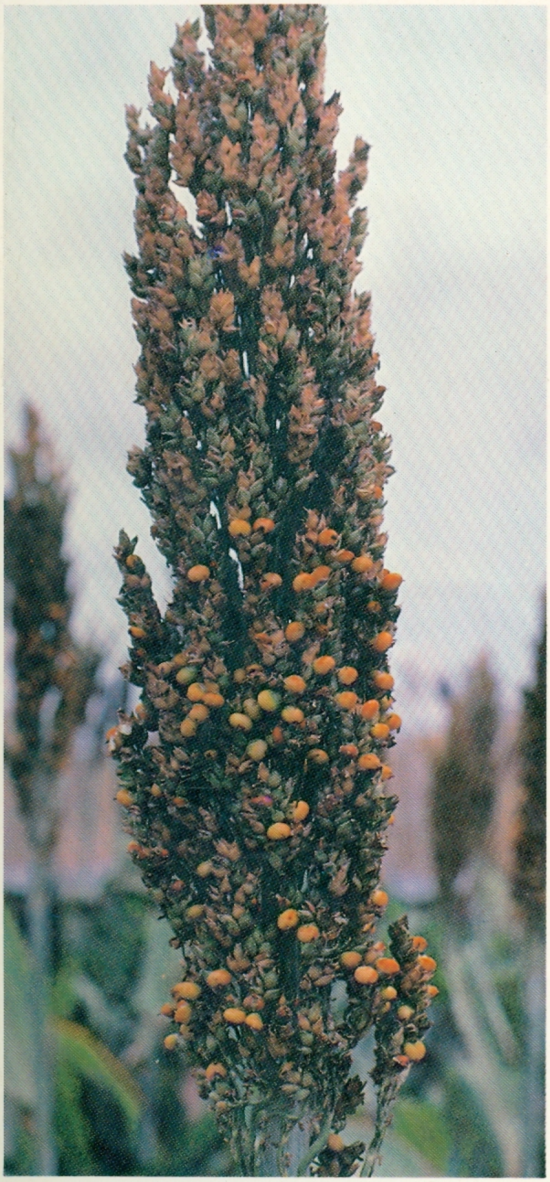
Proceedings
International Sorghum Entomology Workshop



International Crops Research Institute for the Semi-Arid Tropics

Cover: Sorghum head with midge damage (left), female midge fly, *Contarinia sorghicola* (top right), head bug, *Calocoris angustatus* (bottom right).

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Foreword

Sorghum is one of the world's most important human food and animal feed crops in the developing world.

It is also one of the mandate crops of such international and development-oriented institutions as ICRISAT, INTSORMIL, and Texas A&M University, whose sorghum improvement programs are aimed at developing high-yielding and stable varieties and hybrids, in collaboration with national agricultural programs. To achieve this objective much research effort is focused on yield-limiting factors, of which damage by insect and mite species is one of the most important. An end-product of such research is the development of control strategies that are adoptable by small farmers in the semi-arid tropics.

It is now widely accepted that the most appropriate long-term strategy is to work towards an integrated pest management system (IPM) for the crop, based on the use of resistant cultivars, cultural and biological control procedures, and, to a limited extent, chemical insecticides. To achieve this, collaboration and exchange of ideas between international and national research institutions is essential.

As an example of such collaboration, the joint efforts of sorghum researchers in ICRISAT, INTSORMIL, and Texas A&M University, and national collaborators across the world have already led to the production and adoption in Sudan of the first high-yielding hybrid sorghum (Hageen Durra 1), with a yield 4 to 5 times higher than the best local varieties. Also, the first midge-resistant variety from ICRISAT has reached the on-farm testing stage in midge-endemic areas of India.

These are truly outstanding examples of the success that can be achieved by agricultural scientists when they are allowed to work cooperatively through the joint planning of research, the free exchange of germplasm, and the sharing of data.

Workshops such as the recent one on International Sorghum Entomology play an important role in this regard, by fostering personal and professional relationships among the involved scientists and by validating the data on which research and development strategies can be based. We are pleased that our respective institutions planned and hosted this workshop, and believe that these proceedings will provide valuable reference material for many years to come. We congratulate the participants.

L.D. Swindale
Director General
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Deputy Chancellor of
Texas A&M University System and
Member of ICRISAT Governing Board

Setting the Scene

Objectives of the Workshop

K. Leuschner*

It is a great pleasure to welcome you all to the first International Sorghum Entomology workshop. This meeting has been made possible through the generous support of the USAID Title XII Collaborative Research Support Program on Sorghum and Millet (INTSORMIL), the Texas Agricultural Experiment Station of the Texas A & M University, College Station, Texas, USA, and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru, India. We are most grateful to all the three institutions.

The idea of holding such a workshop came from J.C. Davies, H.C. Sharma, and G.L. Teetes in 1981, before I joined ICRISAT. During the International Symposium on "Sorghum in the Eighties" it became evident that sorghum entomology has to play an essential part in the overall improvement of sorghum production. It also became clear that its role should be strengthened accordingly.

Sorghum yields, especially in Africa and Asia, are pitifully low, ranging from 500 to 800 kg/ha. A major reason for this is insect attack, although reliable yield loss data are hard to come by. Over the last two decades interest in sorghum for human consumption and animal feed has increased tremendously and so has the entomology input. A vast amount of literature from developed and developing countries is available and it was necessary to bring together researchers concerned with sorghum insect control to discuss their work and exchange views to evolve future research strategies and possible collaboration.

We have basically two groups of scientists assembled here, one from the so-called developing world and the other from the developed one. Each group has its own research approaches, based on the economic and environmental situation. Notable progress has been made in improving sorghum production in the developed countries; less in the developing ones. This difference has led many scientists to believe that the approach taken in the developed world is the only one leading to success. As a result, they tend to look at the agricultural production systems of developing countries as inferior, although they may be the more stable ones. Certainly both systems have their positive aspects, and in the course of the workshop we will see that both sides can certainly benefit from each other.

Therefore the objective of the workshop is to look into the production systems in temperate and tropical sorghums, to identify their major insect problems and control systems adaptable to farmers' fields, and to identify problem areas where more research or collaboration is needed.

Let us clearly remember that our client is the farmer in the semi-arid tropics and in the temperate regions and he is not prepared to accept any control recommendations that will involve high risks. Therefore his situation and approach should be taken into consideration when we discuss future research strategies.

I hope that we will have a most fruitful time here together, exchanging our ideas and views freely, and carefully considering the comments of others.

Hopefully this will lead to more collaborative research between scientists from temperate and tropical countries.

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Sorghum Production in Relation to Cropping Systems

N.G.P. Rao*

Abstract

*Efforts to enhance agricultural production and productivity involve changes in the components of agricultural systems. Genotype and management changes leading towards higher levels of crop productivity and stability in turn enable design and development of stable and profitable cropping systems. During the period of transition, the genotype and system changes may present different insect and disease problems that need to be tackled by cultural methods and other means. Since the temperate * tropical crosses are being used both in the tropics and in temperate regions, resistance to a range of pests could be incorporated during the breeding process. The Indian experience in developing new hybrids and their influence on cropping systems is described. In the light of the West African experience, the scope for alteration of traditional African cultivars and cropping systems to enhance production and impart stability to African dryland agriculture in the different rainfall zones is presented.*

Resume

***La production de sorgho dans le cadre des systemes d'exploitation agricole**: L 'augmentation de la production et de la productivite en agriculture suppose un changement des differents composants des systemes agricoles. La modification des genotypes et de l'amenagement cultural augmente la productivite et la stabilite des recoltes, ce qui permet d'etudier et d'elaborer des systemes d'exploitation stables et rentables. Cependant, ces changements peuvent entrainer, pendant la periode de transition, des problemes de ravageurs et de maladies qu'il faudrait surmonter par les pratiques culturales ou par d'autres moyens. Etant donne que les croisements de types temperes x tropicaux sont mis en culture a la fois dans les zones tempere'es et tropicales, on peut envisager d'incorporer la resistance a de nombreux insectes nuisibles au cours de la selection. Cette communication presente l'experience faite en Inde dans la creation de nouveaux hybrides et leur influence sur les systemes d'exploitation. L'auteur decrit egalement les possibilities de modification des cultivars traditionnels africains et des systemes d'exploitation en vue d'une production superieure et stable dans le cadre de l'aridoculture des differentes zones pluviome'triques en Afrique de I'Ouest.*

Traditional tropical agricultural systems generally contain a large number of species planted in space and time. Such systems have a structure close to natural ecosystems. In our quest to enhance agricultural production and productivity to meet the demand of growing populations, we have brought about changes in the components of the agricultural systems leading towards changes in land-use patterns. Such changes, involving drastic alterations in genotypes and management practices led to the introduction of specialized farming systems with optimal resource use and productivity, which are evident in developed agriculture. The shift from natural to specialized agricultural systems does disturb the ecological balance and creates problems in regard to insect pests and diseases which need to be tackled, particularly, during the period of transition from subsistence to productive systems. I shall attempt to analyze some of these aspects in relation to sorghum-based cropping systems.

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International Crops Research Institute for the Semi-Arid Tropics. 1985. Proceedings of the International Sorghum Entomology Workshop, 15-21 July 1984, Texas A&M University, College Station, TX, USA. Patancheru, A.P. 502324, India: ICRISAT.

The Indian Experience

The Indian experience of transforming traditional sorghums to more productive forms has been critically analyzed and documented (Rao 1982) and I do not propose to restate this. But I would like to state that the new hybrids, which are of much shorter duration than the traditional sorghums, have had a significant impact on the overall sorghum production in India. In spite of the fact that the hybrid coverage has been confined to the rainy season in some districts, primarily in the states of Maharashtra and Karnataka, even this limited spread had an overall impact on sorghum production as shown in Table 1. The impression that the "green revolution" is confined only to irrigated crops such as wheat and rice is erroneous, and sorghum is an example that shows it could encompass rainfed areas as well.

The change began with the introduction in 1965-66 of an early-maturing (95-100 days) hybrid CSH 1 in the black soil areas of the Deccan, where the traditional sorghums cultivated were of 5 to 5.5 months' duration. CSH 1 is known to be susceptible to shoot fly, stem borer, leaf spots, grain molds, and *Striga,* and is currently being used as a control in most insect- and disease-resistance studies. Although, superior hybrids such as CSH 5, CSH 6, and CSH 9, with slightly better resistance and better grain quality have been developed and propagated, CSH 1 is still being cultivated on a large scale and has stood the test of time. The significant point is that hybrids like CSH 1, CSH 5, CSH 6, and CSH 9 represent altered and optimal plant types whose critical growth phases coincide with periods of optimal soil moisture and yield well in years of normal, subnormal, excessive, and aberrant rainfall. This conferred considerable stability on rainfed sorghum production. By adopting suitable management practices like timely planting, the insect pest problems have been well contained. Using these altered genotypes as the basis, both hybrid and varietal improvement programs are presently oriented towards incorporation of greater levels of resistance against the prevalent insect pests and diseases to further enhance the level of stability.

Initially, high-yielding hybrids were grown as sole crops in place of traditional intercropping and an impression was created that they may not be suitable for intercropping (Jodha 1980). It was demonstrated (Rao and Rana 1980) that sole-crop production and stability are essential for developing suitable intercropping systems. Studies carried out by Rao et al. (1981) on inter- and intra-species competition, spatial arrangements, and interactions demonstrated the design and development of productive and stable intercropping systems that are different from the traditional subsistence intercropping systems.

A large number of intercropping experiments were conducted in India under the All India Coordinated Sorghum Improvement Project (AICSIP), the All India Coordinated Project for Research on Dryland Agriculture (AICPRDA), and ICRISAT, and a wealth of information is now available (Table 2). The significant point is that all these later studies were based on altered cultivars of sorghum. If the studies had been carried out with traditional cultivars, the results would have been different. Intercropping of sorghum with grain legumes and edible oilseeds is now an established practice, and the Government of Maharashtra consciously promotes intercropping of hybrid sorghums.

The short-season hybrids, besides increasing stability of production under low and erratic rainfall conditions, opened up opportunities for two crops per rainy season in better rainfall areas. Growing a following crop of safflower, chickpea, linseed, etc., under rainfed conditions is now feasible after *kharif* (rainy-season) grown hybrid sorghum. The sequence crop yields have been about 300 to 600 kg/ha.

In the *rabi* (postrainy-season) sorghum areas, the kharif fallows are now planted to short-season mung bean or urd bean, and soybean is a potential crop for this purpose. Where such a practice was followed in Marathwada, the grain legume production increased from 227 900 metric tons (tonnes) to 330600 tonnes. A portion of this increase is from

Table 1. All-India compound growth rates (%) of area under cereal crops, agricultural production, and yield during 1967/68 to 1978/79.

	Compound growth rate, 1967/68-1978/79		
Crop	Total area	Total production	Yield (kg/ha)
Sorghum	1.49	2.07	3.62
Wheat	3.16	6.02	2.76
Rice	0.82	2.64	1.80
Pearl Millet	-1.26	0.28	1.53
Maize	0.05	-0.04	-0.07

Table 2. Yields in sorghum-based intercropping systems, averaged over several experiments.

	Average yield (kg/ha)			
Intercropping system	Sorghum as sole crop	Sorghum in inter-cropping system	Intercrop component as sole crop	Intercrop component in inter-cropping system
Sorghum/pigeonpea	3580 ± 190	3240 ± 140	1650 ± 90	940 ± 40
Sorghum/soybean	3300 ± 190	3220 ± 180	1390 ± 70	550 ± 40
Sorghum/groundnut	3360 ± 270	3310 ± 180	1040 ± 140	480 ± 50

the legume preceding rabi sorghum, where legume yields range from 400 to 600 kg/ha.

The potential for ratooning of sorghums and management of ratoons has been studied, and in Jalgaon district of Maharashtra, vast areas of hybrid sorghums are ratooned even under rainfed conditions. The potential is even greater under irrigation.

Under irrigation, both in the Deccan and Malwa plateaus, a rainfed hybrid sorghum followed by irrigated wheat is one of the most productive systems in terms of water-use efficiency and productivity (Table 3).

Cropping systems in sorghum are now taking a different direction. There is a limit to the consumption of coarse grains like sorghum. There are also limits to interstate grain movement, and Maharashtra now being self-sufficient in sorghum, the question of demand and supply and fall in prices tends to limit sorghum production. It is therefore necessary to explore alternative uses for sorghum and one of these would be to utilize sorghum land for grain legumes and edible oilseeds, which are in short supply in India. Consequently, the potential of sorghum-based cropping systems to meet the shortages of grain legumes and edible oilseeds has been examined and demonstrated (Rao and Rana 1980).

The intercropping studies in the sorghum project are now taking a different direction. Earlier we maintained the full population recommended for a sole crop of sorghum in the intercropping system to maintain sorghum yields at the sole-crop level, and the intercrop yield was a bonus. In view of the demand-supply position for sorghum and the need for pulses and oilseeds, we are now trying to reduce the sorghum component and increase the intercrop pulse or oilseed component to enhance the profitability of the system and to meet national needs. Sorghum is still the most productive crop during the rainy season in the black soil belt under rainfed conditions. It is therefore necessary to redesign cropping systems around sorghum.

The West African Situation

Most African farms are small and the prevalent mixed-cropping systems are essentially replacement systems in time and space and are aimed mainly at meeting the farmer's family needs. The

Table 3. Comparative yields of some crop sequences under irrigation in national demonstrations in the Marathwada region, Maharashtra, India.

		Total yield (kg/ha)		
Crop sequence	No. of demonstrations	Mean	Highest	Lowest
Sorghum-wheat	95	7941	9543	5615
Rice-wheat	30	6952	8031	5971
Groundnut-wheat	12	5341	5252	4902

risk is distributed over time, space, and species. The agricultural systems have experienced little change—the traditional sorghum cultivars are low yieiders, tall, and late compared with the duration of the rainy season; plant populations are low; and fertilizer is hardly used. By developing alternative agricultural systems, the components of the cropping systems could be readjusted in such a way that the systems become more stable, productive, and profitable. I shall examine this in the light of my West African experience.

Environmental Resources—Rainfall and Crop-growing Season

The potential crop-growing season in various parts of West Africa varies from 70 to 260 days. The annual rainfall in the sorghum-growing regions ranges from 500 to over 1500 mm. Figure 1 shows the rainfall distribution in the 500 to 700 mm, 700 to 1000 mm, and 1000 to 1300 mm zones and the potential evapotranspiration. Except for the amount of precipitation, the pattern is unimodal and remarkably similar, with the exception of two peak situations in the Guinea savanna.

While crop productivity and stability of a simultaneously planted intercropping system should be the major objective in low-rainfall areas, the longer growing season in higher rainfall areas provides greater opportunities for sequence cropping. With appropriate genotypes and management, there is no reason why higher yields comparable to those obtained elsewhere in the world could not be obtained in West Africa.

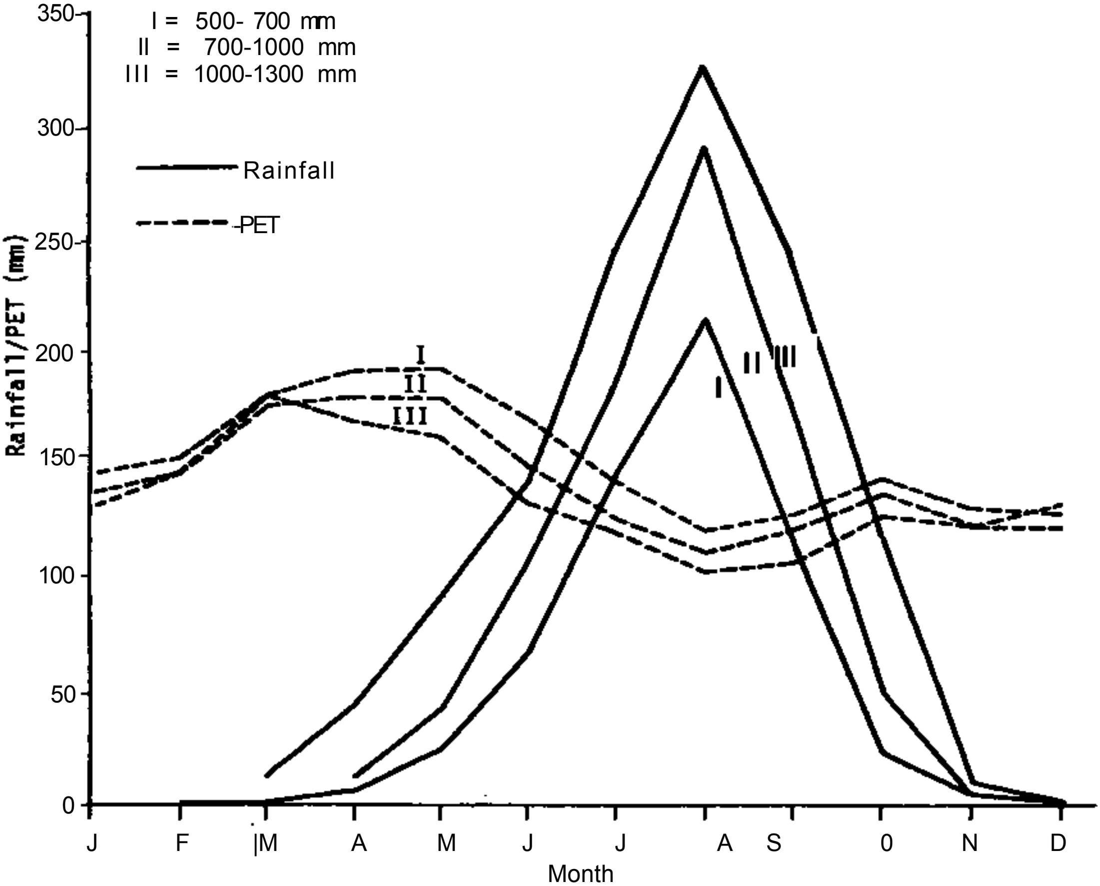

Figure 1. Rainfall distribution and potential evapotranspiration (PET) in three rainfall zones of West Africa.

Sole-crop Productivity and Stability

Breeding efforts in the region have attempted the introduction of short-duration types including hybrids with a duration of 3 to 4 months. In addition, selections were made from crosses between traditional and dwarf cultivars leading to photosensitive high-yielding dwarf varieties with durations similar to local varieties (Andrews 1975).

Some success with respect to yield levels was obtained with short-season varieties, but probably ecological limitations did not favor their spread. The situation on farmers' fields has not changed, and current efforts of most programs are aimed towards breeding improved varieties similar to locals in maturity in the respective agroclimatic zones.

Goldsworthy (1970a) had shown that dry-weight gain after heading in the tall late-maturing Nigerian Farafara took place in the stem. On the other hand, in an early-maturing hybrid, NK 300, over 70% of the dry matter formed after heading was stored in the grain. Comparative yield levels of early-planted Farafara and late-planted NK 300 were 2160 and 4690 kg/ha, respectively. A similar situation existed with Indian cultivars and hybrids (Rao 1982). Goldsworthy (1970b) further demonstrated that, unlike hybrids, the Nigerian locals do not respond to increasing population levels. The situation is similar with Indian local varieties. Yet, unlike the situation in India, the advantages of short-season hybrids have not been utilized in Africa until now.

Genotypic alterations of traditional tropical sorghums are a prerequisite for sole-crop performance as well as cropping system performance. Such modifications do furnish greater resilience to system alterations, and I studied this aspect in West Africa during 1981-83.

Cultivar Alteration for Changing Cropping Systems

Prevalent intercropping systems like the *gicci* system of Nigeria, based on traditional cultivars, are largely of the relay type. The number of components that enter into the system and their populations vary. There is continuous interplanting, sometimes starting early in May and continuing to August. The features and advantages of these systems have been listed by Okigbo (1978), and modifications for improvement have been suggested by Baker (1979).

What is particularly striking is that the prevailing soil and rainfall conditions do permit continuous relay planting. Modifications and readjustments of the components of the system could enable us to develop an alternative that makes the most efficient use of available environmental resources. I will attempt to elaborate on this, based on my brief experience in Nigeria under the ICRISAT-SAFGRAD project.

Alternative production systems for sole and mixed crops based on altered cultivars, if conceived and implemented properly, could result in much-needed improvements in productivity and stability. Suitable short-season cultivars with built-in resistances and flexibility for planting across a range of environments and planting dates could be useful in the drier areas of the north, the moderately heavy rainfall north Guinean zone, and as a late-sown crop in the long-season heavy-rainfall south Guinean zone.

Superior short-season cultivars are known for their better harvest index and better response to increased populations and fertility levels. They are also less competitive and more suitable for the development of stable and productive cropping systems in place of the traditional ones. Such cultivars could be of immediate use and also provide the basis for future improvement.

In other words, the need is for an alternative base with wide adaptation as has been developed with wheat and rice on a global basis and with sorghum on a limited scale. The use of short-season sorghums in place of 6- to 8-month cultivars could lead towards better resource utilization of time, space, and inputs.

To meet this goal, a large number of improved tropical sorghum genotypes (available from ICRISAT, AICSIP, Ethiopia, Sudan, Mali, Burkina Faso, etc.) were screened for insect and disease reactions and adaptation across West Africa. Although a number of breeding lines had to be eliminated, 1982 data from Maroua in Cameroon (dry zone), Samaru (moderately wet), and Mokwa (heavy rainfall, long season), supplemented by visual observations at Kano, Kadawa, and Yandev, lead to useful conclusions. The practice of testing across latitudes and planting dates without plant protection measures ensures, to a reasonable extent, the selection of high-yielding and resistant cultivars which can then be used in a breeding program. Some of the problems encountered during such a process are described.

Seedling Deadheads

Both stem borers and shoot flies cause seedling deadhearts. During normal season plantings, deadheads result primarily from stem borers *(Busseola fusca* mainly), with shoot flies occasionally attacking late plantings. In off-season plantings, *Sesamia* sp predominates and can cause heavy stand loss.

Studies during 1981 at Kano and Samaru revealed significant varietal differences related to seedling deadhearts, mainly from stem borers. Increasing applied nitrogen increased deadhead percentages, which were high under low populations at both Kano and Samaru. Both nitrogen x cultivar and population x cultivar studies indicated that borers prefer vigorous plants but shoot flies prefer weak ones. The interactions indicated scope for selecting vigorous seedlings that resist stem borer attack.

Forty days after planting sorghum in 1982, seedling deadhearts (primarily from stem borer) were studied at Samaru, Kadawa, Mokwa, and Yandev. At Samaru, deadhead percentages in a late-July planting under serious shoot fly attack were also recorded. All the trials were replicated. The varietal differences resulting from 48 entries were statistically significant. Entries that showed lowest deadheart percentages were S36, S40, and S2. We have analyzed shoot fly resistance from five environments. The most stable varieties were S 40, S 36, S35, and S2. The stability for seedling deadheads is reflected in Figure 2.

Stem Tunneling

During 1981, stem borer tunneling was heavier than in 1982. Our studies indicated that stem tunneling did not result in heavy yield loss but stem

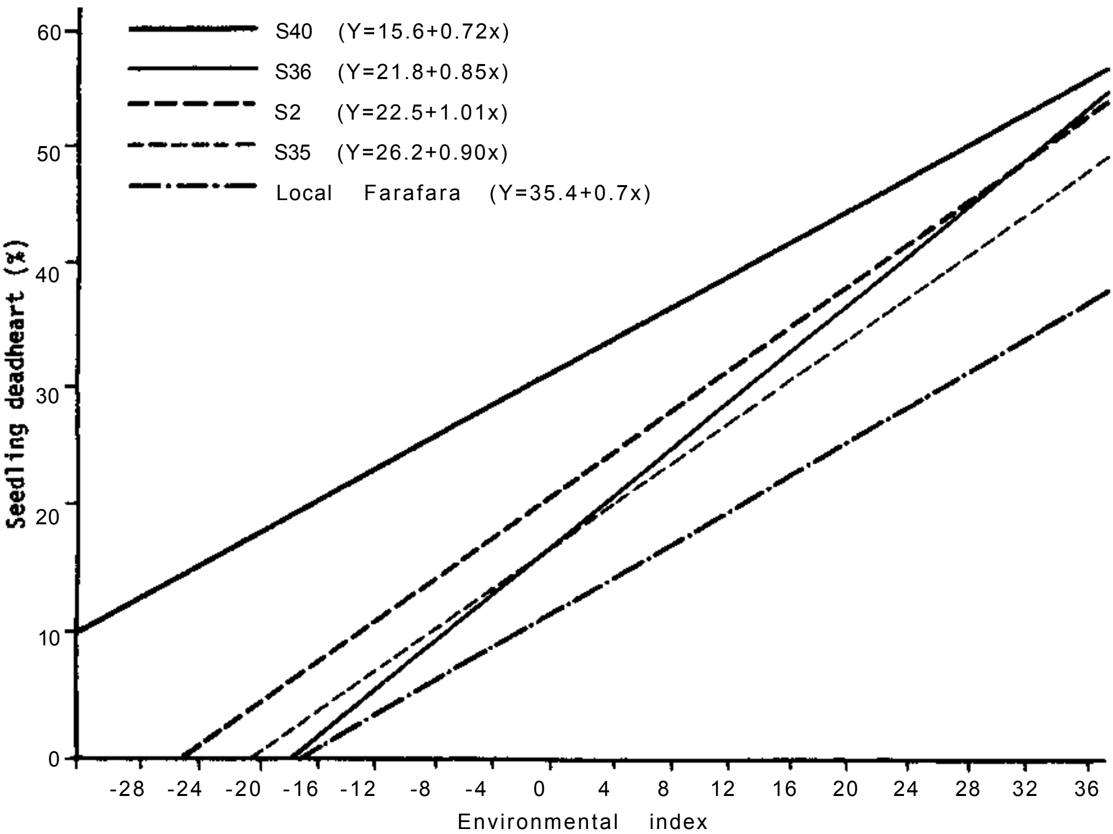

Figure 2. Stability of shoot-fly resistance in five sorghum entries as reflected by seedling dead head (%).

breakage due to heavy tunneling did. Therefore, we shook the plants vigorously at harvest time and estimated percentages of plants that did not break. We identified entries that did not break easily. Apparently, selected entries have reasonable tolerance. During the off-season plantings, screening for *Sesamia* species resistance was possible and a number of highly susceptible lines could be eliminated.

Disease Resistance

During 1981, lines highly tolerant to grey leaf spot *(Cercospora sorghi),* anthracnose *(Colletotrichum graminicola)* and sooty stripe *(Ramulispora sorghi)* were identified. Leaf disease incidence was lower in 1982 than 1981, but the resistance pattern remained the same as in 1981. Late October rains in 1982 caused molds; we used these for mold resistance screening. Eighteen entries with better agronomic traits and less mold incidence were selected.

By screening breeding material in dry and wet locations under various planting dates, it was possible to identify lines less affected by potential pests and diseases but the results have to be confirmed.

Selection of Tropical Cultivars

Fifty lines were selected during the 1981/82 rainy season and off-season and replanted for further yield evaluation in 1982 at Kano and Maroua in Cameroon (dry zones), Samaru (moderately wet north Guinean zone), and Mokwa and Yandev (long-season south Guinean zone).

The trials clearly separated high-yielding from low-yielding lines. We also recorded their reactions to insects and diseases under a range of planting dates. The plant density was kept at 50 000 to 55 000 plants/ha, the optimum recommended for local Farafara. Plant populations of short and early-maturing varieties could go up to 150 000/ha.

Lines S 40, S 35, S 36, S 19/20, and K 4 were promising under August plantings and a range of planting dates. They were less attacked by the prevalent insect pests and diseases, and showed less grain deterioration.

In spite of low rainfall, S 34 at Samaru in the Guinean zone and S 35 at Kano and Maroua in the Sudanian zone gave reasonable yields. During adaptational studies, lines like S 34, S 35, S 36 and K 4 were identified, which are high-yielding and could be used in cropping system studies over a range of West African latitudes.

S.V.R. Shetty used some of these selections together with locals in population and fertility interaction studies to develop more productive cropping systems. His first studies during 1983 were encouraging.

Insect Problems in Relation to Genotype and Cropping System Changes

I have stated before that for tropical agricultural systems to become more productive and stable, radical genotypic changes are a must (Rao 1982). For various reasons, both in temperate and tropical regions, the temperate x tropical crosses have been exploited through the conversion approach in the USA and more conventional approaches in India. Thus the breeding materials handled in both cases have been similar if not the same. The utility and consequences of temperate x tropical crosses have been critically analyzed (Rao and Rana 1982).

With particular reference to the major insect problems, shoot fly and stem borers may be more serious in the tropics and therefore temperate, less adapted sorghums may be more susceptible in this region of the world. Midge is common both in the tropics and in temperate regions.

The levels of resistance available for shoot fly and stem borers are not very high. Fortunately, the incidence of shoot fly and stem borer in the tropics can be managed to a considerable extent through cultural practices and this is a positive feature. The temperate x tropical crosses could be used for breeding optimum plant types, provided the high susceptibility of the temperate genetic backgrounds to shoot fly and stem borer is reduced. If this can be done, the resulting altered cultivars will have great potential as sole crops and in cropping systems. The Indian program is presently trying to follow this approach.

When changes in genotypes and cropping systems in a country occur, the pest complex and the relative importance of individual pests may also change. Even new pests not known so far and new biotypes may show up. A good example is the midge fly, which gained economic importance only after the introduction of new high-yielding hybrids. Late local cultivars suffered especially because of the early generation buildup of midge flies on short-duration hybrids not resistant to this pest.

Since the temperate x tropical crosses are presently being exploited in the USA and the tropics, it should be possible to evolve a mechanism through which resistances to both temperate and tropical insect and disease problems could be synthesized in common cultivars, which in the long run should lead towards the goal of multiple and durable resistance.

Analysis and Conclusions

If the productivity of traditional tropical sorghums is to be enhanced and stabilized, major genotypic alterations are necessary, and the major route is the exploitation of temperate x tropical crosses, irrespective of whether the end product is a hybrid or an improved variety. Agriculture based on such altered genotypes is not incompatible with lower levels of inputs. During the process of transition from traditional to more productive genotypes and agricultural systems, insect and disease problems will have to be encountered and managed until a productive equilibrium is re-established. To enhance this process, resistance breeding will be an important factor in genotype alterations.

In the Indian context, this has been proved beyond doubt in the rainy season, and the altered genotypes that represent intermediate optima furnished the basis for higher levels of productivity and stability in sole crops as well as cropping systems. No doubt further improvement will come over time. If in the near future, there is a shift towards tall sorghums, it will be for a different objective—biomass and energy.

The stagnant African situation needs analysis. In a recent analysis of the African drought, the *Christian Science Monitor* rightly stated, "It was in the African savanna that man evolved and learned to make fire, talk and shape tools of flint. Today, almost 40 000 years later, man has applied science and technology to set off a quiet agricultural revolution all over the planet—except in Africa. Africa, where man began, now needs his most advanced scientific techniques."

In the same article, some of the scientists working in Africa reflected their opinion, "We must respect what exists, otherwise we can destroy. Real progress comes hard and from slogging away. You have to advance step by step and carefully." "In places where draft animals and the plough were introduced not more than 20 years ago, there is already rapid degradation of soil." They tend to plead for existing cultivars, existing maturities, and preservation of existing systems with minor additions and changes. This is what has been done all these years, with no visible effect.

The report on African agricultural research assembled by the members of a committee of consultants for this purpose has been documented by the U.S. National Academy of Sciences (1974). The new role of agriculture in Africa according to them will require "an expanding and changing base of knowledge including the knowledge of the environment—the organisms that live in it, the systems in and by which these organisms can be changed—and the economic and social facts of life in the rapidly changing African societies."The committee emphasized "more, different and if possible better agricultural research. "Kowal and Kassam (1978) stated that blueprints of innovations and changes in the farming methods are not presently available for West Africa.

In the African context, we still seem to have a quarrel with our goals, some pleading largely for the preservation of the existing systems with minor changes and others for radical genotype and system changes. The choice, therefore, is between the evolutionary and revolutionary approaches.

To me there is no choice. Based on my long involvement in the Indian program and my brief West African experience, I feel that unless we bring about genotypic and cropping system changes of a far-reaching and revolutionary nature, we may not witness a rapid change in productivity of African agriculture.

I am of the opinion that the system has to change, but the values have to be preserved.

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Sorghum Entomology Research: Programs and Need in the Developing World

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Abstract

Sorghum on a world basis ranks fifth among the cereal grains. But in spite of its importance, only marginal progress has been made in developing countries in increasing yields. Because of the low market value of sorghum in these countries, researchers have so far paid little attention to this crop. Insect pests take a major toll of sorghum yields (12% in India alone). Although a number of international and national organizations have done good basic research on sorghum insects, their impact has been slow. The reasons for this are described, and areas of research needed are outlined, with emphasis on integrated pest management based on farmers' practices: host-plant resistance, cultural methods, and biological control, with chemical control only if absolutely necessary. A simple preliminary IPM example for India is given. Finally, training of researchers and extension staff is stressed as a major activity needed to implement control methods under farmers' conditions.

Resume

***La recherche sur l'entomologie du sorgho—programmes en* court *et Imperatits dens le Tiers Monde*:** *Le sorgho se situe au cinquieme rang parmi les cereales en grain dans le monde. Malgre son importance, le progres dans le domaine de l'augmentation de ses rendements est negligeable dans les pays en voie de developpement. Le peu d'attention consacree a cette cereale par les chercheurs est due a sa faible valeur commerciale. Les recoltes sont decimees par les ravageurs (12% en Inde seule). L'auteur explique pourquoi les recherches de base menees par certaines organisations nationales et Internationales, quoique considerables, ont eu peu d'impact sur l'agriculture. Les domaines de recherche a approfondir sont proposes, avec /'accent sur la lutte integree (IPM) fondee sur les pratiques culturales: resistance de la plante-hote, methodes culturales et lutte biologique et, s'il le faut absolument, lutte chimique. Un exemple preliminaire de la lutte integree pour l'Inde est donn6. Enfin, la formation des chercheurs et des encadreurs est soulignee comme prioritaire pour l'application des methodes de lutte en milieu reel.*

On a world basis sorghum ranks fifth among the cereal grains in extent of production (after wheat, rice, maize, and barley). Whereas sorghum is grown mainly for animal feed in the Americas, production in Africa and Asia is chiefly for human consumption. Yields in developing countries are generally low; however, over the last decade, substantial increases in production have occurred in certain countries. According to Doggett (1982), yields have increased by 50%—from 484 to 734 kg/ha—in India, one of the major producers, but in Africa average yields have only marginally increased, from 671 to 683 kg/ha. In Mexico, substantial increases—from about 1400 kg/ha in 1961 to 2900 kg/ha in 1980—were achieved; in the USA, production reached a temporary plateau from 1970 to 1980 of about 3300 kg/ha (Leng 1982).

From these figures it becomes clear that most countries in the developing world were not able to achieve the increases possible in sorghum pro-

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ductlon. What are the reasons for this?

In Africa and Asia, sorghum is grown mainly by small farmers who consume most of the produce themselves. Only recently, with increasing urban populations, are markets for sorghum expanding, but townspeople mostly prefer to consume wheat and rice.

Probably because of the nonexistence of a market and because sorghum is a less commercialized coarse grain, the crop has not received adequate attention from researchers, governments, and commercial companies. Because of increased human population pressure, it is now realized that sorghum as a food crop has a higher potential in many ecological and climatic situations in Africa, India, and South America than recognized so far and may be the only viable source for providing the basic staple food for the local diet (Cummings 1982).

Insect Pests as a Factor Limiting Sorghum Production

Constraints to sorghum production are many. They range from climatic constraints to poor soil management, low soil fertility, use of unimproved varieties, diseases, and insect and other pests. Since this workshop deals mainly with insect pests, my paper will concentrate on these, with the realization that important relationships may exist with the other factors mentioned.

Insects attacking sorghum can be grouped into soil pests (wireworms, grubs, and rootworms), foliage feeders, (greenbug, aphids, bugs, armyworms, grasshoppers, and mites), stem feeders (stem borers, shoot fly), earhead feeders (midge, head bugs, bollworm, blister beetles, and head caterpillars), and storage pests. Yield losses caused by these pests are often substantial but have seldom been quantified. Yield losses estimated for India by the National Council of Applied Economic Research (NCAER) in 1967, were about 12%.

The only example for which relatively more accurate information on loss is available is the sorghum midge. In Nigeria, Harris (1961) estimated a 4% grain loss due to midge in the late 1950s and Bowden (1965) quoted 10 to 15 % for Ghana. Midge damage is often associated with head bug damage and therefore, difficult to assess separately.

Shoot fly damage again is hard to estimate because of compensation a n d the tillering ability of sorghum. Damage also varies with planting time (early planting being less infested by shoot fly) and attempts to assess the economic damage level by using insecticide-sprayed control plots often gave unrealistic results. A similar situation has been observed with stem borers. Criteria for estimating yield losses are not clearly defined. For example, experiments at ICRISAT with *Chilo partellus* showed that stem tunneling as a yield loss parameter was inconclusive. Similiar observations have also been reported by Pathak and Olela (1983).

From these few examples it becomes clear that there is little reliable information on yield loss in sorghum due to insect pests in the developing world and the justification for research on pest control in sorghum is based largely on approximate estimates of losses.

Research in Progress and Research Organizations

Research in sorghum entomology in the developing world has mainly been concentrated on insecticide evaluation, and this is still going on to a large extent. However, most insecticides are applied to improved varieties and hybrids; they are rarely used in traditional sorghum farming systems. It was only from the late 1960s onwards that host-plant resistance increased in importance as a possible control mechanism. Resistance to the major insects such as shoot fly, stem borer, and midge was found, and breeders are presently attempting to incorporate these sources into cultivars with better agronomic characteristics.

Cultural and biological control methods have also been evaluated as additional control methods, but so far little success has been demonstrated. Among the less developed countries, India has placed more research emphasis on sorghum entomology than Africa and South America, which are generally lagging behind in this respect. However, some good basic research work has been done by various organizations; some of these (the list is by no means complete) are:

FAO/UNDP:	Food and Agriculture Organization of the United Nations and the United Nations Development Programme
ICIPE:	International Center of Insect Physiology and Ecology

ICRISAT:	International Crops Research Institute for the Semi-Arid Tropics
IRAT:	Institut de Recherche Agronomique Tropicales et des Cultures Vivrieres
ODM:	Overeseas Development Ministry (UK)
ORSTOM:	Institut Francais de recherche Scientifique pour le Developpement en Cooperation
SAFGRAD:	Semi-Arid Food Grains Research and Development Project
USAID:	U.S. Agency for International Development
INTSORMIL:	USAID Title XII Collaborative Research Support Program on Sorghum and Pearl Millet
AICSIP:	All India Coordinated Sorghum Improvement Project
Rockefeller Foundation	
EMBRAPA:	Empresa Brasileira de Pesquisa Agropecuaria

General inputs are given by

IBPGR:	International Board for Plant Genetic Resources

Although the list of research organizations is impressive, progress in sorghum entomology research has been only marginal in the developing world. What are the reasons for the slow progress and what is needed to improve the situation?

Adaption and Implementation Constraints

Tropical countries are agrarian, with 50 to 80% of their people living in rural areas, often far from centers of government (Wortman 1976). Each village is largely self-sufficient, and its social institutions have been developed through the experience of many generations. Revelle (1976) described these societies as "partly closed ecosystems in which most of the energy derived by people and animals from the photosynthetic products is utilized to grow and prepare food, which in turn provides an essential energy input to grow more food and soon in an endless cycle." In the past 15 years, in the attempt to modernize these practices along the lines of developed world agriculture, more efficient high-yielding crop varieties have been introduced; most of these were not resistant to insect pests, and this tended to severely upset local agroecosystems. In addition, most of the newly bred varieties were photoperiod-insensitive, with a shorter maturity duration, so as to utilize water and nutrients more efficiently under the erratic rainfall conditions of the semi-arid tropics. A good example of the advantage of short-duration hybrids was illustrated in 1976 and 1977 when in the Deccan and Malwa plateaus of India the rains ceased by the first week of September. In this situation, all late locals suffered, but hybrids gave a record crop of 2.96 million tonnes in Maharashtra.

These new varieties, however, flower and mature before the end of the rainy season, unlike the traditional landraces, which flower and mature after the rains have declined or ceased. But when the rains stop at the end of September or even in October, grain ripening takes place under high humidity conditions; in this situation grain molds, head bugs, and midge become serious problems since all three thrive best under high humidity. Midge and head bugs are specifically a problem in late-planted short-duration sorghums.

In addition, the insect populations build up on the early-maturing sorghums and are carried over to the late-maturing locals, which are heavily infested. In India, this is happening with all newly introduced varieties and hybrids grown during the rainy season. In Africa, with few exceptions, similar breeding approaches have been adopted and it remains to be seen whether similar problems will arise.

Subsequently, insecticides were recommended to tackle these newly introduced problems. Insecticides are valuable tools for the control of insects but have the disadvantages of undesirable side effects like environmental pollution, buildup of resistance against target insects, and their poisonous effects on humans, domestic animals, and often nontarget organisms. In addition, farmers, especially those far from urban centers, have no easy access to chemicals. Insecticides and application equipment are also costly and their role in a relatively low-value crop like sorghum is often questionable. They also require a certain technical expertise for correct application, proper maintenance of spraying equipment, and an understanding of insecticide handling, which most farmers do not have. In summary, one can conclude that the present approach to controlling insect pests in sorghum upsets the balance of an already fragile agroecosystem.

Sorghum Entomology Research Needed in the Developing World

After this rather negative look into our present insect control approaches, the question arises as to how this problem should be approached in the future.

Development of Control Systems Based on Traditional Systems

Traditional farmers are much less conservative innovators than many agricultural development planners believe (Matteson 1984). Over the centuries they have systematically or intuitively developed agricultural systems adapted to the local abiotic and biotic conditions, which have also included traditional methods of crop protection. In India, early sowing at the beginning of the rainy season is done to avoid shoot fly attack and in some regions also to enable two crops per season to be grown. In India and Africa, farmers developed for the rainy season only long-duration varieties (landraces) that escape grain mold, midge, and head bugs and store better because of low grain moisture content.

The tillering ability of many traditional sorghums helps the plant to recover after shoot fly and stem borer attack. Most of the sorghums grown on residual moisture during the postrainy season in India express levels of resistance to shoot fly and stem borer, insects which could not be controlled by any other means. Many traditional sorghums in Africa have very strong stems which reduce lodging due to stem borer attack. Partial burning of the stems is practiced in parts of Africa to harden them for construction purposes. This also helps to control diapausing stem borer larvae remaining in the stalks. In India most sorghum stalks are used for fodder, which also acts as a control method to reduce the carryover of diapausing stem borer populations.

Traditional sorghum-based cropping systems are most frequently characterized by crop diversity, but monoculture systems are also used. Sorghum may be intercropped with millet, maize, beans, groundnut, pigeonpea, and cotton, to name the most common practices. Some mixed-cropping systems have been shown to have a positive effect in reducing pest populations or diseases, but the opposite has also been demonstrated. Detailed studies at ICRISAT on sorghum/pigeonpea intercrops have shown a tendency to increased incidence of the pod borer, *Heliothis armigera,* on pigeonpea, although the differences were not significant. But it is also well known that in West Africa sorghum can reduce the incidence of thrips on intercropped cowpea.

From the examples given, it is evident that a closer examination of traditional practices and cropping systems by entomologists could give valuable information on how to develop control strategies adaptable to small farms and least damaging to the environment. In fact, considering the various pest control means used by the traditional farmer, one finds that he is practicing nothing but an integrated pest management program, which was only recently rediscovered in the developed world.

Sorghum entomology research in the developing world should therefore be mainly directed towards evolving a practical and easily understandable integrated sorghum insect control program. The main components of such a program should be:

- host-plant resistance,
- cultural control,
- biological control, and
- insecticidal control.

Host-plant Resistance

As already mentioned, progress has been made in identifying sorghum genotypes resistant to one or more of the major insect pests. This was largely possible through the intensive screening of germplasm collections by ICRISAT and other national and international institutions of the world. The maintenance and preservation of germplasm collections in a viable condition should be a continuing effort to preserve wild and cultivated sorghums before they disappear due to man's interference. Germplasm accessions should be properly characterized and made freely available to everyone.

Testing of germplasm and breeding materials is usually done in two ways: (1) by selection of lines in "hot spot" areas, where pest populations consistently occur every year, or (2) by artificial infestation with field-collected or artificially reared insects. Which method is most appropriate or feasible depends on the insect species and the available facilities. The use of "hot spot" areas is the cheapest and the most widely used practice, favored in developing countries with poor research facilities.

The identified resistance source is then handed over to the breeder. In collaboration with the entomologist, he attempts either to strengthen the source, in cases of low levels of resistance, or to utilize it directly in his breeding program. The breeding methodology adopted, pedigree or population breeding, would depend primarily on the strength and heritability of the resistance source, and on whether single or multiple resistance is required.

Breeding programs should be carried out for specific ecological regions. For example, sorghum adapted to India does not grow well in Africa and vice versa. Ideally, each country should have its own sorghum breeding program catering for the specific needs of that country. International agencies should only provide the necessary support in terms of expertise, money, and germplasm or improved source material. Emphasis should be placed more on yield stability than on high yield alone. As mentioned earlier, there is a tendency for breeders, and sometimes entomologists, to look at what has been achieved in developed countries and transfer the technology directly. They tend to forget that breeding for high yield could only be achieved with high levels of external inputs of fertilizer, insecticides, and fungicides.

Although in developing countries there is the need to produce more food, it should be realized that their economic (foreign exchange problems, etc.) and environmental situation is different. Insect problems are more severe in semi-arid and tropical than *in* temperate conditions. Therefore breeding objectives should be focused both on strengthening resistance to yield-limiting factors and on improving yield, to produce a well-adapted and stable-yielding variety or hybrid. Hybrid production should only be attempted in countries where the necessary production infrastructure is available to produce seed cheap enough for the poor farmer.

Cultural Control

Resistance to insect pests will give sufficient control in only a few cases. Cultural control methods practiced by the local farmers could be utilized as supporting control strategies. The influence of soil management, early planting, fertilizers, correct duration, and sanitary methods in relation to pest population buildup on improved and unimproved varieties in various cropping systems should be carefully investigated. In India, for example, change of time to maturity has already tremendously increased head insects like midge and head bugs. Although there are good reasons for growing shorter duration varieties, their advantages should be carefully weighed against their disadvantages. Long-duration traditional landraces are especially photoperiod-sensitive, which is an undesirable character for obtaining higher yield levels. It is true that photoperiod-insensitive types can be more easily handled in breeding for higher yield, but how much research has gone into photoperiod-sensitive types? Andrews (1975) has tried to produce high-yielding dwarf varieties based on local landraces with limited success, it may be worthwhile for physiologists and breeders together to take a second and better look at the problems. In general, a concerted effort by agronomists, breeders, entomologists, and physiologists is needed to exploit cultural practices for insect pest reduction in sorghum.

Biological Control

A number of parasites and predators of the major sorghum insect pests have been recorded by various scientists (Jotwani 1978; van Rensburg and van Hamburg 1975; Greathead 1971). No doubt some potential exists for encouraging the natural enemies of certain sorghum pests such as stem borers, but is it really feasible in most of the developing countries? Sorghum is an annual crop which means that every year's harvest will destroy the habitat in which the insects live. Only a small residual population of parasites and predators can survive on the small insect host populations surviving on alternative host crops. Each year, therefore, the natural enemy population must build up afresh on the host during the crop season. Since most parasites and predators usually lag behind their host in population buildup, their suppression benefit is usually too little or too late. Artificial rearing and release is possible, but seldom feasible, under the small farmer's conditions. Identification and introduction of more effective species from outside the area may be an alternative and should be investigated, but only if these species can be established and remain effective without human help.

It would be more feasible to look into the possibility of encouraging natural enemies by providing them with a more suitable habitat. A diverse ecosystem generally has a richer insect fauna than a monoculture. Mixed-cropping systems should therefore be Investigated for their ability to Increase parasite and predator populations. This type of research is particularly relevant in developing countries. The benefit of incorporating host-plant resistance or tolerance and cultural control methods into sole- and mixed-cropping systems should also be investigated.

Certain resistance mechanisms and plant characteristics make target insects more accessible to natural enemies. For example, open sorghum heads and the resistance to stem borer penetration into the stem in some cultivars exposes the pest to increased predation and parasitism.

Considering these examples, the emphasis in biological control research should be on encouraging natural enemies by providing them a suitable habitat so that they can help supplement other pest suppression tactics. The introduction of exotic parasites or predators if they can be established should also be considered.

