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Stability of resistance to sorghum shoot fly, *Atherigona soccata*

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ABSTRACT

Sorghum shoot fly, *Atherigona soccata* is one of the most important pests of dual-purpose sorghums during the postrainy season in India. Therefore, it is important to identify stable sources of resistance to develop cultivars with shoot fly resistance and adaptation to postrainy season. We evaluated 190 lines adapted to the postrainy season across five locations, of which 30 lines were identified with resistance to *A. soccata*. These lines were further evaluated for three seasons across five locations to identify lines with stable resistance to this pest across seasons and locations. Data were recorded on oviposition non-preference, deadheart incidence, recovery resistance, morphological traits (leaf glossiness, seedling vigor, plant height and days to 50% flowering), and grain yield. The sorghum genotypes CSV 22, ICSB 422, ICSB 425, ICSB 428, ICSB 432, ICSB 458, ICSB 463, IS 2312, IS 5480, IS 18662, Phule Chitra, RSV 1093, IS 18551, and RSV 1235 exhibited resistance to shoot fly damage across seasons, of which ICSB 425, ICSB 428, ICSB 432, IS 2312, IS 5480, and IS 18551 showed non-preference for oviposition. Six genotypes (ICSB 425, IS 2312, IS 18662, RSV 1090, RSV 1093, and IS 18551) also showed good recovery resistance following shoot fly damage. Principal coordinate analysis placed the maintainer lines (B-lines) with shoot fly resistance in two clusters with ICSB 422, ICSB 432, ICSB 435, ICSB 456 and ICSB 458 in one cluster and ICSB 425, ICSB 428 and ICSB 463 in the other; the open pollinated varieties/germplasm lines (restorers) were placed in a different group (CSV 22, IS 5480, IS 2312 and RSV 1093), suggesting the possibilities for developing hybrids with adaptation to the postrainy season. Based on regression coefficient and deadheart incidence, the genotypes IS 2312, ICSB 425, RSV 1090 and ICSB 428 were stable in expression of resistance to shoot fly across seasons and locations. The genotypes CSV 22 and RSV 1093 exhibited high grain yield potential and resistance to shoot fly damage, while Phule Yashoda, IS 2312, RSV 1235, and ICSV 574 were moderately resistant to shoot fly damage, but had high grain yield potential. These genotypes can be used in sorghum improvement for developing cultivars with shoot fly resistance, high grain yield and adaptation to postrainy season.

1. Introduction

Sorghum [*Sorghum bicolor* (L.) Moench] is one of the most important cereal crops in the semi-arid tropics (SAT). In India, sorghum is grown on over 7.4 million ha, with annual production of 7 million tons (Kumara Charyulu et al., 2014). The productivity levels of sorghum under subsistence farming are quite low (500 to 800 kg ha^{-1}), mainly because of biotic and abiotic constraints and low productivity of the cultivars grown. Nearly 150 insect species have been reported as pests on sorghum (Jotwani et al., 1980; Sharma, 1993), of which sorghum shoot fly, *Atherigona soccata* (Rond.), spotted stem borer, *Chilo partellus* (Swin.), Oriental armyworm, *Mythimna separata* (Walk.), shoot bug, *Peregrinus maidis* (Ashm.), sugarcane aphid, *Melanaphis sacchari* (Zehnt.), sorghum midge, *Stenodiplosis sorghicola* (Coq.), mirid head bugs, *Calocoris angustatus* (Leth.) and *Eurystylus oldi* (Pop.), and head caterpillars, *Helicoverpa*, *Eublemma*, *Cryptoblabes*, and *Pyroderces* are the major pests worldwide. Annual losses due to insect pests have been estimated to be $1089 million in the SAT (ICRISAT, 1992). Nearly 32% of sorghum crop is lost due to insect pests during the rainy

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season (Borad and Mittal, 1983), and 26% during the postrainy season (Daware et al., 2012) in India.

Sorghum shoot fly, *A. soccata* is one of the most important pests of sorghum crop in Asia and Africa. The females lay white, elongated, cigar-shaped eggs singly on the abaxial surface of the leaves of 7–25 days old sorghum seedlings. On egg hatching, the neonate larva moves downward between the folds of the young leaves to the growing point, where it cuts the growing point, resulting in drying of the central leaf known as a 'deadheart'. As a result of damage to the main plant, the plant may produce axial tillers with productive panicles, which serves as a mechanism of recovery resistance, if there is enough moisture and nutrients available to the plant and the tillers are not exposed to shoot fly damage.

Timely planting, manipulation of cultural practices, resistant varieties, and need-based application of insecticides can be used for reducing the losses due to shoot fly (Sharma, 1985). However, planting times in the SAT are dictated by the onset of rains, while chemical insecticides are beyond the reach of resource poor farmers. Under these conditions, host–plant resistance is one of the most effective means of pest management. It is compatible with other methods of pest control, there is no cost involvement for the farmers, and is environment-friendly. Therefore, it is important to identify and develop sorghum cultivars with stable resistance to this pest for sustainable crop production (Sharma, 1993).

