Sorghum

Host Plant Resistance to Sorghum Midge, *Contarinia sorghicola*

H.C. Sharma, B.V.S. Reddy, J.W. Stenhouse, and
K.F. Nwanze (International Crops Research Institute for
the Semi-Arid Tropics, ICRISAT Asia Center,
Patancheru 502 324, Andhra Pradesh, India)

Abstract

Sorghum midge (*Contarinia sorghicola* (Coq.) is the most important pest of sorghum worldwide. Research on host plant resistance to sorghum midge started in 1975 at ICRISAT. Considerable progress has been made in identification and utilization of resistance to this insect. Several cultivars with high yield and resistance have been developed in different plant height and maturity backgrounds. ICSV 197, ICSV 745, ICSV 735, ICSV 758, and ICSV 88032 have yield potential comparable to the commercial cultivars, and are either released for cultivation or are in on-farm testing in several countries. Resistance has also been transferred into male-sterile lines (PM 7061A and PMH 7068A). Efforts are underway to develop midge-resistant hybrids.

Nonpreference and antibiosis are the major components of resistance to *C. sorghicola.* Evidence for compensation in grain weight following midge damage is not conclusive. Short and tight glumes make oviposition difficult, and this is the most important factor associated with resistance to midge. Faster rate of grain development and high tannin content of grain are also associated with resistance. Resistance to midge is governed largely by additive gene action, although nonadditive factors may be involved. Host plant resistance will form the backbone of integrated pest management programs in sorghum. Midge-resistant hybrids will play a greater role in future sorghum production.

Introduction

Sorghum, *Sorghum bicolor* (L.) Moench is one of the most important cereals in the semi-arid tropics. It provides food, feed and forage, but grain yields on peasant farms are generally low, partly due to insect damage. Nearly 150 species of insects have been recorded as pests of sorghum (Sharma 1993), of which sorghum midge (*Contarinia sorghicola* Coq.) is the most important pest worldwide.

Because of uneven distribution of rain, the inability of the farmers to plant the entire sorghum crop in an areaat the same time, and differences in flowering time for sorghum cultivars, scheduling planting at times when midge damage can be avoided can be difficult. Chemical control is costly, ineffective, and beyond the affordability of most farmers. Natural enemies exist, but their populations buildup only after yield damage has occurred. Host plant resistance is the most effective means of keeping midge populations below economic threshold levels (Sharma 1993). Breeding for host plant resistance to midge is considered an integral part of achieving and maintaining higher grain yields. In this paper, we summarize work related to screening techniques, identification of stable sources of resistance, breeding for resistance, and mechanisms and inheritance of resistance.

Past Breeding Efforts

Several sources of resistance to sorghum midge have been identified by several workers (Bowden and Neve 1953; Pradhan, 1971; Johnson et al. 1973; Wiseman et al. 1973; Rossetto et al. 1975; Shyamsunder et al. 1975; Jotwani 1978; Faris et al. 1979). However, prior to 1980, efforts to breed for resistance to midge have only been made by Johnson et al. (1973). Breeding for resistance to midge at ICRISAT started in 1980, although some of the sources of resistance to midge were involved in the crossing program between 1975 to 1980.

Resistance Screening Techniques

To improve the efficiency of screening for resistance to sorghum midge, planting dates are adjusted to coincide with flowering and maximum midge density; sequential plantings of identical genetic material at 15-day intervals are employed to minimize the number of escapes. Use of early flowering (<40 days to 50% flowering) midge susceptible cultivars (IS 802, IS 13249, and IS 24439) as infester rows (4 rows of susceptible cultivars after 16 rows of the test material), and spreading midge-infested sorghum panicles in the infester rows at the boot stage (the panicles should be kept moist for 10 days to stimulate termination of midge diapause) are helpful in increasing midge abundance by 3 to 5-fold, and in improving the efficiency of screening and selection for resistance to sorghum midge (Sharma et al. 1988a, 1992). During the postrainy season, or during periods of low relative humidity, overhead sprinkler irrigation should be operated between 1400 to 1600 hours to enhance midge infestation.

Lines found to be potentially resistant to midge under natural infestation were tested across locations in India (Dharwad, Patancheru, Warangal, and Kovilpatti), and also screened under no-choice headcage conditions (Sharma et al. 1988b). Five panicles were screened under the headcage for each genotype/replication. Each panicle was infested with 40 midges for two consecutive days at the half-anthesis stage. Selected lines were further screened for two to three seasons to confirm their stability of resistance. Lines showing resistance to midge across seasons and locations in India were also tested in several countries in the semi-arid tropics (SAT) through the International Sorghum Midge Nursery (ISMN).

Screening world germplasm for resistance. Nearly 15,000 germplasm accessions were screened for resistance to midge between 1980 to 1990. Twenty-five lines have been found to be resistant to midge across seasons and locations (Sharma 1985; Sharma et al. 1993a). Resistance was also confirmed in IS 2579C, TAM2566, AF 28, and DJ 6514, which had earlier been reported to be resistant to this insect. Several lines previously reported to be resistant were found to be susceptible under no-choice headcage screening. IS 2579C, TAM2566, AF 28, DJ 6514, IS 10712, IS 7005, and IS 8891 are stable and diverse sources of resistance to sorghum midge.