Insecticidal Control

I do not want to dwell too much on insecticide research in developing countries. Chemical companies already do a reasonable job in evaluating their products against the major insect species. A certain amount of research by national agencies is necessary to cross-check these results, to improve recommendations, and to develop general policies for insecticide use. In the framework of a sorghum IPM system, insecticides must play a role, since other control means are often inadequate, and insecticides must be available for emergencies. Research should therefore be directed to developing effective spray schedules to be used together with other control means with the objective of spraying as little as possible and only if the economic returns justify this type of investment.

Integrated Sorghum Insect Pest Management

I have listed the major components of a sorghum IPM system which could reasonably be adopted by the farmers in developing countries. Each component will seldom be used alone and it is the responsibility of entomologists, breeders, agronomists, and economists to coordinate them into a feasible control strategy.

At ICRISAT, we have made a preliminary effort to illustrate, based on insect population monitoring over several years, what type of control approaches may be feasible under the environment of Andhra Pradesh, in India. Figure 1 shows the population development trends of our four major sorghum insects in relation to rainfall and varieties with different maturity cycles, planted during the rainy and postrainy seasons at ICRISAT Center.

During the rainy season, shoot fly can be avoided by early planting. Late plantings require resistant cultivars or insecticide protection. Traditional long-duration (150 days) varieties usually escape head bug and midge damage; shorter duration ones need resistance, which is available against midge, and insecticide protection against head bugs. Stem borers are usually less important. Only stem tunneling is observed, which does not normally result in yield loss.

In the postrainy season, at least moderate resistance levels for shoot fly and stem borers are required; these are present in the traditional landraces. Late planting will increase shoot fly and stem borer attack and delay crop growth because the plants will develop under low-temperature conditions. Slow-growing seedlings are more susceptible to shoot fly and stem borer attack, which will be discussed elsewhere during the workshop.

In conclusion, the demonstrated pest and crop growth situation in a specific region shows what possibilities exist to combine resistance with cultural and insecticidal control, ana similar approaches should be possible in Africa and South America.

Training

It is easy to talk about what should be done in sorghum entomology research in developing countries, but implementing such recommendations is certainly hampered by a shortage of scientists and extension staff. Without properly trained and motivated entomologists in research and extension and without adequate research facilities, progress will be slow. It is therefore essential that a concentrated effort be made by development agencies and the concerned countries themselves to improve the situation. ICRISAT, INTSORMIL, and many other institutions have realized this and a substantial part of their budgets goes into training at all levels. But I would also like to stress that without the willingness of the developing countries to send people and then utilize them by providing them the proper incentives, encouragement, and facilities, our efforts will only meet marginal success.

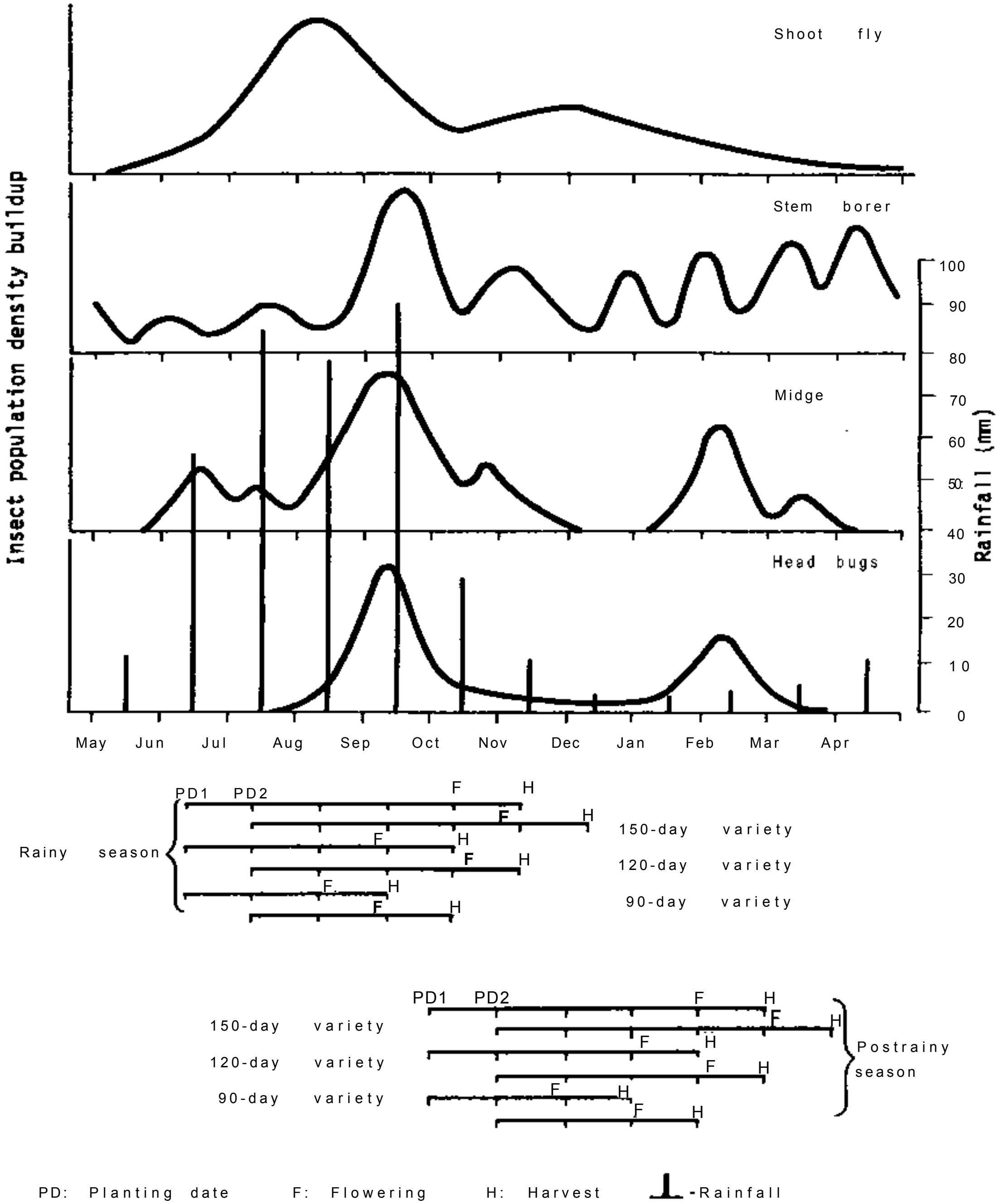

Figure 1. Population development of the four major sorghum insect pests in relation to three sorghum varieties with different maturity cycles (150, 120, and 90 days) and two planting dates, during rainy and postrainy seasons at ICRISAT Center, Patancheru, India.

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Sorghum Entomology Research: Programs and Needs in the Developed World in Relation to Developing Countries

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Abstract

Entomological research objectives differ between developed and developing countries. Crop protection research in the developing world is needed to provide a greater assurance of a food, fiber, feed, and shelter supply. In the developed world, where agricultural products are abundant, crop protection research is aimed at reducing production costs and environmental hazards. These pressures have resulted in the integrated pest management (IPM) approach, but insecticides are commonly used. Despite differences in research needs and objectives, the more holistic pest management approach is applicable to all pest control situations. It may be impractical to attempt to transfer IPM technology packages developed in high-input, temperate zone agriculture to subsistence farming systems in the developing world. But component parts of IPM packages, if evaluated properly, may be transferred. Insect pest control technology in the developing world is addressed and compared with that in the developed world in terms of constraints such as availability of researchers, farming practices, and economics.

Resume

***Imperatifs et projets de la recherche entomologique dans les pays developpes par rapport a ceux des pays en vole de developpement**: Les objectifs de la recherche entomologique variant entre les pays developpes et ceux en voie de developpement. Dans les derniers, la defense des cultures se donne l'imperatit d'assurer l'alimentation humaine et animale, l'hebergement ainsi que l'approvisionnement en fibres. Par contre, dans les pays developpes ou la production agricole est abondante, cette recherche vise a la reduction des couts de production et les risques ecologiques. Ceci a abouti a /'elaboration de l'approche de la lutte integree contre les insectes nuisibles, ce quin'empeche pas toutefois l'usage des insecticides. Malgre les differences dans les imperatifs et les objectifs de la recherche, une approche plus holistique au probleme de la lutte contre les ravageurs, peut etre envisagee pour une diversite des situations. Cependant un simple transfert des techniques de la lutte integree destinees a l'agriculture des regions temperees a forte demande en intrants, vers l'agriculture de subsistance des pays en developpement, s'avererait peu realiste. Toutefois, apres etude prealable, certains composants de ces ensembles technologiques, se preteraient a un tel transfert. Les techniques de la lutte contre les ravageurs pratiquees dans les pays en voie de developpement sont abordees et compares avec celles des pays developpes du point de vue des contraintes notamment la disponibilite des chercheurs, les pratiques culturales et l'aspect economique.*

It is definitive to state that a dichotomy exists between the needs for "improved" crop protection research programs in the developed world and those in the developing world. However, despite the differences in motives for research, the question is: are the techniques for improved crop protection

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different that would lead to differences in research programs either presently existing or those needed in the developed and developing world?

Differences in Motives

Developing World

The need for improved crop protection, and in some cases any crop protection, is to provide greater assurance of a food, fiber, feed, and shelter supply. Numerous reports proclaim that the accelerating deterioration in the world food situation during recent years—mainly a consequence of virtually unlimited population increase—has fallen hardest on the two-thirds of mankind in developing countries where some 500 million people do not have enough to eat. Assuming this to be true, the motive for crop protection research in the developing world is a greater and more stable food supply. Of significant importance, therefore, is the research needed to fulfill this objective.

Developed World

In general it can be stated quite honestly that farming and food, at least in the USA, are subjects that stir comparatively little emotion. In fact, the abundance of food and feed is so taken for granted that only the recent price increases have stirred the reaction of the consuming public. This abundance of farm products, coupled with the subsequent low net return and high production costs, has placed the U.S. farmer in a terrible plight. This poor economic situation (plus the aroused emphasis on environmental quality) appears now to dictate the motives for crop protection research in the developed world.

The objective of crop protection research is to reduce production costs, maintain high yields of good quality, but in an environmentally sound manner. These conditions and pressures are responsible for the much-acclaimed integrated pest management (IPM) approach to crop protection so prevalent in the USA and other developed countries. Integrated pest management evolved in response to economic and environmental pressures. Also, the adverse effects of insecticidal control of pests attacking crops grown in vast monocultures that are ecologically unstable required the development of crop production systems that are less vulnerable to pest attack than those of 1955 or 1960 vintage. For a number of important agricultural crops, considerable progress has been made in this direction. Hopefully, this workshop will be the forum to assess the progress that has been made in sorghum insect pest management.

Sorghum entomology research in the developed world currently appears to be focused on evolving comparatively holistic pest management strategies that incorporate a variable number of components. These components include utilization of natural enemies and abiotic pest density suppressive elements, cultural control, the use of resistant cultivars, biological control, pest monitoring and prediction procedures, and selective use of pesticides. A number of relatively new alternative technologies, or some not so new but receiving renewed interest, show promise of providing additional assistance in the management of pests in the future. These include the sterile insect release method; chemosterilants; confusion by use of pheromones; use of lures of various kinds in combination with traps or toxicants; use of insect growth regulators, repellents, light traps, and antifeedant compounds; and genetic manipulation. This group of technologies and other potential ones of the future are not current sorghum pest control procedures, but they are the additional components which can be fitted into integrated pest management systems for sorghum at some future time.

Sorghum entomology research in the USA is largely the responsibility of the agricultural experiment stations of the land grant universities and the agricultural research services of the United States Department of Agriculture (USDA). Similar State and/or Federal programs exist in other developed countries such as Australia and Argentina. However, sorghum entomology research is not nearly of the magnitude of that for other commodities such as cotton, corn, small grains, etc; it often plays a secondary role and is commonly "bootlegged" from other projects. In any case, current programs of sorghum insect research are heavily oriented to development of insect-resistant cultivars. This concentration on plant resistance has probably evolved because of the low profit margin of the crop. However, sorghum in the USA is commonly treated for insect pests and insecticide use on the crop is relatively high.

Most of the major sorghum entomology research programs in the developed world are represented by scientists participating in this workshop. Of major concern and interest to me is the transfer of developed world crop protection technology to the developing world. This is especially true in the light of the current programs of the U.S.Agency for International Development through the Collaborative Research Support Programs (CRSP) established by Title XII. INTSORMIL, the Sorghum/Pearl Millet CRSP is a cosponsor of this workshop and is a leading funder of sorghum research by U.S. land grant institutions.

Transfer of Crop Protection Technology

In most situations, it will not be practical to transfer these newly developed North American integrated pest management systems, which have been designed with a high level of technology input within a temperate environment, directly into the agricultural production systems of the developing countries. However, the individual components of the systems or certain groups of them often offer great potential for such transfer and can provide for increased food production by reducing losses from pests. The potential for significant food increases in this way, without finding new agricultural land, is indeed great. The Crop Productivity Study Team of the recently published U.S. National Academy of Science World Food and Nutrition Study (1977), while assuming only a 20% reduction in current losses from pests attacking major food crops, estimated that more than 476 million additional people could be fed per year by this saving.

Each candidate pest management technical component to be considered for possible transfer to a developing country will need to be evaluated individually, in terms of its potential for use under the many different and complex situations that will be encountered. It cannot be overstressed that the pest management system to be utilized, whatever the degree of its complexity, must be viewed as a part of the entire crop production process. The new components of the pest management system, or variations of old ones, must be compatible with whatever production practices prevail in the area where they are to be used. As production practices and environmental conditions vary widely from country to country and even within countries, this makes the transfer of crop protection technology most complicated.

In spite of the hopes of idealists and dreamers, the future of plant protection both in the developed and developing world will depend upon the continuation of existing pest control tactics and technology, including the use of those powerful tools—the pesticides. However, as has been stressed by so many elsewhere, these new management systems cannot depend on a single tactic but must take several of the available tactics and combine them into a multifaceted, ecologically oriented, integrated pest management system. This holistic approach—known today in the USA as "integrated pest management (IPM)" and through most of the rest of the world as "integrated pest control"—is widely accepted internationally.

Actually, considerable progress has been made in transferring the basic philosophy of integrated pest control to the developing world. For more than 20 years there has been an increasing international awareness of the importance of a holistic multidisciplinary approach to the problems of pest control. This has been fostered by the FAO, the WHO, and certain bilateral assistance programs (especially those of Canada, France, the UK, and the USA). More recently, Organization for Economic Cooperation and Development (OECD) the United Nations Environment Program (UNEP), the World Bank, and the network of international agricultural research centers of the Consultative Group on International Agriculture Research (CGIAR) have become involved.

However, the problem of actually implementing pest management systems in the developing world is not simply a matter of transfer of the basic concept or philosophy. Considerable adaptive research is required on the potential component tactics of pest management and entirely new systems, adapted to local socioeconomic and ecological conditions, may have to be developed. To emphasize again, in most situations in the developing world, the solution to a pest control problem will not come from the simple transfer of a perfected technology from our socioeconomic milieu. Rather, the solution will come about by the impact of transferred integrated pest control philosophy on the local situation, which results in changes in attitudes and perhaps the renovation of an old local practice in a new context. The end product is a pest control procedure that is well adapted ecologically to the local agroecosystem and is socially and economically acceptable as well.

Even where a reasonable and sound pest control program has been designed especially for a developing country, it may still be extremely difficult to implement on a wide scale, no matter how well conceived the program. This emphasizes the importance of having a strong extension program coupled with adaptive innovative research. The two, research and extension, must be developed together.

Current Level of Pest Control Technology in the Developing World

A very uneven pattern of utilization of pest control technology exists in the developing world, with huge differences between countries in the same geographic region and among crop production systems within the same country. Furthermore, the magnitude and characteristics of pest problems tend to be highly location-specific. The ecological environment, social customs, political events, and the economic situation can all interact to set the magnitude of a particular pest problem and, further, to constrain feasible solutions. Every situation must therefore be evaluated and dealt with on a case-by-case basis.

Similarly, the level of dependence on pesticides varies from country to country. In general, the more developed the country, the greater the level of pesticide used; but there are often large differences between crops in the same country. A few years ago, surveys by the FAO indicated that the entire developing world used only about 7% of the global consumption of pesticides. Lack of financial resources to purchase pesticides is not the only reason for this low use. The present marketing system stresses certain crops and certain countries, and thus produces an uneven supply situation. In times of crisis resulting from a pest outbreak, the pesticides often are not available or are in the wrong place or arrive in the right place too late. Furthermore, the transportation network in many countries is too inadequate to move the pesticides from the capital city to the rural areas where they are needed. Finally, very few developing countries have adequate equipment for the application of pesticides and even fewer have a monitoring system for detecting pest infestations when they are still at manageable levels.

In the developing world, the large estate crops such as rubber, cotton, and sugarcane tend to get a heavier use of pesticides than do the plots of small farmers. In many cotton-producing countries, two-thirds or more of the pesticide use is on this single crop. In some developing countries, use of insecticides to protect stored products is also of considerable importance. Overall, there is a slight trend towards increased use of pesticides in these countries, but the percentage of the world's total use is not increasing.

Insecticides remain the dominant class of pesticides used in the developing world, in contrast to the developed world, where herbicides now represent the major category of pesticide use. The use of insecticides in developing countries is still increasing at a rate that would appear to maintain their dominant position for some time to come. In some developing countries, chlorinated hydrocarbon insecticides, e.g., DDT, BHC, aldrin, and endrin, continue to be used on agricultural crops because of their effectiveness, low cost, safety, and ease of manufacture. In the tropical and semitropical countries, persistence of these chemicals is not nearly the problem that it is in the temperate regions. In most developing countries, the local ecological and economic situation dictates that the pest management strategy be based on resistant crop varieties, cultural controls, and manipulation of natural enemies, with little or no high-level capital input to the system, such as use of pesticides.

Development of IPM Systems

Integrated pest management systems do not just happen. They come about through the careful ecological analysis of pest problems as they exist in the growing crops. Programs of research on integrated pest management systems must relate to the entire pest problem and the full complexity of the field situation. No amount of sophisticated laboratory research will produce an integrated pest management system unless the research is intimately related to real field problems and has an effective and continuing feedback from the field. It is important to realize that research on field problems can be extremely complicated, as it must deal with establishing the complex relationships that exist in the agroecosystem, such as those between the pest and the crop; among pests and noncrop plants; the pest and its natural enemies; the pest, its natural enemies, and plant diversity; and all of these considered together with other crops and the climate, as well as the economic and political aspects. It often appears overwhelmingly complex. Herein lies the dilemma facing the isolated crop-protection specialist in a developing country.

How can that individual in an isolated research station in a remote area attempt to tackle these complex pest problems with his limited equipment, laboratory facilities, library, vehicles, and other resources? Furthermore, how can he cope with the lack of extension personnel or other paraprofessionals to train and encourage farmers to adopt new practices? In many cases, the crop protection man himself serves in both an extension and research capacity. He may also find that the farmers cannot or will not adopt a new practice, because they lack the financial resources or proper motivation. He may *in* fact have difficulties in communicating with the farmer because of language barriers or illiteracy, or even in reaching the farmer because of lack of roads or transport.

There is no easy answer to this dilemma. However, in spite of the odds, sound integrated pest management systems have been developed under such circumstances. Indeed, most operational integrated pest management systems have had a relatively simple, yet effective, beginning.

The first step in these programs was to develop an ecological perspective and then to design the best possible action based on the then available knowledge. This design was, at best, an approximation of an ideal system. This first approximation was then tested in the field, and where difficulties were encountered, they were posed as questions for the parallel solution-seeking research. In this way, even where resources may be quite limited, an effective integrated pest management system can often be developed and adapted to the local situation. The basic strategy of the more sophisticated systems is to manage the pest populations at noneconomic densities so as to optimize economic returns consistent with minimal environmental damage. This should also be the strategy of the simplest pest management systems where it is not possible to bring to bear large, high-powered research teams.

Problems Associated with Technology Transfer to Developing Countries

Pest management systems developed for the temperate part of the world, as stressed earlier in this discussion, may be completely inappropriate to tropical and subtropical conditions of the developing world. This is the result not only of the greatly contrasting physical and biotic conditions, but also of the contrasting problems of modern intensive high-input agriculture and those of traditional subsistence agriculture involving multiple and mixed cropping.

In ecological terms, the agroecosystem represented by modern temperate agriculture is biologically less complex than that represented by traditional agriculture, especially in the tropics. Tropical traditional agriculture has greater genetic diversity and greater natural adaptation to its environment than modern streamlined agriculture. In general, the potential for pest exploitation of an agroecosystem is inversely proportional to its diversity. The pest response to changes in the agroecosystem follows the pattern of the "domino theory." The introduction of a new (or substituted) factor such as a new variety, into the system prompts a series of readjustment changes. This does not dictate against the introduction of new practices of crop production but does stress the need for an enhanced crop protection response capability in most developing nations.

The developing world must deal with an array of crops and pests which are seldom grown in the temperate world: avocado, banana, breadfruit, cacao, cassava, coconut, coffee, guava, mango, papaya, pineapple, millet, plantain, sweet potato, sugarcane, taro, and yams. Many of these crops are of great importance in world commerce and contribute much to the world's food supply. As they are not widely grown in the developed temperate countries, a bank of technological knowledge on their culture and the management of their pests is not available there. Such a bank must be evolved in place in the tropical developing world. Nevertheless, some component tactics from temperate IPM systems designed for other crops can be adapted to these tropical and subtropical crops.

In any attempt to transfer the latest developments in pest control technology to the developing world, it will be very important to reach the decision makers in these countries. Many of the current decision makers received their training before the resurrection of the ecological approach to pest control. As a result, considerable re-education will be necessary, and new approaches to communication with the decision makers will be required to achieve satisfactory results. In addition, the different social and economic values placed on the importance of food, environment, human life, individual rights, etc., require considerable adaptation of pest management systems proposed for the developing world. They also require considerable accommodation on the part of "expatriate" crop protection experts.

Potential Impact of Pest Control Technology Transfer

The losses of food crops such as sorghum to pests in the developing world are enormous; estimates generally run between 25 and 50% of the food produced. A large proportion of these losses could be recovered through improved plant protection methods. At the same time, enhanced protection against crop pests becomes further necessary because other methods of crop improvement will result in increased food production, which will require additional protection for the gains to be fully realized.

However, another major methodological problem complicates any assessment of successful innovations. It is difficult to translate the savings in crop yields that would result from improved pest control into economic terms that reflect the probable distribution of those savings to the population of the country. If an increased supply of a commodity in an area results from the adoption of improved pest control practices, the price of that commodity will probably fall, and the effect of the lower price on small farmers, especially *in* economies that are not centrally planned, would probably be severe. For example, nonadopters and late adopters of improved practices are particularly vulnerable, because their production costs and yields will remain the same, while the price they receive for their produce will decline. Unless additional concomitant measures are taken, the incomes and nutritional status of such farmers are likely to deteriorate. This prospect puts a special premium on selecting methods that are suited for adoption by small farmers.

Increases in yield are important, but improved pest control practices also result in more stable yields from year to year, which can be quite important. Without a sense of stabilty, people are not likely to make investments in agriculture that require more than one growing season for amortization.

A related problem is associated with the level of commercial and industrial development in the country. In many tropical developing countries there is an enormous loss of foodstuff quite independent of damage from crop or stored-product pests. These wastes occur because of lack of food-processing industries, lack of a transportation network to move perishable commodities to consumer markets, lack of refrigeration facilities, and other nonpest reasons. To produce more, by whatever means, of perishable food products in such situations in the hope of improving the country's food supply really does not accomplish much in terms of efficiency of energy use, and the potential benefits of improved pest control will not be fully realized unless associated with other commercial and industrial developments.

Biological control is likely to be the most successful technology when it is designed for a specific region. Because most integrated control schemes include biological control methods, such schemes are also likely to be highly location-specific. Cultural controls generally involve creating microenvironments on the farm that are unfavorable to pest development. Thus it is likely that such manipulations, if identified, will be applicable over wide geographic regions, although some location-specific problems will occur. Genetic control and pesticides, as we know them, have been successful when adopted over wide geographic areas; hence large regional disparities are unlikely to arise from adoption. New varieties that show some resistance to pest species can be crossed with traditional varieties and thus adapted to many regions; hence large differences among regions are not likely to develop from their use.

Innovations in biological control, the use of resistant varieties, and genetic control are not likely to create any direct adverse environmental impacts or effects on labor requirements. If resistant cultivars contain toxic substances in their edible portions, then problems might arise. Also, elimination of a pest like the tsetse fly from Central Africa might increase indirect environmental effects by opening up to crop agriculture or to grazing areas that have so far been unused.

Cultural control will, in general, have little adverse effect on the environment unless the particular practices involve cultivation. In such cases, soil erosion may result if the cultivation is improperly done. Pesticides are the most likely to have an adverse effect on the environment, as their use involves introducing synthetic chemicals into it. Integrated control, because it relies on pesticides in addition to other means of control, is likely to have slightly or moderately adverse effects on the environment (U.S. National Academy of Sciences 1977).

The developing world is on the threshold of a large increase in the use of pesticides. This will occur largely because of the well-established business framework to dispense as much pesticide as possible in the developing world. Only the rather limited financial resources of these countries keep the overall use at the current low levels. If these pesticide inputs are made unwisely, the pest problems can be greatly exacerbated. Furthermore, the impact on the environment and on agricultural workers could be severe. Properly developed pest management systems using pesticides as only one component of many can help to avoid such difficulties.

Education and training must be a core element in any program to develop improved pest management in the developing world. Fundamental training will be required in all aspects of pest management and at all levels to create and strengthen an adequate infrastructure to receive and adapt pest management technology. This should involve the decision-making administrators as well as the lower level technicians. These educational inputs should be developed around an integrated pest management philosophy.

Research and extension, particularly adaptive research and on-the-farm demonstration, will be required at a significant level to develop the required knowledge base and to implement pest management systems successfully in the developing world.

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Regional and Country Reports

Sorghum Insect Pest Situation in Eastern Africa

K.V. Seshu Reddy and E.O. Omolo*

Abstract

The paper describes in brief the sorghum-growing areas, sorghum production and yield, and a range of field and storage pests attacking the crop in eastern African countries: Burundi, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, Uganda, People's Democratic Republic of Yemen, and the Yemen Arab Republic. Also included is a review of crop losses and control methods recommended in the region.

Resume

***Les Insectes nulsibles au sorgho en Afrlque de l'Est**: Cette communication decrit brievement les zones de culture de sorgho, la production et le rendement ainsi que les ravageurs qui s 'attaquent aux recoltes au champ et aux denrees. L'etude porte sur les pays de l'Afrique de l'Est, dont: Burundi, Ethiopie, Kenya, Ouganda, Rwanda, Somalie, Soudan, Tanzanie, et sur les pays avoisinants ouest asiatiques de la Republique ddmocratique populaire du Yemen et la Republique arabe du Yemen. Les pertes des recoltes sont examinees ainsi que les methodes de lutte preconisees dans ces regions.*

Introduction

Sorghum *(Sorghum bicolor [L]* Moench) is the most important cereal crop of millions of people in the eastern African region, which inciudes the following countries: Burundi, Ethiopia, Kenya, Rwanda, Somalia, Sudan, Tanzania, Uganda, People's Democratic Republic of Yemen, and the Yemen Arab Republic (Gebrekidan 1982). For the purpose of sorghum improvement, the Yemens are taken as part of the eastern African region. Of the total 47 million hectares of sorghum grown in the world, eastern Africa cultivates nearly 13%. Sorghum-producing zones, yields, and main uses of sorghum are presented in Table 1. Yields of grain sorghum on peasant farms in this region are very low, ranging from 500 to 1300 kg/ha, compared with 3705 kg/ha in the USA (Gebrekidan 1982; FAO 1983). A major factor limiting sorghum yield in the region is the damage caused by insect pests.

A list of insect pests recorded on sorghum in different countries of eastern Africa is given in Table 2. Leaf and shoot feeders include locusts, aphids, and various genera of Lepidoptera. Outbreak pests such as locusts and various species of armyworm may be devastating and because of their migratory and seasonal occurrence, control must largely depend upon the prompt coordination of regional or international control operations. Most of the head or panicle feeders, which include a range of Hemiptera and Heteroptera, Coleoptera, *Heliothis armigera,* and other Lepidoptera, are usually of minor importance in the region, except for sorghum midge, *Contarinia sorghicola,* which can be very serious. Sometimes various species of panicle-feeding bugs, e.g., *Agonoscelis, Calidea, Calocoris,* and *Lygus,* may also cause considerable grain damage.

The most important field pests in this region are shoot flies and a range of lepidopterous stem borers of various genera, which include *Busseola, Chilo, Eldana,* and *Sesamia.* The shoot fly, *Atherigona soccata,* is a very important seedling pest of sorghum. The stem borer, *Busseola fusca,* is the

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Table 1. Areas, production, grain yields, and uses of sorghum in eastern Africa.

Country	Position of sorghum in cereal production	Production zones	Area ('000 ha)	Annual production ('000 mt)	Grain yield (kg/ha)	Uses: Grain	Uses: Stalks
1. Burundi	Second	Low–altitude regions and central plateaus	100	95	864	Food, beverages	Animal feed
2. Ethiopia	Second	All administrative regions, mainly lowlands	1000	1300	1300	Food, beverages	Animal feed, fuel, house and fence construction
3. Kenya	Second	All provinces, but mostly Nyanza, Western, Eastern provinces	210	220	1048	Food, beverages	Feed, fencing, fuel
4. Rwanda	First	All over the country (low, medium, and high elevation areas)	153	181	1179	Food, beverages	Fuel, house and fence building, mulching in coffee plantations
5. Somalia	First	Countrywide, under rainfed conditions	470	235	500	Food, beverages	Fodder
6. Sudan	First	Countrywide	3000	2100	700	Food, beverages	Animal feed, building material, fuel
7. Tanzania	Second	Mainly Dodoma, Singida, Morogoro, Mtwara, Tabora areas	350	220	629	Food, beverages, commercial poultry feeds	
8. Uganda	Third	Mainly in drier areas	350	450	1286	Food, beverages, yeast in brewing banana beer	Mulching in coffee and banana plantations
9. People's Democratic Republic of Yemen	First	Countrywide (mainly rainfed)	19	15	795	Food	Feed, fuel
10. Yemen Arab Republic	First	Countrywide	670	583	870	Food	Animal feed, leaves stripped and fed to animals, stubbles used as fuel

Sources : FAO (1983); Brhane Gebrekidan (1982).

1. Sorghum is the most important staple food crop grown under rainfed conditions in semi–arid areas of eastern Africa.

Table 2. Insect pests of sorghum in eastern Africa.

Field pests			
Leaf and shoot feeders	Shoot and stem borers	Head feeders	Stored grain pests[b]
Armyworms	Shoot fly	Midge	*Oryzaephilus* spp
Spodoptera exempts (2, 3,4, 5, 6, 7, 8, 10)[a]	*Atherigona soccata* (1,2,3,4,5,6,7,8, 10)	*Contarinia sorghico/a* (2,3,5,6,7,8, 10)	*Rhyzopertha dominica*
Spodoptera exigua (2,3,6,7, 10)	*Atherigona naguii* (9)		*Sitophilus oryzae*
Cutworm	Stem borers	Head bugs	
Agrotis segetum (3, 7, 8)	*Busseo/a fusca* (1, 2, 3, 4, 6, 7, 8)	*Ade/phocoris* sp (3, 7, 8)	*Sitotroga cerealella*
Leaf roller			
Marasmia trapezalis (3, 7, 8)	*Busseola segeta* (7,8)	*Agonoscelis pubescens* (3, 7, 8)	*Tribolium castaneum*
Aphids			
Melanaphis sacchari (2, 3, 6, 7, 8)	*Chilo orichalcociliellus* (3,7)	*Agonoscelis versicolor* (6)	*Tribolium confusum*
Rhopalosiphum maidis (2,3,4,5,6,7,8,9, 10)	*Chilo partellus* (2, 3, 5, 6, 7, 8)	*Calidea dregii* (4,7)	
Schizaphis graminum (4,7)	*Chilo* spp (9, 10)	*Calocoris angustatus* (3, 4)	
Shoot bug			
Peregrinus maidis (3, 7, 8)	*Eldana saccharina* (1, 3, 4, 7, 8)	*Creontiades* sp (3, 7, 8)	
Spittle bug			
Poophilus costalis (3, 7, 8)	*Ematheudes* sp nr *helioderma* (8)	*Dysdercus* spp (2)	
Grasshoppers			
Acrotylus patruelis	*Sesamia albivena* (1)	*Dysdercus superstitiosus* (3, 6, 7, 8)	
Chrotogonus hemipterus	*Sesamia botanephaga* (7, 8)	*Lygus* spp (3, 7, 8)	
Homorocoryphus nitidulus	*Sesamia calamistis* (1,2,3,4,7,8)	*Nezara viridu/a* (3, 4, 7, 8)	
Gastrimargus africanus	*Sesamia cretica* (2,3,5,6,9, 10)	*Taylori/ygus vosseleri* (2, 7, 8)	
Locusts[6]		Head caterpillars	
Locusta migratoria migratorioides	*Sesamia poephaga* (7, 8)	*Celama* sp (3, 7, 8)	
Schistocerca gregaria		*Cryptophlaebia leucotreta* (1)	
		Cynerea spp (1)	
		Eublemma sp (3, 7, 8)	
		Heliothis armigera (1,2,3,4,5,6,7,8)	
		Sitotroga cerealella (1, 3, 7, 8)	
		Head beetles	
		Mylabris sp (3)	
		Pachnoda interrupt a (2)	

Sources : Jepson (1954); Ingram (1958); Le Pelley (1959); Nye (1960); Schmutterer (1969); Bohlen (1973); FAO (1980); Zein el Abdin (1981); Brhane Gebrekidan (1982).

a. Figures in parentheses indicate countries reporting the presence of pest: 1 = Burundi, 2 = Ethiopia, 3 = Kenya, 4 = Rwanda, 5 = Somalia, 6 = Sudan, 7 = Tanzania, 8 = Uganda, 9 = People's Democratic Republic of Yemen, 10 = Yemen Arab Republic.

b. These pests are cosmopolitan and are very common over most of the eastern African region.

most widespread and destructive pest. *Chilo partellus,* a pyralid stem borer, is widely distributed in the region, while C. *orichalcocilielius* is confined to coastal areas. *Eldana saccharina,* principally a pest of sugarcane, is spreading rapidly in eastern Africa, attacking sorghum and maize. It has become a major pest of sorghum in Burundi, followed by *Busseola fusca* and *Sesamia* spp (Gebrekidan 1982). The genus *Sesamia* is important and very widely distributed in eastern Africa. Among the five species recorded in the region, S. *calamistis* and S. *cretica* are the most serious.

Quelea quelea and other grain-eating birds pose serious problems to sorghum growers over the entire region.

Among the stored grain pests of sorghum, the weevils, *Sitophilus* spp, are very destructive over the entire region. The greater grain borer, *Prostephanus truncatus,* known to occur in South and Central America and in the extreme south of the USA has recently appeared in Tanzania, where it has become a serious problem on stored sorghum, maize, and other cereals, pulses, groundnuts, cocoa, coffee beans, and various root and tuber crops. The pest is likely to spread to neighboring eastern and central African countries.

Although assessment of losses caused by insect pests is often difficult, there is some information available on the magnitude of losses associated with these insects in some countries. Jepson (1954) reported 40 to 100% plants infested by *Busseola fusca* in Tanzania. In Uganda a 56% loss of grain yield resulted when sorghum was infested with *Chilo partellus* 20 days after emergence (Starks 1969). Losses due to midge, *Contarinia sorghicola,* often reach 25% in the Sudan, while infestation by shoot fly, *Atherigona soccata, can* be as high as 90% (Schmutterer 1969).

Pests of stored grain are very serious throughout the region. The degree of damage to stored sorghum depends on the altitude, temperature, the type of storage structure used, and the duration of storage. In Ethiopia, it was found that at the end of 1 year's storage, maximum damage to stored sorghum was about 70% at an altitude of 1700 m but only 10% at 2500 m above sea level.

Control of Sorghum Pests

Cultural Control

Early sowing of sorghum has been recommended in many countries of the region to prevent the heavy incidence of sorghum shoot fly, stem borers, and midge. Control of volunteer and wild host plants in and around sorghum fields has been recommended whenever possible, and the destruction of crop residues before planting the next season's sorghum crop has been suggested. Crop rotation and mixed cropping with nonhost crops have also been recommended (Ingram 1958; Nye 1960; Delobel and Unnithan 1981; Zein El Abdin 1981;Seshu Reddy 1983).

Biological Control

Biological control is a very important means of sorghum pest control and has great potential in eastern Africa. Very little work had been done on the biological control of graminaceous stem borers in this region until the Commonwealth Institute of Biological Control began surveys in 1965. Several species of exotic parasites were released (Mohyuddin and Greathead 1970; Girling 1972). Studies of *Eldana saccharina* in East Africa indicated that it had few indigenous parasites, a very low percentage of parasitism, and marked resistance to exotic parasites (Girling 1978). Greathead (1971) reviewed the biological control work done in the Ethiopian region.

Chemical Control

Insecticidal control of sorghum pests is not commonly adopted by the subsistence farmers in the region as it is expensive, often uneconomical, and pesticides frequently are unavailable. However, under experimental conditions, insecticides such as carbofuran, disulfoton, aldicarb, and cytrolane, gave good control of shoot fly, (Zein El Abdin 1981; Gebrekidan 1982). In Ethiopia, carbaryl, endosulfan, and DDT gave good control of *B. fusca* (Megenasa 1982).

Host-plant Resistance

Studies of host-plant resistance to insect pests in this area are very limited. However, identification of sources of and breeding for resistance to major insect pests of sorghum is under way in some countries in eastern Africa (Gebrekidan 1982; Seshu Reddy 1983). In Uganda, Starks and Doggett (1970) made significant advances both in breeding methodology and the incorporation of resistance to *Chilo partellus.*

Conclusion

Sorghum is an important traditional food crop for subsistence farmers in eastern Africa. Sorghum yields are generally low in this region, and a major factor limiting yields is the damage caused by insect pests. However, not much progress has been made towards the development of pest management strategies for sorghum pests, and in some countries information on the identities and ecology of insect pests is still very limited. There is clearly a need both for more basic and for adaptive research. Identification of resistance sources and the development of high-yielding cultivars resistant to the major insect pests, using the rich genetic diversity of sorghum in this region, should receive high priority. Efforts should also be made to find means of taking advantage of the indigenous natural enemies in the region to improve the biological control of key pests, and to integrate this with existing cultural control practices, including intercropping.

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Sorghum Insect Pests in West Africa

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Abstract

Although several species of insect pests are associated with the sorghum crop, only a few are considered primary pests in West Africa: the shoot fly, Atherigona soccata *Rondani; sorghum midge,* Contarinia sorghicola *Coquillett; stem borers, mainly* Busseola fusca *(Fuller); and a complex of head bugs.*

Shoot fly infestations are usually very low, except on late-sown sorghum, when the loss in a crop stand is significant. This may occur in the southern Sudanian zone where rainfall exceeds 700 mm. Midge attack varies between seasons, is usually low in the dry Sahelian zone, but severe south of latitude 13°N. In the region below latitude 11°30'N, with an annual rainfall exceeding 800 mm, B. fusca *accounts for over 90% of the stem borer on sorghum. Further north it is gradually replaced by* Eldana saccharina *Wlk. and* Sesamia calamistis *Hmps.* Acigona ignefusalis *Hmps. though primarily a pest of millet, has been reported on sorghum.*

In recent years there has been an increase in panicle damage by head bugs; Campylomma *spp and* Eurystylus *spp are the most abundant. Cultivars with loose panicles are usually free of damage but the degree of damage increases with compact-head types.*

Other insect pest species include lepidopterous defoliators, grasshoppers and locusts, spittle bug, and a range of head worms and head beetles. These are considered as minor or occasional pests.

Resume

Les Insectes nulsibles au sorgho cultive en Afrlque de l'Ouest*: En Afrique de l'Ouest, plusieurs especes d'insectes se trouvent chez les cultures de sorgho, mais seules quelques-unes sont considerees comme ravageurs d'importance, dont: la mouche des pousses,* Atherigona soccata *Rondani; la cecidomyie du sorgho,* Contarinia sorghicola *Coquillett; les foreurs des tiges, notamment* Busseola fusca *(Fuller); et un complexe de punaises des panicules.*

L 'infestation par la mouche des pousses, normalement tres faible, atteint un niveau sensible chez les sorghos tardifs. Ceci se produit dans la zone soudanienne septentrionale ou la pluviometrie depasse 700 mm. L'infestation de la cecidomyie qui varie d'une saison a l'autre, est normalement inferieure dans la zone sahelienne seche, mais elle saggrave au sud de 13° N. Au sud du parallels 11°30'N, la pluviometrie depasse 800 mm favorisant l'infestation par les foreurs des tiges, 90% etant B. fusca. *En remontant vers le nord, cette espece est remplacee par* Eldana saccharina *Walk. et* Sesamia calamistis *Hmps.* Acigona ignefusalis *Hmps., bien qu'un ravageurdu mil, a ete signale chez le sorgho.*

Au cours des dernieres annees, les punaises des panicules ontpris de l'importance, Campylomma *spp. et* Eurystylus *spp. etant les plus abondants. Les panicules laches s'echappent aux degats qui sont plus graves que les panicules sont compactes.*

Sont consideres comme ravageurs mineurs ou occasionnels : les lepidopteres de'foliateurs, les acridiens, et une diversite de punaises et de vers des panicules.

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Introduction

Of the major crops grown in Africa, cereals constitute one of the primary food sources of the people inhabiting the sub-Saharan region of the continent. The main cereal crops are sorghum, millet, and maize. Rice is also cultivated in riverine areas where the land is usually flooded during most of the season. However, sorghum remains the important cereal crop in West Africa. Africa produced only 7.4% of the total world food agricultural production in 1981. However, while its total cereal production for the same period was only 6%, sorghum accounted for 17%, and 42.8% of this came from West Africa. Niger, Nigeria, and Burkina Faso were responsible for 92.2% of the total sorghum produced in West Africa in 1981 (FAO 1983). The overall picture is not as bright, for while statistics show an 8.3% increase in total sorghum production for the three West African countries over a 10-year period between 1971 and 1981, there was an actual decline of 0.9% in average yields per hectare. The apparent increase was due to an expansion of 11.8% in area cultivated to sorghum during that period.

The decline in yields per unit area of cultivated land is attributed to several factors: low and erratic rainfall in the northern sorghum-growing regions, poor and eroded soils, insect pests, rodents, birds, and diseases, traditional labor-intensive technologies, socioeconomic and marketing constraints, poor to nonexistent capital investment policies, and rudimentary extension services.

Pest Complex

Over 100 insect species have been recorded as pests or potential pests of sorghum, but only some are actually of economic importance and belong to three main orders: Diptera, Lepidoptera, and Hemiptera.

The major insect pests of sorghum are: shoot flies, grain midges, stem borers, and head bugs. Other minor and occasional pests include grasshoppers, lepidopterous defoliators, flower beetles, and head worms.

The taxonomy and bioecology of sorghum insect pests have received considerable attention in West Africa (Risbec 1950; Tarns and Bowden 1953; Bowden 1956; Ingram 1958; Harris 1962; Appert 1964; Jerath 1968; York 1970; Breniere 1970). This paper discusses the incidence, distribution, and seasonal abundance of the major pest species of sorghum in West Africa and briefly covers other species of minor importance.

Seedling Pests

Shoot Fly

Atherigona spp are the major seedling pests of sorghum and infestation usually begins during the seedling stage but may be associated with older plants. The characteristic deadheart symptom makes infestation easy to detect. The predominant species of *Atherigona* in West Africa appears to vary with location. In Burkina Faso, where a detailed study was conducted between 1978 and 1980, 23 species of *Atherigona were* identified from fishmeal traps with *A. marginifolia* (V. Emd.) making up 36% of the male population and *A. soccata* (Rond.) only 14%. A related genus, *Acritochaeta orientalis* (Schmer) was also recorded (Bonzi and Gahukar 1983). In Senegal, 22 species were reported (ICRISAT 1981) but species predominance varied with location.

Studies in Senegal, Burkina Faso and Nigeria have shown that shoot fly infestation on farmers' fields is usually insignificant on sorghum that is planted with the first rains. However, in years when poor rainfall necessitates late planting, crop damage becomes severe even in the northern Sahelian zone of West Africa. On research stations, the highest numbers of shoot fly occur towards the later part of the season (August and September) due in part to staggered planting and favorable humid conditions. Otherwise, the normal pattern of infestation on farmers' fields is seen as nonuniform spots of deadheart tillers, usually in hills resown to fill gaps. In a study in Burkina Faso in 1980 (ICRISAT 1981), out of a sample of 35000 plant hills observed in 140 farms, only 2.7% plant hills showed deadheart tillers due to shoot fly attack.

Leaf Beetle

The cereal leaf beetle, *Lema planifrons* Ws. usually appears in late June and early July and is associated with a delay in rainfall or short drought spells soon after seedling establishment. Millet is the preferred host. The larvae are dirty grey to black in color and feed on the epidermal leaf tissue. Severe infestations result in shredded-looking plant stands.

Plant Pests

Stem Borers

Stem borers are the most widely distributed pests of sorghum and the species distribution and incidence appear to be closely related to rainfall. In the drier areas of the savanna and the Sahel, there is a reduction both in number of pest species and the severity of attack on the crop. In the south, in the presence of other cultivated graminaceous crops such as maize, rice, and sugarcane (especially where an irrigated crop is present all year round), the species complex increases and so does the damage to the crop.

Species complex and distribution. The major stem borer of sorghum is *Busseola fusca* (Fuller). In Burkina Faso this pest is restricted to below latitude 11°3'N (region of Bobo-Dioulasso) where the annual rainfall is usually above 900 mm. However, in Nigeria the species was reported to occur as far north as 12°6'N, where annual rainfall is less than 600 mm. Furthermore, at Samaru (Zaria) in Nigeria, *B. fusca* accounts for 98% of the borer larvae in sorghum stalks, while at Farako-Ba (Bobo-Dioulasso), which is at the same latitude as Zaria, it accounts for less than 40%, with *Sesamia calamistis* Hmps and *Eldana saccharina* accounting for 35% and 26% respectively. Further north of latitude 11 °30'N both in Nigeria and Burkina Faso, *B. fusca* is gradually replaced by the millet stem borer, *Acigona (Haimbachia) ignefusalis* Hmps., which rarely attacks sorghum south of this latitude.

S. *calamistis* and *E. saccharina* appear to be restricted to below latitude 12°N in Burkina Faso and Nigeria. Neither species was observed attacking sorghum above latitude 12°15'N in Burkina Faso, although S. *calamistis* has been recorded on millet in Niger as far north as 14°N. However, while at Farako-Ba these two species make up 61% of the borers on sorghum, at Samaru which is on almost the same latitude as Farako-Ba, they constitute only 2%. The reason for this difference appears to be that maize, the preferred host of these pests, is sown after millet and sorghum in northern Nigeria, whereas in the south of Burkina Faso, maize is planted first, thus providing an initial population buildup with the borers migrating to sorghum and millet after the maize has been harvested.

S. *calamistis,* the predominant *Sesamia* species in the savanna and Sahel zones of West Africa (Burkina Faso, Mali, Senegal, Niger, and northern Nigeria), is replaced by a close relative, *S.botanephaga* (Tarns and Bowden), in the forest zone of Ghana, Ivory Coast, Nigeria, and Togo. S. *botanephaga* is larger and of lighter pink coloration than S. *calamistis* and is particularly damaging to maize and sugarcane.

Seasonal occurrence. The major stem-borer infestation is encountered between August and October. *B. fusca* exhibits two to three generations at Samaru, Nigeria (Harris 1962), but only two at Farako-Ba. Infestations of the first generation usually begin in May in Samaru and the second and third generations, which inflict more severe damage, occur in July and September respectively. The third generation goes into diapause in the stalks.

At the Kamboinse research station of Burkina Faso, the population of S. *calamistis* is rather low during the crop season but increases at the end through the dry season when it becomes the predominant borer on irrigated sorghum. On the contrary, *E. saccharina* is the predominant borer on sorghum in August and September.

Infestation and crop damage. Newly hatched larvae of *B. fusca* usually remain in clusters under the leaf sheath. Later they move around, finally congregating in the funnel where they feed on young leaves. This feeding results in windowpane-like holes (Harris 1962). In younger plants, larvae migrate down the funnel and may destroy the growing point. This gives the characteristic deadheart symptom of borer attack. The growing point in older plants may not be destroyed, in which case larvae tunnel through the internodes where they complete their development or migrate to nearby plants. In the latter case they bore directly into the stem near the base.

In contrast to *B. fusca, Sesamia* larvae on hatching rarely migrate from the leaf sheath area but bore directly into the stem under the sheath. Leaf damage is not associated with *Sesamia*. Larvae of £ *saccharina* are very active and infestation is characterized by frass at the point of stem penetration. Sorghum is a preferred host only next to maize and sugarcane, and infestations of sorghum usually occur in regions where these crops are grown.

In recent years, infestation by the rice borer, *Chilo diffusilineus,* has also been recorded on sorghum in Burkina Faso. Infestations are irregular and are usually insignificant.

Defoliators

Armyworms. Occasional outbreaks of armyworms, *Spodoptera exempts* (Wlk.) and *Spodoptera exigua, are* associated with dry periods during the early part of the cropping season. Severe infestation by armyworm larvae may result in extensive crop loss. The larvae show a range of colors from green to black, with longitudinal stripes of deep yellow and light green. The severity of infestation is associated with the presence of weeds and recently weeded sorghum fields are more severely affected.

Other lepidopterous defoliators include *Spodoptera littoralis, Mythimna separata* (Wlk.), *Amsacta moloneyi* and the leaf roller, *Marasmia trapezalis.* These are occasional pests and the damage they cause is usually not important.

Grasshoppers and locusts. The two major species of grasshoppers, *Oedaleus senegalensis* (Kraus) and *Aiolopus simulatrix, ate* migratory and will attack sorghum both at the seedling stage, when damage is severe, and also at the young panicle stage. Other grasshoppers, *Oedaleus nigeriensis, Krausseiria angulifera* and *Zonocerus variegatus,* occur in lower numbers.

Outbreaks of locusts, *Schistocerca gregaria* and *Locusta migratoria* L, usually start from their breeding grounds in the Lake Chad basin. Damage to sorghum is caused by the swarming phase, when large bands fly over long distances and destroy all plant vegetation in their path. The control of locusts is now internationally organized and the major thrust is on preventing the occurrence of outbreaks through control of the breeding grounds.

