecticide Corpus Christi, Texas 2003

		Mean Squares				
Source	df†	Days to anthesis	Plant height (inches)	Midge rating	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	62.741 *	6.741	3.129 *	3.742	224178.04
Genotypes	17	18.270 *	22.214 *	10.293*	10.642 *	1903494.62 *
Error	34	7..309	3.799	0.776	1.787	96677.81

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Late planting with insecticide Corpus Christi, Texas 2003

		Mean Squares				
Source	df†	Days to anthesis	Plant height (inches)	Midge rating	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	7.018	1..352	5..352 *	2.486	499857.37 *
Genotypes	17	18.257 *	22.202 *	2.741 *	18.422 *	1371011.58 *
Error	34	4.705	3.685	0.547	2.421	74440.40

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Early planting Corpus Christi, Texas 2004

Source	df†	Mean Squares Days to anthesis	Plant height (inches)	Midge rating	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	17.583 *	11.083	0.444	96.576 *	1437559.12
Genotypes	11	25.636 *	43.704 *	0.535 *	17.391	1978469.21
Error	22	1.312	3.628	0.172	14.198	1238680.13

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Late planting without insecticide Corpus Christi, Texas 2004

Source	df†	Mean Squares Days to anthesis	Plant height (inches)	Midge rating	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	3.000 *	2.194 *	3.583 *	39.266 *	993841.42
Genotypes	11	13643 *	22.626	13.280 *	7.398 *	5108557.58 *
Error	22	0.757	3.406	0.614	8.046	611148.22

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

Late planting with insecticide Corpus Christi, Texas 2004

		Mean Squares				
Source	df†	Days to anthesis	Plant height (inches)	Midge rating	Test weight (lbs/bu)	Grain yield (lbs/acre)
Rep	2	3.694	3.694	1.083	50.051 *	1468418.00
Genotypes	11	8.353 *	29.058 *	17.644 *	6.938	1886703.43
Error	22	2.391	1.573	2.477	7.298	1978625.61

† Based on type III sum of squares.

* Significantly different from zero at the 0.05 probability level

VITA

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