A number of genotypes with low to moderate levels of resistance to shoot fly have been identified in the sorghum germplasm collection (Taneja and Leuschner, 1985; Sharma et al., 2003), and resistance to shoot fly is expressed in terms of oviposition non-preference, antixenosis, and tolerance (Sharma and Nwanze, 1997; Dhillon et al., 2005; Chamarthi et al., 2011). Resistance is needed in both the parents to develop shoot fly-resistant hybrids (Sharma et al., 2006). However, expression of resistance to shoot fly damage varies between the rainy and the postrainy seasons (Sharma, 2014; Aruna et al., 2011). While shoot fly becomes a major problem in delayed sowings during the rainy season, it is a major constraint for undertaking early plantings for the postrainy season sorghums, which are largely grown on residual soil moisture between September and February–March. Delays in crop sowings not only expose the crop to terminal moisture stress, but also decrease the grain and fodder yield drastically. Therefore, farmers plant the postrainy season sorghums during the first fortnight of September in Western Maharashtra and October in Marathwada and Karnataka, when the shoot fly populations begin to decline, and there is still enough moisture in the soil for seed germination. As a result of continuous exposure of the crop to shoot fly damage, most of the landraces grown in the postrainy season in India possess low to moderate levels of resistance to this pest. Because of specific requirements for adaptation to postrainy season, resistance to shoot fly and ability to withstand moisture stress and limited research focus, it has not been possible to replace the landrace variety, M 35-1 with improved cultivars over the past 60 years. In addition to season specific adaptation, stability of expression of resistance to insects is also important in stabilizing crop yields across a wide range of environments (Faris et al., 1979). Eberhart and Russell (1966) developed a method for measuring genotypic stability across environments. They showed that both the regression coefficient and the deviations from regression of a cultivar on the environmental indices serve as a useful parameter for measuring genotypic stability for resistance to biotic/abiotic stresses. This approach has been used for testing stability of resistance in sorghum to the midge, *Stenodiplosis sorghicola* Coquillett across seasons (Sharma et al., 1988) or a range of sowing dates with varying insect densities against the sorghum head bug, *Calocoris angustatus* Leth. (Sharma and Lopez, 1990). Therefore, the present studies were undertaken for characterizing a diverse array of sorghum genotypes for stability of resistance to sorghum shoot fly *A. soccata* across seasons and locations, and adaptation to the postrainy season for use in sorghum improvement programs.

2. Materials and methods

2.1. Plant material

The experiments were conducted at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, Telangana, India; Vasantrao Naik Marathwada Krishi Vidyapeeth (VNMKV), Parbhani, Maharashtra, India; Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Maharashtra, India; Centre for Rabi Sorghum (CRS), Solapur, Maharashtra, India; and Directorate of Sorghum Research (DSR), Rajendranagar, Hyderabad, Telangana, India during the 2010/2012 postrainy seasons.

The experimental material consisted of a diverse array of 30 (including resistant – IS 18551, susceptible – Swarna, and a local check) sorghum genotypes, which were selected from a set of 190 lines tested across five locations during the 2010 postrainy season. The test material comprised of five germplasm accessions (IS 2312, IS 2146, IS 5480, IS 18662, and IS 18551 – resistant check), 16 breeding lines/released varieties* (ICSV 700, CSV 22*, ICSV 93046*, M 35-1 Tan, M 35-1*, Phule Chitra*, Phule Yashoda*, PU 10-1, RHRB 19, RSLG 262, RSV 1090, RSV 1093, RSV 1235, ICSV 574, Swarna – susceptible check, and the local check), and eight B-lines (ICSB 422, ICSB 425, ICSB 428, ICSB 432, ICSB 435, ICSB 456, ICSB 458 and ICSB 463). The test material was planted in the field during the postrainy season (October–March). The experiments were conducted using a randomized complete block design (RCBD) with three replications. The experimental plots were given a basal dose of di-ammonium phosphate (150 kg ha^{-1}). Each entry was sown in 2 rows, 2 m long. At ICRISAT – Patancheru, the rows were 75 cm apart. At Parbhani, Solapur and Rahuri, the rows were 45 cm apart, while at DSR, Hyderabad, the rows were 60 cm apart. The seeds were sown at a depth of 5 cm below the soil surface. The field was irrigated immediately after sowing. One week after seedling emergence, thinning was carried out to maintain a spacing of 10 cm between the plants. No insecticide was applied in the experimental plots. Interculture operations were carried out at 15 and 30 days after seedling emergence (DAE). Hand weeding was carried out as and when required. The crop was irrigated at intervals of 20–30 days. The material was tested at five locations over three seasons (2010/12 postrainy seasons, October to March).

2.2. Evaluation of sorghum genotypes for resistance to shoot fly, A. soccata

Shoot fly infestation was optimized through the use of the interlard fish-meal technique (Soto, 1974; Sharma et al., 1992). Thinning in the test material was carried out 7 days after seedling emergence (before egg laying by the shoot fly). Data were recorded on number of plants with deadhearts, number of eggs per seedling and seedlings with eggs at 21 and 28 days after emergence (DAE) in the two row plots. Seedlings with eggs and deadhearts were expressed as percentage of the total number of plants. Overall resistance score (1 = <10% plants with deadhearts, and >80% of the damaged plants producing 2–3 productive tillers; 5 = <50% plants with deadhearts, and >60% of the damaged plants producing 1–2 productive tillers; 9 = >80% plants with deadhearts, and <20% of the damaged plants producing productive tillers) was assessed in terms of tillers with productive panicles at maturity.