Stability of Resistance

Using principle component analysis, TAM2566, DJ 6514, and IS 12666C, were found to be stable for midge resistance under no-choice headcage screening over four seasons (Sharma et al. 1988b). In another study, using canonical variation and D^2 cluster analysis, AF 28 was found to be distinct from other genotypes, while DJ 6514 and TAM2566 were grouped together (Sharma et al. 1990b). IS 3461, IS 7005, IS 8571, IS 9807, IS 19474, IS 21873, DJ 6514, ICSV 197, and ICSV 390 are stable for their resistance to midge across locations in India (Sharma et al. 1993a).

Breeding for Resistance

Both population and pedigree breeding methods have been used to transfer midge resistance into high-yielding cultivars and hybrids. The procedures involved in making crosses, screening and selecting for midge resistance have been described by Sharma et al. (1992). The first step involved identification of resistance sources, conversion and strengthening of the source material, and development of agronomically elite cultivars and hybrid parents. Agronomically elite lines were tested widely for midge-resistance and agronomic performance, and in on-farm trials by the farmers.

A broad-based population for resistance to panicle feeding insects has been developed by using ms_3 and ms_7 male-sterility genes, and is being improved using low to moderate midge pressure. After incorporating 20 resistant source lines into US/R-C_3 population, mass selection, coupled with recombination, is being employed to further advance the population. This population is now in the third selection cycle.

Breeding midge-resistant cultivars. In the first cycle of breeding for midge-resistance, nearly 50 lines with different maturity, plant height, panicle type, and grain size were developed (Sharma et al. 1993a). Most of these lines were derived from DJ 6514, or its progeny ICSV 197 (PM 11344), which were derived from DJ 6514 × IS 3443. Some breeding lines were also derived from crosses involving IS 12666C, IS 2579C, IS 18692, S-GIRL-MR 1, and IS 12573C. Major progress in breeding for midge-resistance was made by using ICSV 197 as a midge-resistance donor. Transfer of midge-resistance from DJ 6514 to ICSV 197 was the most significant development in breeding for resistance to sorghum midge. ICSV 197 is highly resistant to midge, and yields 54% more grain than the resistant parent (Agrawal et al. 1987). Its yield potential is closer to the commercial cultivars. However, its grain size was smaller than the commercial cultivars. Using ICSV 197 as a resistant donor, several high-yielding lines with resistance to midge have been developed (Sharma et al. 1993a, 1994ab). Among these, ICSV 745 has been released in Karnataka, India, and is being tested on farms in Andhra Pradesh, India, and Sudan. ICSV 735, ICSV 758, and ICSV 804 have been released in Mayanmar. ICSV 735 is also under on-farm testing in Sudan. ICSV 88032 is under mini-kit trials in India in midge-endemic areas.

Most of the improved lines and cultivars behaved as restorers on the A_1 male sterile cytoplasm. The pedigrees of the improved lines showed that DJ 6514 mostly contributed to these selections, indicating narrow genetic variability. We also screened our A_1 cytoplasm restorer collection (360 lines) for midge-resistance, and selected ICSR numbers; 70, -114, -146, -154 (ICSV 197), -155, -89054, -89067, -89068, -89069, -90010, -90011, -90015, -90016, -91002, -91003, -91014, -91015, -91027 (ICSV 745), and -91030 for their resistance to midge. These were derived from IS 12611C, DJ 6514, and IS 12573C.

Breeding midge-resistant female parents. The program was primarily aimed to diversify the male-sterile lines for cytoplasms and nuclear genome, and to improve them for resistance to various yield-reducing factors (Reddy et al. 1993). It consisted of: i) screening available A_1, cytoplasm male-sterile lines for resistance, ii) converting promising midge-resistant lines into male-steriles involving alternative male-sterile cytoplasm, and iii) breeding high-yielding midge-resistant A_1 cytoplasm male-sterile lines. The available male-sterile lines were screened for midge-resistance for three seasons. ICSB 88019, ICSB 88020, and ICSB 89002 were selected for midge-resistance. These were derived from DJ 6514.

Promising inbred lines were testcrossed with A_1, A_2, A_3, and A_4 (Maldandi) male-sterile cytoplasms, and converted into male steriles as follows:

* PM 7068, PM 17467, and PM 17682 with A_1, A_2, A_3, and A_4 (Maldandi)
* PM 17500-2-1 with A_1, A_3, and A_4 (Maldandi)
* PM 19268, ICSV 89057, and ICSV 89058 with A_3 and A_4 (Maldandi)

These lines were derived from DJ 6514 and IS 12611C.

To improve the male-sterile lines for midge-resistance, the breeding program consisted of: a) crossing high-yielding (HY) lines and resistant lines (RL) in a single-cross, or threeway-crosses; $HY \times RL_1 \times RL_2$ or $HY_1 \times RL_1 \times HY_2$, b) selection for agronomic desirability in F_2 and pedigree selection from F_3 and beyond; selection for midge-resistance among families, high-yielding ability, and agronomic desirability among individual plants within the selected resistant families, c) test crossing and evaluating the testcrosses of the selected progenies for maintainer reaction from F_4 and beyond; and d) converting the maintainers selected for midge-resistance into male steriles through backcrossing (Reddy et al. 1993).