Spittle Bug

The predominant species in West Africa is *Poophilus costalis* (Wlk.). *P. grisescens* occurs in lower numbers. The greyish to brown soft-bodied nymphs are enclosed within a substance secreted by abdominal lateral glands into the alimentary canal and then exuded through the anus as a spittle. An average of 10 larvae/spittle was recorded in Burkina Faso. Crop damage is caused by the feeding activity of the nymphs—a combined piercing and sucking action during which saliva is injected into the plant tissue and subsequently, the partially digested sap is withdrawn through the inserted stylet. The inner leaves within the whorl are preferred. Leaf damage appears as bands of chlorotic tissue and in severe cases growth is affected and small panicles are produced. Rainfall and humid conditions favor development but decreased infestation occurs during drought periods. Two adult generations were recorded in Burkina Faso, with peaks in early August and mid-September.

Head Insects

In the early years of sorghum research in Africa, considerable attention was given to the "appropriate" sorghum head type. Thus, as recently as the late 1970s, more compact sorghum heads were introduced mainly because they conformed with the then current ideas of "desirable" head types—a concept derived from high-input technology based agriculture. But there is considerable evidence that loose heads are less susceptible to lepidopterous head worms and hemipterous head bugs. They are also less susceptible to grain molds because they dry fast and easily after rainstorms.

The insects that attack the sorghum panicle may be classed into four groups: grain midges, head bugs, head worms, and head beetles. Head bugs and head worms are mostly associated with compact-head types and the local varieties of sorghum with open heads are usually free of these pests.

The earwig, *Forticula senegalensis* is still a controversial pest. Between 25 and 60 insects may be found on a single panicle or within leaf sheaths. Peak abundance occurs in September, when they appear to be more of a nuisance to humans than to the crop.

Sorghum Midge

The sorghum midge *(Contarinia sorghicola* Coq.) was reported in Nigeria as early as 1929 and was subsequently recorded in Chad in 1958, Senegal in 1961, and later in Burkina Faso, Cameroon, Niger, and Mali (Coutin 1969). In Mali and Burkina Faso, adult midge have been recorded to appear in mid-August, with peak populations in mid- or late September. This period coincides with the flowering of the local photoperiod-sensitive sorghum cultivars. In Senegal midge adults have been recorded in February and March on flowering dry-season irrigated sorghum at Bambey. The main midge population appears in mid-August about 60 days after the beginning of the rains and attains a peak in mid-October, with a mean of 15 adults per panicle reported in 1979 (ICRISAT 1980). However, midge infestation is usually low on farmers' fields across West Africa, although records show infrequent reports of severe localized outbreaks, as occurred in Burkina Faso in 1979 in the region below latitude 13°N, corresponding to the 700 mm isohyet (ICRISAT 1980). The level of midge infestation in northern Nigeria is very low in most years, to the extent that even highly susceptible varieties may not attain any more than 5% infestation (ICRISAT 1982).

The midge situation, however, is different further south, where in Ghana the pest appears to have been imported into a progressively deforested, moist, semi-deciduous forest zone of Kumasi by southward-moving immigrant populations of northern origin. Infestation in this region is enhanced by the presence all year round of a range of alternative wild host plants in the forest zones, namely the wild grasses, *Sorghum arundinaceum* and *Pennisetum polystachyon* (Bowden 1965).

Head Bugs

Although reports of head bug damage are common in the sorghum-growing areas of West Africa, the species complex was little understood until recently. Studies in northern Nigeria show that of a total of 17 species of Hemiptera collected from sorghum heads at Samaru and Kano, 80% were mirid bugs. The most predominant was *Eurystylus rufocunealis* (MacFarlane 1984) followed by *Campylomma angustior* Poppius and *C.subflava* Odhiambo. Others include *Paramixia suturalis* Reut., *Taylorilygus vosseleri* Poppius, and *Creontiades pallidas* Ramber, and the other 11 species observed were considered of little economic importance. Numbers of *E. rufocunealis* increased from the third to sixth week after panicle exsertion and reached their highest peak when the grain was in the soft to hard-dough stages. *Campylomma* species are associated with heads in the first weeks after the head appears from the boot leaf, and numbers peaked in 2 to 3 weeks.

In Burkina Faso, *Eurystylus bellevoyei* was the most important species. *Adelphocoris apicalis* and C. *pallidus* were also collected from sorghum heads.

Populations of *Dysdercus volkeri* are associated with early-maturing varieties of millet but will also feed on sorghum grain. The pentatomid, *Agonoscelis pubescens* is a serious pest of research station off-season irrigated sorghum. The feeding action, which results in grain shriveling, may be accomplished by as many as 80 insects per panicle. Usually they occur in very low numbers in farmers' fields. Other pentatomids, *Dolycoris indicus* and *Menida distant!,* also attack sorghum panicles. Two species of lygaeid bugs, *Lygaeus pandurus* Scop. and *L rivularis* Germ. though more common on millet heads, make up a small proportion of bugs collected on sorghum heads.

Head Caterpillars

Species of lepidopterous head caterpillars are widely distributed in West Africa. The two most common are species of *Pyroderces* Meyr and *Eublemma gayneri* Roths. Others include species of *Heliothis* Hbn; *Salebria mesozonella* Bradl. *Sitotroga cerealella* Ot. and *Stathmopoda auriferella* Wlk.

Pyroderces appears to be the most important head caterpillar of field sorghum. The complex is made up of P. *hemizopa* (Meyr), *P. simplex* (Wlsm), *P. tripola* (Meyr) and *P. risbeci* (Ghesq.). *P. hemizopa* is the predominant species in northern Cameroon, where it accounted for 82.5% of head caterpillars on sorghum (Nonveiller 1969). *P. simplex* is the predominant species in Senegal. S. *auriferella* and S. *cerealella are* the only lepidopterous head caterpillars reported in West Africa that are associated with sorghum stored as panicles. Infestations begin in the field and continue in storage, where severe losses may occur.

Usually infestations of head caterpillars are not readily visible on superficial examination, except on occasions when a lot of frass is produced and pushed to the exterior of the panicle. The interior of the infested panicle is made up of a mixture of damaged and dislodged grain, frass, fungus, and pupal cases held together by silken threads produced by the developing larvae.

Head Beetles

A range of blister beetles feed on sorghum and millet heads—anthers, stigmas, petals of flowers, and developing grains. The most common are meloid beetles, namely *Psalydolytta fusca, P. vestita, P. theresa, Cylindrothorax westermanni* Makl., and *Decapotoma (Mylabris) affinis*. There is a wide variation in colors. Some are black with yellowish brown stripes across the wings, others range from dark grey to light brown or greenish blue. These nocturnal insects are usually inactive during the day, but migrate from the plant base to the panicle at night.

A small number of scarabeid beetles, though more frequently associated with millet, are also found on sorghum: *Pachnoda cordata* Dry., *P. interrupta and Pseudoprotaeita burmeisteri* Arr.

Conclusion

Sorghum is infested by a large number of insect pests from the seedling stage up to the mature grain; only a few of these species cause severe damage to the crop. But the actual crop losses suffered in farmers' fields are not well documented. Although there is sufficient evidence of crop damage by insect pests, most reports give figures on pest incidence, and where losses are sometimes quoted for a particular species, the figures are compounded by similar damage from other pests. The introduction of improved varieties and changes in farming practices will result in new pest problems. The case of the head bugs is a good example—cultivars with compact heads harbor more insects.

Very little progress has been made in the control of sorghum insect pests. The use of insecticides on food crops has not been as extensive in West Africa as in India, except in the case of locusts, where an international control program is involved. Cultural practices require increased participation of the village farmer and this presupposes the existence of a product delivery system. Although there are research results that show value returns for such practices, they have not been properly extended to the village farmer. Sources of resistance need to be explored. Considerable progress has been made at ICRISAT and promising varieties identified for resistance to shoot fly, midge, and stem borers. Such resistance genes can be transferred to the local West African sorghums within a reasonable length of time, using recurrent selection or pedigree approaches coupled with suitable screening techniques. The overall approach in pest control should focus on the integration of different control methods. This approach is being developed in the regional integrated pest management project in the Sahel.

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Sorghum Insect Pests in India

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Abstract

The incidence, economic importance, ecology, and biology of important sorghum pests in India are described briefly. Problems created by changes in cropping patterns and introduction of new high-yielding cultivars are discussed; for instance, sorghum earhead caterpillars, considered to be sporadic pests of little economic importance, which have assumed major pest status in some parts of Andhra Pradesh, Delhi, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, and Uttar Pradesh, with the introduction of compact-head sorghums. With integrated pest management, combining cultural practices, biological control, resistant plant varieties, etc., pest populations can be manipulated so that they remain below economic injury levels.

Resume

***Les Insectes nulsibles au sorgho en Inde**: Cette communication presente une description succinte de l'incidence, de l'importance economique, de l'ecologie et de la biologie des principaux ravageurs de sorgho en Inde. Les changements dans l'assolement, ainsi que l'introduction de nouveaux cultivars a rendement eleve entrafnent des problemes. Par example, les chenilles des panicules de sorgho, ravageurs occasionnels jusqu'alors peu importants du point de vue economique, ont pris de l'importance considerable avec l'introduction des sorghos a panicules compactes dans certaines parties de l'Inde : Andhra Pradesh, Delhi, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan et Uttar Pradesh. La lutte integree comprenant, parmi d'autres elements, les pratiques culturales, la lutte biologique, l'exploitation des varietes resistantes, permet de maintenir les populations des ravageurs, donc les degats, au-dessous du seuil economique de nuisibilite.*

Sorghum {*Sorghum bicolor* L Moench) is the third most important cereal crop in India after rice and wheat, grown on 16.11 million ha, with a total production of 10.68 million tonnes (Anonymous 1983). The important states with sizable acreages are: Maharashtra, Andhra Pradesh, Madhya Pradesh, Karnataka, Tamil Nadu, Gujarat, Rajasthan, Uttar Pradesh, and Haryana. Sorghum grain is mainly used as human food, especially in rural areas, and stems and leaves as fodder for cattle.

Average sorghum yields at the beginning of this century were 498 kg/ha, which marginally increased to 673 kg/ha by the 1980s. There is evidence that achievements in the form of higher yields by using improved varieties and modern technology were reduced by breeding only for yield and not taking insect resistance into consideration.

According to Pradhan (1973), the "green revolution" achieved in India with the introduction of high-yielding wheat varieties was due to the absence of any major pests in this crop. Similar attempts in other crops, including sorghum, have failed due to the presence of a number of major insect pests.

Pest problems in sorghum start at the presowing period and continue till harvest. Jotwani and Young (1971) recorded over a dozen insect pests on sorghum, the major ones being shoot fly, stem borer, grain midge, and a complex of earhead pests. Other, more locally economically important, pests that infest the crop at different growth stages are the whjte grub, cutworms, grasshoppers, and leaf-eating beetles. With changes in cropping patterns, such as the use of early-maturing and dwarf varieties, rotations, mixed cropping, and irregular

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planting, the pest complex may change and also minor pests may gain importance. This aspect has been described in great detail by Young and Teetes (1977), Seshu Reddy and Davies (1978), and Gahukar and Jotwani (1980).

Soil Pests

White grubs, *Holotrichia serrata* F. and *Lachnosterna consanguinea* (Blanch.), are serious pests in Rajasthan, Gujarat, Maharashtra, Uttar Pradesh, and Bihar. The larvae feed on the roots of seedlings, resulting in withering of plants within a week. The infestation occurs mostly in patches, and stunting and lodging of full-grown plants are commonly seen in infested fields. Raodeo et al. (1976) estimated an initial beetle population of about 50 million in an area of 876 ha in Parbhani, Maharashtra, and reported a 49.68% sorghum crop loss in this area. By adopting control measures, a 27.8% yield increase was recorded.

Earlier, this pest was of minor importance, localized only in certain pockets of Rajasthan, Gujarat, and Maharashtra, but now has spread to other states of India. This rapid spread of the white grub may be due to the rapid increase in the number of tubeweils. It seems that the lights over the tubewells attract the adult beetles at night, which may result in spread to previously uninfested areas.

In certain areas, larvae of the cutworm, *Agrotis ipsilon* Roll., have also been reported to cut the sorghum roots, which resulted in plant withering and lodging. In sandy loam soil, infestation of termites, *Odontotermes* sp, and *Microtermes* sp, cause similar symptoms. Srivastava et al. (1969) have reported damage to germinating seed by the ants *Monomorium solomonis* L. and *Pheidole sulcaticeps* Roger var. *punensis.*

Seedling Pests

The shoot fly, *Atherigona soccata* (Rondani) (Muscidae:Diptera) causes damage at the seedling stage by killing the central shoot (deadheart symptom). It is prevalent in the sorghum-growing areas of Mediterranean Europe, Africa, and Asia.

The adult shoot fly is about 5 mm in length and can be identified by the presence of three pairs of black spots on the abdomen. The shoot fly is a major pest of sorghum, limiting production of improved grain sorghum varieties and hybrids not resistant to this pest in tropical Africa and Asia (Jotwani and Young 1972). Shoot fly infests seedlings from 8 to 30 days after germination. The female fly lays whitish cigar-shaped eggs, about 1.2 mm long, singly on the underside of the leaves. The eggs hatch in 2 days, and the tiny, dirty-white maggot crawls up to the plant whorl. From there it penetrates down the leaf sheaths, cuts the growing point, and feeds on decaying tissue. The infestation results in withering of the central leaf, which is called the deadheart symptom. The damaged seedling is killed, but may produce tillers.

Pupation takes place inside the plant or in the soil. Under favorable conditions of moderately high temperature (20-30°C) and high relative humidity (above 60%), the life cycle is completed in 15 to 18 days. Extreme temperatures as well as heavy continuous rains adversely affect the shoot fly population.

Infestations of up to 90% have been recorded by different researchers (Hiremath and Renukarya 1966; Rao and Gowda 1967). Yield has been directly correlated with infestation (Rai and Jotwani 1977): for every 1 % increase in shoot fly infestation, there was a proportionate reduction in grain yield. In cvs CSH 1 and CSH 5 and variety CSV 1 (Swarna) yield losses of 30.4, 39.5, and 22.4 kg/ha respectively were observed.

Flea beetle, *Chaetocnema indica* Wse., *Longitarises* sp, and *Phyllotreta chotanica* Duvivier cause considerable damage to the sorghum crop, with infestations as high as 100% (Thobbi and Naidu 1974).

Cotton grey weevil, *Myllocerus undecimpunctulus maculosus* Desbroachers can cause serious damage to sorghum seedlings, particularly in high-yielding hybrids and cultivars. The adults feed on the foliage, starting from the leaf margin. During severe infestations, the entire leaf blade is eaten up, leaving only the midribs. In seedlings the weevils even feed on the tender stems, which often results in total plant loss (Kishore and Srivastava 1976).

Plant Pests

Stem Borers

Only two major stem borers, *Chilo partellus* (Swinhoe) (spotted stem borer) and *Sesamia inferens* Walker (pink borer) have been recorded on sorghum in India. Although the first is found throughout the country, it is more serious in the northern and central regions. In fact, practically all research work has been carried out only on this species. The pink borer is generally confined to the southern states of Andhra Pradesh and Tamil Nadu and usually appears at the later crop development stage; it causes severe damage and Jotwani et al. (1971) reported 55 to 83% grain loss in cv CSH 1.

Spotted Stem Borer

The adult spotted stem borer is a medium-sized (male 12 mm long, female about 17 mm) straw-colored moth with numerous shiny brown spots on the wing margins. Hind wings are papery thin and white. The moth is usually active at night. Batches of 50 to 100 flattened, overlapping, oval, yellowish-white eggs are laid by the females on the underside of the leaves. Depending upon the environmental conditions, eggs may hatch in 3 to 8 days. After hatching, the young larvae congregate inside the leaf whorls and feed on folded central leaves, causing typical pinhole symptoms. The second or third instar leaves the whorl and moves down to the base of the stem, where it penetrates and destroys the growing point, resulting in deadheart formation. If the growing point has already moved upwards, only stem tunneling takes place. The damaged plants become weak and bear very small earheads.

Under favorable environmental conditions, the life cycle from egg to adult is completed within 30 to 40 days. In northern India, low dry-season temperatures induce diapause from November to February, while in the southern states the pest remains active throughout the year. The diapausing larvae remain in stubbles and stems after harvest and serve as a major carryover source for the next cropping season.

Pink Stem Borer

The pink borer, S. *inferens,* has a wide host range. In south India it is a major pest of *ragi,* or finger millet *(Eleusine coracana* Gaertn.). The adults of the pink borer are stout and straw-colored and are nocturnal in habit. Creamy white spherical eggs are laid in clusters between the leaf sheath and the stem of the plant. Under favorable environmental conditions, the life cycle from egg to adult is completed in 6 to 7 weeks and four to six generations have been recorded in 1 year in southern India.

The larvae may penetrate the stems directly and can kill the young plant. In the advanced stage, damage symptoms are similar to those caused by C. *partellus.* Older larvae are cylindrical and distinctly pink in color and measure about 25 mm when full-grown. Unlike C. *partellus,* however, *S. inferens* larvae migrate from one plant to another.

Green Striped Borer

Green striped borer, *Maliarpha separatella* Ragonot, is reported to be a major pest of rice in Africa and in November-December, 1971 and 1972, Sandhu and Chandra (1973) observed these caterpillars in the stubbles and lower stems of sorghum hybrid CSH 1 in Ludhiana, India, also. An average of one larva per stubble was recorded. In 12% of the stubbles, more than one larva was recorded. The larvae exhibited sexual dimorphism; male larvae had five violet to reddish stripes, while female larvae had faintly defined or no stripes. Under laboratory conditions the larval period lasted for 6 to 9 weeks.

Pupation occurred in the basal stem region or in stubbles under field conditions and lasted for 14 to 16 days. Sandhu and Chandra (1975) reported that adult borers are stout (20-25 mm) with a prominent dark red band on the forewings, which is more prominent in females. The eggs are yellowish white, oval, and laid in batches.

Defoliators

The oriental armyworm, *Mythimna separata* (Walker) causes severe damage to sorghum and other cereal crops by defoliation (Kundu and Kishore 1971; Agarwal and Nadkarni 1975; Kulkarni and Ramakrishna 1975; Patel 1980; Sharma et al. 1982; Sharma and Davies 1983). The gregarious larvae feed voraciously on the leaves, mostly at night, and migrate from field to field when food is exhausted. The entire life cycle is completed in 29 to 39 days. Oviposition starts 2 to 7 days after adult emergence, and eggs hatch after 4 to 5 days. There are seven instars within a total larval developmental period of 20 to 21 days.

Other leaf-feeding insects, such as the red hairy caterpillar, *Amsacta moorei* (Butler), though relatively less important, can cause heavy yield losses (Trehan and Talgeri 1947; Srivastava and Goel 1962). Trehan and Talgeri (1947) also studied the biology of the hairy caterpillar. After the first heavy showers in June, the moths emerge from hibernating pupae in the soil. Soon after emergence, copulation takes place; egg laying starts within 8 to 12 h and continues for 3 to 4 days. The creamy white eggs are laid on leaves and shoots of the host plant in clusters of 300 to 400 arranged in a honeycomb pattern. The larval period lasts from 20 to 27 days.

Other polyphagous caterpillars occasionally reported feeding on sorghum foliage are: *Euproctis virguncula* Walker (Sandhu et al. 1974), *Amsacta albistriga* (Walker), *A. lactinea* (Rcm.), and *Marasmia trapezalis* (Gn.) (Mohanasundaram 1972). and *Mocis frugalis* (F.)(Gowda et al. 1975).

Sap-sucking Pests

The sorghum shoot bug, *Peregrinus maidis* (Ashmead) (Delphacidae) feeds largely in the whorls of young seedlings during the rainy and postrainy seasons. The shoot bug is an important pest in central and south India. Adults and nymphs suck the sap of young leaves, resulting in leaf chlorosis, which in severe cases causes stunted growth and shrivelled, chaffy grains (Prabhakar et al. 1981).

Mites

The mite, *Oligonychus indicus* (Hirst) (Tetranychidae: Acarina) has been reported as one of the serious pests of sorghum in Rajasthan and Gujarat. Usually they are found on the undersides of leaves and sometimes on earheads of *rabi* (postrainy-season) sorghum (Shah et al. 1975). Kundu and Sharma (1975) recorded high mite populations on some exotic lines at the Regional Station of Agricultural Research, Valiabhnagar (Udaipur). Under heavy infestation, the leaves turn red.

Aphids

The corn aphid, *Rhopalosiphum maidis* (Fitch), is common in Asia, especially in India. It is often found in sorghum leaf whorls in huge numbers. Large populations of this aphid, which is also a vector for maize dwarf mosaic virus (MDMV), can cause plant death and stand loss at the seedling stage. During the boot stage, populations increase substantially, especially when the earheads are covered for selfing. Heavy earhead infestation just prior to harvest creates problems in harvesting because of the secretion of honeydew by the insects.

The sugarcane aphid, *Melanaphis sacchari* (Zehntner), commonly found in India, sucks sap from the underside of the lower leaves (Jotwani and Young 1972; Young and Teetes 1977). Normally, coccinellids and syrphid larvae keep the aphid population under control.

Pyrilla perpusilla (sugarcane leafhopper), earlier a serious pest on sugarcane, has recently been found in damaging proportions on sorghum. Since the late 1960s and early 1970s, it has been recorded in epidemic proportions on a number of cereals: rice, sorghum, maize, and pearl millet during the rainy season and on wheat in the postrainy season. Population counts taken on different crops grown in the same area, indicated that the number of adults and eggs were higher on sorghum and maize than on sugarcane, its original preferred host (Jotwani and Chandra 1971).

Several species of hemipterous bugs—*Empoasca flavescens* Gill, *Nephotettix virescens* (Dist.), *Vietnara maculifrons* (Mots), *Typhlocyba, Nezara viridula* Linn., *Dolycoris indicus* Stol, *Menida histrio* Fab., *Cletus* sp, *Lygaeus pandurus* (Scop.), etc.—have been reported damaging sorghum by sucking plant sap, which results in reduced plant vigor and ultimately loss of grain yield (Seshu Reddy and Davies 1979; Prabhakar et al. 1981).

The thrips, *Caliothrips indicus* Bagnall, *Sorghothrips jonnachilus* (Ram.), *Taeniothrips traegardhi* (Trybon), and *Xylaplothrips pellucidus* (Ananthakrishnan), were reported damaging grain in the earheads of ratoon crops by sucking on milk-stage grain, which results in reduced grain development. The damaged areas of the seed turn brownish. An average population of 27 thrips (T. *traegardhi)* was recorded on single earheads during November-December (Chandra and David 1971; Ananthakrishnan 1973).

Earhead Pests

Sorghum Midge

The sorghum midge, *(Contarinia sorghicola* [Coquillett]) is a tiny orange-colored fly, about 2 mm long. It is a cosmopolitan pest, found throughout the sorghum-growing areas of the world (Barnes 1956; Harris 1976; Jotwani and Young 1971).

In India, though the midge was first recorded in 1914 by Fletcher, it was never reported as a pest of economic importance until 1965. The first report identifying the midge as a sorghum pest came from research farms in south India, where sorghum germplasm was grown season after season, providing ideal conditions, with flowering earheads continuously available for the midge to breed and multiply rapidly. Similar conditions have now been created in the traditional sorghum-growing areas with the introduction of early-maturing high-yielding hybrids and varieties. As these are sown on different dates along with late-maturing locals, flowering earheads are continuously available in the field for midge oviposition and development. It has been observed that early-sown crops generally escape midge damage, while late-flowering ones suffer serious damage when climatic conditions are favorable.

Biology and Habits

The tiny reddish female fly, easily recognizable by its long ovipositor, lays about 30 to 100 eggs inside the floret. Tiny maggots hatch from the eggs within 2 days of egg laying and start feeding on the ovaries, which results in chaffy florets. Under heavy infestation, no grain development takes place, and the head looks blasted. Larval development may take 9 to 11 days. The presence of larvae can be detected by pressing florets between the thumb and forefinger, when a pinkish fluid appears from infested flowers. Full-grown larvae move towards the apex of the flower for pupation. The pupal stage lasts for about 3 days. After hatching of the adult, the empty pupal case is party exserted from the tip of the floret. The duration of the adult life is very short; males live for just a few hours, while females live for about 24 h; rarely, up to 2 days. Mating takes place immediately after adult emergence. Under favorable conditions, the entire life cycle may be completed within 13 to 14 days.

In the southern states of India, the sorghum midge is reported to be active through most of the year; however, in the northern and central regions, with cooler winters, the midge population declines rapidly when temperatures drop. The larvae undergo diapause within the tough cocoons and overwinter inside the chaffy florets. The diapause is broken with the onset of the next rainy season.

Johnsongrass and sudangrass are reported to be important alternate hosts of the sorghum midge, though it has also been recorded on a number of other related grasses (Young 1970).

Extent of Losses

Puttarudriah (1947) was the first to report on sorghum midge damage. He observed about 75% loss caused jointly by the midge and earhead bug in old Mysore (now Karnataka) State. The first serious outbreak was recorded in Maharashtra in 1970. From 48 to 99% damage on earheads has been recorded by various authors (Taley et al. 1971; Thimmaiah et al. 1974; Gowda 1975; Dakshinamurthy and Subramaniam 1975; Rao 1975). Heavy losses in grain yield (20-26%) have also been reported from Karnataka by Rao (1966) and Thimmaiah et al. (1969). From Maharashtra, Jotwani et al. (1977) reported maximum avoidable loss due to midge, calculated on the basis of yield from covered heads, as 211 to 408 kg/ha.

Earhead Caterpillars

In India, sorghum earhead caterpillars, which until recently were only sporadic pests of little economic importance, have assumed major pest status in some parts of Andhra Pradesh, Delhi, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, Rajasthan, and Uttar Pradesh. About 22 caterpillar species belonging to different families have been reported (Table 1). Most of these species are of occasional occurrence, while a very few occur regularly and cause substantial damage to sorghum grain. The larvae feed on the soft grain, leaving empty glumes, and can be detected in the field by the presence of frass, and webbing for some species.

Changes in plant characters can increase pest damage. One example is the serious damage caused by earhead caterpillars on the new high-yielding cultivars. The earheads of these cultivars are large and compact, and earhead caterpillars can feed and develop under protected as well as ideal microclimatic conditions inside the earheads.

In recent years, the losses caused by earhead caterpillars have been alarming and damage up to 37% has been recorded (Kulkarni et al. 1980). During 3 years of field trials (1977-1979) in Delhi to determine the losses caused by earhead caterpillars on sorghum, several species were found feeding on maturing grains: *Autoba silicula, Heliothis armigera, Dichocrocis punctiferalis, Cryptoblabes gnidiella, Porthesia xanthorrhoea, Ephestia cautella,* and *Sitotroga cerealella,* Of these, the first five are more prominent in Delhi. Kishore and Jotwani (1982) recorded 44.3% avoidable loss due to these earhead caterpillars. Leuschner and Sharma (1983) worked out the percentage avoidable loss for midge, head bugs, and earhead worms from 46 experiments (31 on midge, 5 on head bugs, 10 on earhead worms) conducted all over India. Mean avoidable losses were: for midge, 45.2%; for head bugs, 43.9%; for earhead worms, 28% (Table 2). These authors reported that the minimum economic losses were to the tune of 972 million rupees.

Table 1. Species of sorghum earhead caterpillars recorded in India.

Name	Family	Reference
1	2	3
Earhead caterpillar *Autoba silicula* (Swinhoe)	Noctuidae	David and David (1961), Fletcher (1921), Hardas et al. (1979, 1980), Nayar et al. (1982), Taley et al. (1974)
Earhead caterpillar *Celama internella* (Walker)	Arctiidae	Ayyar (1963), David and David (1961), Nayar et al. (1982)
Earhead caterpillar *Cirphis unipuncta* Haworth	Noctuidae	Taley and Dongardeo (1977)
Rice meal moth *Corcyra cephalonica* (Stainton)	Galleridae	Nayar et al. (1982)
Earhead webworm *Cryptoblabes angustipennella* Hampson	Pyraustidae	Fletcher (1921), Nayar et al. (1982)
C. gnidiella (Milliere)	Pyraustidae	Fletcher (1921), Kulshrestha et al. (1969), Nayar et al. (1982), Srivastava and Singh (1976), Taley et al. (1974)
Earhead caterpillar *Cydia* sp	Tortricidae	Nayar et al. (1982), Rawat et al. (1970)
Castor capsule borer *Dichocrocis punctiferalis* Guenee	Pyraustidae	David and David (1961), Fletcher (1921), Nayar et al. (1982), Kishore and Jotwani (1982), Puttarudriah and Channa Basavanna (1951)
Earhead caterpillar *Ectomyelosis* sp	Pyralidae	Nayar et al. (1982), Rawat et al. (1970)
Earhead caterpillar *Ephestia cautella* (Walker)	Phycitidae	Kundu and Sharma (1973), Kishore and Jotwani (1982), Sachan and Verma (1981)
Earhead caterpillar		
Eublemma gayneri (Rothschild)	Noctuidae	Nayar et al. (1982), Rawat et al. (1970)
£ *hemirrhoda* Walker	Noctuidae	Nayar et al. (1982)
Hairy caterpillar		
Euproctis fraternata (Moore)	Lymantriidae	Kundu and Sharma (1974), Kushwaha and Bhardwaj (1967)
£ *limbata* Walker	Lymantriidae	Rawat et al. (1970)
£ *subnotata* (Walker)	Lymantriidae	Kushwaha and Bhardwaj (1967), Mogal et al. (1980), Usman (1963)
Gram pod borer *Heliothis armigera* (Hiibner)	Noctuidae	Anonymous (1975), Bilapate and Pawar (1980), Paul et al. (1980), Kishore and Jotwani (1971), Rao and Abraham (1956)
Oriental armyworm *Mythimna separata* (Walker)	Noctuidae	Anonymous (1981), Leuschner and Sharma (1983), Sharma and Davies (1983)
M. unipuncta (Haworth)	Noctuidae	Gawande et al. (1979)

Continued

Table 1. *Continued*

Name	Family	Reference
1	2	3
Earhead caterpillar *Nola analis* (Wileman and West)	Nolidae	Anonymous (1982), Hardas et al. (1979, 1980), Taley and Dongardeo (1977)
Earhead caterpillar *Plodia interpunctella* (Hubner)	Phycitidae	Anonymous (1968), Fletcher (1921)
Earhead caterpillar *Porthesia xanthorrhoea* Kollar	Lymantriidae	Fletcher (1921), Kushwaha and Bhardwaj (1967), Kishore and Jotwani (1982)
Earhead caterpillar *Pyroderces hemizopa* Mayer	Cosmopterygidae	Taley and Dongardeo (1977)
Earhead caterpillar *Sathrobrota simplex* (Walsingham)	Cosmopterygidae	David and David (1961), Fletcher (1921), Nayar et al. (1982)
Angoumois grain moth *Sitotroga cerealella* (Olivier)	Gelechiidae	Anonymous (1968), David and David (1961), Kishore and Jotwani (1982), Puttarudriah and Raju (1953)
Earhead caterpillar *Stathmopoda theoris* Mayrick	Heliodinidae	Fletcher (1921), Nayar et al. (1982)
Earhead webworm *Stenachroia elongella* Hampson	Pyraustidae	Ayyar (1963), Darekar and Talgeri (1976), Fletcher (1921), Isaac (1933), Nayar et al. (1982)
Slug caterpillar *Thosea aperiens* (Walker)	Cochlidiidae	Nayar et al. (1982)

Table 2. Extent of avoidable yield losses due to different earhead pests in sorghum.

	Avoidable yield loss (%)		
Insect	Mean	Minimum	Maximum
Midge	43.2	3.6	100.0
Head bugs	43.9	5.8	84.3
Earhead caterpillars	28.0	4.3	44.2
Mean	39.0	4.6	76.2

Source : Leuschner and Sharma (1983).

Rawat et al. (1970) have recorded five different caterpillar pests—Cydia sp, *Ectomyclosis* sp, *Eublemma, Heliothis armigera,* and *Euproctis limbata*—on sorghum earheads at Jabalpur, Madhya Pradesh. Estimated losses in grain yield due to these pests were 18.26%, or 717 kg/ha.

Chouhan (1983) studied the incidence, biology, and control of sorghum earhead caterpillars at two locations, taking into account different earhead types and grain-development stages. At Delhi he observed a higher incidence of *Autoba silicula* and *Cryptoblabes gnidiella,* while in Dharwar, *Euproctis subnotata* and *Heliothis arrnigera* were more prominent (Table 3). The infestation was higher on soft-dough grain and compact-earhead types. Chouhan has also observed a higher incidence of earhead caterpillars at Dharwar than at Delhi, which might be because of the more favorable weather conditions (higher rainfall and humidity).

Earhead Bugs

In India, the earhead bug, *Calocoris angustatus* (Leth.), is a key pest in the southern states of Andhra Pradesh, Karnataka, and Tamil Nadu. The bug attacks from head emergence to hard-dough stage of grain development. Hundreds of adults and nymphs can be observed on a single earhead.

Table 3. Relative incidence of earhead caterpillar on various stages and types of sorghum heads or CSH 1, CSH 6, and CSV 1 at Delhi and Dharwad (rainy season 1981 and 1982).

Earhead type and stage	Average caterpillar number/10 earheads								
	1981			1982			Average of two seasons		
	CSH 5	CSH 6	CSV 1	CSH 5	CSH 6	CSV 1	CSH 5	CSH 6	CSV 1
Open, flowering	1.00 (1.00)a	0.83 (0.88)a	1.00 (1.00)a	1.00 (1.00)a	1.00 (1.00)a	1.00 (1.00)a	1.00 (1.00)	0.91 (0.94)	1.00 (1.00)
Closed, flowering	3.00 (1.71)b	2.50 (1.77)b	2.33 (1.51)b	2.33 (1.51)b	2.33 (1.51)b	2.00 (1.38)a	2.66 (1.61)	2.91 (1.64)	2.16 (1.44)
Loose, soft dough	21.33 (4.61)d	12.50 (3.52)d	8.00 (2.81)c	15.33 (3.90)d	10.00 (2.29)c	6.00 (1.99)b	18.33 (4.25)	11.25 (2.90)	7.00 (2.40)
Loose, hardened	6.33 (2.51)c	6.50 (2.54)c	2.00 (1.38)b	4.66 (2.15)c	5.33 (3.15)d	4.00 (2.42)c	5.49 (2.33)	5.91 (2.84)	3.00 (190)
Compact, soft dough	65.00 (8.06)f	60.50 (10.77)g	58.66 (7.67)c	80.00 (8.93)g	56.00 (4.23)e	52.33 (4.31)d	72.50 (8.49)	58.25 (7.50)	55.49 (5.84)
Compact, hardened	39.33 (6.25)e	25.83 (5.08)f	17.00 (4.12)d	29.00 (5.37)f	25.33 (5.02)f	20.00 (4.47)d	34.16 (5.81)	25.58 (5.05)	18.50 (4.29)
Control (normal dough)	21.33 (4.61)d	20.50 (4.52)c	18.00 (4.24)d	20.00 (4.46)e	18.00 (7.48)g	18.66 (7.23)e	20.66 (4.53)	21.75 (6.00)	18.33 (5.73)
SEm	(0.14)	(0.08)	(0.10)	(0.14)	(0.14)	(0.14)			
CD at 5%	(0.42)	(0.24)	(0.30)	(0.42)	(0.42)	(0.42)			
CD at 1%	(0.60)	(0.34)	(0.43)	(0.60)	(0.60)	(0.60)			

Source: Chouhan (1983).
Figures followed by the same letter in a column are nonsignificant.
Figures in parentheses are transformed values = $\sqrt{x+0.5}$ transformation.

Eggs are laid in the florets from shortly after head emergence until anthesis. The nymphs develop on the milk-stage and soft-dough grain. Grains attacked during the milk stage shrivel and remain very small, causing substantial yield loss (Cherian et al. 1941; Rao et al. 1981).

Kishore and Srivastava (1975) also reported heavy incidence of *Nezara viridula* (Linnaeus) and *Dysdercus koneigii* Fabricius on sorghum earheads at Delhi. The milkweed bug *Lygaeus pandurus* (Scop.) was found in large numbers on sorghum earheads in Rajasthan. Clusters of nymphs and eight to ten adult bugs were recorded feeding on milk-stage grain (Kundu and Sharma 1972).

Earhead Beetles

The blister beetle, *Mylabris pustulata* Thunberg **and** *Lytta tenuicollis* (Pallas) have been reported feeding on the flowers and developing grain of sorghum at Vallabhnagar (Udaipur). On an average, eight adult beetles were found feeding on each earhead.

The metallic green beetle, *Chiloloba acuta* Wied is reported to feed on sorghum pollen grains (Ayyar 1963). A preliminary experiment was carried out under field conditions to estimate the loss in grain yield caused by this beetle. The maximum grain yield per earhead was obtained from noninfested earheads (31g); the minimum yield, from earheads infested by 5 beetles (5.28 g).

Stored Grain Pests

Sorghum is highly susceptible to insect pests during storage. The stored-grain insects attacking sorghum are cosmpolitan and polyphagous. Common insect pests of stored sorghum in India are listed in Table 4.

Table 4. Stored-grain pests of sorghum in India.

Insect	Common name	Insect stage causing damage
Lepidoptera		
Sitotroga cerealella (Olivier)	Angoumois moth	Larva
Corcyra cephalonica (Stainton)	Rice moth	Larva
Ephestia cautella (Walker)	Almond moth	Larva
Coleoptera		
Sitophilus oryzae (Linnaeus)	Rice weevil	Larva and adult
Rhyzopertha dominica (Fabricius)	Lesser grain borer	Larva and adult
Tribolium castaneum (Herbst)	Red flour beetle	Larva and adult
Trogoderma granarium Everts	Khapra beetle	Larva
Oryzaephilus surinamensis (Linnaeus)	Saw-toothed grain beetle	Larva and adult
Latheticus oryzae (Waterhouse)	Long-headed flour beetle	Larva and adult
Lasioderma serricorne (Fabricius)	Cigar borer beetle	Larva and adult

Among the species mentioned, the angoumois grain moth, rice weevil, lesser grain borer, and red flour beetle are considered to be of major importance. The first three pests enter storage through field-infested grain. Venkatarao et al. (1958) reported 61.3% sorghum grain loss caused by the rice weevil in 5 months. Besides causing grain loss, stored-grain pests also reduce seed viability, affecting germination.

Future Lines of Work

Our knowledge about the pest status of many sorghum insects and their economic injury level is still incomplete. More work is necessary on these two aspects in order to develop a sound sorghum insect management program. Such a program should include control components such as host-plant resistance, cultural control, biological control, and insecticides. Most emphasis should be placed on the first three control methods, and insecticides should only be used if absolutely necessary. Training of the farmer is a prerequisite for the success of such a program. Active collaboration with ICRISAT, international agencies, agricultural universities, and the Indian Council of Agricultural Research will also be necessary for the development of a sorghum pest management program.

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Sorghum Insect Pests in South East Asia

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Abstract

The incidence, economic importance, ecology, and biology of the common insect pests of sorghum in southeast Asia, as well as the natural enemies, are described. Sorghum shoot fly, Atherigona soccata *(Rond.) is the major pest of sorghum in Thailand. Thrips,* Frankliniella williamsi *Hood; the grasshopper Patanga succincta (Linn.); the armyworm,* Mythimna separata (Walk.); and the aphids, Melanaphis sacchari *(Zehn.) and* Rhopalosiphum maidis *(Fitch), are the major pests during the vegetative growing phase of sorghum. Green stinkbug,* Nezara viridula *(Linn.), corn earworm,* Heliothis armigera *(Hubn.), and the sorghum webworm,* Stenachroia elongella *(Walk.) are the common pests at the earhead stage. The rice and maize weevils,* Sitophilus oryzae *(Linn.) and* S. zeamais *Mots., are the major storage insects. Chemicals have been recommended for insect control. In addition, other appropriate control measures have also been investigated.*

Resume

***Les Insectes nulslbles au sorgho dans le Sud-Est asiatique**: La communication porta sur Tincidence, l'importance economique, l'ecologie et la biologie des insectes nuisibles au sorgho repandus dans le Sud-Est asiatique ainsi que de leurs ennemis naturals. En Thailande, la mouche des pousses,* Atherigona soccata *(Rond.) se presente comme un ravageur extremement important chez les cultures de sorgho. Les insectes qui s'attaquent au stade vegetatif des plantes sont:* Frankliniella williamsi *Hood; l'acridien* Patanga succincta *(Linn.); la chenille legionnaire* Mythimna separata *(Walk.), les pucerons* Melanaphis sacchari *(Zehn.) et* Rhopalosiphum maidis *(Fitch). Plus tard, au stade de !a panicule se trouvent: la punaise des panicules* Nezara viridula *(Linn.), le ver de la capsule du cotonnier* Heliothis armigera *(Hubn.)et le ver a soie du sorgho* Stenachroia elongella *(Walk.). Les plus importants ravageurs des denrees sont les charancons du riz,* Sitophilus oryzae *(Linn.) et du mai's.* S. zeamais *(Mots.). Enfin, tout en preconisant la lutte chimique, les auteurs examinent d'autres mesures adaptees de lutte contre les ravageurs.*

In southeast Asia, Thailand is the principal producer of sorghum (*Sorghum bicolor* [L] Moench), which is ranked as the third most important cereal crop of the country. The production record for 1983 was 300 000 tonnes produced on 480 000 ha. Vietnam produced 40 000 tonnes in 1981 according to the FAO agricultural report. The total sorghum area in Indonesia is less than 100 000 ha, which is mostly grown in Java south of Semarang and Yogyakarta. The area devoted to the crop is small in other southeast Asian countries and very little research has therefore been done in those countries (W.R. Young, 1984, IADS, Bogor, Indonesia, personal communication).

In Thailand, sorghum is grown in marginal areas where the rainfall is about 1250 to 1500 mm during the cropping season from July to October, or it is planted in August as a second crop after corn. Sorghum is mostly grown in the central part of the country. The sorghum produced is mainly exported to Saudi Arabia, Japan, and South Korea. For Thailand, there is a trend towards an increase in the area planted to sorghum. It is expected that production will reach 1 million tonnes in the near future.

About 30 insect species have been found attacking sorghum (Table 1), but only 14 species are considered to be, or will probably be, of economic

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importance and are discussed in this report. The pests are presented according to the stage of crop growth when damage occurs (Young and Teetes 1977).

Insect Pests of Sorghum in the Field

Sorghum Shoot Fly

Sorghum shoot fly, *Atherigona soccata* Rond., is the most important pest of sorghum seedlings in Africa and Asia (Young 1970). Extensive work on this insect was reported in the Proceedings of the International Symposium on Shoot-fly held at Hyderabad, India, in 1971 (Jotwani and Young 1972; Young and Teetes 1977; Young 1981).

Pattern of Infestation

For any method of shoot fly control the infestation pattern had first to be established. It was observed that only a small percentage of the plants are attacked (showing the deadhead symptom) during the first week after germination. Most of these

Table 1 . Insect pests of sorghum in southeast Asia.

Scientific name	Common name	Pest status	Plant part attacked
Seedling pests			
Atherigona soccata Rondani	Sorghum shoot fly	Key	Growing point
Frankliniella wiliiamsi Hood	Corn thrips	Occasional	Leaf
Foliage feeders			
Adoretus compressus (Weber)	Rose beetle	Occasional	Leaf
Baoris oceliafarri Moore	Skipper	Occasional	Leaf
Callitetrix versicolor Fabricius	Plant hopper	Occasional	Leaf
Marasmia venilialis Walker	Leaf binder	Occasional	Leaf
Melanaphis sacchari (Zehntner)	Sugarcane aphid	Occasional	Leaf
Melanitis leda ismene Cram.		Occasional	Leaf
Mocis frugalis Walker	Looper	Occasional	Leaf
Mythimna separata (Walker)	Armyworm	Occasional	Leaf
Orgyia turbata Butler	Tussock moth	Occasional	Leaf
Patanga succincta Linnaeus	Bombay locust	Key	Leaf
Peregrinus maidis (Ashmead)	Corn plant hopper	Occasional	Leaf
Rhopalosiphum maidis (Fitch)	Corn leaf aphid	Occasional	Leaf and panicle
Stem feeders			
Chilo partellus (Swinhoe)	Spotted stem borer	Occasional	Stem
Ostrinia furnacalis (Guenee)	Corn borer	Occasional	Stem
Sesamia inferens (Walker)	Pink borer	Occasional	Stem
Earhead feeders			
Contarinia sorghicola (Coq.)	Sorghum midge	Occasional	Head
Heliothis armigera (Hubner)	Corn earworm	Occasional	Head
Lamoria sp	Webworm	Occasional	Head
Leptocorisa sp			Head
Nezara viridula (Linnaeus)	Green stink bug	Occasional	Head
Stenachroia elongella Walker	Webworm	Occasional	Head
Stored grain pests			
Carpophilus dimidiatus (Fabricius)	Corn sap beetle	Occasional	Grain
Corcyra cephalonica (Stainton)	Rice moth	Occasional	Grain
Cryptolestes pusillus (Schonherr)	Flat grain beetle	Occasional	Grain
Ephestia cautella (Walker)	Almond moth	Occasional	Grain
Sitophilus oryzae (Linnaeus)	Rice weevil	Key	Grain
Sitophilus zeamais (Motschulsky)	Corn weevil	Key	Grain
Tribolium castaneum (Herbst)	Red flour beetle	Occasional	Grain

plants died completely. The majority of plants were attacked when they were two weeks old but usually survived by producing side tillers, although these tillers were also damaged by shoot fly. Tillers produced by plants which showed deadheart symptoms during the third and fourth week grew faster and usually escaped shoot fly damage. In some varieties more tillers were produced which gave good yields. These results showed that chemical protection, if necessary, should be done during the second week of plant growth and should be effective for about 2 weeks.

Control

Several chemicals have been tested to control sorghum shoot fly. Carbofuran 3G applied at a rate of 37.5 to 50 kg/ha by trench application at planting appears to be the most effective. Wongkamhaeng (1982) observed that fertilizer application induced higher oviposition. Vigorous plant growth did not seem to reduce the shoot fly damage. This led to an investigation on the timing of fertilizer application in combination with chemical control. The results indicated that fertilizer application at planting time, together with the insecticides, gave better control than the fertilizer application at later crop growth stages.

Although granular carbofuran gave good control of shoot fly, its cost is too high for extensive use by small farmers. Carbofuran is also available in liquid formulation for seed treatment. It has been found that carbofuran used at the rate of 1.0 g a.i./kg of seed gives satisfactory shoot fly control. The cost of the treatment per unit area is also lower than the granular application. Hence, it will be more economical for farmers to use the liquid formulation for seed treatment. The treated seeds can also be stored and maintained in good condition for at least 5 months. They may be treated by the seed company before distribution to farmers. Treated seeds are also protected against stored grain pests, especially the rice and maize weevils.

Screening for Resistance

Screening of varieties for shoot fly resistance has been conducted in cooperation with the International Sorghum Pest Resistance Testing Program of ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) in Patancheru, India. Twenty-four cultivars were grown at Suwan Farm, Thailand, in 1983, and compared with Uthong 1, a recommended variety. Shoot fly damage on the Uthong 1 was 83% deadhearts, while the infestation on resistant varieties—PS-14454, PS-18822-4, PS-21112, PS-14093, PS-19230, PS-19794, and PS-18817-2—was in the range of 4 to 43%. Breeding work is under way to incorporate shoot fly resistance into new local high-yielding varieties.

Cultural Control

Time of planting is a practical cultural practice in the management of sorghum shoot fly. In Thailand it has also been observed that in areas where plantings are done at different times, the earliest planted crops are usually free from serious infestation, while those planted late often encounter severe infestation. Thus, it is suggested that planting should be done as early as possible and at the same time over large areas to avoid heavy infestation. This effective cultural control practice is now also used in Israel and other countries (Young 1981). Continuous planting on research stations increases the shoot fly problem; when planting is done only once a year, the shoot fly infestation is less serious, except on late plantings. Sorghum should also be rotated with other crops such as corn, rice, and soybean, to reduce the shoot fly problem.

Control by Trapping

Control of shoot fly by trapping of adults has also been attempted. The square pan fishmeal trap developed by ICRISAT was used. The results showed that the number of deadhearts were not reduced by this method. Further investigations are necessary to find the optimum number of traps per unit area and the best time and location for installing the traps (whether inside or outside the field).

Corn Thrips

Thrips (*Frankliniella williamsi* Hood) sometimes cause serious damage to sorghum during the seedling and early whorl stage, especially during prolonged drought. Thrips feeding induces or hastens the drying of leaves and often causes premature death. However, thrips are not a problem when rainfall is adequate, and normally do not cause serious damage to sorghum in Thailand, because the crop is planted in the middle or late rainy season.

Wechakit and Ketavan (1977) studied the life history of *F. williamsi.* The young thrips are yellowish or straw-colored; the adults, dark brown. The full-grown thrips are about 3 mm in length. The eggs are deposited in the leaves, along the longitudinal veins and hatch in 3 to 4 days. Young thrips molt twice before they become adults. The nymphal stage lasts about 7 days, then it enters into a prepupal stage and after 1.4 days becomes a pupa. The pupal period lasts for 3 days. The thrips are bisexual. The average life cycle is about 17 days.

Control

In case chemical control is needed, the crop may be sprayed with stirophos, diazinon, mevinphos, endosulfan, or dimethoate. Granular formulations are not effective.

Aphids

Two species of aphids—the corn leaf aphid, *Rhopalosiphum maidis* (Fitch), and the sugarcane aphid, *Melanaphis sacchari* Zehntner—attack sorghum. Both species are widely distributed in Asia and Africa (Young 1970). Nymphs of the corn leaf aphid are yellowish in color, but the adults are greenish-blue. During the growing season, there are females only and they reproduce by parthenogenesis. The aphids give birth to apterous forms which molt four times to become adults. In crowded conditions, or when host plants are stressed, the aphids produce winged forms, which molt five times before becoming adults. The nymphal development is completed in 12 days. Reproduction begins 5 days after the final molt. Each female can produce up to 46 young, with an average of 19. The adults live about 11 to 28 days.

The corn leaf aphid is more commonly found on corn than on sorghum. It is found in leaf whorls, but rarely found attacking plants in the elongation stage. It appears again during the boot and heading stage. Honeydew, produced by the aphids feeding on the earhead, induces the growth of black sooty mold.

The sugarcane aphid, *Melanaphis sacchari* (Zehntner) is yellowish green in color. It is more common on sorghum but also feeds on com. The aphid feeds on the underside of sorghum leaves. The whole undersurface of the leaves may be covered by aphid colonies. The leaves below the infested ones are often covered with sooty molds, which grow on the honeydew produced by the aphids. Many hymenopterous as well as some dipterous insects are attracted to the honeydew. Sorghums in Thailand are generally quite tolerant to feeding by this aphid species, because no yield loss has been reported yet.