2.3. Characterization of sorghum genotypes for morphological traits and grain yield

Data were recorded on leaf glossiness and seedling vigor at 10 DAE, days to 50% flowering, and plant height at maturity. Leaf glossiness was evaluated visually on a 1–5 scale at 10 DAE (5th leaf stage, when the expression of this trait is most apparent) in the early morning hours, when there was maximum reflection of light from the leaf surface (1 = highly glossy, and 5 = non-glossy) (Sharma and Nwanze, 1997). Seedling vigor was recorded at 10 DAE on a 1 to 3 rating scale (1 = high seedling vigor, and 3 = poor seedling vigor) (Sharma and Nwanze, 1997). The test material was also evaluated for agronomic desirability at maturity on a 1–5 scale [1 = good—plants with medium height, 1.5–2.0 m tall, large panicles (20–30 cm long), and bold and lustrous grain, and 5 = poor—plants >2.5 m tall, small panicles (10–15 cm long), and small grain]. All the panicles were harvested and threshed to record grain yield, (expressed as q ha^{-1}).

2.4. Statistical analysis

Data were subjected to analysis of variance using Genstat software version 14.0 (GenStat, 2014). Data across years, locations and replications were considered to be random. Significance of differences between the genotypes was tested by *F*-test, while the treatment means were compared by least significant differences (LSD) at $P \leq 0.05$. The association of shoot fly resistance with the grain yield was also computed for each trial, and a bi-plot was used to identify genotypes with resistance to shoot fly and high yield potential for use in breeding programs, and/or for cultivation by the farmers *per se*. The diversity among the genotypes was assessed based on shoot fly damage scores under natural infestation, and the agronomic traits using principal coordinate analysis (Genstat, 2014). Stability of expression of resistance to shoot fly was measured in terms of percentage variation (CV %) in deadheart incidence in each genotype across five locations over two seasons.

$$\text{Coefficient of variation (CV\%)} \frac{\text{Mean deadheart incidence in a genotype across locations}}{\text{SE mean}} 100.$$

The stability of expression of resistance was also assessed from the regression coefficient (*b*-value) based on deadheart incidence in the test genotype in relation to mean deadheart incidence in the trial at each location/season. The genotypes with *b*-values closer '0' will be most stable, while those with values close to '1' will be least stable (Sharma and Lopez, 1990). The coefficient of determination of the regression equation (R^2) also provided a measure of genotypic performance in relation to mean shoot fly incidence in the trial at different locations/seasons.

3. Results

3.1. Relative susceptibility of sorghum genotypes to shoot fly, A. soccata

There were significant differences among the genotypes tested in terms of percentage of plants with shoot fly eggs, percentage of plants with deadhearts, and the overall resistance score during the 2010–2012 postrainy seasons (Table 1). Across seasons and locations, the percentage of plants with shoot fly eggs varied from 18.11% on the resistant check, IS 18551 to 64.38% on the susceptible check, Swarna during the 2011 postrainy season. The genotypes ICSB 425, ICSB 428, ICSB 432, IS 2312, IS 5480, and IS 18551 exhibited non-preference for oviposition (31.84–46.81% plants with eggs as compared to 29.44% plants with eggs in IS 18551 and 75.25% plants with eggs in Swarna during the 2012 postrainy season. Percentage of plants with deadhearts ranged from 8.17% in ICSB 425 to 62.50% in the Local check during 2010, and 20.17% in IS 18551 to 68.62% in Swarna during 2011, and 24.09% in ICSB 425 to 75.58% in Swarna during the 2012 postrainy seasons. The genotypes CSV 22, ICSB 422, ICSB 425, ICSB 428, ICSB 432, ICSB 435, ICSB 458, ICSB 463, IS 2312, IS 18662, RSV 1093, and RSV 1235 exhibited resistance to shoot fly damage across seasons. Of these, ICSB 425, IS 2312, IS 18662, RSV 1090, RSV 1093, and IS 18551 exhibited moderate levels of recovery resistance to shoot fly damage (RR < 6.0 compared to 2.6 to 5.0 of the resistant check, IS 18551 and 6.4 to 9.0 of the Susceptible check, Swarna). The genotypes CSV 22, ICSB 456, ICSB 458, ICSB 463, ICSV 700, ICSV 93046, IS 18662, M 35-1, Phule Chitra, PU 10-1, RHRB 19, RSV 1090, Phule Yashoda and ICSV 574 had 15% less plants with deadhearts than the percentage of plants with shoot fly eggs during the 2012 postrainy season, suggesting that these genotypes exhibited antibiosis against *A. soccata*. Such differences could not be seen during the 2011 postrainy season as the percentage of plants with shoot fly deadhearts were recorded one week later than the egg counts, and continued oviposition by the shoot fly females due to favorable weather conditions.