Since hybrid performance is correlated with per se performance of the parents, high-yielding parents generally produce high-yielding hybrids. Therefore, the selection strategy for male steriles at IAC is based on the line's per se performance rather than its combining ability. Two improved midge-resistant source lines (PM 17467 and PM 17500- 1) were derived from DJ6514 and have been crossed with 12 maintainer lines with diverse origins (Reddy and Sharma 1991). This program resulted in progenies at various stages of conversion from BC_1 to BC_4 (Reddy and Sharma 1992). These were further screened during the 1992 postrainy season, and selection for midge-resistance and agronomic desirability, and backcrossing of the progenies was conducted simultaneously. By the end of the 1992 postrainy season, we had 155 progenies, 13 of which are in BC_1, 8 in BC_2, 52 in BC_3, and 82 in BC_4. Some of the maintainers (30) were evaluated for grain yield, and other traits. The selected lines, SPMD 2669, -2679, -2681, and -2631 were significantly superior to the control (296B) for grain yield and midge-resistance (Table 1).

Table 1. Performance of midge-resistant male-sterile lines developed during 1990-93, ICRISAT Asia Center.

	Grain yield† (t ha^{-1})		Time to 50% flowering (d)		Plant height (m)		Midge‡ score		100-grain mass (g)	
B-line	R	PR	R	PR	R	PR	R	PR	R	PR
SPMD 2669	2.5	2.0	60	64	1.5	1.1	2.0	5.0	3.1	2.9
SPMD 2679	3.2	2.8	63	65	1.5	1.2	2.0	4.7	2.8	2.5
SPMD 2681	2.4	2.0	64	66	1.6	1.2	1.7	3.3	2.9	2.7
SPMD 2631	2.1	2.1	67	66	1.5	1.2	1.7	3.0	3.2	2.8
Controls										
296B	1.6	0.6	70	92	1.4	1.0	5.7	8.0	-	2.1
ICSV 745	2.4	1.6	71	82	1.8	1.4	2.7	3.7	-	2.0
Mean	1.7	1.7	71	75	1.5	1.2	2.7	4.3	-	2.0
SE±§	0.2	0.34	1.0	1.8	0.05	5.3	0.23	0.59	-	0.1

†. One location in each season.

‡. Midge score on 1 to 9 scale where 1 = highly resistant and 9 = highly susceptible.

§ Based on square root transformed values, R = rainy season, 1992; PR = postrainy season, 1992.

Breeding midge-resistant hybrids. As indicated earlier, resistance in hybrids is mostly controlled by additive genes and it is, therefore, desirable for both parents to be resistant. However, if one of the parents is highly resistant, and the other parent is less susceptible, it is possible to produce a hybrid with moderate levels of resistance. Such hybrids have been developed and evaluated for both grain yield and resistance. Data are presented in Table 2. In this process, we have generated hybrids with high grain yield and resistance to midge.

Mechanisms of Resistance

Nonpreference. Nonpreference is one of the components of resistance to sorghum midge (Wiseman and McMillian 1968; Sharma 1985). TAM2566, IS 12666C, and SGIRL-MR-1 are not preferred by the midge females, and suffer less damage (5-11% florets with midge larvae) under natural conditions, but SGIRL-MR-1 becomes susceptible under no-choice conditions (Sharma 1985). Genotypic nonpreference observed under field conditions is highly influenced by the time of flowering and midge density at the time of flowering for different genotypes. Cultivar nonpreference observed in ICSV 197 and TAM2566 in the field could not be confirmed under cage tests, while DJ 6514 and AF 28 show nonpreference under both field conditions and cage tests (Fig. 1). Midge-resistant females, PM 7061A and PM 7068A (Sharma et al. 1993a), are less preferred than the midge-susceptible females (296A and ICSA 42) (Sharma and Vidyasagar 1994).

Nonpreference for oviposition or low oviposition because of short and tight glumes is the most important component of resistance to sorghum midge. Fewer eggs are laid in the florets of midge-resistant genotypes (<50 eggs 100^{-1} florets), compared with the midge-susceptible check, CSH 1 (153 eggs 100^{-1} florets) (Sharma 1985; Sharma et al. 1990a; Franzmann 1993; Table 3).

Table 2. Performance of the parental lines and their hybrids for midge resistance, plant height, grain mass, and grain yield, 1991 postrainy season, ICRISAT Asia Center.