The life cycle of the sugarcane aphid is almost identical to that of the corn leaf aphid. This aphid also exists only in female form and reproduces by parthenogenesis. An aphid may reproduce up to 68 young, with an average of 34. The adults live about 10 to 16 days.

Natural enemies of aphids include ladybird beetles, *Chilomenes sexmaculata* (Fabricius) and *Micraspis discolor* (Fabricius) as the most common predators. The larvae of the syrphid fly, *Syrphus balteatus* (Degeer), and the lacewing, *Chrysopa basalis* Walker, also feed on the aphid, but are not as important as the ladybird beetles.

Control

Chemical control is rarely needed; however, if treatment is necessary, 0.03% dimethoate or 0.2% carbaryl could be applied. Since the aphids occur in colonies, treatment should be limited to the infested spots only, in order to avoid destruction of natural enemies.

Armyworm

Armyworm, *Mythimna separata* (Walker), outbreaks often occur on corn and sorghum over large areas. On sorghum, the infestation often occurs during the whorl stage. The armyworm feeding causes a ragged appearance of the leaves. Although the plants may be heavily infested by armyworms, they can recover by producing new healthy leaves or new tillers. Armyworm damage has relatively little effect on yield.

The armyworm moth is nocturnal. It seeks shelter during daytime. Mating occurs 1 to 3 days after the emergence of the adults. Eggs are deposited 3 to 5 days thereafter. The oviposition period is about 11 days. A female lays an average of 991 eggs in 40 egg clusters (Sepsawadi et al. 1973). The egg clusters are laid In the whorl of the plant at night and hatch in 2 to 4 days. The larval stage lasts from 18 to 26 days. Young larvae normally live in the leaf whorl. The insect undergoes pupation in the soil or in the base of the leaf sheath. The pupation period is 9 to 12 days with an average of 10.5 days. The moths live 7 to 19 days, with an average of 10.5 days.

Several species of parasites have been found attacking the armyworm. The most important are tachinid flies *Exorista xanthaspis* Wiedemann, *Carcelia illota* Curran, and *Dolicholon vicinum* Mesnil. An encytrid, *Litomastix* sp, is also commonly recorded. More than 1000 *Litomastix* parasites may emerge from one larva. The earwig, *Proreus similans* Stal, is also an active predator. It feeds on the eggs as well as the young larvae of the armyworm. A pentatomid bug, *Cantheconidea furcellata* Wolff, is also found feeding on the larvae of the armyworm.

Control

A number of chemicals give effective control of the armyworm; e.g., 0.2% carbaryl, 0.01% methomyl. Chemical treatment is generally not necessary for armyworm attacking sorghum, because of the high tolerance of the plants to the feeding of the insects. Also, during outbreaks of armyworm, their natural enemies were often found in abundance, and grain yield was not significantly reduced. In order to conserve the natural enemies, chemical treatment should be discouraged. However, in experimental plots full protection may be necessary.

Grasshopper

Among the grasshoppers, *Patanga succincta* (L) is the most important one. A serious outbreak was first recorded on about 14 500 ha of corn in 1963, at a time when corn growing in the country was just beginning to expand. Forests were cleared for planting corn, which may have increased populations. An area of 307 200 ha was damaged in 1974 (Roffey 1979). After about 10 years of intensive control, this grasshopper became a sporadic pest in certain areas but is still a major pest along the Thailand and Cambodia border, where control is difficult.

Seedlings may be completely damaged. After attack during the whorl stage, the plants can recover, provided enough soil moisture is available to support growth.

The adult grasshopper is robust, and 40 to 50 mm long. Nithi-Uthai and Mongkolkiti (1975) studied its life cycle. A thorough review and further study on its ecology were undertaken by Roffey (1979). The eggs are laid in the ground in April-May and hatch after about 35 to 41 days. The nymphs molt eight to nine times to become adults. A female lays 1 to 3 egg pods, each containing 96 to 152 eggs. The hoppers appear in July-August. During the first and second instar, they feed on grasses, and in the third they begin to feed on corn leaves. The damage to sorghum plants is mainly caused by adults. During outbreaks, the grasshopper may indiscriminately feed on most food plants available.

Several natural enemies have been reported to suppress the grasshopper population. A fungus, *Entomophthora grylli* Fr., has been found to be a major mortality factor. The fungus is most effective during heavy rainfall between late August and October. The infected hoppers become sluggish and are later found clinging to the tops of corn or sorghum plants. This fungus is a major cause of the fluctuation pattern of the grasshopper population.

A hymenopterous parasite, *Scelio fascialis,* is the most important parasite of grasshopper eggs. Grasshopper eggs are also attacked by predator beetle larvae like *Epicauta* sp and *Mylabris* sp. The sphecid wasp, *Sphex* sp, also preys on grasshopper nymphs and adults.

Control

Visetsulka et al. (1980) suggested the following control practices:

1. Collecting by hand. Grasshopper can be used as human food and therefore, the farmers are advised to catch them for consumption, as well as for sale. The grasshopper is inactive at temperatures below 13°C, during December to February. During this time it will rest on the plants from evening until the temperature rises the following day. At this time it is easy to collect the hoppers by hand or with a sweep net before dawn. This practice is very effective in reducing the grasshopper population.

2. Preserving and augmenting natural enemies. It is observed that from April to June, natural enemies are abundant; therefore, chemical application should be avoided during this period, in order to allow the natural enemies to build up. At the same time, the natural enemies should be collected from

highly populated areas for release into areas where they are less abundant. During heavy rainfall (September-October) in some areas it is easy to find grasshoppers infected by the fungal pathogen. These infected grasshoppers are inactive and can be caught easily. They should be collected and released in noninfested areas to spread the disease. At least it will reduce the grasshopper population during the following planting season. Chemical treatment should not be done at this time, because dead infected grasshoppers will not be effective in spreading the pathogen.

3. Using vertebrate predators. Ducks are good predators; they should be raised on farms and allowed to feed on the young hoppers. In addition, the duck could be eaten or sold.

4. Spraying shelter crops. The grasshopper seeks shelter in groundnut bushes when the temperature increases during the daytime. It does not damage the groundnuts, which can be grown in alternate strips with sorghum to provide shelter for grasshoppers. Chemicals can be applied to the groundnut plants to control the grasshoppers. This will save operational costs. A common insecticide, such as 0.2% carbaryl, can be used as foliar spray.

Stem-boring Insects

A number of pyralids and noctuids are reported as important borers of sorghum in various countries (Young and Teetes 1977). However, there are only a few species known to attack sorghum in southeast Asia, and they are only minor pests.

1. The pyralid, *Chilo partellus* (Swinhoe), is an important borer of sorghum and maize in India and in African countries (Young 1970; Young and Teetes 1977). In southeast Asia, there were reports of this pest infesting sorghum in Indonesia and the Philippines; however, it has not been recorded in Thailand.

2. The pink stem borer, *Sesamia inferens* (Walker) was reported attacking sorghum in the Philippines (Young 1970). In Thailand, this is an important borer of sugarcane and rice, but has not been recorded on sorghum.

3. The tropical corn borer, *Ostrinia furnacalis* (Guenee) was first reported in Thailand as O. *salentialis* (Snellen). It is an important pest of corn in Thailand and the Philippines, but infestation on sorghum is rarely observed. Attack on sorghum was observed in varietal trials and it appeared that only some succulent varieties were susceptible, while the commercially grown ones were not susceptible to borer attack.

Corn Earworm

The corn earworm, *Heliothis armigera* (Hubner), is an important pest of cotton in Thailand. The insect also causes occasional damage to sorghum heads. The larvae feed on sorghum seeds, especially from the grain-filling to soft-dough stage.

The moth is a nocturnal insect. The eggs are laid at night on the sorghum head, and hatch in 2 to 5 days. A female lays an average of 1100 eggs, with a maximum of 2062 (Wangboonkong 1975). During the first and second instar, several larvae may live in the same head; however, in the later instars only a few are found. They are cannibalistic when they are in close contact. The larval period lasts 17 to 25 days. Pupation takes place in the soil. The pupal period is 10 to 14 days and the adults live for about 10 to 20 days.

A number of natural enemies of the corn earworm have been recorded. *Trichogramma confusum* Viggiani and *Trichogrammatoidea bacirae* Nagaraja are important egg parasites. The tachinid flies, *Carcelia* sp nr *rutilla* Rond. and *Tachina sorbillans* Wied., and the ichneumonid wasp, *Eriborus argenteopilosus* Cameron, are larval parasites. More than ten species of predators were found preying on the larvae of the com earworm. It is observed that natural enemies are mainly responsible for keeping the corn earworm at low levels on sorghum heads. Earworms on sorghum are more prone to attack by natural enemies than they are inside the cotton bolls.

Control

To control the corn earworm on sorghum, the infested heads may be sprayed with pyrethroid compounds, e.g., cypermethrin 25% EC or fenvalerate 20% EC at the rate of 20 cc/20 liters of water. Caution should be observed in selecting chemicals to be sprayed on sorghum because of their phytotoxicity.

Green Stink Bug

The green stink bug, *Nezara viridula* Linnaeus, a potential pest of sorghum in Thailand, attacks several crops, such as rice, soybean, and castor bean. The bug also feeds on sorghum. It sucks sap from the grain from soft dough to ripening. The seeds become spotted due to the feeding of the bugs, impairing the grain quality. Heavy infestation may result in chaffy heads. The bugs are found more abundantly on compact-head than on open-head sorghums. Probably the compact head offers better shelter from attack by natural enemies.

The adults are greenish in color. The female is about 14 mm long and 8.5 mm wide. The male is smaller than the female, with a body length of 12.5 mm and width of 6.5 mm. The eggs are cylindrical in shape and are deposited in clusters. The newly deposited eggs are whitish and become orange when nearing eclosion. The incubation period is 4.3 days. The nymph molts five times and becomes an adult in about 21 days. Reared on sorghum, the male lives about 21 days, while the female lives about 18 days. About 50 eggs are laid by a female. Its life-span is longer when reared on soybean. On this crop the adults live about 1 to 3 months, and the female lays about 200 to 300 eggs.

Control

To control the green stink bug, the application of 0.05% dimethoate is recommended.

Sorghum Webworm

The sorghum webworm, *Stenachroia elongella* Hampson, infests the inflorescence of sorghum from the milk stage to maturity. Besides damaging the grains directly, the frass and webs produced by the caterpillar help in retaining dew or rainwater for longer periods, thus promoting the growth of molds and lowering the quality of the grain.

The sorghum webworm is 2.5 to 3 mm across and 20 to 25 mm in length, greenish in color, and the sides of the body are marked with a longitudinal dark brown stripe. The head is dark brown or black.

The sorghum webworm causes more damage on compact-head than on open-head varieties. Therefore, in order to avoid heavy damage from webworm infestation, open-head types should be planted.

Control

Since sorghum grain is used as animal feed or human food, low-toxicity insecticides such as carbaryl are recommended for use in controlling the sorghum webworm.

Insect Pests of Stored Sorghum Grain

Rice and Maize Weevils

Seven species of insects attacking sorghum grain have been recorded and are listed in Table 1. The principal species are the rice weevil, *Sitophilus oryzae* (Linnaeus) and the maize weevil, S. *zeamais* Motschulsky. The grain may be infested by weevils in the field and also in storage under poor sanitation conditions. In Thailand, severe damage occurs within a few months of storage.

Control

To protect the seeds for planting, treating of the grain with malathion at the rate of 30 ppm and pirimiphos-methyl at the rate of 5 to 10 ppm is recommended. Both chemicals are normally used to treat stored food grains also. It has also been found that carbofuran seed treatment at the rate of 1.0 to 1.5 g a.i./kg of seed, which is primarily aimed at controlling sorghum shoot fly, is also a good method to protect the grain from weevil infestation.

Conclusion

Reports on sorghum pests in southeast Asia are predominantly the results of the investigations conducted in Thailand, the principal sorghum-growing country in this region. Current information is still scanty on certain aspects, and further work is needed. With regard to the pest status, there is no record so far on the damage by soil insects such as white grubs and root aphids. The sorghum shoot fly is the predominant pest of sorghum in the seedling stage, as reported in Thailand, India, and the African continent. In controlling the sorghum shoot fly, carbofuran is at present the most effective chemical, to be applied in trenches or used as seed treatment. Other new compounds are also being tested. Adjusting the date of planting to avoid heavy infestation is recommended. The incorporation of genetic resistance to shoot fly attack will be an important means of suppressing outbreaks of the sorghum shoot fly. In applying insecticides to sorghum one must bear in mind that some can cause serious phytotoxicity; thus it is quite risky to apply any chemical without prior knowledge of its phytotoxic effect on plants.

Defoliators such as grasshoppers and army-worms are occasional pests. Thrips and aphids are common sucking insects of sorghum plants during the growing stage. Generally, they do not cause serious damage.

There are at least three important earhead pests, namely: the corn earworm, the green stink bug, and the webworm. All of them find favorable shelter in the compact-head varieties. The compact-head type also tends to retain moisture from rain or dew for a longer period, thus enhancing the growth of molds, resulting in poor grain quality. Consequently, breeders should breed for open panicles.

Rice and maize weevils are the main pests of sorghum in storage.

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Sorghum Insect Problems in Australia

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Abstract

The insect pests that attack grain sorghum in Australia are reviewed. For convenience, they are grouped according to the plant growth stages at which they attack: establishment, vegetative growth, flowering, and postflowering. Reference is made to the importance of stored-grain insect pests and plant damage as a result of insecticide application. A computer pest management system under development is outlined briefly.

A range of soil-inhabiting insects damage the planted seed and seedling sorghum plants during crop establishment. These are of greater importance than the average grower realizes, and with the rapid adoption of minimum tillage practices in A ustralian summer cropping areas, their importance is expected to increase.

The sorghum midge, Contarinia sorghicola *(Coquillett), is the most damaging pest species. Cultural and insecticidal management systems do not provide the levels of control required. Studies toward the development of resistant varieties are outlined and research suggests that plant resistance offers considerable promise toward minimizing sorghum midge damage.* Heliothis armigera *(Hubner) is second in importance to* C. sorghicola *as a pest of sorghum. The development of economic injury levels for the pest is discussed. Resistance to the synthetic pyrethroids developed in the species during the 1982-83 summer. As a consequence, a strategy for insecticide use in sorghum and other susceptible summer crops has been introduced. The system is outlined and the implications discussed.*

Resume

***Le probleme des Insectes nulsibles au sorgho en Australia**: La communication passe en revue les insectes nuisibles au sorgho grain cultive en Australie. Afin de faciliter l'etude, ces insectes sont groupes selon le stade de la plante qui subit leur attaque : etablissement, croissance vegetative, floraison et apres-floraison. L'importance des ravageurs des denrees est signalee ainsi que les degats causes a la plante par Temploi des insecticides. Un systeme de lutte informatise actuellement a l'etude est expose brievement.*

De nombreux insectes habitant dans le sol endommagent les semences et les plantules au cours de letablissement. Leur importance est parfois meconnue par l'agriculteur et empirera encore avec /'adoption rapide des systemes de culture reduisant au minimum le labour dans les cultures d'ete.

La cecidomyie, Contarinia sorghicola *(Coquillett), est l'espece la plus nuisible. Les insecticides et les pratiques culturales n'assurent pas une lutte adequate. Les recherches sur les varietes resistantes recapitulees dans la communication, revelent que la creation de ces varietes est prometteuse dans la reduction de l'incidence de la cecidomyie.* Heliothis armigera *(Hubner) se range deuxieme en importance apres C.* sorghicola. *L'etablissement des seuils de nuisibilite economique de ce ravageur est etudie. Cette espece a acquis une resistance aux pyrethroides de synthese en ete 1982-83. Par consequent, on a introduit une strategic pour l'emploi des insecticides chez le sorgho et d'autres cultures d'ete susceptibles. Ce systeme est presente ainsi que ses consequences.*

Introduction

Grain sorghum production is an expanding industry in Australia. It is based primarily in Queensland, with some acreage in adjacent northern New South Wales. A minimal amount of production occurs in the Northern Territory and the northeastern corner of Western Australia. In 1981, more than 500 000

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ha were planted to grain sorghum in Queensland, with the Australian total area being approximately 600 000 ha, with an average yield of about 2 t/ha (Lloyd 1981). Yields have improved steadily over the years, no doubt as a result of better varieties and management systems. In 1945, for example, yields averaged 1.35 and in the 1960s approximately 1.8 t/ha.

Further yield increases are practicable. Under good conditions, well-managed raingrown sorghum produces 8 to 9 t/ha. Under irrigation, average yields are 4.5 t/ha, with the better crops regularly producing 8 to 10 t/ha. In terms of expansion, it is estimated that in Queensland alone, almost 4 million ha are suitable for sorghum production. Given suitable marketing conditions, therefore, a bright future is forecast for Australian sorghum.

The industry really began in Australia following the introduction in 1932-33 of 30 dwarf sorghum varieties from Egypt, South Africa, and the USA. These formed the base for local varietal improvement. Today, hybrids are almost universally grown.

Of the insect pests that attack the crop, the sorghum midge, *Contarinia sorghicola* (Coquillett), is economically the most important. Within Queensland it is estimated that control costs, residual losses, and uncontrolled damage range between $A5 and 10 million (about U.S.$ 4.17 to 8.34 million) annually. Losses from other insect pests are very much less, *Heliothis armigera* (Hubner) causing the bulk of such loss.

In this paper the various insect pest speoies that attack sorghum are discussed on the basis of the stage of crop growth involved: establishment, vegetative growth, flowering, postflowering, and storage. Data on biology-ecology, pest importance, existing controls, and current research are presented. Additionally, comment is made on a computer-based pest management package which is being developed for extension and grower use.

Pests of Crop Establishment

A broad suite of insect species attack sorghum at this growth stage. Each occasionally can reduce plant stands. A particular difficulty with the majority of these species is that the timing and density levels of infestation cannot be accurately predicted. Furthermore, sorghum production is primarily based on the occurrence of sporadic storm rains to supply adequate moisture for planting. Where serious stand loss occurs, it is often impossible to replant because of depletion of near-surface moisture. Major upset in crop sequence and summer crop viability can follow. The unpredictability of insect attack and the intangibility of the losses that follow, make assessment of economic losses most difficult. The average farmer markedly underestimates the importance of insect pests during the plant establishment period.

False Wireworms

Larvae of four species—*Gonocephalum carpentariae* (Blackburn), G. *macleayi* (Blackburn), *Pterohelaeus alternatus* Pascoe, and *P. darlingensis* Carter—attack the germinating seed and initial growing shoots and roots. Poor plant emergence generally over a field, or more commonly, very patchy emergence of seedlings, is the result (Allsopp 1979). While true economic threshold levels for damaging numbers have not been developed, we feel that a density of one larva under 30 hand-sized soil clods, pieces, or debris prior to planting may lead to damage, and that insecticide seed treatment is warranted. Chlorpyrifos is recommended preplanting at 160 g of 250 g/kg product applied to each 100 kg of seed. Plant escape from wireworms is important, and processes such as the use of press-wheel planters which lead to rapid germination and early growth assist greatly. A research program involving these pests has been under way for some years to develop an understanding of the biology-ecology of the species, with a view to producing a model of the host-pest system (Allsopp 1984).

Cutworm

The cutworm *Agrotis infusa* (Boisduval) rarely causes widespread losses, but isolated heavy infestations do cause damage. Regular field inspections during the first week post-germination, with insecticide use, e.g., chlorpyrifos, diazinon, or trichlorphon, as required is recommended. Presently, there is no major research effort on the pest.

False Wireworm Beetles, Cockroaches, and Inland Field Cricket

False wireworm beetles, *P. alternatus* and G. *macleayi;* cockroaches, *Cosmozosteria* spp; and the inland field cricket, *Modicogryllus lepidus*

(Walker) presently cause problems in the Central Highlands area of Queensland (approximately 22.5 S latitude) and are encountered trivially elsewhere. Seedlings are eaten as they emerge from the soil. Losses are often quite widespread and severe.

Insecticide sprays do not provide control, but Murray and Spackmann (1983) developed an excellent control system based upon baiting. Indicator baiting is recommended to assess densities prior to planting and fieldwide baiting at or immediately after planting when one or more dead insects per mound per night are recorded in preplant checks. The baits are comprised of 100 g of 500 g/kg chlorpyrifos plus 125 ml of sunflower oil mixed into 2.5 kg of crushed wheat or sorghum and broadcast per hectare.

Laboratory investigations on food consumption indicate that the native cockroaches (two species) appear to be the most damaging of the complex. Studies toward further clarification of economic threshold levels are under way, and the biology of the cockroaches is being investigated.

Ants

Ants—*Pheidole* sp—occasionally cause losses by harvesting planted seed from the row. Uneven plant stands result. The problem is most common in areas newly brought into cultivation from pasture. Presumably, in the absence of an abundance of pasture grass seed, ants turn their attention to the new and alternative seed source. With cultivation at an intensive level for a few years, often on a double-cropping system (winter cereal followed by summer cropping), ant problems become negligible. Where problems are anticipated, lindane WP at 200 g a.i. per 100 kg seed is applied as a seed dressing to minimize losses. As above, processes to assist rapid germination aid in reducing damage. No research on ants is currently under way.

Black Field Earwig

This species—*Nala lividipes* (Dufour)—creates some problems in the heavier black alluvial soils, especially in maize. Root and shoot pruning of seedlings cause plant death, while lodging follows when root pruning occurs in later growth stage plants (Hargreaves 1970). No research on the species is currently under way. Limited data indicate that lindane at 1 g a.i./200 row m of planting row will give some control.

General

With the exception of ants and cutworms, soil insects appear to presently cause greater problems than in the past. The upsurge probably relates to a marked change in prevailing soil conservation practices. Formerly, crop residues were destroyed by burning immediately following harvest. Today, to protect soils from erosion and to improve physical structure, some form of stubble retention is employed by almost all growers. The direction in cropping is toward minimum tillage. The change has been to the obvious advantage of soil-dwelling insect species. It is probable that soil insect problems during plant establishment will become more important as the move to minimum tillage and no-tillage practices continues.

Pests of Vegetative Growth

Corn Aphid

The corn aphid, *Rhopalosiphum maidis* (Fitch), is universally associated with sorghum production in Australia. On occasion, enormous numbers are found within the plant whorl. Usually, densities decline rapidly after panicle emergence. A complex of predators (e.g. *Coccinella repanda* Thunberg and *Harmonia octomaculata* [Fab.]) is generally assumed to be responsible for this decline. The aphid is parasitized by *Aphelinus varipes* (Foerster), but parasitism rates are low and the species is not considered to contribute significantly to control.

In general, the corn aphid is not seen as warranting chemical treatment. During 1981-82 the usual density decline with panicle emergence did not occur in sorghum in Central Queensland. Prolonged drought conditions leading up to flowering were conducive to high aphid numbers. Widespread spraying, particularly for *H. armigera* control, was required, and consequent loss of predators may have been a factor. Excessive honeydew developed on the heads and stickiness problems were experienced at harvest. Header blockages occurred, and augering grain to storage was difficult (Spackmann and Murray 1982). It was noted that in areas where as little as 4 mm of rain fell in the week to 10 days prior to harvest, the honeydew problem was not experienced. Some growers solved the problem at harvest by spraying moisture into the grain auger at entry to storage.

Other aphids encountered in sorghum in reasonable numbers include *Hysteroneura setariae* (Thomas), *Melanaphis sacchari* (Zehntner), *Rhopalosiphum padi* (Linnaeus), and *Schizaphis hypersiphonata* Basu.

Heliothis armigera (Hubner)

Heliothis armigera oviposition may occur during vegetative growth with larvae feeding in the whorl. With leaf development, such feeding gives the plant a particularly ragged appearance. Damage during this stage, however, is not usually considered to be of importance. The species is treated in greater detail in a later section.

Armyworm

Abundance of *Pseudaletia separata* (Walker) and plant injury caused are generally very similar to those noted above for *Heliothis armigera.* However, in some seasons, early planting coincides with plague densities of *P. convecta* (Walker). Under these conditions the pest may move through a stand of seedling sorghum causing 100% loss of plants. Insecticides such as chlorpyrifos give control when necessary.

Present studies on the armyworm concern only biological control. In 1979-80 small consignments of the parasite *Apanteles ruficrus* (Haliday) were imported from New Zealand, the particular strain having been introduced to New Zealand previously from Pakistan and reported to have given excellent results (Cumber et al. 1977). Assessment of establishment and effectiveness in eastern Australia is complicated by the presence of an indigenous strain of the parasite. Independently, the Western Australian Department of Agriculture has introduced the species both from New Zealand and Pakistan. Reports indicate that establishment has been effected and that the species is reducing pest densities (D. Rimes, Department of Agriculture, Western Australia, personal communication, 1983). Further introductions into Queensland are planned.

Pests of the Flowering Stage

Sorghum Midge

The sorghum midge, *Contarinia sorghicola* (Coquillett) is undoubtedly the most troublesome species encountered by sorghum producers. It has existed in Australia over a long period. Tryon (1894) recorded *Dipiosis* sp from broom millet and his description leaves no doubt that the species involved was C. *sorghicola* as described and named by Coquillett (1898) from U.S. specimens. Harris (1964), following a study of herbarium sorghums, confirmed *C.sorghicola* as present in Australia in 1912 and incidentally from Africa as early as 1869. A study using similar methods would probably demonstrate similar early records from additional areas.

Despite its worldwide distribution, the sorghum midge has not been recorded from the northeast of Western Australia (G. Smith, CSIRO, Kununurra, Western Australia, personal communication, 1984), despite the production of sorghum in the area for several decades. Opportunities for establishment have existed as early seed was imported without treatment from infested areas of Queensland. *C. sorghicola* became established in the adjacent Northern Territory early in the 1970s. It caused initial commercial losses but has not survived as an economic pest (A. Allwood, Department of Primary Production, Darwin, Northern Territory, personal communication, 1984). Possibly, the off season, which is long, very hot, and dry, may result in insufficient diapause-larval survival to allow development of noticeable densities.

In Queensland, given a continuity of flowering hosts, the midge can breed from September to May-June, with a varying percentage from every generation entering diapause. The numbers recorded in diapause appear to rise as the season advances. In the study by Passlow (1965) 1 diapausing larva per 100 aborted spikelets was recorded in December and more than 200 per 100 in May-June.

To date, Australian researchers have not studied the triggering mechanisms which induce diapause in midge. The ability of the species to survive in diapause has been investigated. As shown elsewhere, it has a remarkable ability to survive over a very wide range of conditions in this stage (Passlow 1965). There can be little doubt that diapause, in eastern Australia, and the ready availability of host material during the breeding season constitute the keys to the success of the species.

A clear relationship between rainfall, warm conditions, and high humidity as the trigger mechanism for initiation from diapause has been demonstrated, provided time for physiological development within diapause has elapsed. Planting to avoid flowering immediately after the major wet season as a method of midge escape has been employed over the years with some success. However, with expansion of cropping into areas of irregular early midsummer rainstorms to provide planting conditions, escape is not a reliable pest mitigation method.

Passlow (1958) recorded *Eupelmus australiensis* Girault as the overwhelmingly dominant parasite in Central Queensland. Surveys carried out in southern Queensland and northern New South Wales during 1975, 1981, and 1982 showed that *Aprostocetus diplosidis* Crawford is the major parasite. Whether a species change is involved or not requires investigation. The data may simply reflect differences in environments.

Passlow (1965) claimed five grass species *(Bothriochloa intermedia, Dichanthium sericeum, Eriochloa procera, Eriochloa pseudo-acrotricha, and Ennoapogon flavescens)* as hosts of C. *sorghicola;* however taxonomic studies by Harris (1979) following extensive surveys by Passlow and Allwood in North Australia during 1972-74 demonstrated that they were not.

Insecticide use gives a degree of control of the species. Prior to the phasing out of DDT, it was the chemical of choice, giving better results than the phosphatic alternatives, primarily because of greater persistence. The pyrethroids introduced for midge control in 1982-83 appear to have reestablished the levels of control obtained previously from DDT. However, the strategy for *Heliothis* pyrethroid resistance management developed in 1983-84 preclude to a large extent the use of these products for midge control for a large part of the season.

In recent years, we have researched the economic injury levels for midge. The approach has been to compare grain yields of panicles exposed to natural midge infestations with yields of equivalent panicles protected during flowering by covering with fine gauze bags. Visiting females are counted on exposed panicles daily at the time of peak numbers.

Data so far indicate that the mean yield loss per panicle per visiting female per day is 0.92 g. This figure has been used to construct the following formula for determining a spray decision. Treatment is appropriate when the cost of spraying is less than

$$\frac{NM \times 0.92 \times N \times V \times 4}{10^6 \times 2}$$

Where NM = Number of midge per flowering head
0.92 = Weight in g lost to one midge
N - Number of flowering heads/ha
V = $ value of the crop/tonne
4 = Residual life of insecticide in days (variable according to insecticide)
10^6 = g/tonne
2 = benefit : cost ratio.

Based on our assessment that cultural and management systems were inadequate for real industry protection from the pest and on the relatively poor cost-benefit response to insecticides, we have moved toward the possibility of the use of host-plant resistance. Development was somewhat tentative initially, mainly as a result of the view that a nonpreference resistance would be of minimal value in plantings of single varieties over areas measured in hundreds of hectares. Page (1979), however, demonstrated by caging known numbers of female midges on panicles that an antibiotic factor was involved. Greater interest in a resistance development program followed. Imported lines such as AF 28, SC 108, SC 165, SC 173, and TAM 2566 have constituted the base from which material has been made available by government research officers for incorporation into private seed company breeding programs for resistant hybrids. In addition, seed companies through their associated American bodies have imported material with resistance factors for direct incorporation into hybrids.

Overall, the result is that we are on the threshold of midge-resistant sorghum production.

Concurrently with work on economic injury levels for midge on hybrids, we have gone through the procedures, as above, to determine the relationship between numbers of females visiting panicles and resultant yield loss in genotypes with various levels of resistance and under a variety of conditions. For the most resistant of the hybrids tested to date (AT x 2754 x RT x *2767),* the mean yield loss per panicle per visiting female per day is 0.19 g (of. 0.92 g for susceptible hybrids).

The potential for resistance is therefore very significant.

Our data are as yet too meager to make recommendations concerning the midge density threshold for spray treatment on commercial midge-resistant hybrids. Presently, seed of these hybrids is not available in any quantity. We expect that by the time such hybrids are readily available, we will have adequate data upon which to make firm recommendations.

Pests of the Postflowering Stage

H. armigera

Eggs may be deposited onto the floral parts from head emergence until the end of flowering, but for practical purposes, oviposition is confined to the preflowering period. One generation only is involved. Larvae partially or completely consume individual grains, with all real damage occurring immediately postflowering and over the following 4 weeks. Webbing is not associated with damage.

We recommend crop inspection within 4 days after 80% of the crop has completed flowering. Most accurate density assessments are obtained by cutting samples of heads and spinning out the larvae into a bucket by twisting the stem between the palms.

A range of insecticides, including the pyrethroids, methomyl and carbaryl, are recommended for control of larvae. Studies by Teakle et al. (1983) demonstrate the potential for *Heliothis* nuclear polyhedrosis virus (Elcar®) for control. More recent work (Teakle and Jensen, unpublished data) indicates that dose response to Elcar does not, for practical purposes, vary with larval age for *Heliothis* in sorghum. The greater quantum intake of virus by third and fourth instars results in mortalities similar to those for first and second instars. There is a potential, therefore, for development of the virus as a control tool.

Twine and Kay (1982) studied the economic injury level for *H. armigera* in sorghum and arrived at a formula for spray intervention, based on their conclusion that the grain consumption per larva amounts to 1.56 g

$$D = \frac{C \times BC \times 10^6}{1.56 \times p \times N}$$

where D = Density of infestation per head
C = Cost of control ($/ha)
BC = Benefit:cost ratio
P = Value of sorghum ($/tonne)
N = Number of heads/ha

Heliothis was not considered a major pest of sorghum until the last decade. Factors which may be related to this change in pest status include lengthening of the growing season, introduction of additional susceptible crops into the same regions (sunflower, soybean, and cotton), and possibly increase in the areas sown to sorghum itself. Changes in crop residue disposal methods could also be involved.

Intensive spraying of summer crops for insect control has resulted in a pyrethroid resistance problem with *H. armigera* in eastern Australia. This was first noted late in the 1982-83 summer season. Severe resistance, with approximately 80% of the larvae surviving a discrimination dosage of the pyrethroids employed (and some which had never been used), occurred in Central Queensland. Incipient resistance was recorded in other areas later in the same season and again through the early stages of the 1983-84 season.

As a consequence, government research workers, primary producers over the whole area, and the marketers of insecticides agreed to a strategy for 1983-84 insecticide use, aimed at prolonging the useful life of pyrethroids for *H. armigera* control and at lessening the pressure toward resistance development to other groups of chemicals. In essence, the strategy involved nil use of pyrethroids in the high-resistance area in Central Queensland, on all crops susceptible to *H. armigera,* and restriction of pyrethroid use to not more than three applications on any one crop elsewhere, and these to be applied to only one generation (or cohort) period of approximately 40 days (10 January to 20 February in most districts). Further, in crops where a continuum of insecticide use is necessary, i.e., cotton, the remaining groups of insecticides are not to be applied to any two consecutive generation/cohort periods.

The strategy at the time of writing (late January) has been adhered to almost universally and gives the appearance of success. Resistance monitoring indicates a fall in level in the Central Queensland area where pyrethroids are banned. Tests at 30% survival are being recorded. It will be interesting to see if levels rise following use of pyrethroids in other areas. Assuming success, the procedure will be adapted and continued in future years in an attempt to conserve the insecticide resources for *H. armigera* control.

Major *Heliothis* studies in Australia to date have been on a host-pest basis. This is changing. It is apparent that advances in management of this wide-ranging pest of summer crops will come from area understanding of its biology-ecology. Serious studies, however, are in their infancy.

Sorghum Head Caterpillar

Cryptoblabes adoceta Turner eggs are deposited on the head from its emergence from the leaf sheath to almost the harvesting stage. Hatching occurs in about 3 days, followed by a larval period of approximately 2 weeks and a pupal stage of 1 week. More than one generation is therefore possible during the development of a crop. Webbing is associated with larval erosion of grain surfaces and consumption of portions of individual grains. Damage intensifies from the soft-dough stage to nearly harvest.

The species is widely recorded through the sorghum-growing areas but significant numbers are generally confined to the more humid coastal and tropical areas.

Insecticidal control is practicable, provided spray penetration of the head can be achieved. Usually endosulfan or trichlorphon is employed. In areas where problems are likely to develop, and particularly in late plantings, open-headed varieties are recommended to allow maximum penetration of pesticide, when required.

Limited research to date indicates that the food intake of 30 head caterpillar larvae equates approximately to that of one *Heliothis* larva. The figure is promoted as an economic injury level and early harvesting is recommended to escape damage, particularly where the grower has access to grain-drying facilities.

Research relative to sorghum head caterpillar is confined to further clarification of an economic injury level.

Yellow Peach Moth

Dichocrocis punctiferalis (Guenee) is a pest of minor significance in the wetter and more humid areas of sorghum production; i.e., tropical and coastal districts. Crop damage is very similar to that caused by the sorghum head caterpillar. Additionally, injury from larvae boring into the stems may occur. Webbing by this species is usually more profuse than by head caterpillars.

Insecticides as recommended elsewhere for *Heliothis* and head caterpillar will give some control and densities of more than five larvae per head are considered to warrant insecticide use.

Locusts

The migratory locust—*Locusta migratoria* (Linnaeus); Australian piague locust, *Chortoicetes terminifera* (Walker); the spur-throated locust, *Austracris guttulosa* (Walker); and the yellow-winged locust, *Gastrimargus musicus* (Fabricius) usually are not pests of consideration but in plague years damage from these species may be severe. Major research is designed to clarify migration aspects, to improve efficiency in pesticide application, and to refine target definition procedures.

Storage Pests

A wide range of storage pests is associated with sorghum grain. A high percentage of the crop is produced for export, and a requirement in a number of markets is for nil insects in such grain. Minimization of infestations is, therefore, of critical importance. Presently, protectants such as fenitrothion and carbaryl plus fumigation with phosphine, when required, constitute the major control tools.

Phototoxicity

The phosphate insecticides; e.g., fenitrothion, monocrotophos, and trichlorfon, have caused plant damage to sorghums in Australia. Yield reductions have resulted from insecticide burn. Prior to release of new sorghum cultivars, each is treated with a range of insecticides, to ensure that the damage spectrum for particular varieties is available for grower information.

Pest Management

Recently we have developed a computer-based pest management package for extension officers' and growers' use. The package is based on our knowledge of the species, their damage, intuitive to researched economic injury levels, scouting procedures, plant stands, crop values, recommended insecticides, their costs, and benefit:cost returns. With additional testing, we hope to make the package available to improve and rationalize existing control procedures.

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Insect Problems on Sorghum In the USA

H.N. Pitre*

Abstract

Some important sorghum insect pests that occur throughout the southwestern and Great Plains (western area) and southeastern areas of the continental USA are discussed. Two key pests, the greenbug and sorghum midge, are considered with respect to sorghum pest management programs. Occasional pests, i.e., spider mites, sorghum webworm, lesser cornstalk borer, fall armyworm, corn earworm, and chinch bug, are ranked in order of importance and estimated annual crop losses in the USA. The crop damage caused by the respective seedling, foliage, stem, and panicle pests is related to efficiency of various cultural, chemical, biological, and plant resistance pest management practices. Problems in integrated management programs for these pests are discussed: development of pest biotypes resistant to insecticides, apathy in the use of effective cultural practices, ineffective sampling strategies and inadequate plant damage threshold levels, the need for improved chemical application technology, improper use of chemicals resulting in ecosystem disruptions, and inadequate knowledge of noncrop hosts and of pest x beneficial agent interactions that can be useful in integrated pest management programs.

Resume

***Le probleme des ravageurs chez le sorgho aux Etats-Unis**: Certains ravageurs importants du sorgho repandus a travers le sud-ouest, les Grandes Plaines (ouest) et le sud-est des Etats-Unis sont decrits. Deux insectes importants, le puceron vert et la cecidomyie, sont etudies dans le cadre des programmes de lutte. Les ravageurs occasionnels, a savoir, les acariens (tetranychidees), le ver a* so/© *du sorgho, le petit borer de la tige de mai's, la chenille legionnaire* Spodoptera frugiperda, *le ver americain de la capsule du cotonnier et* Blissus leucopterus, *sont ranges par ordre d'importance et en fonction des pertes de recolte par an aux Etats-Unis. Les degats causes par les differents insectes de la plantule, des feuilles, de la tige et des panicules sont lies a l'efficacite des diverses methodes de lutte : culturales, chimiques, biologiques ainsi que l'exploitation des varietes resistantes. Les problemes de la lutte integree sont examines, dont : l'evolution des biotypes entomologiques resistants aux insecticides, le manque d'interet pour les pratiques culturales efficaces, les strategies inefficaces d'echantillonnage, l'etablissement inexact des seuils de nuisibi/ite, la necessite de techniques ameliorees pour {'application des insecticides, l'emploi imprudent des insecticides qui enframe un desequilibre ecologique, les connaissances peu suffisantes des plantes-hotes non cultivees et du rapport ravageur x agent benefique, indispensable a tout programme de lutte integree.*

Insect Problems on Sorghum in the USA

Grain sorghum, *Sorghum bicolor* (L) Moench, is often used in rotation with other crops, e.g., cotton and soybean, and is an important component of weed control strategies. Many insect pest and beneficial species share relationships with different crops and surrounding vegetation in the production ecosystem. Therefore, management

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decisions for pests on one crop may influence pest infestations on another crop in the ecological community.

Relatively little attention has been given to the detailed study of many pest species that attack sorghum. Certainly, since Young (1970) reported that only about 10% of the sorghum pests have been studied in some detail, much more information is available in the literature for use in the pest control decision-making process. Geographic distribution, pest status, crop damage, and economic threshold levels have been discussed by Young and Teetes (1977). In this paper certain pest problems encountered in grain sorghum production in the USA will be highlighted, especially some specific crop-pest relationships that need to be investigated in more detail to improve integrated pest management (IPM) programs.

Most pests of sorghum are occasional pests (Young and Teetes 1977), occurring only at certain times in localized areas. Two key pest species have been identified: the greenbug, *Schizaphis graminum* (Rondani), and the sorghum midge, *Contarinia sorghicola* (Coquillett). Secondary pest problems may develop as the result of some change in cultural practices or chemical application for management of key pest species. Occasional pests, which may be held in check by natural control agents, may be encountered in a secondary pest role. For example, insecticidal control of sorghum midge often results in the buildup of lepidopterous pests in sorghum panicles.

More attention should be given to the effective use of insecticides on sorghum for the control of specific pests at different times during the growing season. Naturally occurring beneficial species may suppress pest densities, but the disturbance or removal of these natural enemies from the ecosystem releases the pests to increase to economic densities. Therefore, insecticides should be used with care.

The key and occasional pests selected for discussion in this paper were identified as the most important species causing damage to grain sorghum annually in the continental USA (personal communication with grain sorghum research and extension specialists in state, federal, and private organizations in sorghum production areas in the USA). These pest species attack the crop while it is in the field. Stored product pests are not included in this paper but are addressed by another paper in these Proceedings.

Geographical Distribution of Insect Pest Problems

Many of the sorghum pest species that attack sorghum occur throughout the United States of America; however, some are identified more closely with specific geographical areas than others (Young and Teetes 1977). In the present paper, the most important insect pest problems have been identified for two regions, the arid southwest and Great Plains area and the more humid southeastern region, roughly divided by the Mississippi River for simple areal identification.

In each area, a key pest has been identified to be the most important problem (Table 1). In the western region, the greenbug is the most destructive pest species. Occasional pests include, in descending rank of relative importance (based on correspondence survey), mites, sorghum midge, chinch bugs, and corn earworm. The sorghum midge is the key pest in many areas in the eastern USA, followed in importance by the sorghum webworm, lesser cornstalk borer, fall armyworm, and corn earworm.

Annual loss of grain sorghum in the USA attributed to specific pests was reported by Wiseman and Morrison (1981). These loss estimates (Table 2) correspond closely with the ranked order of importance of the key and occasional insect pests of grain sorghum in the two identified regions.

Insect Pests of Grain Sorghum

Arthropod pest species attack grain sorghum from planted seed through maturity of the grain on the panicle. Soil inhabitants, i.e., wireworms, *Aeolus*

Table 1 . Key and occasional pests of sorghum in recent years in the USA, ranked by importance.

	U.S. region	
Pest rank	Western	Eastern
1	Greenbug	Sorghum midge
2	Mites	Sorghum webworm
3	Sorghum midge	Lesser cornstalk borer
4	Chinch bug	Fall armyworm
5	Corn earworm	Corn earworm

Source: Correspondence survey by Pitre

Table 2 . Estimated annual loss of grain sorghum to selected pests in the USA.

Pest	LOSS (%)
Sorghum midge	4.0
Greenbug	2.5
Fall armyworm and corn earworm	1.5
Sorghum webworm	0.5
Mites	0.5

Source : USDA Agricultural Research Service (1976), cited in Wiseman and Morrison 1981).

spp, damage the planted seed, and white grubs, *Phyllophaga* spp, damage roots of sorghum in the seedling stage (Daniels and Chedester 1976). These and other soil-inhabiting pest species often are established in the field before sorghum seed is planted. These potential pests feed on noncrop plants *or* plant material prior to feeding on sorghum, and infestations can be reduced in density by control of noncrop vegetation in the field. Optimum seedbed preparation to allow rapid seed germination and seedling growth in the absence of noncrop vegetation reduces damage by soil pest species. If seed is planted immediately after seedbed preparation in soil infested with pests that are established on the noncrop vegetation, the pests are capable of reducing or eliminating plant stands unless insecticide controls are applied. A delay in planting of several days to a week or so permits the noncrop vegetation to be destroyed following seedbed preparation, and without suitable plant material for food, the soil pests cannot survive at damaging levels.

The major pest species of sorghum in the USA generally attack and damage plant parts of the crop above or at ground level. These may be classified as seedling, foliage, stem, and/or head or panicle pests. The most important of these pests will be discussed in some detail.

Greenbug

The greenbug is the most damaging aphid pest of sorghum in the USA, although the corn leaf aphid, *Rhopalosiphum maidis* (Fitch) and the yellow sugarcane aphid, *Sipha flava* (Forbes), and others are occasional pests of some importance in certain areas. In general, the corn leaf aphid does not require insecticides for control, whereas the yellow sugarcane aphid can cause economic crop loss if not controlled (Chada et al. 1965).

The greenbug was regarded as a pest of only small grains, especially wheat, until it was reported attacking sorghum in Texas (Randolph and Garner 1961; Daniels and Jackson 1968). Now, the greenbug is a key pest on sorghum in most areas of the USA where the crop is grown, especially in the Great Plains (Young and Teetes 1977). In the northern Great Plains greenbug is most damaging to seedling sorghum, whereas in its southern range it is most damaging at boot or flowering stages (A. B. Maunder, personal communication).

Highly toxic insecticides used for control of greenbug resulted in ecological disruptions, such that the important regulating natural control agents, particularly parasitoids, were decimated. To complicate matters, this pest underwent several biotype changes during the 15 years after its appearance on sorghum. An insecticide-resistant greenbug biotype developed in some areas, which presented pest management problems.

Wood (1961) reported the development of biotype B, which overcame the resistance in wheat to biotype A. Subsequent biotypes have been reported. Biotype C was identified in 1968 when greenbugs attacked grain sorghum in the Great Plains (Harvey and Hackerott 1968; Wood et al. 1969). Biotype D was identified based on its resistance to organophosphorous insecticides (Teetes et al. 1975). Biotype E greenbug was identified based on its ability to damage biotype C resistant wheat and sorghum (Porter et al. 1982). Both biotypes C and E exist in some areas.

Sorghums with low levels of nonpreference and antibiosis, but mainly tolerance to greenbug, have been identified (Hackerott and Harvey 1971; Harvey and Hackerott 1969a, 1969b). Densities of greenbug are lower on resistant sorghum due to nonpreference and antibiosis and the economic injury level is higher due to tolerance resistance mechanisms. Starks et al. (1983) reported usable levels of resistance in some commercial grain sorghum cultivars to biotype E. Most commercial sorghum hybrids are resistant to biotype C but biotype E resistant commercial sorghum hybrids are becoming available. However, very high densities of greenbug on resistant hybrids will still damage these sorghums sufficiently to lower grain yield (L.J. DePew, personal communication).

Sorghum hybrids with greenbug resistance should allow the plants to develop while natural enemies increase (Teetes 1976). Although greenbugs are difficult to kill with insecticides in many areas, the use of highly toxic insecticides is not recommended. Insecticides should be used in limited amounts to conserve beneficial insect species and delay development of insecticide resistance in the greenbug. Host-plant resistance and biological control are compatible in greenbug IPM (Young and Teetes 1977). However, new sources of resistance to greenbug are needed because of the biological potential of this pest for developing other virulent biotypes (Starks and Weibel 1981).

Sorghum Midge

The sorghum midge was reported as the most damaging of all the sorghum insect pests in the USA (Wiseman and Morrison 1981), with the most damage occurring in the southern half of the country. Cultural methods, particularly early, uniform planting, are recommended for escaping sorghum midge damage. Insecticides may be needed on late-planted sorghum to control midge infestations that develop to economically damaging levels during the flowering period. Sorghum midge resistant germplasm (Wiseman et al. 1973; Johnson et al. 1973; Johnson 1975) has been released and hybrids have been developed and can be integrated into effective IPM programs for crop protection from midge.

To effectively manage the sorghum midge, several IPM practices can be combined. However, these control practices are not free of problems. Although early planting is recommended to escape midge damage, changes in crop production practices, e.g., double-cropping (ratooned sorghum or sorghum following wheat), provide a situation in which the midge can damage late-planted sorghum. Midge-resistant hybrids will allow producers to adjust dates to avoid damaging infestations of other sorghum pests, e.g., greenbug (Wiseman and Morrison 1981) and use sorghum in novel farming systems.

Insecticidal control practices are generally based on stages of sorghum flowering in a field and presence of sorghum midge adults on panicles. A sorghum panicle flowers over a 6- to 9-day period (90% on days 2-5 of flowering)(Thomas 1981). Insecticides can be used most effectively during this critical period. There seems to be a certain amount of agreement among researchers regarding acceptable economic threshold levels of sorghum midge that warrant the use of an insecticide to prevent crop damage (Table 3) (Wiseman and Morrison 1981). However, the relationship between sorghum midge numbers and flowering stage in relation to economic threshold levels for application of insecticide is not clearly defined. There is need for more definitive studies to establish economic threshold levels for midge-resistant sorghum hybrids, as well as the relationship of flowering stage to the economic threshold level. Athough preventive insecticide treatments may be recommended in some areas, based on a history of sorghum midge problems, this pest management approach is not always advisable. Problems encountered in the past as the result of excessive or unnecessary use of insecticides should provide sufficient warning against the use of such practices.

Sorghum Webworm

The sorghum webworm, *Celama sorghiella* (Riley), is a pest of sorghum in the more humid areas in the southern USA (Young 1970). The factors responsible for the webworm's increase to pest status den-

Table 3 . Economic threshold levels for sorghum midge on grain sorghum in the USA.

	Control is necessary when		
State	No. midge/head is	and	Bloom stage is
Alabama	> 2		10%
Georgia	1		All bloom stages
Kansas	1-2		Not reported
Missouri	> 1		Not reported
Texas	1		25-30%

Sources: Bottrell (1971); Young and Teetes (1977), (Cited in wiseman and Morrison 1981).

sity in certain areas have not been adequately studied. Larvae infest panicles soon after flowering begins; thus the damage to the grain can be extensive. The economic threshold level for sorghum webworm reported by Young and Teetes (1977) is five larvae per head. Little additional threshold Information is available for consideration in making pest control decisions. The number of webworms per panicle causing direct yield loss needs to be identified when considering the nature of the plant to compensate for grain damage, thus influencing the economic threshold level.

Sorghum webworms often develop economic infestations in sorghum fields that flower late in the season. With the recent development of midge-resistant hybrids (Johnson et al. 1973; Wiseman et al. 1973), sorghum can be planted to avoid midge damage, but this makes the crop vulnerable to sorghum webworm attack. Early planting to avoid late-season infestations and destruction of crop residue to reduce numbers of overwintering insects are recommended cultural practices to reduce crop loss from sorghum webworm. Open-headed sorghum hybrids should be planted because they are damaged less than hybrids with compact panicles (Hobbs et al. 1979).

When economic infestations develop, insecticides can be used effectively if proper application techniques are used. These techniques Include high volume of insecticide spray solutions applied under high pressure and directly over sorghum panicles. Inadequate control is usually associated with poor insecticide coverage. Unfortunately, biological agents, e.g., parasitoids (Young 1970), do not prevent damaging sorghum webworm infestations. There is need for more information on the biology of sorghum webworm on sorghum and related crop damage in order to define adequately the role of this pest in IPM programs.