3.2. Morphological characteristics of different sorghum genotypes

There were significant differences among the genotypes for leaf glossiness, seedling vigor, agronomic score, and grain yield (Table 2). Twenty-five genotypes exhibited high leaf glossiness (score 1.11 in IS 2312 to 3.06 in Phule Chitra) as compared to 2.39 of the resistant check, IS 18551 and 4.72 of the susceptible check, Swarna. The seedling vigor score varied from 1.50 in PU 10-1 to 3.42 in Swarna. Nine genotypes exhibited high seedling vigor, of which 1222 B, ICSB 463, IS 2312, M 35-1, M 35-1 Tan, PU 10-1, and RSLG 262 were also glossy. Days to 50% flowering varied from 73.22 to 81.38 days. This narrow range in flowering is largely due to photoperiod sensitivity of these lines during the postrainy season. The plant height, which is an important consideration in the postrainy season sorghums because of high value of the fodder, varied from 88 to 194 cm, and the lines M 35-1 Tan, RSLG 262, RHRB 19, RSV 1090, Phule Yashoda, and ICSV 574 were taller (174 to 194 cm) than M 35-1 (166 cm) – the commercial cultivar grown on a large-scale in the postrainy season. The genotypes 1222 B, CSV 22, ICSB 422, ICSB 425, ICSB 428, ICSB 432, ICSB 435, ICSB 456, ICSB 458, ICSB 463, RHRB 19, RSV 1093, RSV 1235, Phule Yashoda, ICSV 574, Swarna and the local check exhibited good agronomic desirability (agronomic score 1.0–3.0) in one or both the seasons, of which 1222 B, CSV 22, ICSV 700, IS 2146, IS 2312, IS 5480, IS 18662, Phule Chitra, PU 10-1, M 35-1, RSV 1090, RSV 1093, RSV 1235, Phule Yashoda and ICSV 574 exhibited greater yield potential than the susceptible and the resistant checks across seasons.

3.3. Diversity among the sorghum genotypes with resistance to shoot fly, A. soccata

Based on the deadheart incidence and agronomic traits, principal coordinate analysis placed the test genotypes into seven clusters. The genotypes showing susceptible reaction to shoot fly were placed in clusters A (Swarna) and B (ICSV 574). The B-lines with shoot fly resistance were placed in clusters C (ICSB 422, ICSB 432, ICSB 435, ICSB 456 and ICSB 458) and E (ICSB 425, ICSB 428 and ICSB 463).The open pollinated varieties/germplasm lines were placed in group D (CSV 22, IS 18662, IS 2312, ICSV 700, ICSV 93046, M 35-1, M 35-1 Tan, Phule Chitra, Phule Yashoda, PU 10-1, RHRB 19,

Table 1
Expression of resistance to sorghum shoot fly, *A. soccata* across seasons and locations[1].

Genotype	No. of plants with shoot fly eggs (%)		Shoot fly deadhearts (%)			Overall resistance score[2]		
	2011	2012	2010	2011	2012	2010	2011	2012
1222 B	30.43	54.81	27.51	38.91	46.51	5.0	4.45	6.50
CSV 22	23.86	54.10	18.76	29.41	36.37	8.0	3.67	5.83
ICSB 422	30.61	45.04	13.99	29.81	31.46	7.0	4.00	6.17
ICSB 425	21.17	31.84	8.17	22.65	24.09	6.0	3.22	5.00
ICSB 428	22.60	45.99	12.89	22.34	34.18	4.0	3.33	6.83
ICSB 432	24.49	45.94	19.79	26.68	32.75	6.0	4.56	6.67
ICSB 435	25.94	47.08	22.35	26.99	30.86	6.0	4.33	6.17
ICSB 456	34.87	74.75	17.08	41.64	43.30	3.0	4.33	8.00
ICSB 458	22.91	55.66	21.62	28.04	33.93	6.0	4.11	7.00
ICSB 463	20.74	48.91	22.71	22.84	30.29	7.0	4.11	6.33
ICSV 700	34.10	61.75	21.08	38.85	35.85	5.0	4.89	7.00
ICSV 93046	40.38	53.42	24.76	42.08	36.00	6.0	4.89	6.17
IS 2146	34.59	55.07	28.83	37.65	42.34	8.0	3.67	5.50
IS 2312	22.75	43.26	67.94	24.11	30.94	4.0	3.22	4.67
IS 5480	20.23	46.81	20.83	26.45	28.85	7.0	3.89	5.33
IS 18662	32.43	55.19	28.91	40.51	36.71	4.0	4.56	5.83
M 35-1 Tan	37.05	51.22	32.15	39.14	36.64	6.0	4.11	7.00
M 35-1	31.65	56.77	42.86	30.21	38.60	5.0	3.67	6.67
Phule Chitra	39.18	55.05	35.18	42.76	36.77	7.0	4.11	7.00
PU 10-1	35.41	58.05	31.20	39.79	37.42	6.0	4.00	6.50
RHRB 19	30.79	57.31	28.32	36.38	41.03	6.0	3.56	6.83
RSLG 262	40.30	51.92	48.28	41.52	36.90	6.0	4.44	7.00
RSV 1090	36.15	55.53	46.66	35.21	35.87	5.0	3.33	5.33
RSV 1093	31.52	52.58	21.11	36.73	39.60	5.0	3.56	5.83
RSV 1235	26.23	51.59	42.26	33.78	36.81	4.0	3.89	6.67
Phule Yashoda	29.81	58.50	32.14	36.75	40.85	6.0	3.67	6.67
ICSV 574	59.35	70.43	46.71	61.92	59.94	6.0	3.89	7.33
IS 18551	18.11	29.44	23.39	20.17	25.03	5.0	2.56	4.34
SWARNA	64.38	75.25	53.45	68.62	75.58	8.0	6.45	9.00
Local check	25.05	55.64	62.50	25.74	37.77	7.0	3.89	6.67
Mean	31.60	53.30	30.80	34.90	37.80	5.80	4.00	6.39
SE±	4.93	4.75	11.53	4.54	3.85	0.20	0.38	0.61
LSD	13.84**	13.73**	NS	12.77**	10.83**	–	1.08**	1.75**

** *F*-test significant at $P \leq 0.01$.
[1] Data recorded on number of plants with shoot fly eggs (%) at 21 DAE for 2 seasons and 5 locations, shoot fly deadhearts (%) at 28 DAE for 3 seasons and 5 locations and overall resistance score for 3 seasons and 3 locations.
[2] Overall resistance score (1 = highly resistant, 9 = highly susceptible).