	Midge damage			Plant height (m)	100-grain mass (g)	Grain yield ($t\ ha^{-1}$)	
	Rating (natural)[‡]	Score (cage)[‡]	Chaffy florets (%)			1 sowing	2 sowing
PM 7061B	2.0	1.8	8	1.2	2.0	2.6	5.1
PM 7068B	2.0	2.3	12	1.2	2.4	2.7	5.4
ICSB 42	7.0	9.0	82	1.2	2.2	2.0	4.5
296B	7.0	8.8	60	1.1	2.0	5.0	9.2
PM 15908-3R	2.0	2.0	16	1.3	1.8	6.0	8.4
PM 17422-3R	2.0	1.8	10	1.4	2.0	2.4	7.8
PM 17592-1R	2.0	3.1	15	1.6	2.2	4.3	7.8
ICSV 745 R	2.0	4.1	9	1.3	2.9	4.7	9.3
MR 836	4.0	8.7	37	1.0	2.9	2.3	5.1
296A × PM 15908-3	3.0	6.9	46	1.2	2.5	6.6	18.9
296A × PM 17592-1	3.0	8.7	44	1.4	2.7	6.2	10.2
ICSA 42 × PM 17422-3	3.0	6.5	20	1.6	2.4	5.7	14.0
PM7061A×PM15908-3	2.0	1.6	14	1.5	2.0	7.6	12.3
PM7068A×PM17422-3	2.0	2.3	6	1.6	1.5	6.9	9.4
PM 7061A × ICSV 745	3.0	2.0	13	1.5	2.4	5.9	6.2
296A × MR 836	6.0	9.0	66	1.5	2.9	2.9	8.0
SE[‡]	±0.69	±0.71	±6	±0.03	±0.13	±0.42	±0.48
CV(%)	34	21	34	4	9	36	38

[†] Damage rating where 1 = highly resistant, and 9 = highly susceptible.

[‡] Under cage.

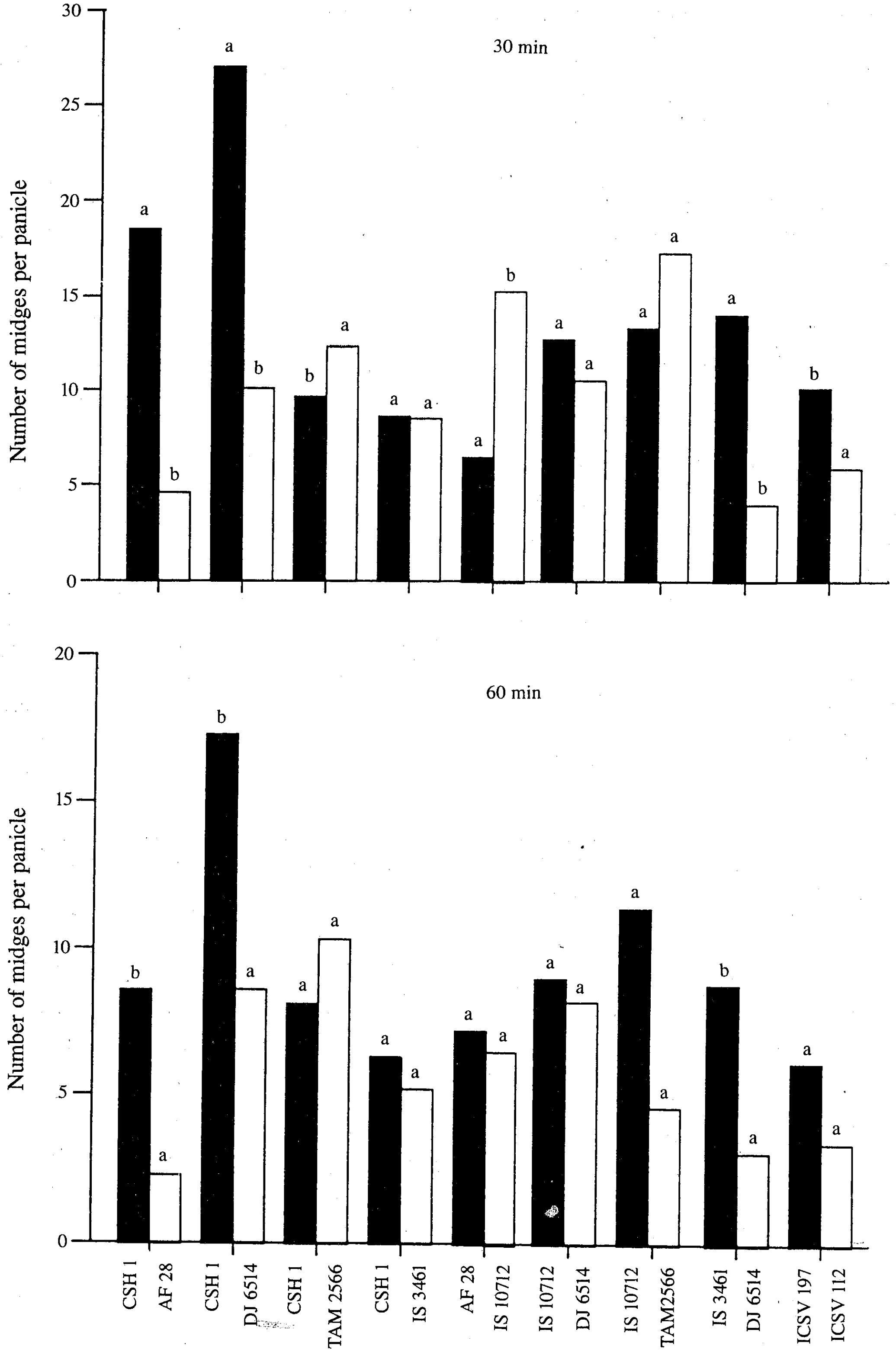

Figure 1. Relative preference of midge females for sorghum genotypes (9 pairs) under no-choice conditions in cage tests (ICRISAT Center, 1990/91 postrainy season). The pairs in which both the bars are designated by the same letter (a or b) are not significantly different at *P* = <0.05.