Spider Mites

Spider mites, mainly *Oligonychus pratensis* (Banks), the Banks grass mite, and the two-spotted spider mite *Tetranychus* spp, are important pests of sorghum (Owens et al. 1976; Daniels 1981) and are closely associated with maturity of the sorghum plant. Mites increase to high levels after sorghum heads, and pest density is positively correlated to hot, dry climatic conditions (Young and Teetes 1977). Mites infest the leaves and sometimes the panicle and produce webbing that covers some plant parts. Plants stressed by drought are damaged more than plants that are not.

Mites cause premature death of leaves and chemical control is sometimes required. Miticides are the only control for damaging infestations of mites (Ehler 1974), but a problem associated with the continued use of chemicals is the potential development of mites resistant to them. The Banks grass mite is now resistant to most registered miticides in Texas (Ward and Tan 1977). Replacement chemicals are needed.

No economic threshold levels are available for mites on sorghum. Research on treatment thresholds, cultural and biological controls, and plant resistance needs attention to improve sorghum IPM programs.

Lesser Cornstalk Borer

Stalk borers, such as the lesser cornstalk borer, *Elasmopalpus lignosellus* (Zeller), sugarcane borer, *Diatraea saccharalis* (Fabricius), and southwestern corn borer, *Diatraea grandiosella* (Dyar) damage seedlings as well as the more mature sorghum plants. These pests tunnel the stalks, often causing stunted, weak plants to lodge, or deadhearts may occur in early whorl-stage plants. The lesser cornstalk borer is recognized as one of the five most damaging pests on sorghum in the southeastern USA (Table 1).

Effective control of the lesser cornstalk borer is usually reported to be difficult to achieve. Most often damaging infestations occur or are detected after plants emerge. However, there are certain factors generally associated with the development of damaging infestations of the lesser cornstalk borer. Sorghum grown in light, sandy soils is more susceptible to attack than that grown on heavy soils, especially during dry periods. Insecticides may be applied as preventive treatments to the soil at planting where sorghum is grown under these conditions and the crop field has a history of being infested with the pest. This insecticide planting treatment may be economical in some years, but may not be in others when the lesser cornstalk borer does not develop to damaging levels.

Economic threshold levels are not well defined and effective sampling strategies are not available to determine insecticide treatment needs for this pest. Early detection of the problem is important if insecticides are to be used effectively to prevent excessive crop damage. Additional advances in insecticide application technology are needed. Presently, insecticide granules or sprays can be applied to the soil surface (15-17.5 cm band) at planting, or post-directed sprays when 5 to 10% of the seedlings are damaged (Gardner et al. 1981).

Several cultural management practices are recommended to reduce damage by lesser cornstalk borer. They include reduced crop residue prior to planting, early planting dates, and rotation to nonhost crops. Crop residue allowed to remain in the field provides overwintering sites for the pest. Also, the trend toward reduced tillage methods provides a more suitable habitat for lesser cornstalk borer larvae, which feed on decaying plant material but will move to the crop when the residues dry. More information is needed on the relationship of crop and nonhost vegetation to establishment and buildup by lesser cornstalk borer in various areas experiencing different cultural practices.

Fall Armyworm and Corn Earworm

Both the fall armyworm, *Spodoptera frugiperda* (J.E. Smith), and the corn earworm *Heliothis zea* (Boddie), feed on leaf tissue in the whorl, but only rarely cause economic loss in sorghum by this feeding activity. Larvae feeding on grain in the panicle may require chemical control.

Early planting dates are recommended to escape high infestations of the fall armyworm (FAW) as well as the corn earworm (CEW) (Pitre et al. 1975; Teetes 1976). Also, hybrids with open panicles are recommended (Teetes 1976) because they are less suitable for these lepidopterous larvae. Predators and parasites appear to be more effective in open-headed sorghums than in those with tight or compact panicles. The use of hybrids resistant to sorghum midge or greenbug may lessen the restrictions on planting dates and require less insecticide use. This also allows beneficial agents (predators and parasites) to increase to levels that can be effective in IPM programs in sorghum.

Threshold levels established for decisions to control FAW and CEW larvae in various areas in the USA do not differ substantially from the levels of one per whorl and two per head (in the absence of natural enemies) reported by Starks and Burton (1979). Henderson et al. (1966) reported that two FAW larvae per whorl of six-leaf stage to boot-stage sorghum caused a 10% yield reduction. Young and Teetes (1977) and Teetes and Wiseman (1979) reported the threshold level to be two larvae per head. These levels need clarification, particularly regarding the different stages of FAW larvae in relation to yield loss at various stages of grain development.

Effectiveness of insecticide treatments could be improved by some of the same factors discussed in reference to sorghum webworm. Unfortunately, chemical insecticide controls on large acreages of whorl-stage sorghum are frequently attempted by aerial application, with less than adequate control obtained, due to inadequate coverage. Chemical applications are usually not made until extensive damage to the foliage is observed, by which time the larvae have developed to late instars and are feeding deep in the whorl. In this location they are protected from the insecticide by a cover of a mixture of plant debris and excrement. Control can be achieved with ground equipment using high volumes of insecticide spray (30-50 gal/acre, depending on the size of the whorl-stage plants). However, in some areas, resistance and/or tolerance to insecticides recommended for FAW control has been reported (Bass 1978; Young 1979). Fall armyworms of western origin appear to be more susceptible than those in the eastern USA. The development of FAW resistance to insecticides must be monitored each year for continued effective use of insecticides in control programs.

Chinch Bug

The chinch bug, *Blissus leucopterus* (Say), is a sporadic pest on grain sorghum in some areas of the USA. This pest moves into sorghum fields from surrounding vegetation, causes wilting of the plants by its feeding, and is most damaging during hot dry periods. Young seedling grain sorghum is most susceptible to economic loss. Effects of chinch bug infestations on yield loss in grain sorghum have been reported by Wilde and Morgan (1978).

As emphasized in previous discussions in this paper on key or occasional pests on sorghum, there is also the need for more definitive investigations of the impact of chinch bug infestations on plant development and yield. Once economic threshold levels have been defined for plants of various growth stages, chemicals can be used more economically for protection of the crop against chinch bug damage. Although in-furrow systemic insecticides may be used to protect seedling sorghum, chinch bug control with insecticide sprays is difficult even when using high volumes of directed spray applied with high pressure using ground equipment. Obviously, there is need to improve insecticide application technology for chinch bug control on grain sorghum.

Pest Control

The available methods of control or suppression of the various important insect pests of sorghum in the USA illustrate the potential for development of effective IPM programs. Cultural and chemical controls dominate the practices employed (Wiseman and Morrison 1981), although attempts are made to integrate biological methods (especially conservation of beneficial agents) into pest control programs. When considering the two most used control practices on specific sorghum pests (Table 4), cultural practices and conventional insecticides rank only somewhat higher than plant resistance and predators and parasites.

The dependence, to a great extent, on insecticides in sorghum insect pest management has resulted in pest control cost to producers, as well as problems similar to those reported after the use of highly toxic chemicals on other crops. These problems include environmental contamination, disruptions in the ecosystem, development of secondary pest outbreaks, and development of pest resistance. Significant progress has been made in the development of sorghums with resistance to certain pests (Harvey 1977). However, more information is needed on pest biology in relation to sampling efficiency and economic threshold levels. Resistant plant varieties and cultural and biological control practices need further development for effective use in integrated sorghum pest management programs.

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Table 4. Control methods (top two) ranked by importance for designated sorghum pests in the USA.

	Control method and rank	
Pest	No.1	No.2
Sorghum midge	Cultural practices	Conventional insecticides
Greenbug	Resistant varieties	Predators and parasites
Fall armyworm and corn earworm	Cultural practices	Predators and parasites
Sorghum webworm	Cultural practices	Conventional insecticides
Mites	Conventional insecticides	Predators and parasites

Source: Wiseman and Morrison (1981).

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Insect Problems on Sorghum in Mexico

Gabriel Diaz Castro*

Abstract

The area planted to sorghum in Mexico has increased over the last 25 years from 116 000 ha in 1980 to 1.5 million ha in 1984. Sorghum now ranks third in production in Mexico, after corn and beans. Entomological problems of sorghum in Mexico have existed since the crop was introduced into the country; however, the importance of insect pests on sorghum was first realized when the sorghum midge Contarinia sorghicola (Coquillett) became a serious problem in 1969, the armyworm Pseudaletia unipuncta (Howard) in 1966, and the greenbug Schizaphis graminum (Rond.) in 1977. Apart from these three major pests, a bug Oebalus mexicana (Fabricius) and the sorghum webworm Celama sorghiella (Riley) can cause considerable damage in certain years and parts of the country. The incidence of these insects, their economic importance, ecology, and control are discussed.

Resume

***Lea problems des Insectes nulslbles au sorgho au Mexlque**: Au Mexique, la superficie cultivee en sorgho a augmente au cours des 25 dernieres annees de 116000 hectares en 1980 a 1,5 millions d'hectares en 1984 de sorte que le sorgho arrive actuellement en troisieme position apres le mais et les haricots parmi les productions agricoles. Le probleme des insectes a existe depuis l'introduction de cette espece dans le pays; cependant son importance n'a ete reconnue qu'avec l'aggravation de l'incidence de la cecidomyie,* Contarinia sorghicola *(Coquillett) en 1969, de la chenille legionnaire* Pseudaletia unipuncta *(Howard) en 1966 et du puceron vert* Schizaphis graminum *(Rond.) en 1977. A part ces trois principaux insectes, d'autres ravageurs occasionnels cause des digats considerables dans certaines parties du pays : la punaise* Oebalus mexicana *(Fabricius) et le ver a soie du sorgho* Celama sorghiella *(Riley). Cette communication presente une description de ces insectes concernant leur importance economique, l'ecologie et la lutte.*

Introduction

The insect problems of sorghum in Mexico probably began with the introduction of this crop into the country. Sorghum is not an old crop in the country. By 1960 only 116 000 ha were planted to sorghum. However, this area has expanded rapidly in the last two decades, and at present exceeds 1.5 million ha, with a tendency to increase further.

When sorghum became important in the country, the first two insect pests to appear were the sorghum midge, *Contarinia sorghicola* (Coquillett), and the armyworm, *Pseudaletia unipuncta* (Haworth), which rapidly increased over the last few years. Several years later, two other insects became important—the greenbug, *Schizaphis graminum* (Rond.), and the brown bug *Oebalus mexicana* (Fabricius). The sorghum webworm, *Celama sorghiella* (Riley), is present in the northeastern part of the country and from time to time becomes an important pest.

Sorghum Midge

The presence of the sorghum midge was first detected in Tamaulipas soon after the sorghum crop was introduced into the area. The populations

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increased in a few years and soon became a major factor limiting sorghum production.

In the central part of Mexico, the sorghum midge was first detected in the state of Guanajuato in 1969. A survey was conducted within the sorghum area of Guanajuato, Jalisco, and Michoacan, which showed that the midge was present in low populations in two of the survey areas. One notable exception was the area of Guanajuato, where populations were very high and the damage was estimated at 50% for commercial fields and 30% in experimental plots.

The survey could not be continued after 1969 because the midge infestation was too low for us to make further valid population and yield loss estimates. At present this insect is found in the total area planted to sorghum in the central part of Mexico, but it seldom reaches levels of economic importance. However, in other parts of the country, Sinaloa and Tamaulipas, it can cause yield losses up to 75% in a crop in which control measures are not applied in time or which is planted late.

The small size of the insect makes it difficult for the farmers to detect it, and usually they only realize the damage when the kernels fail to develop. Since the insect deposits its eggs in the flowering parts where eggs and larvae are protected against most insecticide treatments, chemical control has to be directed against females ovipositing in flowering sorghum.

Several studies have been made and it has been found that it is fairly easy to control sorghum midge with insecticides during the flowering stage; however, chemicals are expensive, and it may not be economical to use them in a low-value crop like sorghum. Later studies have shown that early planting would be an effective cultural practice with no increase in production costs to avoid the midge peak during flowering. But this practice will only work if all farmers in an area can finish their plantings within a short time.

Armyworm

The armyworm, *P. unipuncta,* was first recognized as an economic pest in the central part of Mexico in 1970. At that time chemical control measures were applied when the population reached 1 to 2 larvae per 1 m row. Control results were unsatisfactory.

During 1972, armyworm caterpillars appeared from 15 July to the beginning of August. Damage was quite severe in Michoacan, Jalisco, Aguascaliente, Queretaro, and Guanajuato.

During 1974 again, the armyworm caused serious damage in these states, and at that time several insecticide trials were conducted for control of this insect. Three products gave satisfactory control (Table 1).

In 1976, the presence of the armyworm again caused alarm among the sorghum producers. The populations were high and the damage was severe in fields where the pest was not controlled in time. Again in 1976, several insecticide trials were conducted in different parts of the state of Guanajuato (Table 2).

Even though the larval populations in all the

Table 1. Insecticides tested for control of armyworm *Pseudaletia unipuncta* (Haworth) on sorghum in Guanajuato, Mexico.

Product		Dose/ha	Larvae surviving insecticide treatment (no./m.row)[7]
Cyolane	25%	1.0 lt	2.66a
Crthene	75%	1.0 kg	3.16a
Dipterex	80%	10 kg	7.16ab
Toxaphene	8%	2.0 lt	11.00b
Galecron	80%	0.1 kg	11.16b
Lannate	90%	0.4 kg	11.33bc
Birlane	20%	2.0 lt	15.66c
DDT	75%	2.0 lt	16.66c
Check	-	-	17.66c
Sevin	80%	2.0 kg	18.33c

Source: CIAB (1974).

1. Means followed by the same letter are not significantly different at the 0.05 level (Duncan's multiple range test).

Table 2. Insecticides tested for control of the armyworm *Pseudaletia unipuncta* (Haworth) on sorghum in Guanajuato, Mexico.

Product	Dose/ha	No. live larvae / m row[1] Before application	After application
Lannate	0.4 kg	9.00	0.25a
Tamaron	1.0 lt	5.50	0.50ab
Orthene	1.0 kg	6.25	0.50ab
Cyolane	1.0 lt	8.50	0.75ab
Fostion	1.5 lt	13.25	1.25abc
Gardona	2.0 lt	13.75	1.25abc
Shell WL-43775	0.7 lt	10.75	3.00bc
Furadan	1.0 kg	14.75	3.50c
Check		9.50	3.75c

Source: CIAB (1976).
1. Means followed by the same letter are not significantly different at the 0.05 level.

experimental plots were reduced significantly after insecticide application, differences between the effectiveness of the products were clearly visible.

By 1979, the problem of the armyworm on sorghum reached devastating proportions in the states of the central part of Mexico.

Even though we have the means of control, this pest can inflict severe damage in a very short time. Therefore early discovery of outbreaks and immediate control are essential. These goals cannot always be achieved, mainly because of lack of spraying equipment. Apparently the farmers had learned from this and acted much faster and more efficiently during the moderate armyworm outbreak in 1982.

Green bug

The first greenbug *(Schizaphis graminum* Rond.) outbreak was observed in 1972; however, at that time the crops were close to maturity and therefore damage was negligible. The bug sucks on developing grain from milk to dough stage. Since then, the insect has become a pest of importance in the central part of Mexico and when the weather conditions are favorable (high temperature, low relative humidity), the populations increase and cause serious damage. In general, the greenbug is not a major insect problem in Mexico, although it can reach damaging proportions in certain areas and years, depending on environmental conditions.

Table 3. Insecticides tested for control of the greenbug *Schizaphis graminum* (Rond.) on sorghum in Guanajuato, Mexico.

Product		Dose/ha	Greenbugs surviving treatment (no./m row)
Malathion	1000E	1.3 lt	33a
Folidol	50%	1.0 lt	36a
Perfekthion	40%	1.3 lt	37a
Thiodan	35%	2.5 lt	40a
Pirimor	50%	0.4 kg	45a
Folimat	800	0.5 lt	46a
Tamaron	50%	0.6 lt	50a
Metasystox	50%	0.4 lt	56a
Check	—	—	556b

Source: CIAB (1980).
1. Means followed by the same letter are not significantly different at the 0.05 level.

Table 4. Insecticides tested for control of the brown bug *Oebalus mexicana* (Fabricius) on sorghum in Mexico.

Product		Dose/ha	Av. dead insects[1] (no./m row)
Lannate	90%	0.2 kg	107a
Lorsban	480	1.5 lt	105a
Carbicron	100	0.5 lt	90ab
Roxion	40	1.0 lt	84ab
Tamaron	50%	1.0 lt	71bc
Thiodan	35%	1.0 lt	53cd
Sevin	80%	1.5 kg	36de
Malathion	1000E	1.0 lt	29e
Parathion M	2%	20.0 kg	22ef
Sevin	7.5%	20.0 kg	7f
BHC	3%	20.0 kg	4f
Diazinon	25%	1.0 lt	3f
Check	—	—	Of

Source: CIAB (1981).

It has been found that the greenbug is easily controlled with almost any insecticide. Several insecticide trials have been performed in commercial fields, and the results indicate that most chemicals gave satisfactory control, provided applications were made correctly (Table 3).

Brown Bug

This pest, *Oebalus mexicana* (Fabricius), has been present in Mexico since sorghum was introduced. However, within the past 7 or 8 years, populations have been increasing continuously.

During 1977, some reports came from farmers, worrying over the presence of the bug; however, closer inspection of the problem indicated that populations were not high enough for concern.

In 1980, the brown bug populations were high and the damage to sorghum was very serious; 100% yield losses have been reported from unprotected fields. Several insecticide tests were conducted for an immediate recommendation, and

Table 5. Insecticides tested for control of the brown bug *Oebalus mexicana* (Fabricius) on sorghum in Mexico.

Product		Dose/ha	Av.dead insects[1] (no./m row)
Carbicron	100	0.5 lt	96a
Lorsban	480	1.5 lt	92a
Lannate	90%	0.2 kg	82ab
Roxion	40%	1.0 lt	75ab
Tamaron	50%	1.0 lt	64bc
Thiodan	35%	1.0 lt	46cd
Malathion	1000E	1.0 lt	37d
Parathion M	2%	20.0 kg	35d
Sevin	80%	1.5 kg	21 de
Sevin	7.5%	20.0 kg	
BHC	3%	20.0 kg	6e
Diazinon	25%	1.0 kg	5e
Check	—	—	1e

Source: CIAB (1981).
1. Means followed by the same letter are not significantly different at the 0.05 level.

Table 6. Insecticides tested for control of the brown bug *Oebalus mexicana* (Fabricius) on sorghum in Mexico.

Product	Dose/ha	Number of bugs / m row		
		Before application	After application	
			Alive	Dead
Lorsban 480	1.0 lt	101	4	74
Thiodan 35%	1.0 lt	90	3	71
Roxion 40%	1.0 lt	108	8	96

Source: CIAB (1981).

Tamaron was found most effective when applied in time. Further insecticides being tested and effective against the bug are listed in Tables 4 and 5.

Again in 1981, the insect appeared in the whole sorghum-producing area, but earlier than in previous years. The bug remains in the young sorghum plants or in grasses, and as soon as the sorghum heads appear, attacks the developing grain.

During July and August, several insecticide applications were necessary to control the bug effectively.

Special aerial insecticide trials were performed in plots of 2 ha for each treatment. Three selected products gave a good control of the bug (Table 6); however, phytotoxicity was a problem, with some products and needs to be studied further.

Future Outlook

Entomological research on sorghum insects in Mexico will concentrate on the biology and ecology of the armyworm and the brown bug. These are the two pests which cause most concern to sorghum producers and entomologists in Mexico, and a sustained control campaign against both pests is required.

Sorghum Insect Pest Problems in Central America

R. Reyes*

Abstract

This paper presents a literature review of the two major sorghum insect pests in Central America: the sorghum midge, Contarinia sorghicola *Coq., and the fall armyworm,* Spodoptera frugiperda *J.E. Smith. Their importance, distribution, seasonal abundance, host plants, and life cycle, as well as their cultural, biological, and chemical control are discussed.*

Resume

***Le probleme des Insectes nulsibles au sorgho en Amerique centrale**: L'auteur recapitule la documentation sur deux importants insectes des cultures de sorgho en Amerique centrale: la cecidomyie,* Contarinia sorghicola *Coq. et la chenille legionnaire,* Spodoptera frugiperda *J.E. Smith. La communication porte sur leur importance, la repartition, la frequence saisonniere, les plantes-hdtes, le cycle de vie, ainsi que la lutte culturale, biologique et chimique contre ces insectes nuisibles.*

Sorghum occupies a very important place among the basic grains in Central America, being used for both human 2nd animal consumption. Usually it is grown in small and medium-sized farms under a maize-sorghum cropping system, covering a total area of 318 000 ha (Guiragossian 1983) and giving an average grain yield of 1.22 t/ha (Hawkins 1983). Sorghum is attacked by several insect pests, which are a major constraint to yields; the most important are: sorghum midge, *Contarinia sorghicola* Coq., fall armyworm, *Spodoptera frugiperda* J.E. Smith, and the stem borer *Diatraea* spp. The first two pests are considered the most destructive, causing usually about 5 to 10% yield reduction, which can go up to 90%; hence the major research has concentrated on these (Salazar 1969; Garcia 1976; Salguero et al. 1979; Nolasco 1980).

Sorghum Midge

The sorghum midge was first recorded in 1969 in El Salvador. Although this pest is not yet well known to farmers, its importance is increasing with the increase in area planted to sorghum. Further, continuous cropping during all three farming seasons—May-June, August-September, and, under irrigation, December-February—favors sorghum midge population buildup within a year, and from one year to the next (Salazar 1969).

Distribution

The pest distribution is closely related to the sorghum crop distribution. Larios et al. (1982) and Hawkins (1983) showed that the maize-sorghum system is generally limited to the foothills near the Pacific coastal plains and the rolling lands and valleys of the interior of Central America. According to Salguero et al. (1979) in Guatemala, this pest has not been found above 1000 m altitude; the major incidence has been found on the Pacific coast. The same was found by Reyes and Andrews (1981a) in El Salvador.

Seasonal Abundance

Under experimental station conditions, where improved flowering varieties were available during

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both wet and dry seasons, breeding was continuous throughout the year; however, the highest numbers of adults were observed from April to June, and from September to January. The numbers were very low during February to March, and July to August (Garcia and Reyes, unpublished, Centro Nacional de Tecnologia Agropecuaria, El Salvador).

Under farmers' conditions, the incidence was very low in the plantings of the first season; the incidence increased in the second season (Salguero et al. 1979; Reyes and Andrews 1981 b; Reyes and Arevalo 1982).

Host Plants

In El Salvador, Reyes and Andrews (1981a) found that the host plants of the sorghum midge are all members of the genus *Sorghum.* The most common are johnsongrass (*Sorghum halepense),* also listed by Hernandez (1976) in Nicaragua, the native local and improved and sorghum grain-fodder varieties of *Sorghum bicolor,* and broomcorn *Sorghum bicolor.* In johnsongrass, the first adult females were observed in early April at the beginning of the wet or rainy season. There were two increases in the degree of damage: a major one from April through June and a minor one from October through December. In broomcorn, the damage usually was not more than 10% in the period June to November.

Degrees of damage of no more than 2% were recorded from November to December in the northern and southwestern areas of the country, where the majority of farmers plant native or local sorghum; widely varying degrees of damage were recorded in the eastern part of the country.

Reyes and Arevalo (1982) in El Salvador found that hybrid varieties that flowered before native sorghum flowered suffered very low midge damage; however, hybrid grain varieties which flowered from 17 to 25 October recorded 0.2% damaged spikelets and served as an adult infestation source for the neighboring native sorghum, flowering 14 to 28 November and caused a grain yield loss of 21 %.

Life Cycle and Behavior

Salguero et al. (1979) in Guatemala reported that the life cycle of the midge ranged from 16 to 31 days, but the highest adult emergence was from 18 to 22 days. These data are in accordance with those obtained by Reyes and Arevalo (1984) in El Salvador. On sunny days, oviposition took place from 0800 to 1200 h, with peak activity from 0900 to 1030 h. On cloudy days and in the rainy season, oviposition continued the whole day (Reyes and Andrews, unpublished, Centro Nacional de Tecnologia Agropecuaria, El Salvador). The adult midges do not move far from their point of emergence. Reyes and Andrews (1981 b) found that the female oviposition was very low in plots located 30 m away from a midge emergence source; the midges concentrated for oviposition in the nearest plots. Reyes and Arevalo (1984) found that midge can reproduce either in fertile or sterile spikelets.

Cultural Control

Sequeira et al. (1976) in Nicaragua suggested the following control measures for sorghum midge: early and uniform planting during the first and second season; use of early and uniform-flowering varieties; where different varieties are sown, staggered planting for uniform flowering; elimination of

Table 1. Promising midge - resistant sorghum varieties identified in Central America.

Variety	Country	Reference
SC 237-14 TAM 2566 SC 423-14 SC 173-12 TAM 428	Guatemala	Salguero et al. (1979)
IS 12573-C DJ 6514 SGIRL-MR 1 AF 28 TAM 2566 ENTM 2	Honduras	Nolasco (1980)
AF 28	Nicaragua	Van Huis (1976)
AF 28 TAM 2566 IS 12664 MRT 1152 IS 14775 PM 9020 IS 8264 IS 12666C DJ 6514 MRT 1145 PM 7348 MRT 1159	El Salvador	Reyes and Arevalo (1983)

weed hosts which could be an adult infestation source; uniform cultural practices; burning and/or incorporation of sorghum stubble after harvesting.

Apparently, all Central American varieties are midge-susceptible. Some attempts have been made to identify resistant varieties, and several promising ones have been found (Table 1). According to Van Huis (1976) in Nicaragua, AF 28 has been used to incorporate resistance in a breeding program since 1974.

Biological Control

Four hymenopterous parasites have been identified as associated with the pest. Van Huis (1976) and Hernandez (1976) in Nicaragua, reported three parasites—Tetrastichus *diplosidis* Crawford (= *Aprostocetus diplosidis),* Eulophidae; *Eupelmus popa* Girault, Eupelmidae; and *Tetrastichus* sp, Eulophidae—giving parasitism rates of 16.3%, 0.5%, and 2.5%, respectively. Reyes and Arevalo (1984) in El Salvador, found two parasites: *Aprostocetus diplosidis* and *Eupelmus popa;* they also mentioned two other Hymenoptera, *Tetrastichus coimbatorensis* Roehwer, and *Tetrastichus ?gala* Walker, whose role as midge parasites was not determined. They suspected that T. *coimbatorensis* Roehwer could be a parasite of *A. diplosidis* Crawford. *A. diplosidis* was the most important on midge. None of these Hymenoptera attacked the sorghum crop. Garcia and Reyes (unpublished, Centro Nacional de Tecnologia Agropecuaria, El Salvador) mentioned that *A. diplosidis* and T. *coim batorensis* adult populations were higher from May to August.

The literature on predators is scarce. In El Salvador the minute bug *Orius tristicolor,* the large big-eyed bug, *Geocoris bullatus,* and a wasp of the genus *Polistes* have been found (Reyes, unpublished, Centro Nacional de Tecnologia Agropecuaria, El Salvador).

Chemical Control

Several insecticides have been reported to control the sorghum midge (Table 2). Usually two applications are recommended: the first, when 25 or 30% of the plants are in early flowering; the second from 3 to 5 days after the first one. An average of one female per flowering head during the flowering period caused 14% grain damage. This population level has been considered as an economic threshold for deciding upon chemical control measures (Reyes and Andrews 1981b). Also Reyes and Andrews (1979) stated that dust formulations were as effective as or better than liquid ones, pointing out their usefulness in places where water is scarce. No insecticide residues could be detected in grain and no severe phytotoxicity symptoms could be observed.

Fall Armyworm

The conspicuous and distinctive damage which the fall armyworm, *Spodoptera frugiperda* J.E.

Table 2. Insecticides found effective for control of sorghum midge *Contarinia sorghicola* Coq. in Central America.

Insecticide	Dose (kg ai/ha)	Country	Reference
Isofenphos	0.36	El Salvador	Garcia (1976)
Fenthion	0.36	El Salvador	Garcia (1976)
		El Salvador	Garcia and Reyes (1978)
		El Salvador	Reyes and Andrews (1979)
		El Salvador	Reyes (1981)
Methyl parathion	0.36	El Salvador	Reyes and Andrews (1979)
	0.24	Nicaragua	Sequeiraetal. (1976)
Diazinon	0.24	Nicaragua	Sequeira et al. (1976)
	0.24	Guatemala	Salguero et al. (1979)
	0.21	El Salvador	Reyes and Andrews (1979)
Carbaryl	1.30	Nicaragua	Sequeiraetal. (1976)
Malathion	0.82	El Salvador	Reyes (1981)

Smith, inflicts on a large number of crop plants has made it one of the most important pests of food crops in Central America. However, most of the studies have been conducted on maize, and not much research has been done on sorghum. Andrews (1980) published a literature review on this pest in Central America and selected nearby areas.

Distribution and Seasonal Abundance

This pest has been recorded all over Central America. In Guatemala it has been observed from sea level to at least 1500 m altitude (Andrews 1980).

In Nicaragua and El Salvador, the pest causes more damage to the second planting (August) than to the first (May-June)(Sequeira et al. 1976; Andrews, unpublished data). In El Salvador, three peaks of moth activity were observed: a minor one in late May, a higher one in late September, and the highest in late December to early January (Reyes and Andrews, unpublished, Centro Nacional de Tecnologia Agropecuaria, El Salvador). However, in Nicaragua, Sequeira et al. (1976) stated that moth abundance is cyclic and peak activity is correlated with the new moon.

Life Cycle and Behavioral Studies

In El Salvador, Chereguino and Menendez (1975) stated that this pest went from egg to egg in 33.5 and 27.7 days on *Amaranthus spinosus,* a weed host, and maize, respectively.

In sorghum, this pest causes damage by feeding on the developing whorl leaves. It also acts as a cutworm and stem borer and feeds on developing sorghum heads (Andrews 1980). The same author also mentioned that a "true armyworm" behavior is uncommon; populations seldom reach densities which lead to mass migrations.

Cultural Control

Andrews (1980) suggested that the easiest means of fall armyworm control for poor small-scale farmers of Central America might be to hand-pick and destroy larvae. Sequeira et al. (1976) recommended planting at the full moon to minimize risk of damage to very young plants, uniform planting, high plant density, weed host control, and crop rotation.

With regard to resistant varieties, Deras (1975) in El Salvador reported I-83 and I-87 as promising.

Biological Control

Eleven parasitic species have been reared from eggs and larvae (Table 3). Lacayo (1977) reported an average parasitization rate of 18% and Tachinidae as the most important parasites. Efforts have been made both in Nicaragua and El Salvador (Cort6s and Andrews 1979) to introduce the egg parasite *Telenomus remus* Nixon; there is no evidence that establishment has been achieved.

Lacayo (1977) reported that the fungus *Nomuraea* (= *Spicaria) rileyi* (Farlone) Samson was slightly more common than *Aspergillus flavus* Link and together they accounted for the death of 15% of the larvae collected.

Three predators have been recorded on *Spodoptera frugiperda* in Central America. *Doru* sp commonly inhabit whorls, where they have been observed feeding on small and medium-sized larvae. Huezo de Mira[1] reared these earwigs from eggs and larvae of S *frugiperda.* A wasp *Polistes* sp, takes an undetermined percentage of the larvae. *Zelus* spp can consume two to three medium-sized armyworm larvae per day in the laboratory (Cortes and Andrews 1979). Mancia and Cortes (1976) in El Salvador list more parasites and predators of S. *frugiperda* found in bean *(Phaseolus vulgaris).*

Chemical Control

Andrews (1980) reported that a common practice throughout Central America is the application of granular insecticides directly into the whorl. Persistence of granular formulations is greater than that of dusts or sprays. Applications may be made by hand, without specialized equipment. This selective placement offers an advantage over sprays and dusts applied to the entire plant surface which may favor the increase of stem borers and other pests by eliminating their natural enemies. At present phoxim is probably the most widely used compound; on larger farms methomil (0.29 kg/ha a.i.) is often applied as a spray. Synthetic pyrethroids, in some cases, gave control comparable to that of phoxim (Table 4) (Garcia 1977); however, the cost of control is lower with phoxim (Huezo de

1. Personal communication, Areli Huezo de Mira, Departamento de Parasitologia Vegetal, CENTA, San Andres, El Salvador.

Table 3. Parasites of *Spodoptera frugiperda* recorded from Central America.

Family	Genus and/or species	Country	Reference
Tachinidae	*Archytas marmonatus* (Townsend)	Nicaragua	Lacayo(1977)
	Lespesia (= *Achaetoneura) archippivora* Riley	Nicaragua	Saenz and Sequeira (1972)
		Nicaragua	Lacayo(1977)
Braconidae	*Apante/es* sp	Nicaragua	Lacayo(1977)
	Che/onus texanus (Cresson)	Nicaragua	Saenz and Sequeira (1972)
		Nicaragua	Lacayo (1977)
		El Salvador	Cortes and Andrews (1979)
	C. (Microchelonus) sp	El Salvador	Cortes and Andrews (1979)
	Rogas laphygmae Viereck	Nicaragua	Saenz and Sequeira (1972)
	Rogas sp	Nicaragua	Lacayo (1977)
Eulophidae	*Euplectrus* sp	Nicaragua	Lacayo (1977)
	Pachyscapha near *insularis* Howard	Nicaragua	Lacayo (1977)
Ichneumonidae	*Pristomerus* sp	Nicaragua	Lacayo(1977)
Trichogrammatidae	*Trichogramma* sp	Nicaragua	Lacayo (1977)
		El Salvador	Cortes and Andrews (1979)

Mira and Reyes 1978). Other compounds frequently reported as effective include carbofuran, monocrotophos (0.71 kg/ha a.i.) and metamidiphos (0.86 kg/ha a.i.). Reyes and Andrews (1980) obtained excellent control on S. *frugiperda* and *Diatraea* sp applying only 0.19 kg/ha a.i. of granular phoxim into sorghum whorls; a small, cheap, hand-operated bamboo applicator was used to apply controlled low dosages.

Andrews (1980) mentioned that in El Salvador researchers consider 12 to 15% early infested plants as the critical economic threshold level. Huezo de Mira and Lainez (1983) determined the effect of S. *frugiperda* infestation on sorghum grain yield, using three levels of infestation with third and fourth instar larvae on sorghum plants at different growth stages. They found that when two larvae per plant were released not more than 22 days after sowing, S. *frugiperda* acted as a cutworm, inflicting major grain yield losses of about 60%. In older plants, S. *frugiperda* acted as a whorlworm, causing 37 to 41 % grain yield losses. In both cases, the

Table 4. Insecticides reported effective in control of fall armyworm, *Spodoptera frugiperda* in Central America.

Insecticide	(Dose) (kg ai/ha)	Country	Reference
Phoxim	0.38	El Salvador	Garcia (1977)
Deltamethrin	0.03		
Fenvalerate	0.14		
	0.16		
Permethrin	0.10		
Phoxim	0.36	El Salvador	Huezo de Mira y
Cypermethrin	0.09		Reyes (1978)
Deltamethrin	0.06		
	0.13		
	0.19		

grain losses were economically and statistically significant.

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Sorghum Insect Problems in Brazil

Paulo Afonso Viana*

Abstract

Sorghum is a relatively new crop in Brazil, grown commercially only since 1968. Insect pests are a major yield-limiting factor: the sorghum midge is one of the most damaging pests, and recent outbreaks of the greenbug on sorghum have spurred new interest in this insect. The maize weevil, rice weevil, and Angoumois grain moth are the most destructive pests of stored grain sorghum. The lesser cornstalk borer and the fall armyworm are widespread, causing damage to a large range of crops, including sorghum. Methods of control of these insect pests, such as host-plant resistance, cultural, biological, and chemical control, are reported.

Resume

***Le probleme des Insectes nulslbles au sorgho au Brasil**: La culture du sorgho, au Bresil, est relativement recente et sa commercialisation ne date que depuis 1968. Sa production est limitee avant tout par les insectes dont les plus nuisibles sont la cecidomyie et, plus recemment, le puceron vert. Les charancons du riz et du mais ainsi que l'alucite des cereales infestent les stocks de sorgho grain et entralnent des digats importants. Le petit borer de la tige de mat's et la chenille legionnaire* Spodoptera frugiperda *sont largement repartis sur un grand nombre de cultures y compris le sorgho. Les methodes de lutte* contre *ces insectes par la resistance de la plante-hote et la lutte culturale, biologique et chimique, sont decrites.*

Sorghum *(Sorghum bicolor* [L] Moench) is a relatively new crop in Brazil. According to Trevisan and Schaffert (1977), the sorghum crop was grown commercially in Brazil after 1968 using technology from countries which were traditional sorghum growers such as the USA, India, Argentina, and Mexico.

There is currently, in Brazil, considerable potential for raising the level of sorghum production, especially in the semi-arid areas where its drought tolerance and ability to grow well on many different soils have advantages over corn production. In Brazil, sorghum has a high yield potential in many different geographic zones (Fig. 1), but 90% of the Brazilian production is concentrated in the states of Sao Paulo and Rio Grande do Sul (Rosinha et al. 1983).

Statistics for sorghum production in Brazil show a tremendous increase in grain production from 2000 to 235 000 metric tons (tonnes) during the years 1969-1982. This was largely due to an increase in the production area from 1 000 to 117 000 ha, since yields remained relatively unchanged in the range of 2000 to 2300 kg/ha (Table 1).

Table 1. Production, area harvested, and yield of sorghum in Brazil.

Year	Production (000 mt)	Area harvested (000 ha)	Yield (kg/ha)
1969-71	2	1	2222
1980	180	78	2305
1981	212	92	2314
1982	235	117	2004

Source: FA0 (1982).

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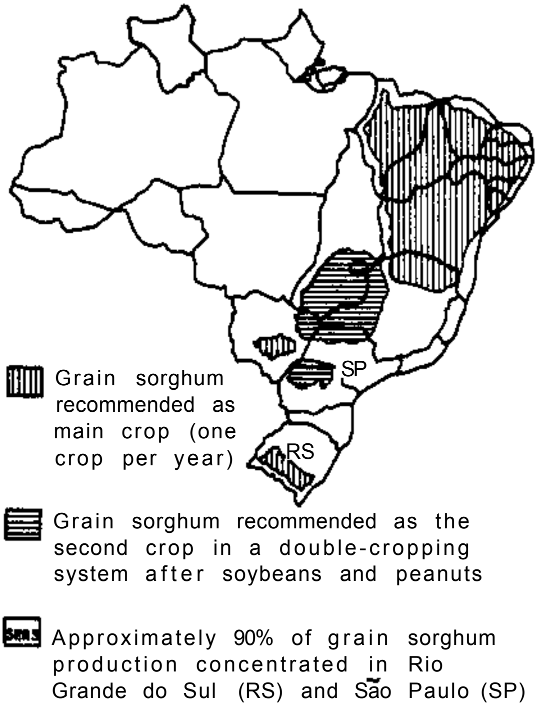

Figure 1. Sorghum crop in Brazil (Source: Rosinho et al. 1983).

In Brazil, among many factors, insect pests play a major role in limiting sorghum yields. The insects attacking sorghum are largely the same as those attacking corn.

Silva et al. (1968) published a list of insects attacking sorghum in Brazil (Table 2). Since 1968, new insect species have been added to that list by Rossetto et al. (1972), Veiga (1976), Reis et al. (1979), Gravena (1979), Menschoy (1982), and Cruz et al. (1983). However, extensive studies have not been carried out over large enough areas to provide information about insect distribution levels and consequent damage. We do not have enough information to forecast pest appearance or recommend control measures.

Among the insects attacking sorghum in Brazil, the sorghum midge, *Contarinia sorghicola* (Coq.) has been considered one of the most important, being a key pest in many of the areas where sorghum is grown. The sorghum midge was first recorded in Brazil in the state of Sao Paulo in 1967 by Rossetto et al. (1967a) and 10 years later, Lara et al. (1977) reported that the sorghum midge infestation was severe. The most important factors favoring serious sorghum midge outbreaks are a humid climate and staggered plantings. This is true in southern and central Brazil, where sorghum is grown between October and March under relatively high humidity and consequent high midge populations.

Recent outbreaks of the greenbug, *Schizaphis graminum* (Rond.) on sorghum in Brazil have spurred a great deal of renewed interest in this insect, since it is considered to be a key pest in grain sorghum in many regions of the world. There are still many states in Brazil where its presence has not been formally reported but it is present in the principal areas of sorghum production, causing substantial damage. It is believed that the greenbug has a high potential to become the key sorghum pest in Brazil in a short time. Government agencies, universities, and private seed companies are very concerned and are developing effective measures of control for this pest.

The maize weevil, *Sitophilus zeamais* Motschulsky; the rice weevil, *Sitophilus oryzae* (L); and the Angoumois grain moth, *Sitotroga cerealella* (Oliv.) are the most destructive stored grain sorghum insects in Brazil. They frequently cause almost complete destruction of grain, especially under poor storage facilities. According to Gallo et al. (1978), the losses caused by insects attacking stored grain in Brazil are estimated to be 20% of the original weight. In tropical developing countries where the weevils breed continuously, the yield loss may be even higher, because the lowered nutritional quality of the damaged grain has not always been taken into consideration.

Apart from the main pests mentioned above, some less important ones can cause damage occasionally localized areas in certain years. The lesser cornstalk borer, *Elasmopaipus lignosellus* (Zeller); fall armyworm, *Spodoptera frugiperda* (J.E. Smith); corn leaf aphid, *Rhopalosiphum maidis* (Fitch); and many others fall in this category.

In Brazil, the lesser cornstalk borer is widespread and causes damage to a large range of crops including: sorghum, corn, wheat, groundnut, soybean, beans, sugarcane, and cotton. No damage estimates have been reported for sorghum, but Sauer (1939) found that the damage caused on corn fields corresponded to 20% of the planted area, while in sugarcane, damage was up to 25% of the planted area. The fall armyworm has also been reported to attack a range of crops, such as sorghum, corn, rice, and wheat.

Table 2. Insects reported damaging sorghum in Brazil.

Scientific name	Common name	Pest status	Plant part attacked
Scaptocoris castanea	*	Secondary	Roots
Rhopalosiphum maidis	Corn leaf aphid	Secondary	Leaves, inflorescence
Spodoptera frugiperda	Fall armyworm	Occasional	Leaves
Mocis /atipes	*	Secondary	Leaves
No/a sorghiella	Sorghum webworm	Secondary	Panicle
Diatraea saccharalis	Sugarcane borer	Secondary	Stalk
Corcyra cephalonica	*	Secondary	Stored grain
Cryptoblabes gnidiella	Christmas berry webworm	Secondary	Panicle
Elasmopalpus lignosellus	Lesser cornstalk borer	Occasional	Stalk of seedling
Pyralis farina/is	Meal moth	Secondary	Stored grain
Sitotroga cerealella	Angoumois grain moth	Key	Stored grain
Sitophilus oryzae	Rice weevil	Key	Stored grain
Sitophilus zeamais	Maize weevil	Key	Stored grain
Carpophilus spp	*	Secondary	Stored grain
Tribolium castaneum	Red flour beetle	Occasional	Stored grain
Contarinia sorghicola	Sorghum midge	Key	Panicle
Heliothis zea	Corn earworrn	Secondary	Panicle
Agrotis ipsilon	Black cutworm	Secondary	Stalk of seedling plants
Schizaphis graminum	Greenbug	Occasional	Leaves, panicle
Oligonychus spp (mite)	*	Secondary	Leaves
Plodia interpunctella	Indian meal moth	Secondary	Stored grain
Loxa flavicollis	*	Secondary	Panicle
Rhopalosiphum pseudavenae	*	Secondary	Leaves
Nezara viridula	Southern green stinkbug	Secondary	Leaves, stem
Diabrotica speciosa	Rootworm	Secondary	Leaves

* Common name not available in the American common names lists.

Methods of Control for Common Insect Pests

Many methods for control of insect pests, such as host-plant resistance, cultural, biological, and chemical control have been tried to control insect pests of sorghum.

The role of plant resistance as a control method against the sorghum midge is highly promising. Some varieties and lines, such as: AF 28 (Rossetto et al. 1975; Veiga et al. 1976); AF 112 (Rossetto and Banzatto 1967b); IS 8100C, IS 25008C, IS 25001C, and SGIRL-MR 1 (Faris et al. 1976), have been tested in Brazil and showed resistance to the sorghum midge. Our group at Sete Lagoas (CNPMS) is concentrating on the development of resistance to sorghum midge and greenbug. Preliminary screening of varieties and lines from the world collection and EMBRAPA breeding material is currently being conducted.

Some cultural measures can be used successfully against the sorghum midge; the main ones are: reduction of the diapausing carryover population by good crop sanitation management, uniform and early planting over large areas, and elimination of alternative hosts by cutting wild sorghum grasses and forage sorghums before they flower. The best and cheapest control is achieved by planting early (Rossetto et al. 1972). This reduces midge damage on the main crop and chemical control is reserved only for use on later flowering crops.

Many species of beneficial insects play an important role in the natural and biological control of sorghum insects. One of the possible factors contributing to the increase of the sorghum midge and greenbug in Brazil was the lack of its native parasites and predators. Rossetto et al. (1967b) and Lara (1974) reported the following hymenopterous parasites: *Tetrastichus* spp, *Inostema* sp, and *Eupelmus popa* (Gir.) parasitizing the sorghum midge. Gravena and Batista (1979) reported the following greenbug predators in decreasing order of abundance: *Scymnus* sp, *Cycloneda sanguines* (L), and *Chrysopa cincta.* Hymenopterous parasites such as *Aphidius colemani* and *Diaeretiella rapae* Curtis were also reported by these researchers. Unfortunately, these natural enemies are not normally sufficient to keep the pests in check.

Among the methods of control, insecticides (because of their low cost and quick positive results) are widely used to control sorghum insect pests in Brazil. This holds true mainly for the sorghum midge, fall armyworm, lesser cornstalk borer, and stored grain insects. The control of the lesser cornstalk borer has been preventive, since the borer is difficult to control with insecticides due to its protected habitat. Chemical control of the sorghum midge, greenbug, fall armyworm, and other caterpillars has been usually recommended. Recommendations are based on threshold density levels of the insect. Sound integrated management strategies to control these pests have been studied under Brazilian conditions but have not yet been perfected for practical use. Gallo et al. (1978), Reis et al. (1979), Gravena and Batista (1979), and Menschoy (1982) have listed some insecticides to control the most common sorghum insect pests occurring in Brazil (Table 3).

Under current government agricultural policy in Brazil, priority is given to increasing grain sorghum production for animal feed in order to release corn for human food (Rosinha et al. 1983) and for export. Research institutions such as EMBRAPA (Empresa Brasileira de Pesquisa Agropecuaria), state research enterprises, universities, and private companies have among their research objectives a major research program on sorghum entomological problems, including screening for resistance and developing a group of cultural, biological, and chemical control tactics to be used in future pest management programs.

Table 3. Some insecticides recommended to control the most common insect pests attacking sorghum in Brazil.

Insect pest	Insecticide and a.i. percentage	Formulation	Dosage/ha
Plant pests	Carbaryl 85%	WP	1.0 Kg
Contarinia sorghicola	Chlorpyrifos 48%	EC	0.3 l
	Diazinon 40%	WP	1.0 Kg
Schizaphis graminum	Dimethoate 50%	EC	0.5 l
Rhopalosiphum maidis	Malathion 50%	EC	1.0 l
	Pirimicarb 50%	G	0.15 Kg
Mocis latipes	Chlorpyrifos 48%	EC	0.6 l
Spodoptera frugiperda	Monocrotophos 40%	EC	0.5 l
Diatraea saccharalis	Trichlorfon 80%	SP	1.0 Kg
Heliothis zea			
Elasmopalpus lignosellus	Carbaryl 85%	WP	10 Kg
Agrotis ipsilon	Chlorpyrifos 48%	EC	1.0 l
	Carbofuran 5%	G	25 Kg
Stored sorghum grain pests			0.5 g/kg grain (protection 60 days)
Sitophilus oryzae	Malathion 2%	D	1.0 g/kg grain
Sitophilus zeamais			(protection 150 days)
Sitotroga cereafella			2.0 g/kg grain
			(protection 180 days)
	Gardona 1%	D	1 g/kg grain
	Phosphine		Tablet - 3g/m^3 chamber (dosage variable with temperature)

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Soil Insects, Shoot Fly, and Greenbug

Importance of Soil Insect Pests in Relation to Sorghum Production

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Abstract

Two types of soil insect pests of sorghum are recognized: (1) those that spend all their life stages in the soil—such as white grubs, wireworms, root aphids, etc.—and cause damage underground to germinating seed, roots, and stem; and (2) those that spend part of their life in the soil but damage the crop above ground, either in their larval, nymphal, or adult stage; for instance, cutworms, grasshoppers, flea beetles, etc. Though none of these is specific to sorghum, infestations, when they do occur, can cause economic losses. Soil insect pests of sorghum are considered under four stages of crop growth—germinating seeds, roots, vegetative stage, and earhead stage. Distribution, bio-ecology, nature and symptoms of damage, and control measures are discussed under each pest. Integrated pest management, combining cultural, mechanical, and chemical methods, is suggested.

Resume

***Importance des Insectes habitant dans la sol dans la cadre da la production da sorgho**: Il existe deux types d'insectes nuisibles au sorgho qui habitent dans le sol :(1) ceux qui passent tous les stades de leur vie dans le sol, tels que les vers blancs, les vers fil de fer,* Tetraneura nigriabdominalis *Sasaki, etc., et endommagent les semences en cours de germination, les racines et les tiges au-dessous du sol; (2) ceux qui passent une partie de leur vie dans le sol mais s 'attaquent aux parties aeriennes de la plante au stade larvaire, de nymphose ou d'adulte, tels que les vers gris, les acridiens, les altises, etc. Ces ravageurs ne sont pas specifiques au sorgho, cependant leurs infestations, quand elles se produisent, entrainent des pertes sensibles des recoltes. Les insectes sont consideres en fonction de la germination des semences, du developpement des racines, de la croissance vegetative et du remplissage des grains. Pour chaque insecte sont donnes: la repartition, la bioecologie, la nature et les symptomes des digats ainsi que les mesures de lutte. L'auteur preconise la lutte integree englobant les methodes culturale, mecanique et chimique.*

Introduction

Sorghum bicolor (L) Moench, the grain sorghum, ranks fifth in acreage and production among the world's major cereal crops, following wheat, rice, corn, and barley (Young and Teetes 1977). It is grown worldwide and is *one of* the major cereal crops in India, with an area of 16 million ha and a total production of 11 million tonnes (Gahukar and Jotwani 1980). North America produces slightly more than 50% of the world's sorghum grain; Africa and Asia, with about three-fourths of the world's sorghum acreage, produce one-third of the world's sorghum crop.