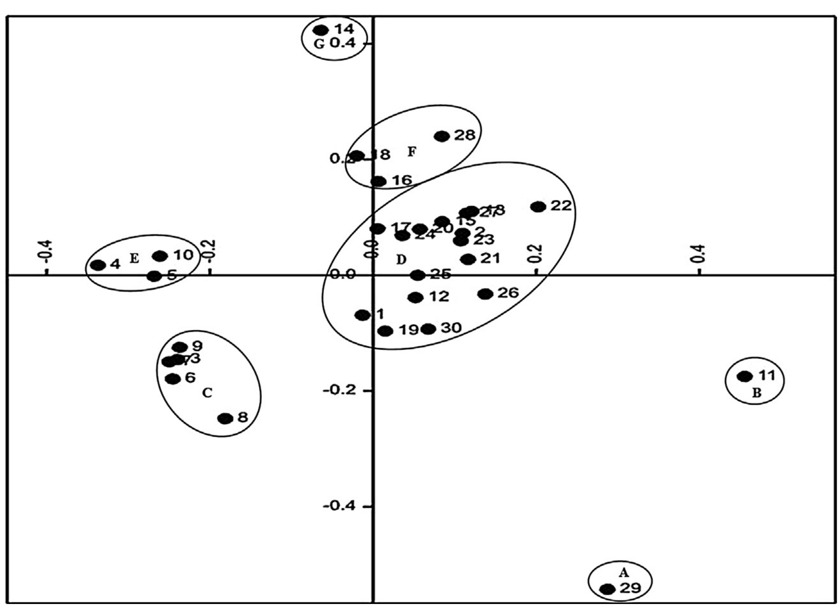

Fig. 1. Diversity among the 30 sorghum genotypes (principal coordinate analysis) based on shoot fly damage (*Atherigona socata*) and different agronomic traits. (1 = 1222 B, 2 = CSV; 3 = ICSB 422; 4 = ICSB 425; 5 = ICSB 428; 6 = ICSB 432; 7 = ICSB 435; 8 = ICSB 456; 9 = ICSB 458; 10 = ICSB 463; 11 = ICSV 574; 12 = ICSV 700; 13 = ICSV 93046; 14 = IS 18551; 15 = IS 18662; 16 = IS 2146; 17 = IS 2312; 18 = IS 5480; 19 = M 35-1 Tan; 20 = M-35-1; 21 = Phule Chitra; 22 = Phule Yashoda; 23 = PU 10-1;24 = RHRB 19; 25 = RSLG 262; 26 = RSV 1091; 27 = RSV 1093; 28 = RSV 1235; 29 = SWARNA; 30 = local check).

Table 2
Agronomic traits of sorghum genotypes evaluated for resistance to sorghum for shoot fly, *A.soccata*[1].

Genotype	Glossy score[a]	Seedling vigor score[b]	Days to 50% flowering	Plant height (cm)	Agronomic score[c]		Grain yield (q/ha)		
					2010	2011	2010	2011	2012
1222 B	2.81	1.92	75.6	123.9	3.0	1.7	8.45	40.32	26.66
CSV 22	3.47	2.00	77.5	171.7	2.0	2.0	10.57	67.97	29.48
ICSB 422	2.61	2.17	81.1	110.1	3.0	2.0	4.51	23.93	18.84
ICSB 425	1.50	2.50	78.9	100.0	3.0	2.7	3.08	25.40	19.97
ICSB 428	2.11	2.67	81.3	109.3	3.0	2.0	5.07	24.31	16.57
ICSB 432	2.33	3.00	78.4	111.7	2.0	2.0	2.75	21.45	18.34
ICSB 435	2.39	2.83	73.2	92.5	2.0	2.0	11.16	26.38	20.35
ICSB 456	2.58	2.83	78.5	100.2	2.0	1.0	8.71	24.67	15.07
ICSB 458	2.56	2.67	76.9	88.5	2.0	2.7	4.50	24.18	14.70
ICSB 463	2.25	1.58	73.6	101.3	3.0	2.7	1.43	24.02	18.08
ICSV 700	3.00	2.08	78.3	147.8	4.0	3.0	15.03	40.78	26.11
ICSV 93046	2.47	2.75	75.8	170.7	4.0	3.0	8.65	46.04	25.21
IS 2146	2.72	2.83	76.6	171.7	5.0	5.0	13.32	34.47	27.82
IS 2312	1.11	1.58	79.1	171.1	5.0	5.0	14.96	41.76	34.24
IS 5480	2.22	2.17	78.4	163.4	5.0	5.0	14.90	44.21	26.35
IS 18662	1.86	2.17	76.4	156.1	5.0	3.7	8.40	45.86	27.74
M 35-1 Tan	1.81	1.92	76.0	175.2	4.0	3.0	11.08	47.67	21.48
M 35-1	2.08	1.92	76.6	166.7	5.0	2.7	8.49	38.82	25.42
Phule Chitra	3.06	2.50	73.5	156.3	4.0	2.0	6.66	51.60	27.12
PU 10-1	2.72	1.50	74.3	157.1	5.0	3.7	2.70	55.10	30.90
RHRB 19	2.28	2.08	77.6	182.6	3.0	2.0	6.79	37.99	28.04
RSLG 262	2.75	1.58	79.3	190.7	5.0	3.7	3.44	40.29	28.74
RSV 1090	3.25	2.00	77.5	174.8	4.0	2.3	8.20	45.57	28.24
RSV 1093	2.67	2.08	80.5	167.4	3.0	2.0	12.71	62.21	33.75
RSV 1235	2.50	2.67	74.3	161.2	3.0	2.7	14.98	46.47	28.24
Phule Yashoda	2.53	2.58	77.3	186.8	2.0	2.0	8.90	56.60	30.50
ICSV 574	2.33	2.33	78.3	194.6	2.0	1.7	11.82	52.80	30.11
IS 18551	2.39	2.33	76.2	173.3	5.0	5.0	9.10	37.16	24.59
SWARNA	4.72	3.42	75.5	119.4	3.0	1.0	7.23	48.08	19.84
Local Check	3.25	2.42	75.5	154.8	2.0	2.3	7.54	56.82	22.40
Mean	2.60	2.30	77.10	148.40	3.40	2.70	8.50	44.40	24.80
SE±	0.43	0.21	1.45	8.25	0.20	0.30	3.28	23.01	3.10
LSD (*P* 0.05)	1.13**	0.6**	4.11**	23.35**	–	0.8**	NS	NS	8.69**