Antibiosis. Fewer midge flies emerge from the panicles of midge-resistant cultivars, compared with susceptible ones (Sharma 1985; Melton and Teetes 1984; Sharma et al. 1990a; Fig. 2). Post-embryonic developmental period (egg to adult) of the sorghum midge is prolonged by 5-8 days when reared on midge-resistant genotypes, such as DJ 6514, IS 3461, IS 15107, or IS 7005. Adult emergence is delayed by 4–8 days on DJ 6514, IS 8571, IS 10712, IS 19474, IS 19512, ICSV 830, ICSV 197, and TAM2566. Antibiosis to midge is also expressed in terms of smaller size of larvae, reduced fecundity, and/or low larval survival (Melton and Teetes 1984; Waquil et al. 1986; Sharma et al. 1993c).

Tolerance. Conflicting reports exist on the compensation in grain weight due to damage by sorghum midge. Montoya (1965) reported slight compensation for midge damage. He observed that as the mean percentage spikelet damage increased from 5-47%, the weight of 1000 undamaged grains increased from 30.3 to 35.1 g. Harris (1961) found no relationship between midge damage and the weight of surviving kernels. Hallman et al. (1984) observed that a significant inverse relationship existed between the extent of midge damage and the weight of undamaged kernels in two of the three susceptible hybrids, and three of the seven midge-resistant hybrids. However, the relationships were not significant at damage levels below 40%. They suggested that at the economic threshold levels, grain yield was not compensated for following midge damage.

Manual removal of spikelets at the half-anthesis stage up to one-third anthesis does not result in a significant reduction in grain yield (Henzell and Gillieron 1973). This indicates that there is some compensation in grain yield as a result of reduction of number of spikelets panicle^{-1}. However, studies by Hallman et al. (1984) indicated that partial sterility does not simulate midge damage. Manual removal of spikelets may not compare with midge damage because the midge larva feeds on the juices of the developing grain without removing the plant structures. In studies conducted at ICRISAT Asia Center, 1000 grain mass and 100 grain volume were greater in panicles in which 25-30% of the spikelets were removed, and infested with midges under headcage than in the normal uninfested panicles. The panicles were exposed to midges under headcage and natural infestation, respectively (Table 4). Increase in grain mass and volume in the infested panicles (over the noninfested panicles) was greater in hybrids based on midge-resistant females (PM 7061A and PM 7068A) than those based on the midge-susceptible females (ICSA 42 and 296 A). Similar differences were also observed for the midge-resistant and midge-susceptible restorers. Thus, it appears that midge-resistant genotypes have a better capability for compensation in grain weight than the midge-susceptible ones.

Table 3. Oviposition, larval numbers, adult emergence, and grain damage in six sorghum cultivars under no-choice conditions over four seasons at ICRISAT Asia Center (1982–84).

Cultivar	Eggs per 100 florets		Larvae per 100 florets		Adults emerged per panicle		Midge damage Chaffy florets (%)	
DJ 6514	37	(6)[a]	8	(2)[a]	15	(3)[a]	15	(22)[b]
AF 28	21	(4)	6	(7)	24	(4)	33	(34)
TAM2566	37	(5)	41	(6)	33	(6)	30	(33)
IS 15107	38	(6)	59	(7)	71	(8)	39	(38)
CSH 1 (S)	153	(12)	142	(12)	404	(19)	81	(65)
Swarna (S)	141	(11)	127	(11)	318	(18)	83	(66)
SE		± (0.9)		± (3.2)		± (1.2)		± (4.1)
CV (%)		28		15		24		21

Figures in parentheses represent: a = Square root transformed values, and b = Arcsin transformed values. S = Susceptible check.