A number of insect pests are responsible for heavy yield losses in sorghum. Among them, soil-inhabiting insects, numbering over 100 species reported from all sorghum-growing areas of the world, cause damage to sown seeds, seedlings, roots, vegetative parts, and earheads.

Soil insect pests of sorghum are of two types: (1) those that spend all their life stages in the soil-such as white grubs, wireworms, ants, earwigs, crickets, and termites—damaging seeds in the soil, seedlings, roots, or underground stem; and (2) those that spend part of their life in the soil and

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attack above-ground plant parts. These include cutworms, armyworms, grasshoppers, chafer beetles, blister beetles, and myriopods. Based on the feeding habits, the soil insect pests of sorghum are grouped into five categories: pests of seeds in the soil, seedling pests, root feeders, vegetative part feeders, and earhead feeders.

The roots of sorghum seem to be toxic to some root feeders such as the western corn rootworm D*iabrotica virgifera* Lec. (Brauson et al. 1969). Some of the regional reports of soil insects in relation to sorghum production are that of Hayes (1922), Burkhardt (1958), Bottrell (1971), Gahukar and Jotwani (1980), Gardner et al. (1980), Demange (1982), and Fougeroux (1983).

Although none of the nearly 100 soil insect pests identified on sorghum is specific to this crop, some of them, such as white grubs in India, are assuming major pest status. With changes in cultivation practices, cropping season, and introduction of high-yielding varieties into nontraditional areas with irrigation, there is every likelihood of minor pests becoming major ones.

Soil Insects Damaging Seed

Ants

Ants, although they can be predators of the sorghum midge (Taley and Garg 1976) can also be destructive, as they not only are carriers of pests, such as aphids (Barbulescu 1979) and phytophagous mites (Margal and Channabasavanna 1979), but also directly damage sown seed. The thief ant, *Solenopsis molesta* (Say.) is the most injurious pest of planted sorghum seed in south central Kansas when weather and soil conditions are unfavorable (Bryson 1941). Hayes (1920) reported instances when thousands of acres of sorghum required replanting because of seed damage due to this ant. Smith et al. (1940) listed S. *molesta* as a destructive species in sorghum production and suggested tilling the soil just prior to planting to minimize damage. At times these ants are so abundant and active that they seriously damage and destroy all seed planted in a field (Srivastava and Bryson 1956).

Srivastava et al. (1969) have reported two species of ants, *Monomorium salomonis* L. and *Pheidole sulcaticeps* Roger, attacking germinating seeds of sorghum in the field. Three or four ants usually surround each seed and eat out the endosperm, so that no germination takes place. In India, ants have been known to cause over 75% damage to seed sown in the premonsoon season.

Injury by ants to seed in the soil could be prevented by seed treatment with aldrin, lindane, or heptachlor at 0.5 (0.86 g), 4 (6.92 g), and 5 (8.65 g) ounces respectively per 100 lb (45.4 kg) of seed (Burkhardt 1959). Soil treatment with 2 lb (0.91 kg) of aldrin or heptachlor or 1.5 lb a.i./acre (0.4 ha) dieldrin, broadcast or drilled in, prior to sowing gives excellent crop stands (Burkhardt 1959).

Soil Insects Damaging Seedlings

Crickets

Mital et al. (1980) have reported *Plebeiogryllus* sp and *Gryllotalps* sp causing considerable damage to germinating seeds. Nymphal crickets feed gregariously on the germinating seed in the soil. Insecticides such as lindane 0.65% dust, chlordane 10% dust, DDT 50% wp, and formathion drilled into the soil at 1.5 to 2 lb a.i./acre (0.6-0.9 kg), or carbofuran seed treatment (5% a.i.) all gave significantly higher seed germination over the control.

Earwigs

The black field earwig *Nala lividipes* (Duf.) is reported to be a pest of field crops, including sorghum, in Queensland, Australia. This earwig lives in the loose surface cultivated soil and normally feeds on organic material such as decaying stubble, but when the earwig population increases in the summer, the insects attack seedling roots and young plants. The eggs are laid in the soil in groups of 25 to 30, and development takes place during the summer. The populations decrease towards the winter. The females appear to overwinter in the soil and oviposit in spring. Lindane applied at 1 g a.i. per 200 m of planting row, together with the seed in the same furrow, gives good seedling stand (Hargreaves 1970; Passlow 1973).

Root-feeding Soil Insects

White Grub

Members of the genus *Phyllophaga are* injurious to a wide range of agricultural crops, including sorghum, in North America (Metcalf et al. 1962). Damage by the white grubs, *Phyllophaga crinita* Burm., to grain sorghum has increased in severity in some areas and approximately 40 000 acres

(16 000 ha) are damaged annually on the Texas High Plains (Teetes and Wade 1974; Teetes et al. 1974, 1976; Young and Teetes 1977). The incidence of damage by scarabaeids has increased markedly on a wide variety of crops, including grain sorghum, in Zimbabwe (ZAR 1979), Sudan (Pollard 1956), Queensland (Passlow 1973), China (IAS 1982), and India (Veeresh 1983).

There are a number of reports on white grub damage to sorghum from India (Ayyar 1943; Kushwaha 1961; Desai and Patel 1965; Srivastava et al. 1971; Veeresh 1977a; Patil et al. 1981; Bhattacharjee and Bhatia 1982; Brar and Sandhu 1982; Parasnath and Singh 1983). Veeresh (1983) has compiled a comprehensive review on Indian white grubs.

Of nearly 12 subfamilies of the huge family Scarabaeidae, only members of two, the Melolonthinae and Rutelinae, are true phytophages in their larval stages. Some adults (chafers) of the subfamily Rutelinae and Cetoniinae are defoliators or pollen feeders and occasionally cause damage to the earheads of sorghum (Usman 1967; Pal 1977; Bhagawat and Kadam 1975; Agarwal et al. 1980).

The white grub problem is regional in nature and depends on several factors that influence the outbreak of the pest. A knowledge of the biology of a given species under local conditions is essential for effective management of the pest. Most of the tropical and subtropical white grub species have a 1 -year life cycle, while the temperate species usually have a 2- to 4-year life cycle.

Adults emerge after the first summer rains, mate, and lay eggs singly, 5 to 10 cm deep in soil (Hawley 1949; Veeresh 1977a). Eggs hatch within 2 weeks, and larvae undergo three molts. The first and second larval stages last about 1 month each, while the third stage takes longer (60 to 120 days), in situations where there is one life cycle per year. In most places the grubs feed actively between June and September. Pupation takes place in an earthen cell below the root zone. The pupal period lasts for about 2 weeks. The adult hatches within the pupal cell but remains there until the next summer rains.

Larval feeding causes seedling death, plant stunting, and lodging. Economic damage depends on the larval density. In the case of *Lachnosterna (Phyllophaga) crinita,* a density of two larvae per square foot (0.186 m^2) causes economic injury. The economic threshold level is about one larva per square foot (Teetes 1973; Teetes and Sterling 1976).

Soil condition (texture and drainage) and rainfall were correlated with the infestation level of *Phyllophaga trichophora* (Fairm.) *(Holotrichia trichophora)* in Xiuxian county, Shanxi, China. It was found that in May-June 0.5 larvae/m^2 indicated a light infestation; five larvae/m^2, a heavy infestation (IAS 1982).

Soil pH seems to have no influence on the population of white grubs (Vittum and Tashiro 1980). Soil moisture plays a major role in the activity of the pest. According to Hawley (1949), large grubs and pupae of the Japanese beetle are resistant to desiccation and waterlogging, while eggs and first-instar grubs are the stages most sensitive to desiccation. Delay in egg development was observed by Regniere et al. (1981) in water-saturated soils.

Larvae of *Holotrichia serrata* were found resistant to drought and survived up to 4 months under moisture stress but did not survive under waterlogging, which forced them to the soil surface, where predatory birds picked them up (Veeresh 1977a).

More than 200 species of scarabaeids are recognized as potential pests of crops in India, causing damage during either the larval or the adult stage or both, but only two species are serious pests of cultivated crops. *Holotrichia serrata* is widely distributed all over India and *Holotrichia consanguinea* is prevalent in the northern plains. The behavior, biology, and life cycle are similar in both, except for the time of adult emergence, which depends on the onset of the summer rains. In southern India, beetles start emerging from the middle of March; in northern India, during June-July.

There is a direct relationship between the adult and the host plant in certain areas and the amount *oi* damage caused by the larvae (Veeresh 1978). With changes in traditional agricultural practices and more land under irrigation, the problem of white grubs, especially on hybrid sorghum in India, is on the increase (Veeresh 1980a).

Adult *Holotrichia* sp stay within 100 m of the place they emerged. The larva during its total larval period is able to move a maximum distance of 6 m in a crop row (Shivayogeswara and Veeresh 1983a, 1983b).

Control of White Grubs

Campaigns to collect adults have been successful in controlling *Holotrichia serrata and H. consanguinea* (Veeresh 1974a; Raodeo et al. 1975; Yadava et al. 1977a).

Natural enemies, such as fungi, bacteria, viruses, parasites, and predators, control the population of white grubs in nature (Veeresh 1980b).

Cultural practices—for instance, continuous hoeing, harrowing, or plowing during the period of larval activity—can reduce the population below the economic threshold level (Veeresh 1977b).

Success of chemical control depends on the insecticides used and the method of application. To get good control, insecticides must be applied when the larvae are still young. Chlorinated hydrocarbons like heptachlor, chlordane, DDT, and BHC are still used against white grubs in several parts of the world. BHC 10% dust at 125 kg/ha drilled in the seed furrow at sowing has proved effective against white grubs in sorghum fields. Fifty kilograms BHC 10% dust mixed with an equal quantity of farmyard manure, applied at sowing, has also given satisfactory control. Several granular insecticides, such as phorate 10G, carbofuran 36, disulfoton 5G, dasanite 5G, quinalphos 5G, applied at 1.5 to 2 kg/ha a.i., are also effective, but may be too costly for sorghum in developing countries (Veeresh 1973, 1977b, 1981b; Yadava et al. 1977b).

Integrated pest management may be the only effective way to eliminate the white grub from a locality. Adult collection, application of insecticides at the early stages of the pest, and fall plowing, if followed sequentially, will reduce the white grub population substantially (Veeresh 1981a). If white grubs are eliminated from a particular locality, the field will be free from the pest for 4 to 5 years.

Wireworms

The larvae of click beetles are commonly known as wireworms. They are easily recognized by their shiny, wirelike, yellow or orange bodies and by their habit of feeding on underground parts of plants. Sometimes damage caused by the ground beetle larvae is confused with wireworm damage. Although wireworm damage to grain sorghum seedlings is reported by several authors (Burrage 1964; Ostatichuk 1969; Srivastava et al. 1969; Bynum and Archer 1977; Gorbunova 1978), it is seldom severe in tropical countries. With the introduction of irrigation, the incidence of wireworms on sorghum seedlings may increase, as soil conditions will become favorable for development not only in the wet season but also during the dry season, which may increase the population buildup (USDA 1971).

A number of ground beetle species, including *Gonocephalum elongatum* F., G. *depressum* F., and G. *hoffmannseggi* S., have been reported to feed on the roots of grain crops (Nair 1970). *Gonocephalum* spp are known to damage germinating seeds of sorghum in Queensland (Passlow 1973).

The life history of wireworms closely resembles that of white grubs. Eggs are placed singly, 3 to 15 cm deep, in the soil. A female may lay 50 to 300 eggs, which hatch in 3 to 4 weeks. Damage by larvae is recognized by seedlings cut at soil surface level. The full-grown wireworms pupate in June-July, 10 to 25 cm below the soil; adults hatch 3 weeks later. The life cycle may take 1 to 3 years and overlapping generations occur.

The management of wireworms depends upon the various soil conditions and farm practices. The effect of soil fertilizers on wireworm *(Agriotes* sp) has recently been studied in Belorussia (USSR). Soil cultivation combined with mineral and organic fertilizer use reduced the wireworm problem by 65% (Gorbunova 1982). Phosphorus and potassium had little effect, but nitrogen showed good control effect. Animal dung did not reduce larval numbers, but reduced the plant feeding of the wireworms by providing an alternative food source for them.

Soil insecticides are only effective in controlling wireworms when they are present in the topsoil during the summer. Therefore insecticide application should be properly timed. Several baits have also been found effective (Bynum and Archer 1977; Doane 1981). Soil (pitfall) traps have been found more efficient in attracting wireworm larvae than plain traps (Bynum and Archer 1977). Seed treatment with insecticide is also a recommended practice for wireworm control in sorghum (Teetes et al. 1974).

Root Aphids

Root aphids are known to cause injury to grain sorghum. The *ragi* (finger millet) root aphid, *Tetraneura nigriabdominalis* Sasaki, often appears on sorghum roots during June-September in southern India (George 1929; Krishnamurti 1948; Gadiyappanavar and Channabasavanna 1973).

The presence of root aphids at the base of the plant is usually indicated by the activity of ants. Up to 150 nymphs and 200 adults may be found on one plant. The affected plant shows water-stress symptoms and seed setting is reduced.

Older plants are preferred to younger ones. Dispersal is by alates and by ants *(Camponotus compressus* [F.] and *Solenopsis geminata* [F.]) which transport nymphs and alates. Organophosphorus and carbamate granular insecticides give good control of root aphids.

Weevils

Weevil grubs feed on roots *of* many plants, including sorghum, but seldom cause economic loss. The adults may cause injury by defoliation in young crops. Several species of *Myllocerus* build up to damaging levels after heavy rainfall followed by bright sunshine, high humidity (85±5%) and mean air temperatures of 28±2°C (Singh and Singh 1977).

The sugarcane rootstock weevil, *Anacentrinus deplanatus* (Sy.), is also reported on grain sorghum as an economic pest in central Texas (Bryson 1941; Goode and Randolph 1961). The insect overwinters as an adult in trash near the soil surface. Granulated dieldrin or heptachlor application to the soil prior tc planting is recommended for control.

Soil Insects Damaging Vegetative Parts of Grain Sorghum

These include termites, cutworms, armyworms, flea beetles, weevils, and grasshoppers.

Termites

The larger genera such as *Macrotermes, Odontotermes,* and *Pseudacanthotermes,* usually damage the plant under a mud sheathing. They girdle the stem at or just below ground level, which results in wilting or total plant loss (Sands 1973). Although there are no reports elsewhere of severe damage to sorghum from termites, there are a few reports from India (Gahukar and Jotwani 1980; Kushwaha 1960; Sharma 1964). In Karnataka, India, sorghum husk heaped around the base of the trunk is used as a deterrent against termite attack on trees.

Grasshoppers

Grasshoppers lay eggs in the soil during November-December, which remain there until the onset of the rains.

Some grasshoppers are endemic to certain sorghum-growing areas of the world, including India (Coleman 1911; Seshagiri Rao 1943; Kushwaha and Bharadwaj 1977), Nigeria (Hergert 1975), and Pakistan (Wahla and Khan 1980).

The Deccan wingless grasshopper *Colemania sphenarioides* (Bol.) is endemic in a few districts of Karnataka, Maharashtra, and Andhra Pradesh, where it appears year after year in the same area. In some years the population is so high that aerial sprays are necessary. Similarly, *Hieroglyphus nigrorepletus* Bol. is a severe pest of sorghum in Rajasthan (Kushwaha and Bharadwaj 1977).

Scraping of field bunds before the onset of the rains and deep plowing after harvest will expose the eggs to desiccation and predators, thus reducing the severity of the pest.

Cutworms, Armyworms, and Hairy Caterpillars

Cutworms, armyworms, and hairy caterpillars are all feeders on above-ground vegetative parts, but they spend the pupal stage in the soil, which is crucial to their survival. The fall armyworm, *Spodoptera frugiperda* (J.E. Smith), is a key pest of sorghum in Georgia and other areas of the USA. The amount of foliar damage to whorl-stage sorghum caused by larvae of the fall armyworm depends on the soil pH (Gardner and Ronny 1982; Henderson et al. 1966). In India, the armyworms *Mythimna separata, Pseudaletia unipuncta, and* the hairy caterpillars Amsacta moorei, A. *al bistriga,* and *A. lactenia* , survive as pupae in the soil during the summer (Pandey et al. 1970; Agarwal and Nadkarni 1974; Rangarajan et al. 1974). Deep plowing after harvest to expose the pupae to heat and predators is one of the recommended control practices against these pests.

Soil Insects Damaging Earheads

Chafer and blister beetles are important earhead pests. Among the chafers, *Rhinyptia indica, R. meridionals, Schizonycha ruficollis, Adoretus lasiopygus, Serica assamensis, Anotona stillata,* and *Pachyrhinadoretus rugipennis,* occasionally cause severe damage to flowers and developing grain (Usman 1967; Bhagawat and Kadam 1975; Putturama et al. 1976; Pal 1977; Agarwal et al. 1980). These scarabaeids develop in the soil. Emerging adults attack the sorghum earheads in swarms and can cause considerable yield loss.

The blister beetles commonly found on the earheads of sorghum are *Cylindrothorax tenuicollis* (Pallas); *Psalydolytta attricollis, Epicauta cognata,* and *Zonabris pustulata* (Kundu et al. 1971; Kulkarni et al. 1978). The adults attack during the flowering stage of the earhead and cause economic loss. Eggs are laid in the soil and the larvae develop there.

Cultural methods, such as plowing and dusting of the earheads with insecticides at the time of attack, are recommended control practices for both pest groups.

Integrated Control of Soil Insect Pests of Sorghum

The integration of cultural, mechanical, and chemical control methods may be best suited for all the soilborne insect pests of sorghum.

Simple techniques such as manipulation of the soil (plowing, hoeing, forking, mulching) during the off season will help reduce such pests as wireworms, white grubs, grasshoppers, armyworms, cutworms, and hairy caterpillars through mechanical injury, exposure to heat, and bird predation (Veeresh 1977).

Collection of egg masses and adults (Agarwal and Nadkarni 1975; Veeresh 1974a) and attracting the pests to trap crops or light traps (Veeresh 1974b) will reduce the severity of the pests. Seed furrow application, seed treatment, or spot application of insecticides, combined with mechanical and cultural methods, may give satisfactory control of soil insect pests.

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Resistance Screening and Mechanisms of Resistance in Sorghum to Shoot Fly

S.L. Taneja and K. Leuschner*

Abstract

The development of efficient and reliable screening techniques, identification of stable resistance sources, factors associated with resistance, and finally the mechanisms of shoot fly resistance in sorghum are described. Population dynamics studies based on adult fly catches in fishmeal-baited traps and monthly planting of sorghum indicated two peak activity periods, in August and in November-December. A highly significant and positive correlation has been observed between the trap catches and shoot fly incidence (egg laying and deadheart formation). A field-screening technique using infester rows of a susceptible cultivar and fishmeal provided sufficient and uniform shoot fly pressure for large-scale testing of germ plasm and breeding lines. To confirm the resistance observed in the field and to differentiate between various resistance mechanisms, a cage-screening technique providing multiple and no-choice conditions is used. Out of nearly 14000 germplasm lines screened in the field, 42 lines were found to be less susceptible over five seasons. Five germplasm lines—IS Nos. 1054, 1071, 2394, 5484, and 18368— were found to be quite stable across locations. The most obvious factors associated with shoot fly resistance have been seedling vigor, glossiness, morphological characters, and biochemical factors. Ovipositional nonpreference was found to be the primary resistance mechanism; however, some degree of antibiosis and recovery resistance has also been found to exist.

Resume

***Mecanismes et crlblage de la resistance a la mouche des pousses**: La communication porte sur le perfectionnement des techniques de criblage efficaces et fiables, l'identification des sources de resistance stable, les divers Elements lies a la resistance et les mecanismes de resistance a la mouche des pousses chez le sorgho. L'etude de la dynamique des populations fondee sur le piegeage des mouches avec appat de farine de poisson ainsi que sur le semis echelonne mensuel, indique deux periodes de pointe en aout et en novembre-decembre. On constate une correlation tres significative et positive entre le nombre de mouches piegees et /'incidence, a savoir, la ponte et la formation des "coeurs morts". Une technique de criblage au champ ou la mise en place des rangs d'un cultivar sensible et la farine de poisson favorisant l'infestation par l'insecte, a permis un essai a grande echelle des accessions de sorgho et les lignees en selection grace a une pression parasitaire adequate et uniforme. Afin de confirmer la resistance constatee en milieu reel et de distinguer entre les differents mecanismes de resistance, on a utilise la methode de criblage en cage avec un choix soit unique soit multiple des cultivars. Parmi les 14000 accessions mises a l'essai au champ, 42 se sont revelees moins sensibles au cours de cinq campagnes. Cinq lignees IS, dont 1054, 1071, 2394, 5484 et 18368, ont une resistance assez stable en divers milieux. Les elements les plus importants qui sont lies a la resistance sont la vigueur des plantules, la surface vernissee des tiges ainsi que certains caracteres morphologiques et biochimiques. Un element important est la non preference pour fa ponte. Cependant, il existe egalement un certain degre d'antibiose et de tolerance.*

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Introduction

Shoot fly *(Atherigona soccata* Rondani) is an important pest of sorghum in Asia, Mediterranean Europe, and Africa, but is absent in the Americas and Australia. It attacks the sorghum from 1 to 4 weeks after seedling emergence. White, elongated, cigar-shaped eggs are laid singly on the under surface of the leaves parallel to the midrib. The larva after hatching crawls along the leaf sheath and moves upward to reach the plant whorl. From there it moves downwards between the fifth and sixth leaf till it reaches the growing point, and cuts around it, causing drying of the central leaf and the typical "deadheart" symptom. The shoot fly completes its life cycle (from egg to adult) within 17 to 21 days (Kundu and Kishore 1970). The fly population varies across seasons and years, depending upon environmental factors and cropping systems.

The first report on sorghum varieties resistant to shoot fly was by Ponnaiya (1951 a), who screened 212 genotypes and found 15 less damaged. Rao and Rao (1956) screened 42 sorghum varieties for shoot fly resistance and reported 14 varieties to be resistant. Jain and Bhatnagar (1962) reported that four out of 196 sorghum varieties tested were highly resistant to shoot fly. Blum (1965) screened 250 sorghum germplasm lines in Uganda and classified several varieties from India as highly resistant. A systematic screening of the world sorghum germplasm collection for resistance to this pest was started in India in 1962 under the cooperative efforts of the Accelerated Hybrid Sorghum Project (ICAR); the Entomology Division, Indian Agricultural Research Institute; and the Rockefeller Foundation (Singh et al. 1968; Anonymous 1971, 1978) and a number of resistant genotypes have been reported. At the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), shoot fly resistance screening was started in 1974. The main thrust of the Sorghum Entomology group at this Institute focuses on (1) developing an efficient, reliable, and repeatable resistance screening technique; (2) identifying strong and stable shoot fly resistance sources; and (3) helping plant breeders to incorporate this resistance into elite backgrounds. This paper summarizes the work done at ICRISAT on shoot fly resistance and the resistance mechanisms involved.

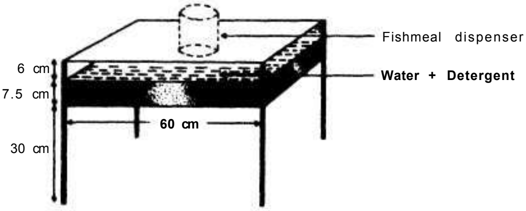

Figure 1. Square pan galvanized metal trap for monitoring sorghum shoot fly activity at ICRISAT Center, Patancheru, India. (Source: Seshu Reddy et al. 1981)

Screening Techniques

Development of an efficient and reliable screening technique is one of the most important prerequisites for an effective host-plant resistance program. A reliable screening technique should help to create uniform insect pressure at the desired level at the most susceptible stage of the crop. Studies carried out at ICRISAT on this and related aspects are described below.

Population Dynamics

Shoot fly population dynamics can be studied through the actual damage to the sorghum seedling (deadheads) and presence of adult flies by egg count on seedlings and fly catches in traps baited with an attractant. Fishmeal had been reported to attract shoot flies (Starks 1970) and was used in traps for pest monitoring at ICRISAT (Seshu Reddy et al. 1981) and several other locations.

Shoot fly monitoring through fishmeal-baited traps has been done at ICRISAT since 1976 to determine the periods of peak activity and to utilize this information to obtain maximum shoot fly pressure for screening purposes. A square pan galvanized metal trap (60x60x7.5 cm) with a lid, (Campion 1972), with fishmeal placed in a dispenser kept at the center of the trap (Fig. 1), is used. The trap is filled with water (20 l) to which a small quantity of detergent (100 g) is added. Fishmeal is changed after every 3 days and water every 6 days. The trapped flies, which tend to sink to the bottom, are scooped out with a gauze net for counting and removing. Recently the square pan metal trap has been replaced by a plastic trap which is simple and easy to operate (ICRISAT 1983; Pawar et al. 1984). It consists of a 1 -liter plastic jar with fly entry holes on the sides (Fig. 2). The top of the jar contains a

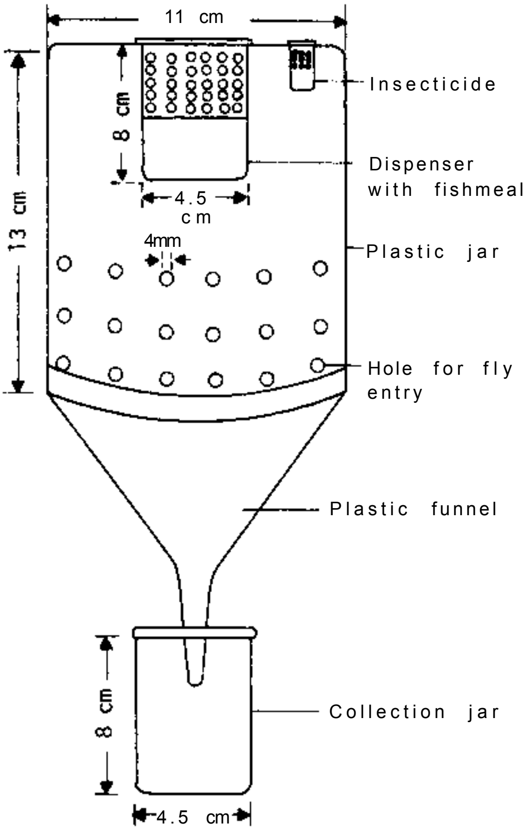

Figure 2. Design of the trap presently used at ICRISAT for monitoring sorghum shoot fly activity.

fishmeal dispenser and a vial containing a volatile insecticide. The bottom is fitted with a plastic funnel whose outlet is attached to a collection jar. The fermented fishmeal in the dispenser remains attractive for a week. In a test where the two traps were run concurrently at six locations on the ICRISAT farm for 3 months (mid-January to mid-April), the plastic trap caught as many flies as the metal one.

Results obtained from trap catches during 1977-83 (Fig. 3) indicate that the shoot fly population is very low from April through June. It increases in July and peaks in August, after which it declines gradually. As many as 32 species of shoot flies have been found in fishmeal-baited traps (Seshu Reddy and Davies 1978), and the collected flies were identified during 1977-79. The proportion of *Atherigona soccata* in the total trap catches varied considerably over time, being low during April to September (< 50%) and high from October to March (Fig. 4). The seasonal trend in *A. soccata* trap catches over 7 years (t 977-83), indicated two population peaks, one in August and another in October-November. Based on these peaks, planting of the crop can be adjusted so that the test material is exposed to sufficient insect pressure. Planting is done by the end of July and October for rainy- and postrainy-season testing, respectively.

Shoot fly infestation has been studied by planting sorghum at monthly intervals in two locations at the ICRISAT farm during 1977-79. Egg and deadheart counts were taken at 14 and 25 days after seedling emergence, respectively. In addition, fly monitoring was carried out through fishmeal-baited traps. The results have been summarized in Figure 5. The two parameters (egg laying and deadhearts) that have been used to quantify the shoot fly incidence were highly significant and positively correlated (r = 0.73). The correlation of total shoot fly catches to the A. *soccata* catches in the fishmeal-baited traps has been found to be highly significant (r = 0.84). Furthermore, there has been no significant difference in the correlation coefficients when either the total trap catches or the A. *soccata* catches were compared with egg laying (r = 0.63 and 0.61, respectively) and with deadhearts (r = 0.56 and 0.58, respectively). Thus the total catch in fishmeal traps can effectively be taken as an estimate of sorghum shoot fly population, although the proportion of A. *soccata* in the total catch did vary considerably (14 to 97%) over time (Fig. 4).

A significant and positive correlation has been found between the eggs laid and shoot fly catches in traps (r = 0.63). A similar trend has been observed between the deadhearts and shoot fly catches (r = 0.56). Environmental factors (temperature, humidity, and rainfall) tend to influence the shoot fly catches in traps as well as the damage, which is mostly a function of the fly population. Among the various environmental factors, evening humidity, maximum temperature, rainfall, and morning humidity in that order influenced shoot fly catches in the traps. The most significant factors responsible for egg laying have been the fly population and temperature (maximum and minimum), whereas variation in the deadheart formation is mostly influenced by the fly population, temperature, and evening humidity.

Knowledge of peak activity periods of shoot fly during the season enables us to plant the test material at the appropriate time so as to provide suffi-

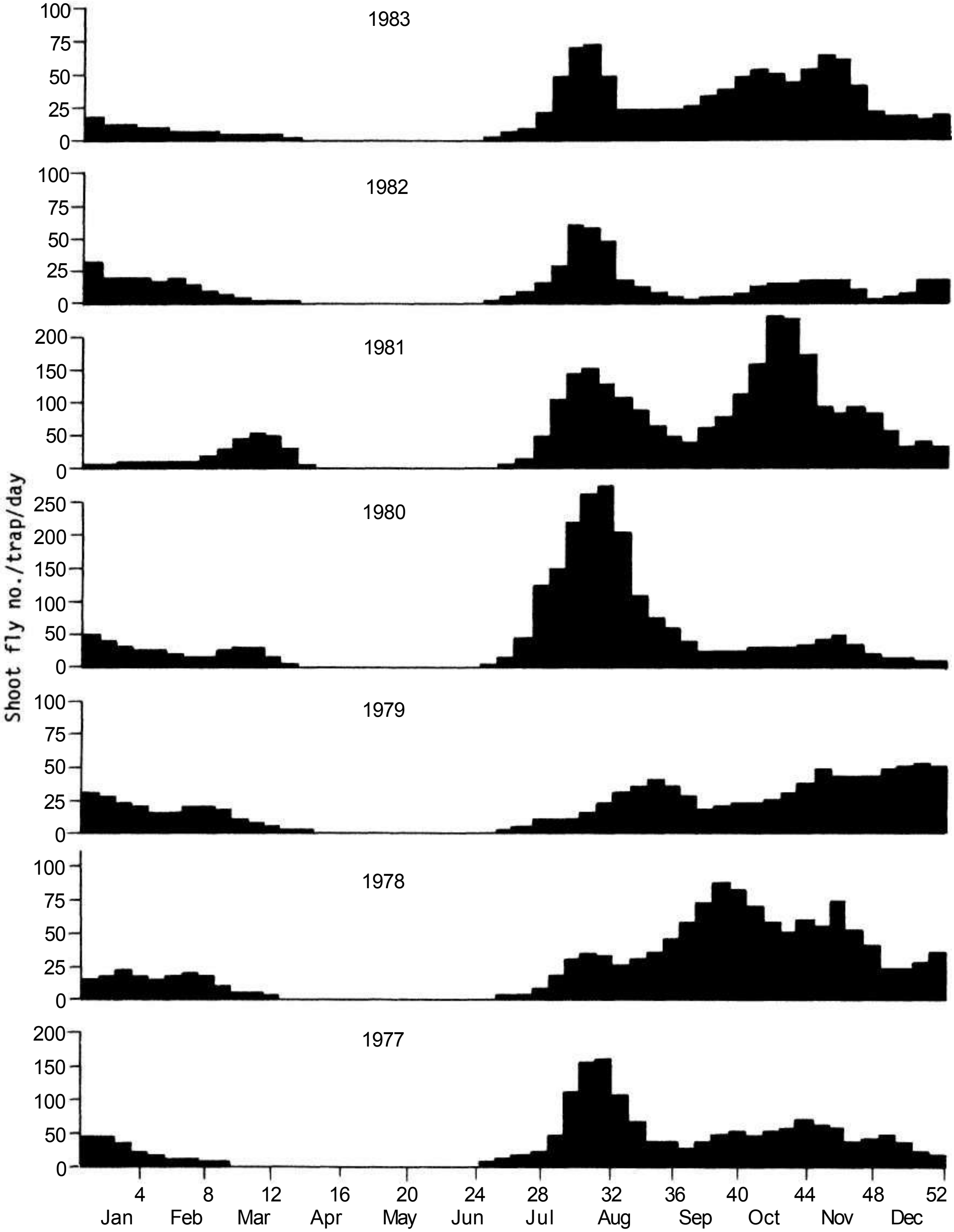

Figure 3. Shoot fly *(Atherigona soccata)* catches in fishmeal-baited traps at ICRISAT Center, Patancheru, India (1977-83).

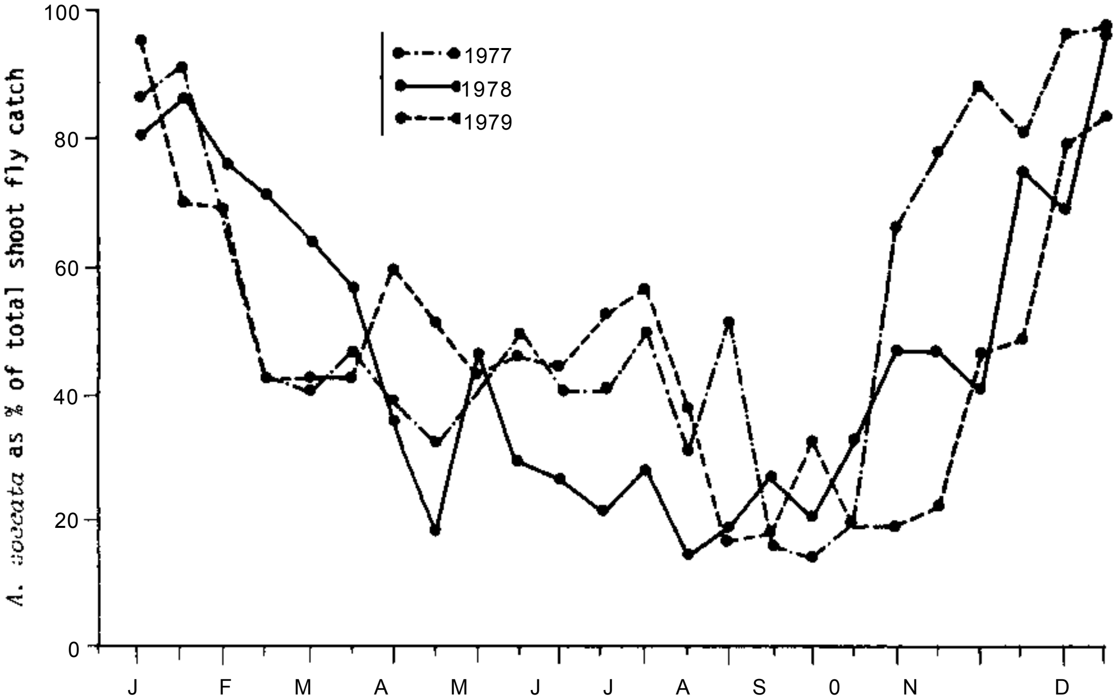

Figure 4. Proportion of *Atherigona soccata* in total shoot fly catches in fishmeal-baited trap.

cient insect pressure. However, for effective screening, it is also important to expose the material to uniform insect pressure. A field- and cage-screening technique has been developed to screen large amounts of test material rapidly.

Field-screening Technique

To ensure high and uniform shoot fly pressure under field conditions, an interlard fishmeal technique has been adopted. The interlards of a susceptible cultivar (CSH 1) are planted 20 days prior to the test material, in 4 rows, leaving 24 rows for the test material. One week after seedling emergence, fishmeal is spread uniformly in the interlards. The young seedlings and fishmeal smell attract the shoot flies, which lay their eggs on interlard seedlings. Thus one life cycle (17-21 days) of shoot fly is completed on the interlards before the test material reaches the stage susceptible to attack. To ensure uniform insect attack, fishmeal is again spread 1 week after seedling emergence of the test material. To test the insect uniformity, a susceptible control is planted at frequent intervals across the field. Our experience over the last 6 years indicates that this method provides sufficient and uniform shoot fly pressure across the field (Table 1).

Cage Technique

To confirm the resistance observed under field conditions and to study various resistance mechanisms, a cage-screening method has been adopted. This technique was earlier developed by Soto (1972) and has been modified at ICRISAT to simulate field conditions more closely. The modified version also has the advantage of requiring no artificial rearing of shoot flies.

Shoot flies used for cage screening are collected from a trap baited with fishmeal. This trap (Fig. 6) is a modified version of the plastic trap described earlier (Fig. 5) for monitoring shoot fly population. No insecticide is used in this trap. The flies after entering the trap move up into the collection jar due to their positive phototactic behavior, and the jar can be easily removed and emptied. To ensure a positive light gradient towards the collection jar, the container and the funnel are made of colored (opaque) plastic, whereas the collection jar is transparent. All shoot flies are collected every morning and evening and *A. soccata* are separated from other species. The trap-collected flies, most of which are mated females, are kept in holding cages for 1 day, with sorghum seedlings. They start laying eggs as soon as they are put inside the test cages.

The cage-screening technique can be used for multiple- as well as no-choice conditions. For a multiple-choice test, the material is planted in the

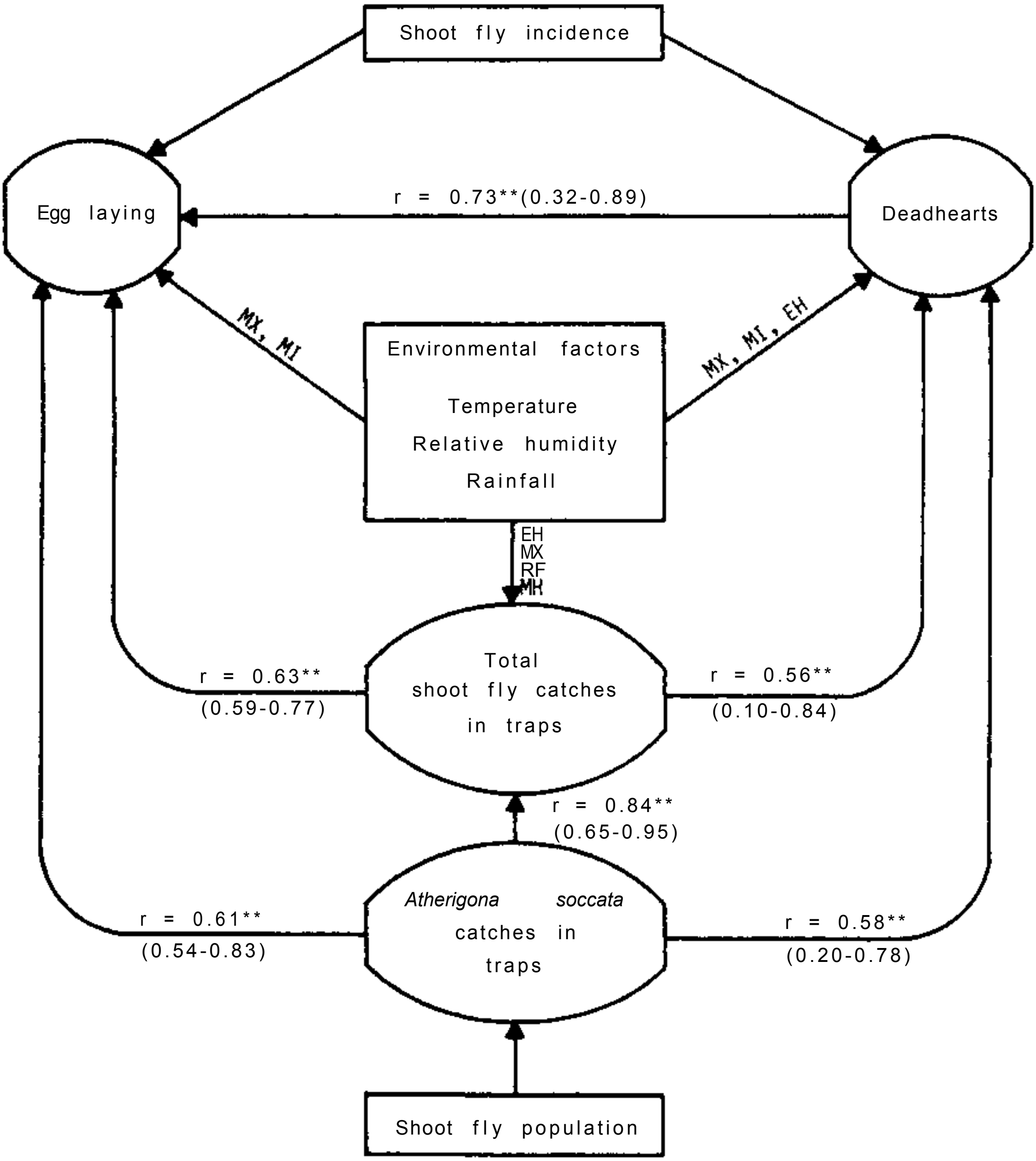

Figure 5. Interaction of factors affecting shoot fly population and damage. MX, MI = maximum and minimum temperatures; MH, EH = morning and evening relative humidity; RF = rainfall.

Table 1. Incidence of shoot fly on susceptible sorghum hybrid CSH 1 planted at frequent intervals in the field in screening sorghum for shoot fly resistance.

Season	Field	No.of CSH 1 spots in a field	Mean incidence (% dead hearts)	CV%	Probability value	Test of uniformity[2]
Postrainy 1979-80	1	10	82.8 (64.0-95.7)[1]	11.9	0.676	Uniform
Rainy 1980	1	18	92.7 (80-100.0)	8.7	0.002	Not uniform
	2	35	89.6 (75.0-100.0)	8.1	0.238	Uniform
	3	13	78.7 (54.2-100.0)	16.0	0.700	Uniform
	4	13	89.9 (76.0-100.0)	7.6	0.118	Uniform
Postrainy 1980-81	1	9	52.9 (36.7 - 70.0)	19.7	0.871	Uniform
Postrainy 1981-82	1	54	84.7 (66.7-100.0)	9.0	0.067	Uniform
Postrainy 1982-83	1	6	87.0 (76.5-100.0)	9.7	0.656	Uniform

1. Figures in parentheses show the range.
2. Using Kolmogoror- Smirnov statistic (Pearson and Hartley, 1976).

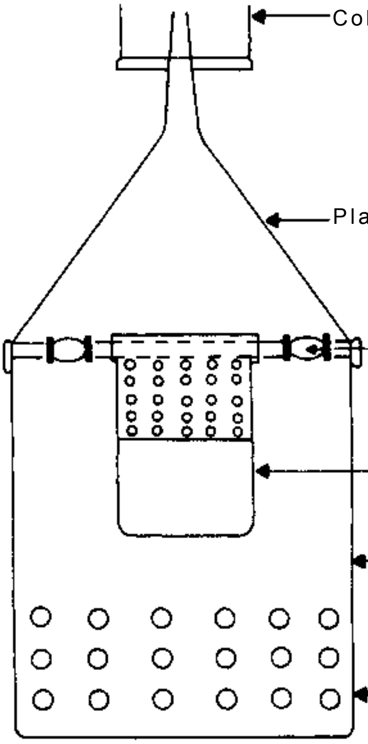

Figure 6. Shoot fly trap developed at ICRISAT to collect live flies.

field in 3.4 x 2 m beds with row spacing of 15 cm. Ten days after seedling emergence, the bed is covered with a 3.4 x 2 x 1 m screened cage; 100 trap-collected flies are released into the cage and left for 3 days (or 150 flies for 2 days). The flies lay eggs during this period, after which the cage is removed and the material exposed to natural field conditions. An egg count is taken after removal of the cage and a deadheart count is taken on the seedlings 1 week later. For a no-choice test, the material is planted in 1 x 1 m beds and caged with a 1 x 1 x 1 m cage 10 days after seedling emergence; 40 flies are released into each cage and kept for 2 days. As in the multiple-choice test, an egg count is taken after the cage is removed and a deadhead *count on* seedlings, 1 week later.

Identification of Resistance Sources

A number of sorghum lines have been reported to be resistant to shoot fly (Ghode 1971; Rao et al. 1972; Ramnath et al. 1974; Kundu and Sharma 1975; Singh and Narayana 1978; Singh et al. 1978; Lakshminarayana and Subba Rao 1975; Mote et al.

Table 2. Sorghum germplasm lines identified as less susceptible to shoot fly at ICRISAT Center, Patancheru, India.

Pedigree	Origin	Glossy	Trichomes	Shoot fly incidence (%)	
				Egg laying[1]	Deadhearts[2]
IS 923	Sudan	G	+	48.6	43.9
IS 1034	India	NG	+	35.8	36.4
IS 1057	India	NG	+	42.4	41.1
IS 1071	India	G	+	54.7	47.6
IS 1082	India	G	+	45.3	38.5
IS 1096	India	G	+	42.1	40.3
IS 1104	India	G	+	50.8	43.6
IS 2122	USA	G	+	45.5	40.7
IS 2123	USA	G	+	40.6	35.0
IS 2146	Nigeria	G	+	39.5	38.0
IS 2195	India	G	+	43.2	34.5
IS 2309	India	G	+	40.0	36.5
IS 2265	Sudan	G	+	32.4	37.5
IS 2269	USA	G	+	42.0	40.0
IS 2291	Sudan	G	+	43.5	42.7
IS 2309	Sudan	G	+	37.6	40.4
IS 2312	Sudan	G	+	43.6	43.0
IS 2394	South Africa	G	+	47.4	41.8
IS 3962	India	G	+	39.5	35.7
IS 4224	India	NG	+	42.6	40.6
IS 4646	India	G	+	41.9	39.0
IS 4663	India	G	+	46.6	38.9
IS 4664	India	G	+	38.4	33.8
IS 5072	India	NG	+	42.7	40.2
IS 5210	India	G	+	43.4	42.3
IS 5469	India	G	+	43.9	44.6
IS 5470	India	G	+	41.1	36.9
IS 5480	India	G	+	46.4	35.3
IS 5484	India	G	+	43.4	36.6
IS 5511	India	NG	+	45.4	42.7
IS 5538	India	G	+	41.4	40.8
IS 5566	India	G	+	37.0	36.4
IS 5604	India	G	+	39.0	38.9
IS 5613	India	G	+	42.5	37.6
IS 5622	India	G	+*	44.1	42.1
IS 5636	India	G	+	46.6	44.5
IS 5648	India	G	+	41.9	37.0
IS 18366	India	G	+	44.2	40.9
IS 18368	India	G	+	45.4	41.1
IS 18369	India	G	+	36.3	38.3
IS 18371	India	G	+	42.7	36.8
IS 18551	Ethiopia	G	+	36.8	31.3
CSH 1	India	NG	+	66.4	67.6
IS 1054 (Maldandi)	India	NG	+	59.1	49.9

1. Mean of 4 seasons (replicated).
2. Mean of 5 seasons (replicated).
G = Glossy; NG = Nonglossy; + = trichomas present on leaves; +* = trichomas present only on upper leaf surface.

1981; Bapat and Mote 1982a, 1982b; Salunkhe et al. 1982; Sharma et al. 1983). At ICRISAT, screening for shoot fly resistance has been carried out in the field using the interlard fishmeal technique. Of nearly 14 000 germplasm lines screened so far, 42 lines have been found less susceptible over five seasons (Table 2).

The glossy trait in sorghum appeared to be associated with shoot fly resistance (Maiti and Bidinger 1979). Four hundred and ninety-five sorghum lines exhibiting the glossy trait have been screened for shoot fly resistance in the rainy and the postrainy season under field conditions. Shoot fly incidence was higher in the rainy season (mean 83.0%) than in the postrainy season (40.2%). Twenty-seven lines showed less than 70% deadheads in the rainy season, while 36 had less than 20% deadhearts in the postrainy season (Table 3).

Stability

Stability analysis (Finlay and Wilkinson 1963) of 44 lines (42 less susceptible + susceptible and standard check) tested over five seasons indicated that five lines (IS Nos. 1054, 1071, 2394, 5484, and 18368) were quite stable across locations. Four lines (IS Nos. 2123, 2195, 4664, and 18551) showed low incidence (< 35%) as well as moderate stability (Fig. 7).

Diversity

The classification of the 42 less susceptible lines according to geographical origin showed that 32 came from India, 5 from Sudan, 3 from the USA, and 1 each from Nigeria and South Africa (Table 2).

Factors Associated with Resistance

A number of factors have been found to be associated with shoot fly resistance in sorghum; the most obvious are seedling vigor, glossiness, morphological characters, and biochemical factors.

Seedling Vigor

Any condition such as low temperature, low fertility, drought, etc., which reduces the seedling vigor of a plant makes it more susceptible to shoot fly. Fast seedling growth may prevent the first instar larva from reaching the growing tip, although leaf margins may be cut without causing deadheart. Fast seedling growth operates similarly in pearl millet resistance to shoot fly (H.C.Sharma, personal communication). As Table 4 indicates, in the postrainy season, shoot fly incidence was higher in sorghum lines that were less vigorous at seedling stage;

Table 3. Distribution of shootfly incidence on glossy sorghum lines during rainy and postrainy seasons at ICRISAT Center, Patancheru, India.