[a] Leaf glossiness (1 = highly glossy, and 5 = non-glossy).
[b] Seedling vigor (1 = high seedling vigor, and 3 = poor seedling vigor).
[c] Agronomic score (1 = good, and 5 = poor).
** *F*-test significant at $P \leq 0.01$.
[1] Data on leaf glossy score, days to 50% flowering and plant height were recorded for 3 seasons and 5 locations, seedling vigor for 2 seasons and 5 locations, agronomic score for 2 seasons and 1 location, and grain yield for 3 seasons and 5 locations.

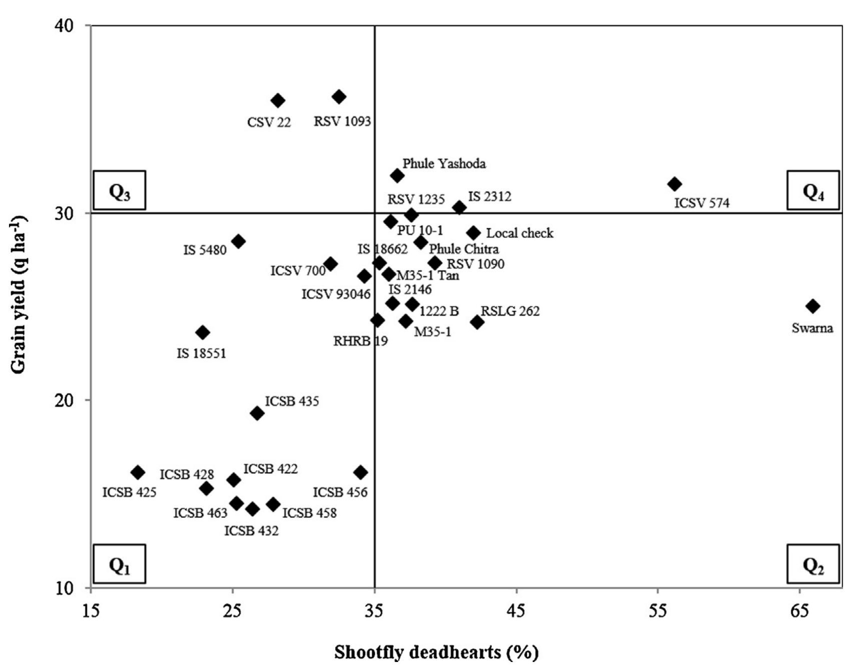

Fig. 2. Expression of resistance to sorghum shoot fly, *A. soccata* in 30 sorghum fenotypes and their grain yield potential during the postrainy season.

Table 3
Stability of expression of resistance to sorghum shoot fly across seasons and locations.