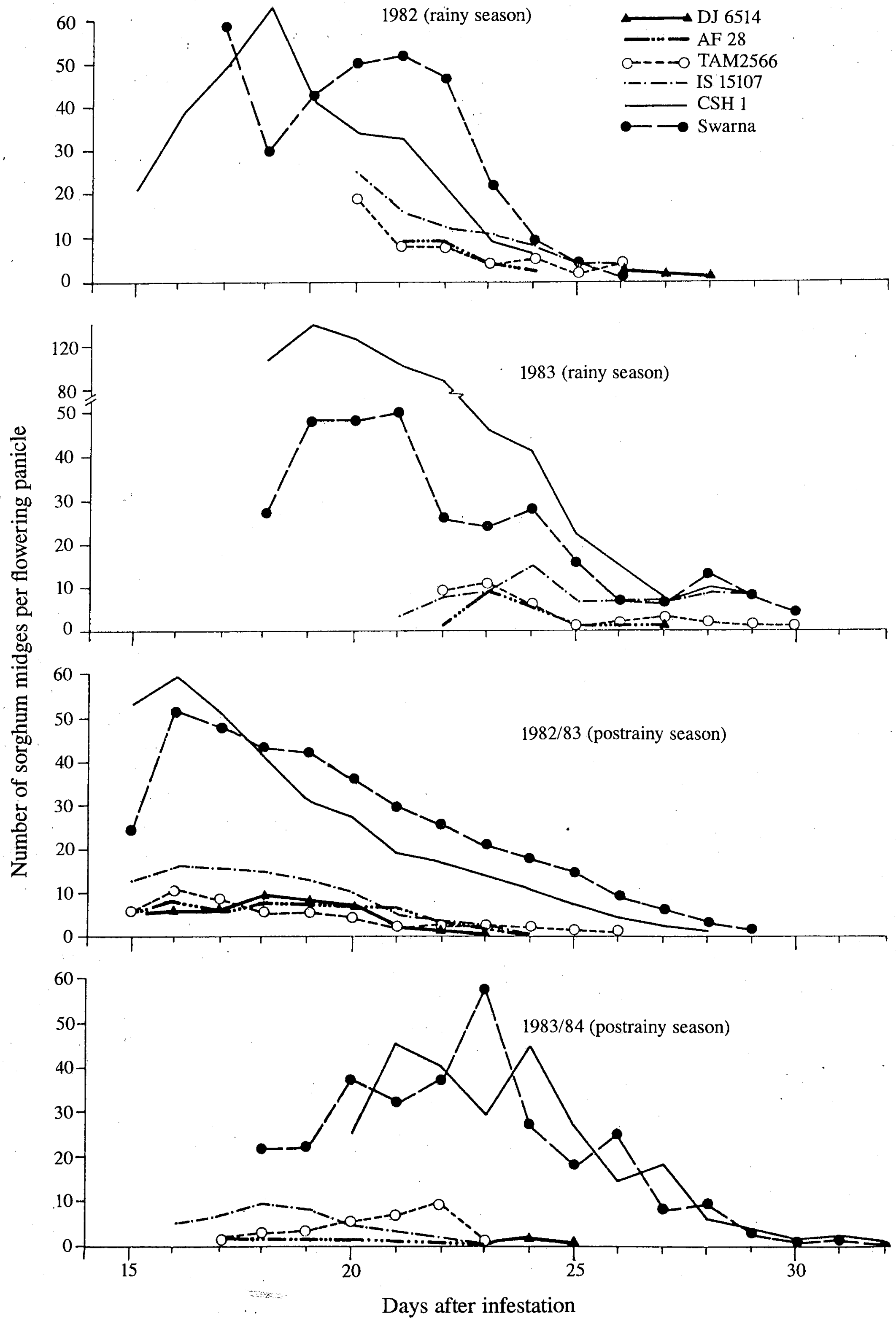

Figure 2. Midge emergence in six sorghum genotypes infested with 60 midges per panicle under a head cage (ICRISAT Center, 1982–84). Susceptible checks were CSH 1 and Swarna.

Table 4. Grain weight and volume of sorghum hybrids and restorers based on midge-resistant and midge-susceptible females (ICRISAT Asia Center, 1991/92 postrainy season).

	1000-grain mass (g)			100-grain volume (cc)		
Genotype(s)	C	N	Difference	C	N	Difference
PM 7061A	28.9	22.9	6.0	2.4	1.8	0.6
PM 7068A	26.5	21.0	5.5	2.4	1.7	0.7
ICSA 42	29.9	26.9	3.0	2.6	2.1	0.5
296A	30.0	26.3	3.7	2.6	2.5	0.1
Midge-resistant restorers	27.5	22.2	5.3	2.3	1.8	0.5
Midge-susceptible restorers	26.7	25.3	1.4	2.3	2.0	0.3
SE	±1.57	±1.2	±95.0	±0.1	±0.5	±37.0

C = Panicles infested with 40 midges for two days. N = Normal uninfested panicles.

Factors Associated with Resistance

Susceptibility to sorghum midge is positively and significantly correlated with the length of glumes, lemma, palea, anther and style (Sharma et al. 1990a). Rate of grain development between third and seventh day after anthesis is negatively associated with midge damage (Sharma et al. 1990a). Short and tight glumes make oviposition difficult and leave limited space between glumes and ovary for the development of midge larva. Componential analysis of the factors associated with resistance to sorghum midge has shown that sources of resistance are diverse, and that these lines have different combinations of factors conferring resistance to this insect (Sharma et al. 1990b).

Santos and Carmo (1974) suggested that tannin content of grain may be one of the factors imparting resistance to sorghum midge, but there are distinct exceptions, e.g., DJ6514 (Sharma et al. 1993c). Amounts of tannins and proteins have been found to be greater in some midge-resistant lines than in susceptible ones, while the soluble sugars are lower in midge-resistant lines. Composition of the sorghum grain varies over seasons, and these changes have been linked with the variation in expression of resistance to midge (Sharma et al. 1993e).