Shoot fly incidence	Postrainy 1981/1982		Rainy 1982	
(% deadhearts)	No. of lines	%	No. of lines	%
Up to 20	36	7.3	0	-
20.1- 30.0	113	22.8	0	-
30.1 - 40.1	125	25.3	0	-
40.1- 50.0	95	19.2	0	-
50.1- 60.0	68	13.7	4	0.8
60.1- 70.0	30	6.1	23	4.7
70.1- 80.0	18	3.6	91	18.5
80.1- 90.0	9	1.8	267	54.4
90.1-100.0	1	0.2	106	21.6
Grand mean over all lines				
Egg laying (%)	45.1 ± 8.6		83.7 ± 7.8	
Deadhearts (%)	40.2 ± 7.6		83.0 ± 6.5	

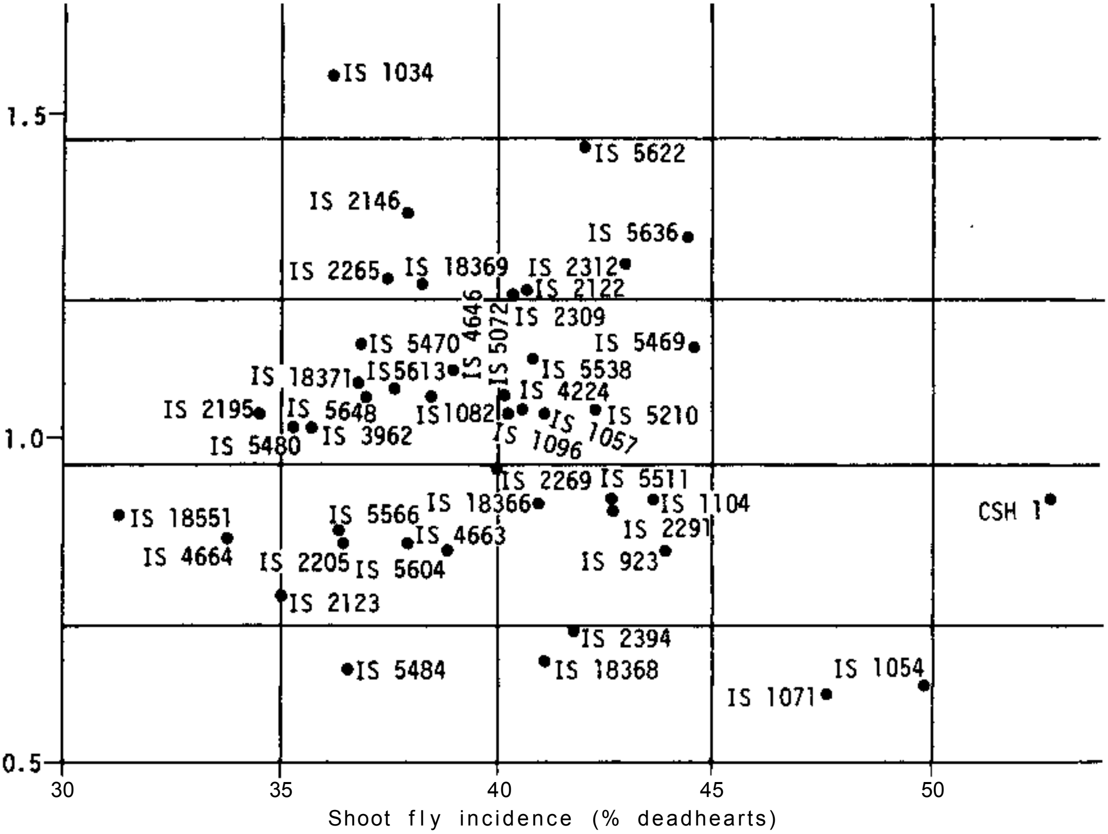

Figure 7. Stability analysis of lines less susceptible to shoot fly at ICRISAT Center, Patancheru, India, over five seasons.

however, the same trend was not observed in the rainy season. Sharma et al. (1977) and Singh and Jotwani (1980d) also indicated that height and fast growth of seedling contribute to shoot fly resistance.

Glossiness

The glossy (pale green shiny leaves) trait in sorghum has been reported to be associated with shoot fly resistance (Blum 1972; Bapat et al. 1975; Marti and Bidinger 1979; Bapat and Mote 1982b). This is also evident from the fact that most of the lines less susceptible to shoot fly (37 out of 42) exhibit the glossy character during the seedling stage (Table 2). Further evaluation of all the glossy lines for their shoot fly reaction during the rainy and postrainy seasons indicated that shoot fly incidence was higher in nonglossy lines (score < 4) than in glossy ones in the postrainy season (Table 5); however, glossiness contributed less to shoot fly resistance during the rainy season. Thus, most of the less susceptible lines are glossy, but all the glossy lines are not necessarily less susceptible to shoot fly.

Morphological Characters

Many workers have established the association of prickle hairs (short, pointed trichomes) present on the leaves and leaf sheaths with shoot fly resistance (Blum 1968; Langham 1968; Maiti et al. 1980). Three wild species of sorghum that were found to be immune to shoot fly had pubescence (trichomes) on the lower surface of the leaves, which may contribute to resistance (Bapat and Mote 1982b). The presence of trichomes on the leaves of sorghum was associated with reduced

Table 4. Effect of seedling vigor on shoot fly incidence during rainy and postrainy seasons at ICRISAT Center, Patancheru, India.

Seedling vigor score`	No.of lines	Egg laying (%)		Deadhearts (%)	
		Postrainy season	Rainy season	Postrainy season	Rainy season
1.0-1.5	37	38±7.0	83±7.0	21±6.3	82±6.0
1.6-2.0	111	39±8.0	83±7.5	22±6.2	84±5.2
2.1-2.5	71	42±8.1	84±7.1	23±6.2	82±6.6
2.6-3.0	172	48 ±8.6	84±7.5	27±7.0	84±5.4
3.1-3.5	50	51±8.5	85 ±7.4	30±7.5	84±5.8
3.6-4.0	36	53±9.7	87±5.1	31±8.1	86±5.9
4.1-5.0	15	55±10	88±6.7	33±9.4	87±6.1

1. Vigor scored on scale of 1 -5: 1 = most vigorous; 5 = least vigorous.

shoot fly susceptibility and they were the major factor, though not the only one, involved in shoot fly resistance (Maiti and Gibson 1983; Gibson and Maiti 1983). All the 42 lines less susceptible to shoot fly have trichomes on the undersurface of leaves (except for IS 5622, which has trichomes only on the upper surface) but here again not all the sorghum lines with trichomes are less susceptible to shoot fly, though all the less susceptible lines have trichomes.

Biochemical Factors

Ponnaiya (1951b) reported the presence of irregular-shaped silica bodies in the plant tissue from the fourth leaf onwards in the resistant varieties and from the sixth leaf onwards in the susceptible ones. He suggested that the relatively late appearance of these silica bodies in the susceptible varieties make them prone to shoot fly attack for a longer period. Blum (1968) found distinct differences in lignification and silica deposition; however, he was unable to establish a definite relationship between these anatomical characters and seedling resistance. Percentage *of* nitrogen, reducing sugars, total sugars, moisture, and chlorophyll content of leaf in susceptible cultivars were higher than in resistant ones (Singh and Jotwani 1980c). Lysine was present in the leaf sheath of susceptible cultivars but absent in all the three resistant cultivars tested. Lysine being an essential amino acid, its absence in the resistant cultivar may play an important role in the antibiosis mechanism. Khurana and Verma (1982) observed higher quantities of total amino acid contents in shoot fly resistant sorghum

Table 5. Effect of glossiness on shoot fly incidence during rainy and postrainy seasons at ICRISAT Center, Patancheru, India.

Glossiness score'	No.of lines	Egg laying (%)		Deadhearts (%)	
		Postrainy season	Rainy season	Postrainy season	Rainy season
1.0	129	36±8.0	82±7.5	19±5.1	81±5.7
1.1-1.4	137	45±7.6	85±7.3	25±6.7	84±6.1
1.5-1.9	119	46±9.2	84±7.1	26±7.2	85±5.6
2.0	61	53±9.9	87±5.9	31±8.3	87±4.8
2.1-3.0	31	56±8.7	87±7.1	34±8.3	86±6.3
3.1-4.0	9	68±11.2	89±6.1	43±10.6	89±4.9
4.1-5.0	15	74±7.3	92±5.8	65±6.5	84±8.2

1. Glossiness scored on scale of 1-5: 1 = most glossy; 5 = nonglossy.

lines than in susceptible ones. Susceptibility of sorghum to shoot fly was found to be positively correlated with phosphorus and negatively with total phenol content (Khurana and Verma 1983).

Resistance Mechanisms

All the three mechanisms (ovipositional nonpreference, antibiosis, and recovery resistance) suggested by Painter (1951) are known to exist in sorghum for shoot fly resistance.

Ovipositional Nonpreference

A number of workers have reported nonpreference for oviposition as a primary resistance mechanism for shoot fly in sorghum (Blum 1967; Jotwani et al. 1971; Soto 1974; Narayana 1975; Sharma et al. 1977; Singh et al. 1981; Singh and Jotwani 1980a). It has also been observed at ICRISAT that susceptible cultivars are preferred for egg laying in terms of higher number of eggs per plant and plants with eggs. Significantly higher egg laying was observed on susceptible cultivar CSH 1 over four seasons as compared with resistant cultivars under field conditions (Table 2). Under no-choice conditions, more eggs were laid on resistant cultivars, particularly IS 1082, IS 2122, and IS 2195, than under multiple-choice conditions (Table 6), which indicates the exsistence of ovipositional nonpreference under multiple-choice conditions. In another experiment where two susceptible (CSH 1 and Swarna) and two resistant (IS 2205 and IS 18551) cultivars were exposed to shoot fly in cages, resistant cultivars recorded significantly fewer plants receiving eggs and total number of eggs than susceptible ones (Table 7).

Antibiosis

Although ovipositional nonpreference seems to be the primary mechanism for shoot fly resistance in sorghum, evidence of some degree of antibiosis is also available (Jotwani and Srivastava 1970; Blum 1972; Young 1973; Soto 1974; Sharma et al. 1977) Survival and development of shoot fly was adversely affected when the pest was reared on resistant varieties (Narayana 1978). Singh and Jotwani (1980b) found that the larval and pupal periods were extended by 8 to 15 days on resistant varieties. Not only were the growth and development retarded but the survival and fecundity of the shoot fly were also adversely affected on resistant varieties. Raina et al. (1981) observed that some sorghum cultivars possessed strong antibiosis in

Table 6. Incidence of shoot fly on some sorghum lines under choice and no-choice conditions at ICRISAT Center, Patancheru, India, 1982.

Pedigree	Choice		No choice	
	Egg laying (%)	Deadhearts (%)	Egg laying (%)	Deadhearts (%)
IS 1082	53.1	292	85.3	727
IS 2122	55.4	40.7	91.3	82.1
IS 2195	63.3	50.5	76.3	73.9
IS 4663	67.0	49.0	59.3	54.5
IS 4664	41.7	36.4	55.3	36.3
IS 5470	64.4	50.0	71.7	52.2
IS 5484	48.1	41.8	72.1	58.7
IS 5566	47.7	40.5	62.8	55.3
IS 18551	57.2	42.7	51.6	44.0
PS 21171	70.1	46.7	58.6	51.3
PS 21217	48.3	32.7	54.9	40.4
PS 21318	51.1	43.8	60.8	48.3
CSH 1 (Susceptible control)	93.1	92.3	100.0	95.3
SE	±9.9	±8.2	±7.7	±6.8
CV (%)	29	30	19	20

Table 7. Egg laying of shoot fly on different cultivars under low and high insect pressure in cage conditions, ICRISAT, 1983.

Cultivar	% plants with eggs		Total eggs/plant with respect to			
			Total Plants		Plants with eggs	
	Low pressure[1]	High pressure[2]	Low pressure	High pressure	Low pressure	High pressure
IS 2205 (Resistant)	13.9(20.6)[3]	23.0(28.0)[3]	0.16	0.30	1.08	1.22
IS 18551 (Resistant)	7.8(14.6)	16.3(23.4)	0.09	0.19	1.05	1.17
CSH 1 (Susceptible)	54.1(47.5)	79.4(63.5)	0.79	1.77	1.39	2.21
Swarna (Susceptible)	27.3(31.0)	56.3(48.9)	0.33	0.96	1.20	1.72
SEm	±(2.53)	±(1.95)	±0.06	±0.08	±0.03	±0.07
CV(%)	(25)	(13)	53	29	8	13

1. Low pressure = 50 shootflies released/for 2 days.
2. High pressure = 100 shootflies released/cage for 2 days.
3. Figures in parentheses are angular transformations.

which mortality among the first instar larvae was very high and growth of the surviving larvae was significantly lower. The longevity of the female was also reduced.

Recovery Resistance

Many cultivars are able to produce side tillers after the main shoot is killed by shoot fly, which in turn can produce a reasonable yield if the plant is not attacked again. This depends upon the fly population, especially on susceptible cultivars, but there is also evidence that tillers of resistant or less susceptible cultivars are less preferred by the shoot fly for egg laying (Deeming 1972). Doggett (1972) and Blum (1972) have established the existence of recovery resistance as a secondary mechanism of resistance.

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Mechanisms of Resistance to Shoot Fly in Sorghum: A Review

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Abstract

The sorghum shoot fly is an important pest of sorghum at the seedling stage. Host-plant resistance to this pest was first reported in 1951. Many promising sorghum cultivars have since been identified through systematic screening of the world germplasm collection. This review deals with the progress made during the past 33 years in elucidation of the underlying mechanisms involved in the expression of resistance. Both ovipositional nonpreference and antibiosis have been reported for several sorghum cultivars. The role of physical and chemical factors in resistance is discussed. Study of larval and adult behavior on resistant and susceptible cultivars has provided further insight into the mechanisms of resistance. Biochemical techniques such as analysis of plant volatiles may be useful tools for resistance screening in the future.

Resume

Mecanismes de la resistance a la *mouche des pousses chez le sorgho—une recapitulation : La mouche des pousses est un important ravageur des plantules de sorgho. La resistance de la plante-hote a cet insecte fut signalee pour la premiere fois en 1951. Depuis lors, de nombreux cultivars prometteurs ont ete identifies suite a un criblage systematique de la collection mondiale des ressources genetiques. L 'auteur recapitule le progres fait au cours des 33 dernieres annees dans la mise en evidence des mecanismes profonds a la base de cette resistance. Chez plusieurs cultivars il s'agit de l'antibiose et de la non preference pour la ponte. Le role des elements physiques et chimiques dans la resistance est explique. L 'etude du comportement des larves et des adultes sur des differents cultivars resistants et sensibles a permis d'approfondir nos connaissances sur les mecanismes de resistance. Les techniques bio-chimiques telles que /'analyse des substances vegetales volatiles seront utiles pour le criblage de la resistance dans l'avenir.*

Introduction

Sorghum, *Sorghum bicolor* (L.) Moench, is an important food and feed crop, especially for subsistence farmers in the semi-arid tropics. More than 100 species of insects are known to cause various levels of damage to this crop (Young and Teetes 1977). Of these, the sorghum shoot fly, *Atherigona soccata* Rondani; stem borers, primarily *Chilo partellus* Swinhoe; and the sorghum midge, *Contarinia sorghicola* (Coquillett), cause extensive damage to seedlings, full-grown plants, and earheads, respectively. The shoot fly has been reported from almost all sorghum-growing areas of the Old World. With the introduction of newly developed high-yielding hybrids that are highly susceptible to shoot fly, the problem became even more serious (Jotwani 1981). Conventional methods for the control of shoot fly are not practical or cost effective for subsistence farmers. Resistant cultivars are a realistic alternative to chemical control, if they are able to compete economically with the commonly used hybrids and varieties.

The potential of plant breeding for pest resist-

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ance is primarily limited by the genetic variation in the host species. The first reported attempt to screen a collection of 214 sorghum lines for shoot fly resistance was by Ponnaiya (1951a). A systematic search for sources of shoot fly resistance was started in India under the All India Accelerated Sorghum Improvement Project. Results of this study, which involved the screening of over 12 000 lines, have been reported by Singh et al. (1968). Improved screening techniques to obtain high shoot fly infestations were employed at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) near Hyderabad, India, to screen the world sorghum germplasm (Seshu Reddy and Davies 1978). A number of sources for resistance were identified in both of these studies. Some of these cultivars have been evaluated in other countries, and even though none of them is immune to shoot fly attack, they show various levels of resistance. Several studies have been conducted to elucidate the mechanisms of resistance in these cultivars.

Mechanisms of Resistance

Ovipositional Nonpreference

Almost all ovipositional nonpreference studies with the shoot fly in the past were based on choice tests conducted either in the field or under greenhouse conditions. In the earliest studies on sorghum resistance, Ponnaiya (1951 a, 1951 b) and Rao and Rao (1956) did not detect any oviposition nonpreference by the shoot fly in resistant cultivars. Jain and Bhatnagar (1962) screened 196 cultivars of sorghum for shoot fly resistance in a replicated field trial and reported significantly less oviposition on resistant varieties as compared with susceptible ones. Blum (1967) and Jotwani et al. (1971) suggested that resistance to shoot fly in sorghum as observed in the field was primarily due to nonpreference for oviposition. Blum (1969b) reported that nonpreference was evident when evaluated under low shoot fly population. Singh and Jotwani (1980a) indicated that the efficacy of this mechanism was reduced under heavy shoot fly population pressure. Recently, Raina et al. (1984) studied ovipositional nonpreference on seven selected cultivars of sorghum (Table 1). Some of the same cultivars had been tested in several earlier studies. In a single-choice test, shoot fly females exhibited a highly significant nonpreference for oviposition on IS 2146, IS 3962, and IS 5613. In another test where females were given no choice for an oviposition substrate but could escape into an outer cage, ovipositional nonpreference was evident for five of the seven test cultivars. IS 2146 and IS 3962 were consistently nonpreferred for oviposition in both of the tests. However, none of the test cultivars expressed immunity to shoot fly infestation.

Table 1. Relationship of leaf trichomes to oviposition preference of the shoot fly and deadheart formation on selected cultivars of sorghum.

Test cultivar	Trichomes			Plants with eggs at 21 days(%)		Plants with dead-hearts[1] at 28 days (%)	
	No./mm^{2-}	Angle	(μ)	Maiti et al. (1980)	Raina et al. (1984)	Maiti et al. (1980)	Raina et al. (1984)
IS 5613	45.3	24.4	35.4	5	25**	24	7**
IS 2146	44.9	26.7	30.0	10	18**	6	4**
IS 3962	40.4	27.1	36.9	8	32**	18	21**
IS 2312	31.8	28.1	46.5	17	70	7	23**
IS 1082	21.1	21.6	34.6	4	65*	38	16**
IS 2195	21.1	23.0	35.1	5	59*	16	28**
IS 1054	8.5	20.3	27.0	11	78	17	41*
CSH 1	0.0			62	86	51	69

Sources: Maiti et al. (1980); Raina et al. (1984).

1. Deadheart data from Raina et al. (1984) are based on those plants that had received eggs. * and** indicate that the cultivar mean was significantly different from the control (CSH 1) mean at 5% and 1 % levels, respectively.

Blum (1968) reported the presence of silicified prickle hairs in sorghum varieties possessing seedling resistance to shoot fly but expressed doubts about their practical significance. Maiti and Bidinger (1979) reported that of about 8000 shoot fly resistant sorghum lines screened, most possessed trichomes on the abaxial surface of the leaf. Maiti et al. (1980) reported that the presence of trichomes on the leaf surface was related to a lesser frequency both of oviposition by the shoot fly and of subsequent larval damage. The relationship of trichome density, angle to leaf surface, and length to oviposition and deadheart formation is shown in Table 1. CSH 1, which is trichomeless, was significantly different from all other test cultivars for deadheart formation. However, trichome numbers appeared to play some role in imparting resistance to oviposition as the three cultivars that expressed most significant differences, all had >40 trichomes/mm^2 of leaf area.

From studies of the oviposition behavior of shoot fly, Raina (1982) reported that color, texture, and width of the sorghum leaf were important factors in selection of the oviposition substrate by the female. Soto (1974) reported that leaves of some of the sorghum cultivars resistant to shoot fly were pale green compared with the dark green color of the susceptible cultivars. Maiti and Bidinger (1979) also reported that the trichomed resistant cultivars had more erect, narrower, yellowish green, and glossy leaves. In a choice test to study oviposition behavior on resistant and susceptible cultivars, Raina et al. (1984) reported that the first landing by the female was always random. In the case of cultivars IS 2146, IS 3962, and IS 5613, the contact was very brief and did not result in oviposition. However, females did subsequently lay eggs on these three cultivars after the alternate susceptible CSH 1 plant had received several eggs. Since the shoot fly females deposit an oviposition-deterring pheromone at the time of egg laying (Raina 1981 a), it was suggested that this deterrence from CSH 1 eventually overrode the nonpreference for a resistant cultivar.

In order to determine if any emitted volatile chemical defense system existed in cultivars IS 1082 and IS 2146, capillary gas chromatographic leakograms of these two were compared with that of CSH 1 by the SIMCA method (Statistical Isolinear Multiple Component Analysis) at the Institute of Biochemical Ecology, University of Goteborg, Sweden. No significant qualitative differences were found between CSH 1 and the two test cultivars (Dr. L. Lundgren, personal communication). However, these results do not preclude the possibility that some other cultivars may emit volatiles that deter shoot fly females from oviposition. This method could provide a useful tool for rapid screening of sorghum cultivars for resistance to shoot fly.

Antibiosis

In the preceding section, we have seen that nonpreference for oviposition may work best if shoot fly females have a choice of laying eggs on a preferred cultivar grown in the vicinity of a nonpreferred one. Since this is not a practical strategy, antibiosis alone or in combination with ovipositional nonpreference would be highly desirable as an operating mechanism.

The earliest work that referred to antibiosis as a possible mechanism of resistance to shoot fly in sorghum was that of Ponnaiya (1951 a, 1951 b). He attributed this to an early deposition of irregular-shaped silica crystals in the resistant cultivar, M.47-3. Blum (1967), Jotwani and Srivastava (1970), and Lakshminarayana and Soto (see Young 1972, p. 175) observed that when seedlings of resistant cultivars were manually infested with shoot fly eggs, reduced seedling infestation was still maintained, indicating a postoviposition factor. Blum (1968) confirmed Ponnaiya's observation that plants of resistant cultivars possessed a higher density of silica bodies in the abaxial epidermis of the leaf sheaths. He also reported a distinct lignification and thickening of the walls of cells enclosing the vascular bundle sheaths within the central whorl of young leaves. Campbell et al. (1982), from their studies of the feeding behavior of the greenbug, *Schizaphis graminum* (Rondani), reported no physical differences between the sorghum cultivars in the location or extent of lignification around the vascular bundles. They further suggested that resistance probably involved natural plant products such as p-hydroxybenzaldehyde, dhurrin, and procyanidin.

As discussed earlier, most shoot fly resistant cultivars of sorghum have a high density of leaf trichomes. Based on the report that trichomeless cultivars of pearl millet accumulate more dew and stay wet longer (Burton et al. 1977), Raina et al. (1981) suggested that a similar situation in sorghum would facilitate the movement of freshly hatched larvae to the base of the central shoot. On the other hand, trichomed cultivars would tend to dry faster, making the downward journey of the larvae more difficult. This assumption is supported by evidence that higher shoot fly infestation was obtained in a greenhouse when the seedlings with eggs were sprayed with a mist of water just before egg hatch (Raina, unpublished observations).

Singh and Narayana (1978), Singh and Jotwani (1980b), and Raina et al. (1981) studied the biology of the shoot fly on susceptible and resistant sorghum cultivars. They reported that the survival and development of the shoot fly were adversely affected when reared on resistant cultivars. Raina et al. (1981) reported very high mortality among the first-instar larvae on IS 2146, IS 2312, and IS 5613. IS 2146 and IS 2312 also sustained the least growth of the larvae, with the larvae usually confined to the upper region of the central shoot. The survival rate and longevity were also significantly reduced for flies reared on IS 2146. Blum (1972) had also reported that the larvae in a resistant cultivar were usually found in the upper region of the shoot, and the growing point of these seedlings was sometimes still undamaged. In normal feeding, the larva cuts the central shoot at its base, which causes deadheart formation (Raina 1981b).

Biochemical analyses of sorghum cultivars resistant and susceptible to the shoot fly have revealed significant differences in sugars, reducing sugars, nitrogen, and certain amino acids (Singh 1973; Singh and Jotwani 1980c). Whereas the resistant cultivars contained lower concentrations of sugars, reducing sugars, and nitrogen, an essential amino acid—lysine—was altogether absent in three of the test cultivars. Woodhead et al. (1980) reported a positive correlation between high concentrations of cyanide (released by the enzymic hydrolysis of the cyanogenic glucoside, dhurrin) and phenolic acids and reduced feeding by various species of grasshoppers. Similar studies with shoot fly resistant cultivars may yield additional information regarding the role of these chemicals.

Based on the available information, it is proposed that three different factors, individually or in combination, may contribute to the expression of antibiosis to the shoot fly in sorghum: (1) trichomed cultivars hinder the movement of newly hatched larvae to the base of the shoot, (2) resistant cultivars have greater silica deposits and lignification of cells, which may restrict larval penetration to the base of the central shoot, and (3) biochemical deficiencies or the presence of chemical factors in resistant cultivars may adversely affect the development and survival of the larvae and reduce the fecundity of the resulting adults.

Tolerance

After the infestation of the main shoot by the shoot fly, most sorghum cultivars respond by producing several synchronous tillers, many of which are able to escape further attack and produce viable heads. This form of resistance has been referred to as tiller survival (Blum 1969a) or recovery resistance (Doggett et al. 1970). Blum (1972) reported that resistant cultivars of sorghum had a very high rate of tiller survival compared with susceptible cultivars. He also suggested that tiller survival was related to the rate of tiller growth, so that the faster a tiller grew, the greater were its chances of avoiding infestation. In Africa, it was reported that farmers actually preferred an initial infestation of their sorghum by the shoot fly that led to profuse tillering and subsequently a good harvest (Doggett 1972). However, tolerance can be greatly influenced by the growth conditions of the plant and thus may not always be predictable at various locations, particularly those with irregular patterns of rainfall.

During the last three decades, we have built a large inventory of sorghum germplasm and acquired basic knowledge about shoot fly biology. We need to have a better understanding of shoot fly behavior, particularly in relation to its host. Investigation of the biochemial aspects of resistance should be given more attention, particularly for known resistant cultivars such as IS 2146.

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Insect Behavior in Sorghum Resistance Mechanisms

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Abstract

An insect's behavior may be influenced by its host plant in three stages: in locating the plant from a distance it may be influenced by the appearance and I or odor of the plant. Having reached the plant, it may respond to physical and/or chemical features of the plant surface. When it pierces the plant tissues it may be affected by the chemicals released from the cells or by the physical toughness of the tissues.

Very few studies have been made of the behavior of insect pests on sorghum. There is no evidence that insects are attracted to the plant from a distance, but chemical and physical features of the plant surface are known to affect the success of Chilo partellus *larvae in reaching the whorl, and the readiness with which* Locusta migratoria *will eat the leaves. When tissues are damaged, hydrocyanic acid (HCN) and phenolic acids are produced enzymically and these affect the feeding behavior of some insects. Aphids, which probe intercellularly, do not normally encounter these chemicals, but are affected by the characteristics of the pectins forming the cell walls.*

Sorghum does not possess one key feature that endows it with resistance against insect pests; its resistance depends on a number of small characters that can vary in their expression. Insect behavior also varies, depending on the genetic constitution, physiological condition, and previous experience of the individual. Consequently, the effectiveness of any resistance developed in sorghum will inevitably vary. This is not a reason for abandoning the search for effective resistance, but emphasizes the necessity of close liaison between the insect behaviorist and the plant breeder.

Resume

***Le comportement des Insectes lie aux mecanismes de resistance chez le sorgho**: Le comportement d'un insecte peut etre influence par sa plante-hote a trois stades :(1) Dans le repdrage de la plante a une distance, l'insecte est influence par l'aspect et parfois l'odeur de la plante. (2) Arrive sur la plante, l'insecte reagit aux elements physiques et parfois chimiques a la surface de la plante. (3) Lorsqu'il perce les tissus de la plante, ilsubit l'effet des produits chimiques liberes par les cellules ou bien de la durete physique des tissus.*

Il existe tres peu d'etudes sur le comportement des ravageurs vis-a-vis les plantes de sorgho. Iln'y a pas d'evidence que la plante exerce une attraction a une distance. Il est pourtant connu que les elements chimiques et physiques a sa surface influencent le passage des larves de Chilo partellus *allant vers le verticille, et la predilection de* Locusta migratoria *pour les feuilles. Lorsque les tissus sont endommages, les enzymes produisent les acides cyanhydrique et phenique qui affectent le rhythme d'alimentation de certains insectes. Les aphides qui rongent entre les cellules ne rencontrent pas normalement ces acides, ils sont plutot influences par la nature des pectines elaborees dans les parois cellulaires.*

La resistance du sorgho aux ravageurs n'est pas fondee sur un seul element particulier, elle englobe plusieurs petits caracteres d'expression variable. Le comportement des insectes varie egalement selon la constitution genetique, la condition physiologique et /'experience acquise par l'individu. Par consequent, l'efficacite de toute resistance chez le sorgho est sujette a des variations.

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Loin d'etre une raison pour abandonner la recherche d'une resistance efficace, ceci accentue la necessite d'une collaboration etroite entre l'entomologiste qui etudie le comportement des insectes, et le phytoselectionneur.

Introduction

Plant resistance that depends on nonpreference by the insect pest is effected by mechanisms which alter the behavior of the insect in a way favoring the plant. Resistance depending on antibiosis also has a behavioral component, although commonly acting primarily on the insect's physiology (Painter 1951). Yet, despite the obvious importance of insect behavior, it has been almost totally neglected by entomologists and plant breeders alike in studying and developing resistant crop varieties.

In this paper the aim is to review briefly the existing work on the behavior of insect pests of sorghum in relation to the plant, and to consider how this knowledge helps to understand resistance. Only those pests which attack the vegetative parts of sorghum are considered. Finally, the practical role of insect behavior studies is discussed.

Behavior in Relation to Plant Resistance

The insect interacts behaviorally with its host plant in different ways, which can be regarded as successive stages in a hierarchical system. The first, arrival on the plant from a distance, may be the result of specific attraction, or of a random process, as it is in some aphids. Some plants produce odors which repel insects. This invasive stage involves the olfactory and visual senses of the insect.

The second stage concerns the response of the insect to the surface properties of the plant. Contact chemoreception and mechanoreception are probably the principal senses involved, although olfaction may also be important. The plant tissues remain undamaged, and one might expect many effective defense mechanisms, especially against disease vectors, to operate at this stage.

Finally, the insect pierces the tissues of the plant, usually in order to begin feeding, but sometimes, as in Delphacidae, to lay eggs. At this stage the insect is exposed to a new range of chemicals. These may be phagostimulatory, they may have no effect on the insect, or they may be deterrent. A complex array of chemicals is already present in the plant cell, but others may be produced by enzymic action when the tissues are damaged and by oxidation of precursors exposed to the air. In sorghum, hydrocyanic acid (HCN) is produced by hydrolysis of the glucoside, dhurrin, and phenolic acids are derived from phenolic esters. It is probably at this stage, too, that the insect first encounters the factors conferring hardness or toughness on the plant. The insect responds behaviorally, by continuing to feed or by being deterred from doing so. If it continues to feed, its physiology will be affected, and this, in turn, will influence its subsequent behavior.

Thus the failure of an insect to establish itself on the plant, known as nonpreference by those concerned with varietal resistance, can be a consequence of factors operating at any one or all of these three stages. Antibiosis, in the case of sorghum, only operates after the insect is established on the plant.

Attraction from a Distance

There is no information about attraction of pest insects to sorghum; attraction is not even known to occur. Arrival on the plant may be the result of a random process.

The shoot fly, *Atherigona soccata* (Rondani), is attracted by decomposing fishmeal (Reddy et al. 1981) as well as by ammonium sulfide and skatole, but how, if at all, this relates to the host plant is not clear. Reddy et al. (1981) found that deadhearts caused by *A. soccata* were attractants in one experiment, but not in another (see their Table 3) and it is inferred, since mainly females are attracted, that the behavior relates to location of the host plant for oviposition. However, *A. soccata* normally oviposits on healthy plants, and the attraction to fishmeal is probably related to feeding on protein for vitellogenesis rather than to oviposition. Reddy et al. (1981) indicated that most of the flies which are attracted are immature and suggest that attraction varies with the vitellogenic cycle. Variation in protein hunger in relation to vitellogenesis is known to occur in other Muscidae (Dethier 1976).

Fewer eggs are laid by *A. soccata* on sorghum cultivars that are pale green in color (Jotwani 1981). Although there is no firm evidence on this species, it is known that other species of fly are attracted differentially to their host plants by differences in spectral reflectance patterns from the leaf surface (Prokopy and Owens 1978). Singh and Jotwani (1980) showed that in 17- and 24-day-old plants, the number of eggs laid was correlated with the percentage of chlorophyll in the leaves, but it is not known if the choice is made before or after the insect alights on the leaf.

Behavior on the Plant Surface

Once on the plant, insects can often determine its suitability as a host from the physical and chemical characteristics of the surface parts. There is evidence that this is the case with some of the sorghum pests.

Shoot Fly

The sorghum shoot fly, *A. soccata,* is relatively specific to sorghum (Davies and Reddy 1981) and females withhold egg laying when presented other grass species (Ogwaro 1978). The inference is that sorghum exhibits some specific characteristics that are perceived by the fly at, or close to, the plant surface that stimulate oviposition.

Ogwaro (1978) describes the shoot fly probing at the leaf surface with its legs and ovipositor in the process of host selection. There are only a few chemoreceptors on the ovipositor, but contact chemoreceptors and basiconic sensilla, presumably with an olfactory function, and numerous mechanoreceptors are present on the tarsi (Ogwaro and Kokwaro 1981). Consequently, the insect has the capacity to respond to physical and chemical features of the plant surface. We do not know of any surface features that are specific to sorghum. Woodhead (1982) showed that unusually large amounts of p-hydroxybenzaldehyde are sometimes present in the surface wax of young sorghum plants, but there is no evidence linking this to shoot fly behavior.

The amount of oviposition by *A. soccata* on different sorghum cultivars is reduced when there are large numbers of trichomes on the leaf (Maiti et al. 1980), but no behavioral studies have been conducted to show that trichomes interfere with fly behavior.

Stem Borer

In contrast to A *soccata, C. partellus* is nonspecific in its oviposition behavior, readily laying eggs on inert materials in cages (Roome et al. 1977). Nevertheless, if plant leaves are present, they are preferred, so clearly there is some measure of recognition and preference. The physical characteristics of leaves are particularly important. Brown, dry leaves are preferred to green, turgid leaves, and when offered a range of wire mesh screens to lay on, the insects oviposit preferentially on fine gauze. As a preliminary to oviposition the insect touches the leaf surface with its antennae and tarsi as well as the ovipositor, which is well-endowed with mechanoreceptor hairs (Chadha and Roome 1980).

The eggs of C. *partellus* are usually laid on lower leaves of sorghum, often near the base of the plant, while the first-instar larvae feed only in the whorl. The newly hatched larvae consequently have to move into the whorl from the site at which eggs were laid. During this phase of the life history larvae are influenced by the surface features of the plant.

Larval movement up the culm is a positive phototactic response to the light sky, but the rate of climbing is influenced by the cultivar and plant age. An extensive bloom of wax on the culm physically interferes with climbing, as the wax filaments become entangled with the prolegs so that the insect has difficulty in maintaining a purchase. If the wax is wiped off the plant the speed of climbing is increased (Bernays et al. 1983). A heavy wax bloom partly accounts for the reduced ability of larvae to establish on older plants of cv IS 1151 in dry weather, when this cultivar is more resistant than the less waxy cv IS 2205 plants of similar age. In wet weather, the wax is washed off and the relative susceptibilities of the cultivars are reversed. The chemical nature of the surface wax also affects larval climbing behavior. Wax on young plants of cv IS 2205 plants interferes with the phototactic response, often causing a larva to stop, "search," wander in circles, or reverse direction. Waxes from the susceptible cultivars IS 1151 and CSH 1 do not affect larval behavior in this way (Woodhead et al. unpublished).

The success of newly hatched larvae in reaching the whorl is greatly influenced by the morphology of the host plant. The phototactic response to the light sky does not give a precisely vertical orientation and the insect does not readily distinguish vertical from near-vertical surfaces. Consequently, on plants with stiff, upright leaves, the larvae often move up the abaxial surface of a leaf instead of continuing to climb up the culm. A return to the culm demands a reversal of phototaxis, and experiments with leaf models show that the chemistry of the wax and the physical nature of the leaf edge are Important. The climb reversal normally occurs when the insect reaches a leaf edge and moves on to the adaxial surface. On a model with unsuitable or with no wax, or the leaf edge reversed so that the spines point downwards, the insect usually fails to reorientate (Bernays et al. in press).

A difference in the erectness of the leaves does correlate with the difference in susceptibility between young plants of cv IS 1151 and cv IS 2205. More larvae become established on the former, partly because a higher proportion move out on to the more erect leaves of cv IS 2205 plants and fail to find their way back to the culm. Often, they leave the plant on a silken thread (Bernays et al..1983).

The movement of the larva up the culm is also hindered by anatomical complexity at the leaf base or, especially in older plants, by damage at the junction of the leaf blade and sheath. On some plants, the leaf bases are curled down at the edges, producing pockets into which larvae wander, sometimes becoming trapped for long periods. Hairs in the leaf axil, which collect debris, also hinder larvae returning to the culm from an excursion on to a leaf blade. Such small anatomical features reduce the success of the larvae in reaching the whorl (Bernays et al. 1983). These anatomical features become especially important in older plants, where the distance to be travelled is greater and more obstacles are encountered.

An insect on the surface of the plant is also exposed to the vagaries of the weather. Hatching in early morning ensures that insects avoid making the climb during periods of excessively high temperatures, and the principal problems the larva has to contend with are rain and high winds. Winds are commonly slack early in the morning, but increase as the temperature rises. The higher the windspeed, and the more gusty it is, the greater the chance that the insect will be blown off the plant. At speeds of 4 m/s and above, it is common for over 50% of the insects to be blown off a plant. The effect varies among cultivars, reflecting different surface properties of the plant. On older, waxy cv IS 1151 plants, on which the insects find it difficult to get a grip, larval loss at high windspeeds is about 90%.

Insects tend to take longer to reach the whorl during wet conditions, sometimes becoming trapped in water drops, especially at the leaf axils. Sometimes this results in a considerable reduction in the ultimate success of the insects reaching the plant whorl.

Grasshoppers

These occasional pests of sorghum differ from *Chilo* larvae in being much more mobile and thus frequently faced with the necessity of determining the acceptability of a newly encountered plant. As a grasshopper which is about to feed moves over a plant surface, it repeatedly touches the leaf surface with the tips of its maxillary and labial palps. These palps bear large numbers of contact chemoreceptors which have the capacity to perceive and distinguish between, plant surface waxes (Blaney and Chapman 1970). Many nonhost plants are recognized by grasshoppers by the quality of the surface wax and are rejected without further testing. Young sorghum causes this response and Woodhead (1983) found that 80% of the third instar nymphs of *Locusta migratoria* rejected 10 cm high sorghum following palpation. Woodhead (1982, 1983) showed that this response is mediated by a number of chemicals. p-Hydroxybenzaldehyde is an unusual component of the wax of some sorghum cultivars and can be present at levels deterrent to *Locusta.*

Of the more usual wax constituents, Woodhead (1983) found that n-alkanes with 19, 21, and 23 carbon atoms from cv 65 D sorghum were deterrent, while other n-alkanes between C 18 and C 28 had no effect on feeding. The ester containing a C 12 fatty acid was deterrent, while that with C 22 acid was not. None of the free fatty acids, alcohols, or aldehydes present in the wax had any effect on larval feeding. Differences in surface waxes may contribute to cultivar differences in resistance to attack by grasshoppers. Atkin and Hamilton (1982) found that the major alkanes in the surface waxes of cvs CSH 1 and IS 1082 sorghums were C 27, C 29, and C 31. These did not deter feeding, unlike the shorter-chain alkanes present in wax of cv 65 D sorghum.

Behavior Influenced by Internal Constituents of the Plant

Shoot Fly

After hatching, the larva of *A. soccata* moves down the leaf blade and down the culm within the outer sheaths, finally boring into the growing point. On some resistant cultivars a larva is unable to bore into the center of the culm and dies at the base within the leaf sheath (Blum 1967). These resistant cultivars are characterized by extensive lignification of ceils round the vascular bundles and by very large numbers of silica bodies in the epidermis. Blum (1968) inferred that these features form a physical barrier which prevents the larvae from penetrating to the center of the culm. Ranking the six cultivars examined by Blum (1967) gives a suggestive correlation between resistance and physical plant characters.

Stem Borer

Field experiments by Woodhead et al. (1980b) showed that damage to the whorl leaves of sorghum by first instar larvae placed directly into the whorl was inversely correlated with the amount *of* HCN produced when *the* leaves were crushed. There was *no* correlation with phenolic acids which are produced in a similar way and which are known to deter feeding by grasshoppers. No experiments relating the behavior of C. *partellus* larvae to HCN or to phenolic acids produced by sorghum have been conducted.

Grasshoppers

Locusta migratoria is stimulated to feed primarily by sugars in the plant which are present in dry weight concentrations well within the range producing maximum stimulation (Bernays and Chapman 1978; Woodhead and Bernays 1978). A few amino acids and phospholipids are also weak phagostimularrts. HCN, which is released when the tissues are crushed, is known to be a respiratory poison, but it was shown that L *migratoria* behaviorally responds to the acid. A cannula, 0.6 mm external diameter, was implanted through the labium of a fifth instar larva so that it opened into the cibarial cavity. It was long enough to allow the insect free movement. Such insects, deprived of food for 5 h, were allowed to start feeding and after 2 min, 3 to 5µl of HCN solution was injected into the cibarial cavity. All concentrations above 0.1 mM caused an immediate cessation of feeding; higher concentrations had a marked repellent effect, causing the insect to back away. Similar behavior was sometimes observed when the insect bit plants with high cyanide release rates (Woodhead and Bernays 1978). The overt behavior is a response to the HCN released at the time of the bite and it may not necessarily be related to the quantity *of* cyanogenic glucoside present, as Bernays et al. (1977) found with the grasshopper *Zonocerus variegatus* feeding on cassava, *Manihotesculenia.* Dhurrin, the cyanogen in sorghum, does not influence feeding at the concentrations at which it occurs in the plant.

L migratoria feeding is also deterred by the chemical fraction of sorghum containing phenolic acids. Several phenolic acids are produced when the plant tissues are crushed (Table 1). The individual acids have no effect at the concentrations at which they occur in the plant, but Adams and Bernays (1978) showed that their effects were additive and that collectively they were deterrent. Moreover the deterrence due to the phenolic acids was additive with that produced by other components, such as HCN.

Production *of* HCN and phenolic acids declines steadily as plants get older. Where p-hydroxybenzaldehyde has been detected on the leaf surface, it is also more abundant in the early plant growth stages. These features are common to a wide range of cultivars (Woodhead et al. 1980a; Woodhead 1982), though other patterns do occur. Direct experimental evidence is lacking, but Woodhead and Bernays (1978) found that extracts of young sorghum which included these components were feeding deterrents for *L migratoria,* while the comparable extracts from older plants were not. There is a close correspondence between the decline of these components in the plant and the increase in feeding by the insect. Woodhead et al.

Table 1. Chemicals from sorghum cv 65D that are feeding deterrets against *Locusta migratoria.*

Chemicals in the surface wax	Chemicals produced by crushing the tissues
p-hydroxybenzaldhyde	HCN
C_{19} n-alkane	p-hydroxybenzoic acid
C_{21} n-alkane	Caffeic acid
C_{23} n-alkane	Ferulic acid
Ester of C_{12} fatty acid	p-coumaric acid
	o-coumaric acid
	Gentisic acid
	Vanillic acid

Sources : Woodhead and Bernays (1978); Woodhead (1982, 1983).

(1980b) showed, with 24 cultivars grown In the field, that those producing high levels of phenolic acids were never eaten in large quantities by L *migratoha* or *Acrida exaltata.* In these experiments HCN appeared to have no marked effect, but it was never produced in large amounts. General damage by leaf-feeders, primarily grasshoppers, to the same cultivars in the field was also inversely correlated with phenolic acid and, less strongly, with HCN production.

Oriental Armyworm

Other insects which crush the tissues in the same way as *L. migratoria* are likely to encounter the same chemicals, but they do not all respond in the same way. Larvae of *Mythimna separata* distinguish between sorghum cultivars in the amounts they eat, but the amounts are not correlated with HCN or phenolic acid levels (Woodhead et al. 1980b); no other constituents of sorghum have been examined in this context.

Shoot Bug

The shoot bug, *Peregrinus maidis,* will feed from parafilm sachets containing sucrose. The addition of 1.0 mM HCN to a 10% sucrose solution has no effect on the form of the salivary sheaths produced in the sachet; they remain short and unbranched, just as in sucrose alone; however, the initial probe lasts for a longer time and much less honeydew is produced over a 17-hour period (Fisk 1980). A possible interpretation of these apparently conflicting results is that P. *maidis* does not respond behaviorally to cyanide, but it becomes poisoned as a result of ingestion. Perhaps the relatively small amount of damage produced by P. *maidis* (in comparison with chewing insects) as it probes in a plant causes only a small amount of HCN production, since there was no correlation between number of insects and HCN levels in the field (Woodhead et al. 1980b) and it is known that 0.2 mM HCN in 10% sucrose has no effect on feeding (Fisk 1980).

As with *L migratoria,* the individual phenolic acids produced in sorghum had no effect at naturally occurring concentrations, but effects were additive and honeydew production over 17 h was reduced by a mixture of phenolic acids in proportion to tne total concentration. The phenolic esters, from which the phenolic acids are derived in the plant, also caused the insect to produce long, branched sheaths in feeding sachets. Examination of salivary sheaths in sections of leaf tissue showed that the amount of branching was proportional to the concentration of phenolic acids produced when the leaf was crushed and the number of unbranched probes ending in the phloem was lower in plants with higher phenolic acid levels (Fisk 1980). Thus, it appears that the production of high phenolic acid levels in the parenchyma interferes with the capacity of the insect to locate the phloem.

In field observations on one sorghum cultivar P. *maidis* invaded plants less than 20 cm tall, but the insects were never present on two successive days and no eggs were laid. By contrast, all plants more than 40 cm tall were colonized by 29 days after emergence, and eggs were laid on all of them (Fisk et al. 1981). Older plants have lower phenolic acid levels than young plants and it is a fair inference that seedling sorghum gains a measure of resistance against P. *maidis* by virtue of the high level of phenolic acids produced when tissue is damaged. Field-grown sorghum cultivars with high levels of phenolic acids were only infested by low numbers of P. *maidis,* but the converse was not true (Woodhead et al. 1980b).

Aphids

The behavior of biotype C *Schizaphis graminum* on sorghum has been monitored by measuring voltage fluctuations in a current passing through the plant and the aphid (Campbell et al. 1982). About half of each 180-min test period involved aphid salivation and sheath formation. Dreyer and Campbell (1984) found that on susceptible cv BOK 8 sorghum, the average time for aphids to reach the phloem was 114 min from the start of probing. Once the phloem was reached the insect continued to ingest uninterruptedly, sometimes for more than 12 h(Montllor et al. 1983).

S. *graminum* probes between epidermal cells and probably does not generally penetrate cells in the parenchyma, probing between them through the middle lamellae. This is achieved partly through the activity of pectinases in the saliva. Campbell et al. (1982) found considerable differences in the probing behavior of biotype C S. *graminum* on susceptible and resistant sorghum cultivars. On the resistant cultivar, more frequent probes were made with short periods of ingestion and the total period of ingestion from the phloem did not exceed 6 min in a 3-hour recording period. By contrast, on the susceptible cultivar, relatively few probes were made and these were associated with a prolonged period of phloem-feeding. This behavior is consistent with chemical deterrence in the resistant cultivars, but nothing is known concerning differences in possible deterrent chemicals in the resistant and susceptible cultivars. Evidence does exist for a different type of resistance mechanism in relation to differences in the behavior of biotypes C and E. Cultivar IS 809 is resistant to biotype C, while cv BOK 8 is susceptible. Both cultivars are susceptible to biotype E. Dreyer and Campbell (1984) suggest that the resistance of cv IS 809 results from a high percentage of methylesters in the pectin and biotype C greenbug is relatively deficient in pectin methylesterase. Biotype E, however, has a high methylesterase activity and hydrolyzes cv IS 809 pectin at twice the rate of biotype C. In this case, resistance appears to be a quality of the middle lamellae and the low level of activity of an appropriate digestive enzyme.

Although aphids probe intercellularly, there is some evidence that they ingest non-phloem liquids in the mesophyll (Campbell et al. 1982). Todd et al. (1971), Dreyer et al. (1981), Dreyer and Jones (1981), and Rose et al. (1981) have shown that feeding by S. *graminum* on artificial diet through a parafilm membrane is reduced by a range of different compounds (phenolics, flavonoids, and diterpene acids). Some of these, such as p-hydroxybenzaldehyde and dhurrin, are known to occur in sorghum. Whether or not these compounds have any effect on cultivar resistance depends on the damage produced during probing, but since dhurrin occurs within the vacuoles of epidermal cells while the aphid probes between the cells, this compound, at least, is unlikely to be relevant.

Woodhead et al. (1980b) recorded that the abundance of *Rhopalosiphum maidis* on 24 cultivars of sorghum in the field was not related to the production of HCN or phenolic acids. This lack of effect would be expected if the aphid penetrates the plant intercellularly as Kimmins (1982) indicates. However, Al-Mousawi et al. (1983) found that S. *graminum* does damage mesophyll cells when feeding on wheat. Kimmins found that aphid salivary sheaths in young sorghum plants often did not pass directly to the phloem, some branches ending in the mesophyll and bundle sheath regions. Experiments in which the leaf tissue was infiltrated with sucrose suggested that the insect may be responding to chemicals in the intercellular spaces.

Variations in Behavior

The responses of insects are very variable and while there is relatively little information concerning variation in response to sorghum, there are a number of pointers. Conditioned learning may play an important role in the early stages of host-plant selection, though there is as yet very little good evidence for this. Blaney and Winstanley (1982) showed that *L migratoria* learned to recognize the surface properties of nonhost plants after experiencing deterrence by the internal chemicals due to biting. On sorghum, Woodhead and Bernays (1978) observed that L. *migratoria* rejected young plants after palpating the surface, following one or more bites. The insects apparently associated the quality of the leaf surface with the deterrent effect of the chemicals released on biting.

Montllor et al. (1983) showed that when biotype C *Schizaphis graminum* was conditioned to the resistant cultivar IS 809 for 1 to 3 days, the aphids reached the phloem and started a sustained period of ingestion more quickly than unconditioned aphids. Fewer probes were made during a period of 24 h and the behavior became similar to that on a susceptible cultivar. But despite this, the aphid did not fully adapt to the cultivar, and size, longevity, and fecundity were much lower than for aphids on a susceptible cultivar.

The physiological state of an insect is well known to affect its response to food quality (see e.g. Bernays et al. 1976). Woodhead (1983) observed that the percentage of *L migratoria* rejecting sorghum following palpation declined when the insects were without food for 4 to 6 h.

Insect age may also be important and, whereas third instar nymphs of *L. migratoria* are deterred by 0.25% dry weight of p-hydroxybenzaldehyde, fifth instar nymphs are unaffected below l.0% dry weight (Woodhead 1982).