Genotype	Shoot fly deadhearts (%)	Coefficient of variation (%)	Regression equation	R^2 (%)
1222 B	41.49 ± 6.63	15.97	$Y = 1.93X + 22.35$	38.77
CSV 22	30.82 ± 3.38	10.96	$Y = 0.84X + 9.07$	76.62
ICSB 422	25.49 ± 3.68	14.44	$Y = 0.55X + 20.89$	39.25
ICSB 425	21.08 ± 3.09	14.65	$Y = 0.35X + 27.52$	11.25
ICSB 428	28.13 ± 4.16	14.79	$Y = 0.45X + 22.27$	33.42
ICSB 432	25.79 ± 3.85	14.93	$Y = 0.63X + 18.56$	57.05
ICSB 435	28.50 ± 3.46	12.12	$Y = 0.76X + 13.10$	66.90
ICSB 456	37.67 ± 5.86	15.55	$Y = 0.51X + 15.57$	86.54
ICSB 458	30.03 ± 4.20	13.98	$Y = 0.69X + 14.25$	79.69
ICSB 463	24.78 ± 2.77	11.19	$Y = 0.93X + 11.86$	63.61
ICSV 700	34.58 ± 5.30	15.34	$Y = 0.53X + 16.54$	75.94
ICSV 93046	36.39 ± 3.88	10.66	$Y = 0.69X + 9.77$	68.58
IS 2146	35.48 ± 4.28	12.06	$Y = 0.59X + 13.89$	61.42
IS 2312	33.24 ± 6.02	18.10	$Y = 0.14X + 30.25$	6.84
IS 5480	25.38 ± 2.55	10.03	$Y = 0.98X + 9.98$	59.78
IS 18662	35.27 ± 4.45	12.61	$Y = 0.67X + 11.04$	86.51
M 35-1 Tan Bulk	35.76 ± 4.73	13.23	$Y = 0.56X + 14.61$	68.98
M 35-1	36.42 ± 3.97	10.90	$Y = 0.59X + 13.29$	53.12
Phule Chitra	39.16 ± 4.03	10.30	$Y = 0.71X + 6.80$	80.04
PU 10-1	37.12 ± 5.71	15.38	$Y = 1.93X + 22.35$	38.78
RHRB 19	36.46 ± 4.67	12.80	$Y = 0.59X + 13.36$	72.79
RSLG 262 (Mailee)	38.78 ± 5.76	14.86	$Y = 0.45X + 17.51$	63.93
RSV 1090	35.62 ± 5.44	15.26	$Y = 0.43X + 19.32$	54.18
RSV 1093	32.99 ± 4.83	14.65	$Y = 0.58X + 15.73$	75.47
RSV 1235	33.46 ± 4.22	12.63	$Y = 0.61X + 14.48$	63.65
Phule Yasodha	38.68 ± 4.88	12.62	$Y = 0.49X + 15.74$	55.92
ICSV 574	58.42 ± 5.76	9.85	$Y = 0.30X + 17.20$	29.12
IS 18551	21.10 ± 2.96	14.05	$Y = 0.73X + 19.46$	45.08
SWARNA	66.79 ± 5.31	7.95	$Y = 0.46X + 3.85$	58.23
Local check	38.99 ± 5.43	13.93	$Y = 0.30X + 23.14$	25.71

RSLG 262, RSV 1090 and RSV 1093) and F (IS 2146, IS 5480 and RSV 1235). The resistant and susceptible checks were placed individually in groups G (IS 18551) and A (Swarna), respectively, suggesting that there is considerable diversity among the sorghum lines with resistance to shoot fly (Fig. 1). Scatter plot based on grain yield and shoot fly deadhearts indicated that the genotypes CSV 22 and RSV 1093 have high grain yield (>30 q ha^{-1}) and resistance to shoot fly damage (<35% plants with deadhearts); while Phule Yashoda, IS 2312, and RSV 1235 exhibited moderate levels of shoot fly resistance (30–45% deadheart incidence), but had a grain yield potential of >30 q ha^{-1} (Fig. 2) These genotypes can be used for developing cultivars with shoot fly resistance and high grain yield potential. The genotype ICSV 574 suffered high shoot fly damage, but exhibited a grain yield potential of >31 q ha^{-1}. It will be highly desirable to improve this genotype for shoot fly resistance for cultivation in the postrainy season. The susceptible check, Swarna suffered high shoot fly damage, and had low grain yield.

3.4. Stability of expression of resistance to sorghum shoot fly, *A. soccata*

In general, the genotypes with low variance (CV%) had high coefficient of determination (R^2), except M 35-1; while the genotypes with low b-values (slope of the regression coefficient) also had low coefficients of determination (variation explained by levels of shoot fly deadhearts in a test genotype in relation to mean shoot fly deadheart incidence in the trial at a particular location), except 1222 B, PU 10-1and RSLG 262 (Table 3, Fig. 3). Therefore, regression coefficient and R^2 values can be used to identify genotypes with stability of expression of resistance to shoot fly damage. The percentage variation in shoot fly deadhearts in CSV 22, ICSB 463, ICSB 435, ICSV 93046, IS 2146, IS 5480, M 35-1, Phule Chitra and ICSV 574 was 9.85 to 12.12% as compared to 18.10% in IS 2312. The susceptible check, Swarna was also stable in expression of susceptibility to this pest. Based on regression analysis, IS 2312 was the most stable genotype (least *b*-value), followed by the local check, ICSV 574, ICSB 425, RSV 1090, ICSB 428, ICSB 456, and RSLG 262 (*b*-values 0.14–0.50). The coefficient of determination (R^2) was also low for these genotypes (11.25–54.18%), except RSLG 262 and ICSB 456. The genotypes ICSB 422, ICSV 700, IS 2146, M 35-1 Tan, M 35-1, RHRB 19, RSV 1093 and Phule Yashoda were moderately stable in their expression of resistance to shoot fly; while 1222 B, ICSB 463, IS 5480 and PU10-1 were unstable in expression of resistance to shoot fly damage (*b*-values 0.84–1.93).