Inheritance of Resistance

Resistance to *C. sorghicola* is inherited quantitatively and is controlled by quantitative gene action, and some cytoplasmic effects (Widstrom et al. 1984; Agrawal et al. 1988). Susceptibility to midge is completely or incompletely dominant in some parents. Boozaya-Angoon et al. (1984) reported that resistance is controlled by recessive genes at two or more loci. Resistance is controlled by more than one gene in TAM2566 (Johnson 1974). At least two pairs of recessive genes determine the resistance of AF28, and genes with minor effects are also present (Rossetto and Igue 1983). Resistance of Tift MR88 has been reported to be under recessive gene control (Hanna et al. 1989). SGIRL-MR-1 and PI 383856 behave differently, and resistance of SGIRL-MR-1 is lost when used as a female parent (Widstrom et al. 1984). DJ6514 and TAM2566 are good general combiners for resistance to sorghum midge. Both general and specific combining ability of the parents is important (Patil and Thombre 1985). Mean performance of parents and general combining ability effects are highly correlated (Agrawal et al. 1988).

We studied the gene action for resistance to sorghum midge at ICRISAT Asia Center under uniform insect pressure using the headcage technique (Sharma et al. 1994). The results indicate that general combining ability effects (GCA) were greater than the specific combining ability effects (SCA) for resistance to sorghum midge. GCA effects of the midge-resistant lines (PM 7061A and PM 7068A) were significant and negative, and such effects for the midge-susceptible lines (ICSA 42 and 296A) were positive (Table 5). Similar trends in GCA effects were also observed for the midge-resistant (ICSV 745, PM 15908-3, PM 17422-3, and PM 17592-1) and midge-susceptible (CS 3541, MR 750, MR 836, MR 844, and MR 923) testers. For genotypic nonpreference by the midge-resistant females, the SCA effects were greater than the GCA effects. Considerable differences were found for the variance components,

Table 5. General combining ability (gca) effects of the lines and testers for five parameters in sorghum for midge resistance (ICRISAT Asia Center, 1990-91).

Lines/ Testers	1990 MD-C	1991 MD-C	1990 DR-C	1991 DR-C	1990 DR-N	1991 DR-N	1991 MF	1991 YLD1	1991 YLD2
Lines									
PM 7061B	-3.82	-13.04**	-0.87**	-2.42**	-0.45	-1.06**	-1.67**	-0.05**	-0.02
PM 7068B	-6.98*	-11.94**	-1.42**	-1.58**	-1.23**	-0.72**	0.85	0.01	-0.06*
ICSB 42	12.89**	12.99**	1.32**	2.44**	1.03**	0.91**	-0.63	-0.04**	0.06*
296B	-2.09	11.99**	0.96**	1.56**	0.66*	0.87**	1.45*	-0.02	0.02
SE(gi)	± 2.975	± 1.967	± 0.329	± 0.238	± 0.269	± 0.229	± 0.630	± 0.013	± 0.023
SE(gi-gj)	± 4.208	± 2.783	± 0.466	± 0.337	± 0.381	± 0.323	± 0.892	± 0.018	± 0.032
Testers									
ICSV 745	-7.98	-10.39**	-1.89**	-0.94*	-1.15**	-0.71*	-2.29*	-0.01	-0.01
PM 15908-3	-3.76	-3.59	-2.26**	-0.99**	-1.82**	-0.88*	-1.54	0.07**	0.17
PM 17422-3	-10.84*	-16.73**	-2.19**	-2.46**	-0.82*	-1.29**	-1.95*	0.07**	0.02
PM 17592-1	-6.33	-2.49	-0.82	-0.26	0.02	-0.05	-0.70	0.01	0.03
CS 3541	3.83	-2.72	0.49	0.51	0.52	0.87*	1.29	-0.05**	-0.06
MR 750	1.62	-4.68	1.58**	-0.77*	0.69	0.45	0.79	0.01	-0.06
MR 836	7.86	17.09**	2.24**	1.59**	1.10**	0.79*	0.43	-0.07**	-0.13**
MR 844	9.66*	14.88**	1.87**	1.92**	1.27	0.70*	1.79	-0.02	-0.02
MR 923	6.11	8.63**	0.99*	1.39**	0.19	0.12	-2.43*	-0.04*	-0.08*
SE(gi)	± 4.463	± 2.951	± 0.493	± 0.358	± 0.403	± 0.342	± 0.945	± 0.019	± 0.034
SE(gi-gj)	± 6.312	± 4.174	± 0.699	± 0.716	± 0.571	± 0.485	± 1.337	± 0.028	± 0.048

*,** = Significant at *P* 0.05 and *P* 0.01.
MD-C = Midge damage under headcage.
DR-C = Midge damage rating under headcage.
DR-N = Damage rating under natural infestation.
YLD1 and YLD2 = Grain yield plants^{-1} in first and second planting during 1991.
MF = Number of midge flies five^{-1} panicles.

GCA, and SCA effects under natural and headcage screening, and over season; this may explain different patterns of gene action observed by different workers.