4. Discussion

Shoot fly is one of the most important biotic constraints for increasing the production and productivity of postrainy sorghums, and hence, it is important to develop sorghum cultivars with resistance/tolerance to this pest. Fourteen genotypes exhibited resistance to shoot fly damage across seasons, of which ICSB 425, ICSB 428, ICSB 432, IS 2312, IS 5480, and IS 18551 exhibited non-preference for oviposition; while CSV 22, ICSB 456, ICSB 458, ICSV 700, IS 18662, Phule Chitra, PU 10-1, and RSV 1090 had less number of plants with deadhearts than the number of plants with shoot fly eggs, suggesting that these lines have antibiosis as one of the components of resistance to *A. soccata*. The genotypes ICSB 425, IS 2312, IS 18662, RSV 1090, RSV 1093, and IS 18551 also showed moderate levels of recovery resistance following shoot fly damage. Oviposition non-preference (antixenosis), antibiosis, and tolerance are the major components of resistance in sorghum to shoot fly (Doggett et al., 1970; Raina et al., 1981; Sharma and Nwanze, 1997; Dhillon et al., 2005, 2006a; Kumar et al., 2008), and the genotypes having glossy and trichomed leaves are relatively less susceptible to shoot fly damage (Maiti and Bidinger, 1979; Maiti and Gibson, 1983; Sharma and Nwanze, 1997; Dhillon et al., 2005, 2006b).

Twenty-five genotypes exhibited high leaf glossiness, of which nine genotypes had high seedling vigor, suggesting that sorghum lines with leaf glossiness trait that exhibit resistance to shoot fly damage do not necessarily have high seedling vigor as has been reported earlier (Taneja and Leuschner, 1985). The lines

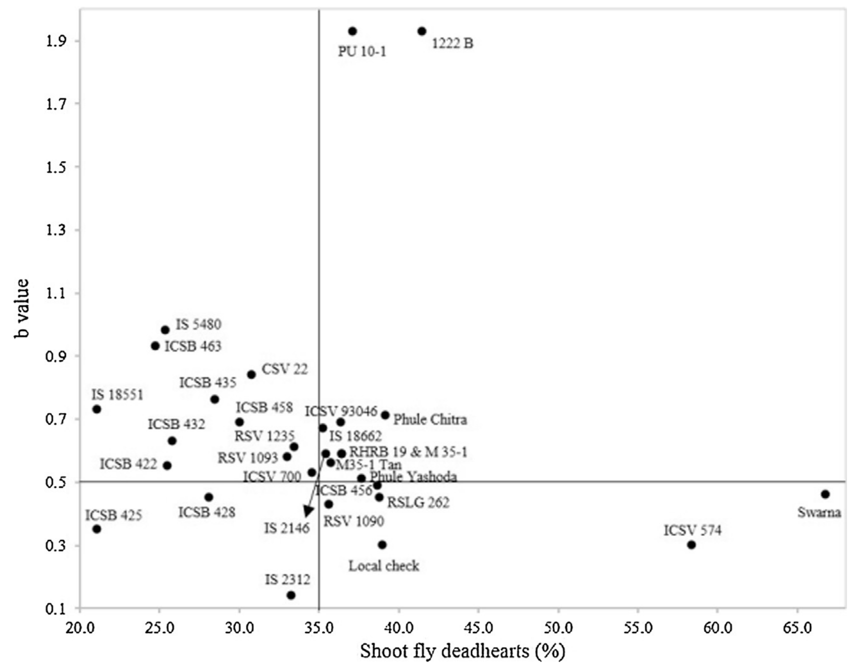

Fig. 3. Stability of resistance to sorghum shoot fly, *A. soccata*.

M 35-1 Tan, RSLG 262, RHRB 19, RSV 1090, Phule Yashoda, and ICSV 574 were taller than M 35-1—the commercial cultivar grown on a large scale during the postrainy season. These lines could be used for developing high yielding postrainy season sorghums as fodder yield is as important as the grain yield in the postrainy season. Several genotypes exhibited good agronomic desirability and shoot fly resistance, and these could be tested on farmers' fields for adaptation during the postrainy season. There was considerable genetic diversity among the shoot fly-resistant and -susceptible genotypes. Based on the deadheart incidence, and morphological and agronomic traits of the genotypes tested, principal coordinate analysis placed the test genotypes into different clusters. The B-lines with shoot fly resistance were placed in clusters C (ICSB 422, ICSB 432, ICSB 435, ICSB 456 and ICSB 458) and E (ICSB 425, ICSB 428 and ICSB 463); while the open pollinated varieties/germplasm lines (restorers) were placed in groups D (CSV 22, IS 18662, IS 2312, ICSV 700, ICSV 93046, M 35-1, M35-1 Tan, Phule Chitra, Phule Yashoda, PU 10-1, RHRB 19, RSLG 262, RSV 1090 and RSV 1093) and F (IS 2146, IS 5480 and RSV 1235), suggesting the possibilities for developing heterotic hybrids with postrainy season adaptation. Genotypes with low b-values also had low coefficients of determination, suggesting that these measures can be used to identify genotypes with stable resistance to shoot fly damage. Based on this criteria, the genotypes ICSB 425, ICSB 428, and IS 2312 were stable in their expression of resistance to shoot fly damage, and these can be used to develop high yielding sorghums with resistance to shoot fly.

CSV 22 and RSV 1093 exhibited high grain yield potential (>30 q ha^{-1}) and shoot fly resistance (<35% plants with deadhearts); while Phule Yashoda, IS 2312, and RSV 1235 suffered 30–45% deadheart incidence, but had a grain yield potential of >30 q ha^{-1}; and these genotypes may be improved for resistance to shoot fly for large-scale cultivation during the postrainy season. The genotype ICSV 574 though suffered more shoot fly damage, but exhibited high grain yield potential because of its ability to produce more tillers following shoot fly damage (exhibiting recovery resistance to shoot fly damage), and it will be highly desirable to improve this genotype for shoot fly resistance for cultivation by the farmers in the postrainy season.

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