The expression of resistance to sorghum midge has not been observed in the genic-cytoplasmic male-sterile lines of the midge-resistant genotypes. Midge-resistant male-sterile lines (A-lines) are as susceptible to midge as the midge-susceptible A-lines. However, the maintainer lines (B-lines) of the midge-resistant females are significantly less susceptible than the corresponding A-lines (Table 6). This suggests that the expression of resistance to midge may be controlled by both cytoplasmic factors and the nuclear genes (Sharma et al. 1993b).

Resistance based on DJ 6514 is not expressed in western Kenya and Yemen, while AF 28 and IS 8891 show resistant reaction at these locations (Sharma, H.C., unpublished). This may be because of the environmental influences on the factors conferring resistance to midge in DJ 6514 or the prevalence of a different biotype of midge at these locations.

Potential for Success

Host plant resistance to sorghum midge has the greatest potential to combat the notorious *Contarinia sorghicola* worldwide. This will be more effective for controlling this pest because of difficulties involved in chemical control, since the larvae remain hidden inside the glumes once the eggs are laid by the midge females. Also, a limited window to apply insecticides for midge control at flowering occurs during the morning hours. Insecticides not applied at flowering and at the peak activity periods of midge are least effective. Midge-resistant cultivars will form the backbone of integrated pest management practices in sorghum. This will not only help keep the

Table 6. Effect of pollination by midge-resistant (DJ 6514) and midge-susceptible (Swarna) restorers on midge emergence (number of midges emerged per panicle) on midge-resistant and midge-susceptible male-sterile lines (ICRISAT Asia Center, 1991/92 postrainy season).

	Pollination treatments (PT)				
Genotypes	Swarna pollen	DJ 6514 pollen	Without pollination	B-Line	Mean
ICSA 42	996 (31.5)^{gh}	617 (24.6)^{ef}	354 (18.6)^{d}	1202 (34.7)^{hi}	792 (27.3)
296A	1500 (38.6)^{i}	1564 (39.4)^{i}	1137 (33.6)^{hi}	1182 (30.0)^{fg}	1346 (35.4)
PM 7068A	1097 (32.0)^{gh}	699 (26.3)^{fg}	407 (19.8)^{de}	27 (4.1)^{a}	555 (20.8)
PM 7061A	84 (9.0)^{ab}	168 (12.0)^{bc}	247 (15.5)^{cd}	17 (5.1)^{a}	132 (10.4)
Mean	919 (28.0)	762 (25.6)	536 (22.6)	607 (18.4)	706 (23.7)
LSD for comparing					
Genotypes					(4.04)
Pollination treatments					(4.04)
Genotypes × Pollination treatments					(5.70)

† Figures in parentheses are square root transformed values.
Figures followed by the same letter are not significantly different at $P < 0.05$.

midge populations under check, but also should offer greater flexibility in planting dates for optimum utilization of soil moisture, designing appropriate crop rotations and crop combinations, and conserving natural enemies and environmental quality.

Need for Future Research

1. Future research should focus on developing high-yielding hybrid parents.
2. Utilize diverse sources of resistance in breeding to broaden the genetic basis, and increase the levels of resistance.
3. Relative contribution of componential characters in different sources of resistance.
4. Cause of breakdown of midge-resistance in eastern Africa and Yemen in lines derived from DJ6514.
5. Nature and number of resistance genes in different sources.
6. Molecular markers for midge resistance.
7. Differences in behavior, biology, and genetic constitution of midge populations in different ecological zones.

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Sorghum Midge Resistance Research in Australia

R.G. Henzell, B.A. Franzmann, and **R.L. Brengman**
(Hermitage Research Station, Department of Primary Industries, Warwick 4370, Queensland, Australia)

Introduction

Breeding for host plant resistance to the sorghum midge and associated entomology research commenced in Australia in 1975. This followed a report that worthwhile resistance exists in sorghum (Johnson et al. 1973, Wiseman et al. 1973, Rossetto et al. 1975). Further, this research was commenced because the sorghum midge is a major constraint to profitable production in Australia, costing producers approximately $A10 million per year. Locally, the research was given further weight due to community concerns of chemical pesticide usage.

This paper outlines the Australian breeding program for midge resistance, the associated entomology research, acceptance by grain growers and future prospects.

Entomology

Mechanisms of resistance. When genotypes are compared in small plots, visiting antixenosis is often evident (Franzmann, 1988), and this component is at least partly responsible for differences in seed set between susceptible and resistant hybrids observed in the field. However, this component would be of little value in commercial crops where no choice is available.

The data in Table 1 (and in Franzmann 1993a) indicate that the primary mechanism of resistance in genotypes developed in Australia is ovipositional antixenosis (i.e. few eggs are laid in the resistant genotypes). These data were collected in a cage test where individual panicles of three hybrids (ATx3197/RQL20, midge susceptible; AQL38/RQL36 and AQL39/RQL36, both with a moderate to moderately high levels of resistance and crosses between the highly resistant females, QL38 and QL39 and the male QL36, which has a low level of resistance) were infested at the rate of 12 female midge/100 sessile spikelets for 6 hours.

The cause of this mechanism of resistance is not known. It is probably structural, because of the positive correlation between midge resistance and both small glume size (Sharma et al. 1990) and the extent to which the glumes are apparently appressed. Females take