Finally, there are genetic differences between insects. In all the work on the behavior of insects on sorghum the results are based on average performance; individual variation is neglected, though it is potentially of great importance. Genetic variation becomes of obvious importance in the development of biotypes. There are five known biotypes of *Schizaphis graminum.* Biotype E feeds and reproduces on cultivars resistant to biotype C (Porter et al. 1982). It is probably able to do this because it possesses a more active pectin methylesterase, which enables it to reach the phloem more quickly (Dreyer and Campbell 1984).

Variations in the Plant

In addition to variations that occur between cultivars and in relation to plant age, the expression of any character conferring resistance on a plant may vary with the environmental conditions. It is well known that levels of HCN production by sorghum are affected by weather. Reports on the effects of moisture stress are conflicting (Hogg and Ahlgren 1963), but it is generally concluded that drought conditions increase the HCN content of plants. These workers also reported a positive correlation between temperature and cyanide content, but no regular diurnal variation in HCN levels. Woodhead (1981) has also shown that 5-fold differences in phenolic acid production by a single cultivar can be induced by different growing conditions, and damage by insect pests and pathogens usually causes the levels to increase. The accumulation of wax bloom on the culms of older plants of cv IS 1151 sorghum is prevented by rain, making the plant more susceptible to *Chilo partellus* (Bernays et al. 1983), also morphological features may be affected by environment.

As a consequence of such variation in the expression of factors conferring resistance on the plant, the amount of protection afforded will also vary. Woodhead et al. (1980b) obtained only weak correlations between HCN levels and damage by leaf-chewing insects to 24 cultivars in the field but in none of the cultivars did the concentration reach the level known to have an effect on feeding by *Locusta migratoria.* Deterrence was hardly to be expected in these circumstances, but it would be wrong to conclude that HCN never provides an important defense for sorghum plants, even of these same cultivars.

The Practical Value of Behavior Studies

Detailed studies of insect behavior of the type outlined in this review provide an understanding of how plant resistance to insect attack works. Does this really have any practical value? Plant breeders can, after all, produce highly effective resistant cultivars without this knowledge.

Even the sparse information already available to us can be of value in a variety of ways, from immediate help with the production of new cultivars, to long-term considerations of the kind of resistance that should be developed and how it should be used. The immediate practical impact should be in providing plant breeders with screening techniques which are appropriate to the pest of concern. In the slightly longer term, behavioral studies that define critical resistance mechanisms can provide plant breeders with a basis on which to focus their attention, reducing the burden of mass screening and maximizing the use of their expertise.

The information now available indicates that sorghum is not characterized by any key chemical providing plant defense against insect attack. Rather, resistance results from a number of different features (Table 1). Because of the different behavior patterns of the various pests, the features that confer resistance vary with the pest (Table 2). Hence, we should not expect to find any simple gene-for-gene relationship between the insect and its host plant as is believed to occur in some other cases. As a result, it is unlikely that, at the present time, a very high, stable level of resistance can be achieved. Varietal resistance in sorghum is likely to remain very much a relative phenomenon. This is not entirely disadvantageous, since the diversity of resistance mechanisms does give the plant breeder the capacity to develop series of resistant lines with different resistance mechanisms. This is of critical importance in discouraging the evolution of adapted insect populations or biotypes.

The work of Woodhead and Bernays (1978) illustrates one other important point. The plant may possess features of potential value as defense mechanisms which are present in amounts too low to be effective. In normal screening programs such material would be discarded; only behavior studies show that there is a resource which could provide a useful defense. So potentially valuable genetic resources can be conserved and possibly enhanced by breeding.

However, given the complexity of the situation and the known variability in the expression of resistance-conferring characters, one might ask, "Is the development of effective varietal resistance in sorghum a practical proposition?" Experience with *Schizaphis graminum* suggests that the

Table 2. Characteristics of sorghum which confer resistance against different pest insects.

Insect	Behavior affected	Sorghum characteristic
Atherigona soccata	Oviposition	Leaf color ?[1]
		Abundance of trichomes
	Penetration of culm	Silica bodies in epidermis ?
		Lignification round vascular bundles ?
Chilo partetlus	Establishment of larva	Wax, physical and chemical properties
		Microanatomy of leaf axil, edge of leaf blade
		HCN?
Schizaphis graminum		Chemistry of middle lamellae
		Secondary chemicals if cells damaged
Peregrinus maidis	Feeding	Phenolic acids
Acrididae	Feeding	Wax, chemical properties
		HCN
		Phenolic acids

1. ? indicates correlation, but not proved experimentally.

answer is, "Yes, it is." In other cases the answer at present is equivocal. Cultivars certainly do differ in their susceptibility to insect pests, but it is a common experience that high levels of resistance are not consistently obtained. Given the lack of key resistance factors and the variability of both plant and insect, which behavior studies indicate, this should come as no surprise. It seems highly unlikely that consistently high levels of resistance are obtainable at the present time. This is not to suggest, however, that useful levels of resistance cannot be achieved. Experience already shows that they can, with *Atherigona soccata* for instance, but perhaps expectations might have to be modified. It may be that the lack of understanding of the interactions between insects and the sorghum plant has led us to strive for the unattainable. A really close liaison between entomologists and plant breeders is essential if realistic goals are to be set and achieved.

In the long term, there is no doubt that long-lasting, effective varietal resistance will be achieved and that the study of insect behavior has a key role. There is enormous potential for hybridization and genetic engineering in the production of resistant plants. This will involve the transfer of characters which are known to produce absolute levels of resistance, and this will be possible only when we know enough about the behavior of the pests, on host and nonhost plants, to provide guidance for the work of the geneticists. At present our knowledge of pest behavior is inadequate to support the development of rational breeding strategies based on an understanding of resistance mechanisms. Priority must be given to this area if varietal resistance is to be exploited fully in the future.

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Biology and Control of the Greenbug Attacking Sorghum

K.J. Starks and Z.B.Mayo, Jr.*

Abstract

The greenbug, Schizaphis graminum *(Rondani), has been present in the Great Plains of the USA for about 100 years, but was not a key pest of grain sorghum until 1968, when a* **new** *biotype became predominant. Overwintering of the pest is by parthenogenetic females, and each year northern areas are reinfested by alate individuals carried by jet winds. When small grains or grasses become nonpreferred hosts, infestations move to sorghum. On sorghum, a wingless female greenbug reaches reproductive maturity in about a week and gives birth to about 80 young during the next 3 weeks. During the feeding process, a toxic substance is injected into the plant. Damage progresses upward on the plant as lower leaves are killed. Natural enemies such as* Lysiphlebus testaceipes *(Cresson) and ladybird beetles become very active, but often not until the economic threshold level has been surpassed. The organophosphate insecticides usually applied are relatively effective and economical, but they present environmental problems, and a resistant biotype has occurred. As an adjunct to insecticides, plant resistance to greenbug was quickly located and developed through cooperative efforts by public and private agencies. However, again a new biotype caused a temporary setback. The control strategies mentioned need to be combined with cultural control in a systematic integrated program. To furnish information for such a program, fundamental research is needed on the nature of injury, alternative sources of plant resistance, and cytogenetics of the greenbug.*

Resume

Blologle du puceron vert et lutte contre ce ravageur du sorgho ; *Le puceron vert,* Schizaphis graminum *(Rondani), est present depuis pres d'un siecle dans les Grandes Plaines des Etats-Unis, mais ce n'est qu'en 1968 ou la predominance d'un nouveau biotype a fait de cette espece un ravageur important du sorgho grain. L 'hivernage est assure par des femelles parthenogenetiques et chaque annee les zones septentrionales sont reinfestees par les individus ailes emportes par les vents du sud. Le sorgho subit l'attaque lorsque les insectes y transferent leur preference en quittant les petits grains et d'autres graminees. Chez le sorgho, la femelle non ailee attaint la maturite dans une semaine environ et donne naissance a pres de 80 individus dans les trois semaines qui suivent. Le puceron injecte une substance toxique dans la plante pendant l'alimentation. Les feuilles inferieures sont detruites les premieres, les degats s'avancent ensuite vers le sommet. Les digits depassent souvent le seuil economique avant que les ennemis naturals tels que* Lysiphlebus testaceipes *(Cresson) et les coccinelles ne deviennent actifs. Les insecticides organophosphates, quoique efficaces et abordables du point de vue economique, posent des problemes ecologiques: dans ce cas its ont entraine l'evolution d'un biotype resistant. La resistance de la plante au ravageur a ete alors identifies et elaboree grace aux efforts des agences publiques et privees. Ce progres est malheureusement retarde par /'apparition d'un nouveau biotype. Il faut completer ces methodes de lutte par des pratiques culturales dans le cadre d'un programme de lutte integree. A cette fin, il nous faut des recherches de base sur la nature des degats, d'autres sources de la resistance vegetale et la cytogenetique du puceron vert.*

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Introduction

The place of origin of the greenbug, *Schizaphis graminum* (Rondani), like that of many Insects that have become cosmopolitan, Is unknown. The earliest available record of the pest is 1847, In Italy, where 5 years later the species was described (Rondani 1852). By 1907 the pest had been reported as a resident of four continents: Europe, Asia, Africa, and North America (Webster 1909). It is now known that the greenbug is also widely distributed in South America. In the USA, for about 100 years, greenbug damage was confined to small grains, although the literature on the pest mentions sorghum, *Sorghum bicolor* (L) Moench, as an incidental host as early as 1863 (Hays 1922; Webster and Phillips 1912). Sorghum became a primary cultivated host in 1968, when outbreaks occurred widely in the Great Plains. The addition of sorghum as a preferred plant afforded the greenbug a summer host and increased economic damage to the extent that yield losses and control costs in 1976 exceeded $80 million in Oklahoma alone (Starks and Burton 1977).

In recent years the voluminous list of publications on the greenbug belies the relatively small number of scientists doing research on the pest. This paper will make no attempt to give a comprehensive review of the literature, since there are several review articles that include the greenbug among sorghum pests (Walker et al. 1972; Young and Teetes 1977, 1980; Peters and Starks 1981).

Biology

The greenbug would rank high among the most important phytophagous pests in the USA. Because it is an important pest, is easy to rear, and reproduces readily and rapidly, the greenbug has been the subject of many biological studies. However, its small size has limited physiological investigations, and its reluctance to reproduce sexually makes genetic studies difficult.

Life Cycle

The greenbug was first described in the genus *Aphis.* Then it withstood a long period in the genus *Toxoptera* until 1931, when it was placed in the genus *Schizaphis,* where it is the type species. Depending upon the classifier, there are few species in *Schizaphis,* and only three or four of these occur in the USA. Within S. *graminum* there are wide differences in appearance of individuals. Body colors range from pale to dark green. Cornicle markings are sufficiently different to use for separating some biotypes. In fact, some biotypes consistently differ in body size and shape. The effect of diet on aphid polymorphism has been well documented (Mittler 1973), but differences in appearance among greenbug biotypes remain noticeable when the same variety of a host is used.

Greenbugs are holocyclic on Gramineae, but other species of *Schizaphis* alternate generations on *Pyrus* spp. At one time the greenbug was confused with a species of *Metopolophium* in South Africa, so Rosaceae may wrongly appear as the alternate host in the literature. Greenbugs feed on aerial portions of plants, but in winter they may infrequently find shelter 1 to 3 cm below ground on small grains.

The terminology for aphid forms in the life cycle is extensive. Most species produce at least five different kinds of adults, and some of these differ sufficiently to have been mistakenly described in different genera. In the case of the greenbug, parthenogenetic females are mostly wingless, but some are winged. Usually winged viviparae produce fewer nymphs, but all of these develop into wingless adults. Oviparous females are wingless, while the small males that have been reported from some biotypes are winged. Alary polymorphism is influenced by temperature (Mayo and Starks 1974), while the production of sexual morphs seems to be influenced by photoperiod and temperature. No doubt nutrition and crowding are also involved in both phenomena (Wadley 1931), but studies are complicated because the triggering effect may go back at least two generations to embryonic development. The situation is made more confusing by some individual aphids producing both a few nymphs and eggs, while others give birth before becoming winged.

The greenbug typically undergoes four molts, with instars lasting about 30 h each. From birth to reproduction takes about 1 week, though the time can be considerably lengthened by low temperatures. Adult viviparae are about l.8 mm long and half as wide, with a conspicuous dorsal stripe on the abdomen. On sorghum, each greenbug produces about 80 young over a 3-week period, but again temperature influences both the rate and length of reproduction. There can be 10 to 12 generations during the growing period of sorghum in the southern Great Plains, but usually the population collapses after five to six generations. Oviparae and males fit an orderly life scheme if they appear in the last generation in the fall. In fact, both have been found in the spring and fall of the year, but not always at the same time. Each female lays about four eggs, securely stuck to leaves or other objects such as cages. Eggs are roughly 0.7 x 0.4 mm and change color, from very pale yellow to pale green and finally black, in about 3 days. Embryonic development in the egg has been reported (Webster and Phillips 1912), but, interestingly, all such developing eggs apparently came from bluegrass, *Poa* spp. Hatching efforts have been unsuccessful when eggs were taken from small grains, even though the eggs have been subjected to low temperatures (Wadley 1931).

Biotypes

Eastop (1973) stated that the term "biotype" is a taxonomic concept used mainly by nontaxonomists. The following comments will add credence to Eastop's remark, since biotype will be used according to the definition in Maxwell and Jennings (1980) and will not necessarily refer to taxonomic characters, although morphological differences are apparent in some biotypes and groups vary significantly in chromosome lengths (Mayo and Starks 1972).

Aphids, like midges, are notorious for producing biotypes that differ in behavior and interactions with plants and chemicals. The greenbug is no exception. The rapid, parthenogenetic reproduction and frequent migration permit new, true-breeding biotypes to replace disadvantaged ones unexpectedly and quickly over large geographical regions. Since 1958, the greenbug in the Great Plains has evolved four major biotypes that have overcome plant resistance (Wood 1961; Porter et al. 1982), allowed reproduction at higher ambient temperatures (Wood and Starks 1972), extended the range of preferred hosts to sorghum (Harvey and Hackerott 1969), and necessitated higher dosages of insecticides for effective control (Teetes et al. 1975b). These biotypes in the Great Plains have been assigned letters from A to E. Certainly biotype A was not the first one since Wadley (1931) concluded that barley was a secondary host, but this crop is now preferred by greenbugs attacking small grains. Just as A was not the first, E will not be the last, biotype. There are probably already many potential biotypes represented by small numbers of individuals in the agroecosystem. One or more of these may become predominant; still others will probably occur, since recent cytogenetic research shows that massive chromosome translocations have taken place. Biotype C, previously the dominant biotype on sorghum, is a mixture of biotypes, judging from variations in chromosome lengths. A segment of the biotype C population may have given rise to E, which can better withstand the previous resistance bred into commercial sorghum. Biotype E has replaced C in much of western Texas (Puterka et al. 1982) and Oklahoma, Kansas, and Nebraska, but has made little progress toward becoming the dominant biotype in eastern Texas. There is no evidence that applied plant resistance selected out the new biotype in the field. Biotypes B and E have overcome resistance in wheat without the resistance being released in cultivars.

Biotypes of the greenbug are not confined to the Great Plains. There are both sympatric and allopatric populations. In the eastern USA, there are biotypes that attack forage and turf grasses (Ratcliffe and Murray 1983; Kindler et al. 1983). A biotype attacking Kentucky bluegrass differs so greatly from the Great Plains biotypes that it cannot maintain colonies on sorghum. Other countries have other biotypes. Arriaga et al. (1983) in Argentina and Lara et al. (1983) in Brazil are able to use resistance sources that are not effective in the USA. Similar results have been reported by Barbulescu (1980) in Romania. Confusion of biotypes will continue until exact distinguishing characteristics can be compiled and scientists devise satisfactory and acceptable methods of exchanging specimens.

Aphids on Sorghum

At least six species of aphids have been reported as colonizing sorghum in the USA. However, only three of these become abundant over a large area. The corn leaf aphid, *Rhopalosiphum maidis* (Fitch), is a warm-weather species that reaches high densities in leaf whorls and under bagged heads. Usually in a field only scattered plants are heavily infested, and direct economic damage is difficult to demonstrate (Wilde and Ohiagu 1976). Even so, plant resistance in sorghum has long been known, and recently new sources were found in several converted Zerazera sorghums (Teetes 1980). Plant resistance has also been reported in India, where the corn leaf aphid apparently is more damaging. In several countries it has been reported as a vector of viral diseases. The corn leaf aphid and greenbug share natural enemies.

The yellow sugarcane aphid, *Sipha flava* (Forbes), can be a devastating pest of cereal crops, sugarcane, and grasses, but usually this aphid is a problem only in the Gulf Coast states. About every 10 years outbreaks have extended northward to Kansas. Not only does the yellow sugarcane aphid inject a systemic toxicant during feeding, but it is difficult to control with insecticides, has few natural enemies, and no known useful plant resistance in sorghum (Starks and Mirkes 1979).

The sugarcane aphid, *Aphis (Melanaphis) sacchari* Zehntner, is reported as a sorghum pest in Asia and Africa (Wang 1961; Matthee 1962). It behaves similarly to the greenbug, but its economic importance is unknown. Hsieh (1982) found that a high level of resistance in PI 257295 was conditioned by a single dominant gene pair.

Damage by the Greenbug

The greenbug damages grain sorghum in three ways: (1) copious amounts of sap are extracted, thereby depriving the plant of water and nutrients; (2) a chemical is injected during the feeding process, and this causes enzymatic destruction of cell wall which leads to chlorosis and eventually necrosis of leaf tissue; and (3) devastating viruses such as the maize dwarf mosaic virus (MDMV) may be transmitted (Berger et al. 1983), or the plants may be predisposed to diseases such as charcoal rot (Teetes et al. 1973). There is also an effect on grain quality, but little research has been done on this aspect of damage. Forage sorghum, sweet sorghum, and broomcorn are also attacked by the greenbug, but less is known about injury to these types than grain sorghum in the USA.

Seasonal Development of Infestations

The greenbug has been collected from at least 78 species of Gramineae (Dahms et al. 1954), including grasses growing as far north as Manitoba, Canada (Robinson and Hsu 1963). In general, grasses with relatively broad leaves such as johnsongrass, *Sorghum halepense* (L) Pers., and *Agropyron* spp (Kieckhefer 1983), are preferred over species with narrow leaves. Even though the greenbug has many wild hosts in the Great Plains, large infestations are generally confined to sorghum, wheat, barley, oats, and rye.

To overwinter in the Great Plains, the greenbug must continue feeding and reproducing, and withstand winter climatic conditions. Food is usually available, since forage grass and small grains in the vegetative stage are abundant in the extreme south, and winter wheat extends northward into South Dakota. Even though the greenbug can withstand relatively low temperatures, especially under snow cover, individuals usually do not survive through the winter beyond southern Kansas. Instead, most of the Great Plains each spring is reinfested by alate greenbugs transported northward by low-level jet winds. The northward migration progresses until greenbugs reach South Dakota by April 15 (Kieckhefer et al. 1974). Usually the initial greenbug buildup is in small grains, but johnsongrass is a primary host in some areas. When small grains start to head or aphids become crowded, there can be a resurgence northward, and these migrants are usually the ones that alight on sorghum. The timing of the main influx of greenbugs into sorghum fields varies among localities. Some areas experience problems with greenbugs on seedling sorghum, while others do not get damaging infestations of greenbugs until plants are in the boot stage. Many areas of the Great Plains have damaging infestations of the greenbug each year, while other areas commonly have light infestations. But about every seventh year, outbreaks may sweep northward into Canada, resulting in extensive damage to small grains as well as sorghum.

Colonies of greenbugs on sorghum usually locate themselves on the undersurface of the lower functional leaves. As lower leaves die, infections may move upward on the plant and even reach the panicle. Underneath heavily infested plants the soil can be darkened from molds living on the abundant honeydew excreted by greenbugs. Rains, blowing sand, and biotic enemies can suppress aphid increase in the field, but population increases as high as 20-fold per week have been recorded (Bottrell 1971). More than 40 000 greenbugs in various developmental stages have been estimated on a single large sorghum plant. The infestations may persist through grain maturation, but usually densities decline rapidly by the time of anthesis. Fall infestations can move from sorghum to newly planted small grains, where stunted plants and stand losses result.

Control

The greenbug was a new pest on grain sorghum In 1968, but it was a familiar pest in the Great Plains. Its long association with small grains had allowed time for research on the pest's life history and behavior, and on natural enemies and insecticidal control. Even so, it was necessary to determine population profiles, and economic thresholds on sorghum (Teetes and Johnson 1973).

Insecticidal Control

Insecticide use on sorghum is still lower than on such field crops as cotton; nevertheless, the greenbug had a large impact on insecticide use on sorghum. Andrilenas (1975) reported that 2% of the U.S. sorghum acreage was treated with an insecticide in 1966; 39% in 1971. This increased usage was largely due to attacks by the greenbug on irrigated sorghum.

The detrimental effects of pesticides on the environment have been well publicized in the last 25 years. Yet, without insecticides for greenbug control, many farmers growing irrigated sorghum in the Great plains would have been economically forced to grow alternative crops. Soon after the greenbug moved to sorghum, some organophosphorous insecticides such as methyl parathion were found to cause phytotoxicity to sorghum, but others were quickly judged effective and were rapidly approved by regulatory agencies (Daniels 1972; Cate et al. 1973; DePew 1974).

Initially, chemical treatment for greenbug control on sorghum was relatively cheap and highly effective at dosages as low as 100 g/ha when applied either as granular or liquid concentrate formulations. Commercial aerial application became a common method of application. Unfortunately, many growers used the highest instead of the lowest approved effective dosages, or used prophylactic treatments. The intense use of chemicals for greenbug control on sorghum and wheat resulted in the development of insecticidal resistance as a recessive character (Teetes et al. 1975a; Peters et al. 1975). Also, the insecticides were not sufficiently selective, so beneficial insect and pollinator numbers were considerably, if briefly, reduced in treated fields. After treatment for greenbug, some arid areas experienced problems with mites such as *Oligonychus pratensis* Banks. The mites, normally secondary pests of sorghum, were dispersed by the aphid treatments, and insecticide-resistant individual mites were selected within the population (Young and Teetes 1977).

Insecticides will retain their importance for greenbug control on sorghum since they are still effective and economical. However, if we have learned from experience, they should be used in the future as a component of pest management schemes involving multiple pests.

Cultural Control

The manipulation of cultural practices has been a successful means of controlling insect pests for many years. An example is escaping sorghum midge damage by planting for early, uniform flowering of hybrids in an area and good johnsongrass control (Summers et al. 1977). Since pests are seldom able to bridge adverse cultural changes, there is little danger of resistant biotypes developing as they have with plant resistance and insecticides.

However, cultural control has had its problems also. It is given low research priority. Although tradition is less of a problem than previously, growers in the USA understandably prefer to use familiar methods of culture. Also, for cultural control recommendations to be readily and widely accepted, they must be compatible with sound agronomic practices. For example, greenbug density buildup is favored by a thick plant canopy, good soil moisture, and high soil fertility (Archer et al. 1982), but these conditions cannot be greatly altered, because they are essential for high grain yields. Harvey et al. (1982) suggested delaying the planting of sorghum in northwestern Kansas until after the first week in June to escape peak flights of greenbug. In other areas, growers must plant early to take advantage of soil moisture conditions and to lessen damage from other pests.

Aphid predators find shelter in vigorous weeds, either within a field or along fence rows, but the destruction of weeds is necessary to reduce growth competition with sorghum plants. Thus, the entire agroecosystem must be considered before changes are recommended to control an insect such as the greenbug. Conversely, research is needed to determine the impact of cultural changes promoted for reasons other than pest control. Burton (1984) found that wheat had fewer greenbugs in surface residue plots than in clean-plowed ones. Similar information is needed on the effects of conservation tillage of sorghum.

Biological Control

The destruction of insect pests by entomophagous enemies has high public appeal since the relationship has the scenario of a play with villains and heroes. Realistically, research has suggested complex and delicate interactions involving biotic and abiotic factors.

Natural enemies, along with climatic hazards, keep the greenbug from reaching its reproductive potentials. In most areas, greenbug populations on sorghum rapidly reach a density peak, and then, even more rapidly, collapse. A second peak is often evident, followed by another sudden collapse. During peak abundance, native parasites and predators are very evident. The most common parasite is *Lysiphlebus testaceipes* (Cresson), a small, efficient braconid long associated with the greenbug and other cereal crop aphids (Hunter and Glenn 1909). *L. testaceipes* readily attacks all instars of the greenbug, disrupts feeding, dislodges individuals from the plant, and prevents aphid reproduction (Hight et al. 1972). A sorghum plant may have thousands of golden mummies stuck on the leaves and stem. Other indigenous parasites such as *Aphelinus nigritus* (Howard) are much less numerous. Exotic parasites, including *A. varipes* (Forester), *A. asychis* (Walker), and *Praon gallicum* Stary have been increased and released (Jackson et al. 1971; Rogers et al. 1972) in sorghum and small grains, but few of these have become established.

Parasites, especially L. *testaceipes,* are believed to be the most important natural enemies in the Great Plains. However, Hamilton et al. (1982) indicated that predators may be of greatest significance in influencing greenbug numbers in Missouri. A wide array of predators can be found on sorghum. Perhaps the most common is the convergent ladybird beetle, *Hippodamia convergens* Guerin-Mandeville. The transient adults of this coccinellid are active early in the season, while the ferocious larvae later become more important in controlling the greenbug. Other aphid predators include *Chrysopa* spp, syrphid larvae, and numerous species of spiders. Again, exotic predators have been introduced (Eikenbary and Rogers 1973), but a major impact on greenbug control has not been documented.

Beneficial insects associated with aphids have inherent problems. By necessity, initial development lags behind that of the prey, and many parasites are believed to be density-dependent. By the time beneficial insects establish and effectively reproduce in sorghum, greenbug numbers may approach or even exceed the economic threshold level. Then, if insecticide treatment is given, the beneficial insects must once again become established. Early augmentation releases of either *L. testaceipes* (Starks et al. 1976a) or convergent ladybird beetles (Starks et al. 1975) have been mostly unsuccessful, largely due to interference by secondary parasites such as *Charips* sp and *Pachyneuron siphonophorae* (Ashmead).

Research on the use of microorganisms to control the greenbug has been minimal, though field infections, especially during periods of high relative humidity, are common. Additional research is needed on all phases of biological control, particularly in relation to other control factors such as plant resistance (Bergman and Tingey 1979).

Plant Resistance

Development of resistance to greenbug in commercial grain sorghum was a commendable cooperative effort involving several plant breeders and entomologists affiliated with state, federal, and private agencies. Sources of resistance such as SA 7536-1, KS 30, IS 809, and PI 264453, were located shortly after the outbreak of biotype C in the summer of 1968 (Hackerott et al. 1969; Harvey and Hackerott 1969; Wood 1971; Weibel et al. 1972) and made available to seed companies. The mechanisms of resistance were determined in the laboratory (Schuster and Starks 1973; Teetes et al. 1974a), and levels of resistance were evaluated in the field (Harvey and Hackerott 1974; Johnson et al. 1974; Teetes et al. 1974b).

Genes were rapidly transferred to good agronomic backgrounds, and all the major seed companies in the Great Plains made greenbug resistance a part of their research and development programs. The task was made relatively easy because resistance was controlled by a single incompletely dominant factor (Weibel et al. 1972), and segregating material in the seedling stage could be rapidly screened in the greenhouse (Johnson et al. 1976; Starks and Burton 1977) since resistance persisted throughout the vegetative development of the plant (Starks and Wood 1974). By 1976 about 2 million ha of grain sorghum were planted to resistant hybrids (Frederiksen et al. 1978). The use of insecticides for greenbug control was reduced to about half the amount used prior to the widespread availability of plant resistance. This translated into a significant reduction in production costs and a conservation of energy.

Hybrids for both irrigated and dryland culture received greenbug resistance from one or both parents. Different sources of resistance were thought to contain a common gene traceable to *Sorghum virgatum* (Hack.) Stapf. (Hackerott et al. 1969). However, PI 220248 and PI 264453 were quickly found to retain resistance to biotype E (Starks et al. 1983), and fortunately had been incorporated into breeding populations (Starks et al 1976b). Thus resistance in commercial hybrids was again widely available by 1983.

The future of the present commercial resistance is unknown, since no accurate method of predicting biotypes is available. Efforts are under way to locate additional sources of resistance. Additional resistant entries that were recently found include Capbam (probably derived from PI 264452), IS 923, and a locally converted line, J 242. Other plant introductions have resistance but are grassy.

Possible alternative sources of commercial resistance are the bloomless and sparse-bloom characters in sorghum. Six independently inherited gene pairs give a lack of or reduction in the white, powdery wax on leaves and stems (Peterson and Weibel 1978; Peiretti et al. 1980). For unknown reasons, plants with either bloomless (bm bm) or the sparse-bloom (h h) condition are less preferred by greenbugs than the bloom (Bm Bm) plants (Starks and Weibel 1981). However, the lack of bloom apparently makes plants more susceptible to drought stress (Ross 1972). Efforts are under way to combine bloomlessness with drought tolerance.

The chemical nature of plant resistance to the greenbug has been difficult to determine, partly due to the lack *of* an adequate artificial diet for bioassaying. Recently, improvements have been made in the synthetic diet for the greenbug (Cress and Chada 1971; Dreyer et al. 1981), and feeding deterrents such as phenolic acids and dhurrin have been found (Juneja et al. 1972; Dreyer et al. 1981). Exact results are difficult to obtain because levels of resistance and probably levels of biologically active chemicals vary with temperature and with the age and nutritional status of plants (Schweissing and Wilde 1979). Even if the chemical nature of greenbug x plant interactions remains elusive, resistance can still be an important and integral part of greenbug control.

Integrated Greenbug Management

Exclusive reliance upon a single control measure for a pest invites vulnerability to disaster. Although there has been heavy reliance upon insecticides, the control of the greenbug on sorghum has combined pest suppression measures more than usual. Insecticides are still the most effective and available method of controlling the greenbug, but they need to be more selective and should be used at the lowest effective dosage, and only when a scouting report indicates the economic threshold has been reached. Plant resistance will not rid the sorghum plant of the greenbug; it can, however, apply a constant level of reproduction suppression and delay the attainment of the economic threshold. Plant resistance and biological agents can be complementary in greenbug population suppression (Starks et al. 1972; Teetes et al. 1975a). Parasites and predators require a low density of greenbugs or some other prey to survive, and plant resistance allows this reserve food supply.

Much research has yet to be done. The occurrence of greenbug biotypes is frustrating for those of us working on plant resistance. More basic information on sexuality and cytogenetics is required before we can hope to understand the evolution of biotypes. Aphid migration furnishes reinfestations for northward-grown crops (Kieckhefer 1975). A means of delaying this movement is needed. Both current and projected cultural practices need to be evaluated for influences on the greenbug. The greenbug should not be viewed as an isolated problem, but instead considered as one of many challenges in the production of sorghum, one of several crops grown in the Great Plains.

Note: Mention of a pesticide does not constitute a recommendation for use by the USDA or University of Nebraska, nor does it imply registration under FIFRA as amended.

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Stem Borers

Lepidopterous Stem Borers of Sorghum

K.M. Harris*

Abstract

Major sources of published information on the distribution, biology, ecology, and control of lepidopterous stem borers of cultivated sorghums are reviewed on a world basis. The three major stem borer pests are Chilo partellus *(Swinhoe) in India and East Africa,* Busseola fusca *(Fuller) in Africa south of the Sahara, and* Sesamia cretica *Lederer in northeastern Africa and the Mediterranean. In addition, 23 species are recorded as minor pests of sorghum in various parts of the world, including six species of* Chilo *in Africa, Asia, and the Pacific; four species of* Diatraea *in the Americas; six species of* Sesamia *in Africa, and one,* S. inferens, *in Asia and the Pacific. It is noted that in countries outside Africa, interactions of stem-boring species with sorghum are historically recent and may possibly be unstable. The need to keep the entire sorghum stem borer complex under observation is stressed and the need to maintain and develop varietal resistance in plant breeding programs is emphasized.*

Resume

Lea lepidopteres borers des tiges du sorgho*: La communication pr6sente une recapitulation de la documentation principale sur la repartition, la biologie, l'ecologie et la lutte contre les lepidopteres borers des tiges chez les sorghos cultives dans le monde. Les principaux borers sont :* Chilo partellus *(Swinhoe) en Inde et en Afrique de l'Est,* Busseola fusca *(Fuller) en Afrique au sud du Sahara, ainsi que* Sesamia cretica *Lederer en Afrique du Nord-Est et la region m6diterran6enne. En outre, 23 especes sont signalees comma ravageurs mineurs de sorgho dans les differentes parties du monde, notamment six especes de* Chilo *en Afrique, en Asie et la region du Pacifique; quatre especes de* Diatraea *en Amerique; six especes de* Sesamia *en Afrique dont une,* S. inferens, *en Asie et la region du Pacifique. Il faut noter qu'en dehors du continent africain, l'interaction entre les especes de borers et le sorgho est recente et ne serait pas de nature permanente. L'auteur souligne la necessite de tenir ces especes sous observation et de maintenir et d6velopper la resistance varietale dans le cadre des programmes de selection.*

Jepson (1954) published a critical review of the world literature on lepidopterous stem borers of tropical cereals and of sugarcane, and his review is still a useful summary of work on host ranges; bionomics; population and crop loss assessments; parasites, predators, and pathogens; and cultural, biological, and chemical control. He stressed the need for an ecological approach to stem borer problems, and this is particularly relevant to current development of integrated pest management programs. His tabulation of records from maize, rice, sorghum, millets, and sugarcane lists 45 species in 15 genera but only 7 of these species had been definitely recorded from cultivated grain and fodder sorghums. Young (1970) gave a detailed review of published information on the biology, ecology, and control of 19 species recorded from sorghum, and a brief review of stem borers of sorghum *is* also included in Young and Teetes (1977). The Indian literature has been summarized by Gahukar and Jotwani (1980), and abstracts of the world literature, based on the *Review of Applied Entomology*

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(A), have been collated in the following *CAB Annotated Bibliographies,* issued by the Commonwealth Institute of Entomology:

- E.30 Biocontrol of graminaceous stemborers 1973-78.
- E.38 Arthropod pests of *Sorghum* 1975-79.
- E.49 *Diatraea saccharalis* 1973-80.
- E.52 *Busseola fusca, Chilo partellus, Sesamia calamistis* (Control and crop losses) 1976-80.
- E.105 Stemborers of *Sorghum* 1973-83.

These are derived from the *CAB Abstracts* data base, which is searchable on-line through DIALOG, DIMDI, and ESA IRS systems. The 26 species now known to be associated with cultivated sorghums as major or minor pests are listed in Table 1, which also includes summaries of their geographical distribution.

The Pyralidae are relatively small, inconspicuous moths usually with drably colored wings. The genus *Chilo* is taxonomically difficult but has been thoroughly revised by Bleszynski (1970). Noctuidae are generally larger and more robust but are also relatively inconspicuous moths. The African species of *Sesamia and Busseola,* which comprise most of the stem boring species of Noctuidae on sorghum, were revised by Tarns and Bowden (1953).

C. *partellus, B. fusca,* and S. *cretica* are the only species generally considered to be of major importance on sorghum at present, although this situation could easily alter in future if changes in distribution, climate, agronomic practices, or varietal susceptibility favored any of the minor pest species.

The most complex interaction between stem borers and wild and cultivated species of sorghum occurs in tropical Africa and probably reflects a long association of indigenous borer species with the crop and its precursors.

Damage and Crop Losses

Most stem borer species produce similar symptoms on attacked host plants. Young larvae generally feed initially in leaf whorls of growing plants, producing characteristic repetitive patterns of small holes and "window-paning" where they have eaten through or partly through the rolled leaves. Later they tunnel into the stems and may kill the central leaves and growing point, producing "deadhearts," a symptom that may also result from attack by the sorghum shoot fly, *Atherigona soccata* Rondani. Once inside the main stem, larvae tunnel extensively and eventually pupate within the galleries, having first eaten a passageway to the exterior through which the adults will emerge. Tunneling weakens stems, which may cause lodging, and must also interfere with the supply of nutrients to developing heads of grain.

There have been many subjective and some objective assessments of crop losses attributable to borer, often based on counts of percentage stems bored at or before harvest, but correlations of these counts with yield sometimes fail to demonstrate any reduction in yield and may even show that attack at harvest is highest on high-yielding plants (Ingram 1958; Harris 1962). This is possibly a result of preferential oviposition by female moths on larger plants or other selective behavior by adults and/or larvae or may be a simple mechanical trap effect of larger plants which offer a greater leaf area for ovipositing females to land on. Objective crop loss assessment methods have been devised and are summarized in the FAO manuals on crop loss assessment but have seldom been used on sorghum. Overall losses may be of the order of 5 to 10% in many sorghum-growing areas, especially where early attack causes loss of stand, and avoidable grain losses on the hybrid sorghum CSH 1 and on the variety Swarna have been estimated in India to be about 55 to 83% (Jotwani et al. 1971; Jotwani 1972).

Major Pest Species

Chilo partellus (Swinhoe)

This is the sorghum or *jowar* stem borer, also known as the spotted stem borer. It is a major pest of sorghum in India, Pakistan, and East Africa, and also occurs in other areas, including Malawi, Botswana, and South Africa, and southeast Asia. It seems to be absent from West Africa, although it has been recorded in the Sudan and could presumably spread through the Sahel zone.

Adults are nocturnal and live for 2 to 3 days, during which each female lays 200 to 600 scale-like eggs in overlapping batches of 10 to 80 eggs on the undersides of leaves, mostly near the midribs. Larvae hatch after 4 to 5 days and feed in the leaf whorls before tunneling down into the stems.

Larval development is completed in 2 to 4 weeks during the growing season and adults emerge from pupae in the stems after a further 5 to 12 days. Five or more successive generations may develop, with an average life-cycle of 25 to 50 days, but during *winter* or dry seasons larvae diapause in stems and stubble for up to 6 months before pupating. In southern India, where conditions are more equitable, breeding is continuous, and up to ten generations develop during a year.

Table 1. Distribution of major* and minor lepidopterous stem borers of cultivated sorghums.

Stem borer	Distribution
Pyralidae	
Crambinae	
**Chilo partellus* (Swinhoe) [=C. *zonellus]*	East Africa, South Africa, Malawi, Sudan, Afghanistan, India, Sri Lanka, Nepal, Bangladesh, Sikkim, and Thailand (CIE Distribution Map 184)
Chilo infuscatellus Snellen	USSR (Tadzhikistan), Pakistan, India, Bangladesh, southeast Asia, Indonesia, etc. (CIE Distribution Map 301)
Chilo suppressalis (Walker)	Spain, Pakistan, India, Bangladesh, southeast Asia, China, Korea, Japan, Philippines, Indonesia, Papua-New Guinea, West Irian, and northern Australia (CIE Distribution Map 254)
Chilo sacchariphagus (Bojer) *[=Proceras venosatus* (Walker)]	Madagascar, Mauritius, Indonesia, Malaysia, China, etc. (CIE Distribution Map 177)
Chilo aurici/ius Dudgeon	India, Thailand, Philippines, etc. (CIE Distribution Map 300)
Chilo orichalcociliella (Strand) *[=Chilotraea argyrolepia* (Hampson)]	East Africa, Malawi, Madagascar, and Nigeria
Chilo diffusilineus de Joannis	West Africa
Acigona ignefusalis (Hampson) *[Haembachia ignefusalis; = Coniesta ignefusalis]*	West Africa
Acigona loftini (Dyar)	USA and Mexico
Diatraea saccharalis (Fabricius)	USA, Central and South America (CIE Distribution Map 5)
Diatraea grandiose Ha (Dyar)	USA and Mexico
Diatraea crambidoides (Grote)	USA, Central and South America
Diatraea lineolata (Walker)	USA, Central and South America
Pyraustinae	
Ostrinia furnacalis (Guenee)	USSR, China, Pakistan, India, Sri Lanka, Bangladesh, southeast Asia, Japan, Philippines, New Guinea (CIE Distribution Map 294)
Ostrinia nubilalis (Hubner)	USA and southern Europe (CIE Distribution Map 11)
Gallerinae	
Eldana saccharin a Walker	West and East Africa, Zaire, Mozambique, and Saudi Arabia (CIE Distribution Map 291)
Phycitinae	
Elasmopalpus lignosellus (Zeller)	USA, Central and South America (CIE Distribution Map 114)
Noctuidae	
**Busseola fusca* (Fuller)	Africa South of the Sahara
**Sesamia cretica* Lederer	Sudan, Egypt, West Mediterranean, Ethiopia, Somalia
Sesamia inferens (Walker)	Pakistan, India, Bangladesh, Sri Lanka, southeast Asia, China, Japan, Philippines, Indonesia, New Guinea, Solomon Islands (CIE Distribution Map 237)
Sesamia calamistis (Hampson)	Africa south of the Sahara
Sesamia botanephaga Tarns & Bowden	West and East Africa
Sesamia nonagrioides (Lefebvre)	North Africa and west Mediterranean
Sesamia poephaga Tarns & Bowden	West and East Africa
Sesamia penniseti Tams & Bowden	West Africa

Much research work in India has dealt with-chemical control, and applications of sprays, dusts, or granules to the leaf whorls or incorporation of granular formulations in the soil have been used to protect young plants from borer and shoot fly. Many different active ingredients have been tested, including malathion, BHC, carbaryl, chlorfenvinphos, carbofuran, disulfoton, endosulfan, endrin, and mephosfolan, with varying degrees of success. It seems unlikely that chemical control can be used extensively against this pest on low-yielding crops but potentially high-yielding hybrid sorghums may justify chemical protection. Cultural control measures, such as plowing in stubble and destroying crop residues, may be useful in some areas. Biological control by exchange of parasites, predators, and pathogens between African, Indian, and other sources and by the conservation and augmentation of indigenous agents might also be beneficial. Sources of varietal resistance, mainly operating through antibiosis, have been detected, assessed, and used in India (Singh et al. 1980; Jotwani and Davies 1980; Lal and Sukhani 1982; Khurana and Verma 1982) and further development of this work, combined with an extension of recent research on oviposition behavior (Roome et al. 1977; Lal and Pant 1980) and on the dispersal and survival of young larvae (Roome 1980; Hamburg 1980; Chapman et al. 1983; Bernays et al. 1983) will provide an adequate foundation for the development of integrated pest management programs.

Busseola fusca (Fuller)

This is the African maize stem borer which is also the most important stem borer on sorghum in Africa south of the Sahara. Adults live for up to a week and the night-flying females lay a few hundred eggs each in batches of 30 to 100 under leaf sheaths. Larvae hatch about a week later and disperse over the leaves before entering the leaf whorl where they feed before tunneling into the stems. The life cycle takes about 2 months, and during the dry season diapausing larvae survive for up to 6 months in dry stems from the preceding crop, which are often used as fencing or building materials. Insecticide applications to the leaf-whorl, either as dusts, granules, or sprays, can give effective control of young larvae before they can enter the stems, and in Nigeria a cheap sprayer has been developed for this purpose (Barry and Andrews 1971).

Cultural control by partial burning of stems after the grain has been harvested has also been developed in Nigeria (Adesiyun and Ajayi 1980) and some progress has been made in the selection of resistant lines (Barry 1980). Kaufmann (1983) has recorded differences in mortality and development when populations from sorghum in northern Nigeria were transferred to maize in southwest Nigeria and vice versa and suggests that adaptation to different host plants may be causing genetic divergences within the species. In Zimbabwe, the female sex pheromone of this species has been identified and used in field trials to trap males (Hall et al. 1981).

Sesamia cretica Lederer

This species of *Sesamia* is a major pest of sorghum in the Mediterranean and Middle East and also attacks maize. The life cycle is similar to that of *B. fusca* but young larvae tunnel directly into the stems soon after hatching, although some may feed on the leaf whorl and upper leaves. Most recent research has been done in Egypt (Abul-Nasr et al. 1969) and the Sudan (Arsura et al. 1977), but this species is also present in Spain, where it occurs with *Sesamia nonagrioides* (Badolato 1977).

Minor Pest Species

Chilo Spp

C. *orichaicociiielia* was considered to be second in importance to C. *partellus* as a pest of sorghum in coastal areas of East Africa (Nye 1960) and C. *diffusilineus* is considered to be of some importance on sorghum in Upper Volta (Bonzi 1982). The other species are mainly pests of rice (C. *suppressalis)* or of sugarcane' (C. *infuscatellus; C. sacchariphagus;* C. *auricilius).*

Diatraea Spp, *Acigona loftini,* and *Elasmopalpus lignosellus*

D. saccharalis, D. grandiosella, D. crambidoides, D. lineolata, and *A. loftini are* all primarily stem borers of sugarcane and/or maize and are restricted to tropical and subtropical areas of the USA, the Caribbean, and Central and South America. Some species of *Diatraea are* occasional pests of sorghum and sources of resistance have been Identified (Teetes 1980). E. *lignosellus* occasionally attacks maize, groundnut, sorghum, and a variety of other crops and is much more polyphagous than the other stem boring species. It is also restricted to the New World.

Ostrinia nubilalis and *O. furnacalis*

O. *nubilalis,* the European corn borer, has been extensively studied on maize, especially in North America, but it does not extend far into the warm temperate and tropical regions where sorghum is mostly grown and is therefore not a major pest on that crop. The related Asian corn borer, O. *furnacalis,* which mainly attacks maize, has a more tropical distribution and could possibly become a pest of sorghum in southeast Asia (Young 1970).

Acigona ignefusalis and *Eldana saccharina*

These are both stem borers of cereals in Africa south of the Sahara. *A. ignefusalis* is primarily a pest of pearl millet, *Pennisetum americanum,* and, next to *B. fusca,* is the second most common borer on sorghum in northern Nigeria, where millet and sorghum are commonly intercropped. Its biology and ecology in this area have been studied by Harris (1962). *E. saccharina* has a similar distribution in Africa, where it is mainly a pest of sugarcane and maize, and it has been studied in Uganda and Ghana by Girling (1978, 1980).

Sesamia Spp

In addition to S. *cretica,* which is noted above, five other species of *Sesamia,* namely S. *calamistis, S. nonagrioides, S. botanephaga, S. poephaga,* and S. *penniseti,* attack sorghum in various parts of Africa, mainly in the semi-arid areas of West Africa, and S. *inferens,* which is mainly a pest of rice and sugarcane, is a polyphagous and widespread species that may sometimes attack sorghum in Asia and the Pacific.

Conclusions

Th e present interactions between cultivated sorghums and lepidopterous stem borers should be considered within a historical context as well as within the general agricultural and ecological contexts. Cultivated sorghums almost certainly originated in Africa, probably in the highlands of Ethiopia and East Africa, and have been spread worldwide comparatively recently. Doggett (1970) suggests first cultivation of the crop in this area at about 4000 B.C.

Spread to India, China, and the Far East probably started after 1500 B.C., and introduction to the New World is post-Columbus. In Africa the interaction with indigenous species of Lepidoptera, especially *B. fusca,* the various species of *Sesamia,* and possibly C. *partellus,* has been longest and it is there that resistance mechanisms and parasite/predator/pathogen complexes are likely to be best developed in cultivated and wild sorghums. Elsewhere the interactions are more recent and possibly less stable. In Asia, the Pacific, and the Americas, the crop is exposed to many stem borer species that are primarily adapted to other hosts, both cultivated and wild, and there is always a danger that host preferences may switch, especially where there are major changes in varietal susceptibility or in agronomic practices. This has happened on maize in Africa where the indigenous borer, *B. fusca,* has successfully transferred to the exotic crop, and it could happen elsewhere with sorghum. It is therefore important to keep the whole stem borer complex under observation and it is essential that tolerance and resistance to borer attack should be maintained and developed in plant breeding programs.

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Methods of Artificial Infestation with *Diatraea* Species and Evaluation of Stem Borer Resistance in Sorghum

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Abstract

This paper presents a review of the techniques used to infest and evaluate host-plant resistance of sorghum lines to three species of stem borers of the genus Diatraea. *Proven techniques for creating timely and uniform artificial infestations are described, and methods of evaluating resistance/susceptibility of sorghum lines, hybrids, or varieties are discussed with reference to commonly used damage ratings.*

Resume

***Methodas d'infestation artificielle par les especes de* Diatraea *et evaluation da la resistance aux borers des tiges chaz las sorghos** : Dans cette communication, l'auteur examine les differentes techniques d'infestation et d'evaluation de la resistance de la plante-hdte a trois especes de borers du genre* Diatraea.

Les techniques eprouvees d'infestation controlee sont decrites, ainsi que les methodes d'evaluation de la resistance ou bien la sensibilite des accessions, des hybrides ou des varietes selon le systeme normal de notation des degats.

Introduction

Sorghum is an important crop for food, feed, and structural material, especially in the semi-arid countries, for subsistence farmers in marginal agricultural areas; however, sorghum has a low commercial value. For this reason, chemicals for controlling sorghum pests are usually not recommended because they are not economical to use. Management of the more than 150 pest species that can and do attack sorghum (Seshu Reddy 1983) is therefore usually attempted or effected by using a combination of resistant varieties, cultural control, and the natural biological control agents that occur in sorghum-producing areas.

In attempting to develop improved lines, hybrids, or varieties, most improvement programs have integrated host-plant resistance (HPR) to the most important pest species as a component of their breeding programs. Depending on the pest species and the resources available, the screening and breeding for resistance is done under natural or artificial infestation. Most sorghum screening for lepidopterous pest species in the past was conducted in the field, using natural populations and infestation (Teetes 1980a). Many programs now use artificial infestations.

This paper presents the procedure and techniques being used at the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT), in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Central America regional program sorghum breeder, for infesting, screening, and improving HPR to *Diatraea* spp stem borers. Some of these techniques have already been adopted or adapted by entomologists working with other lepidopterous pest species in other parts of the world (Jotwani and Davies

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1980; Wiseman et al. 1980; Burton et ai. 1982; Mihm 1983a, 1983b). It is hoped that leaders of other programs will find some of the techniques useful, and use them to develop more resistant sorghums in the future.

Sorghum Stem Borer Pests

Teetes (1980b) listed nine stem borer species that are known to attack sorghum, but placed them in the category of occasional pests. Similarly, the findings of Guthrie et al. (In press) that all 209 temperate sorghum genotypes tested were highly resistant to *Ostrinia nubilalis* (European corn borer, or ECB) might explain why ECB is not considered a key pest of sorghum in the temperate zone of the USA. As in maize, the resistance of the sorghums tested to first-generation ECB was caused by antibiosis to first and second larval instars (leaf feeding resistance) (Dharmalingam et al. 1984), and resistance to second-generation larvae was determined to be resistance to sheath and collar feeding (Guthrie et al. In press).

House (1981) lists rating scales for evaluating sorghum resistance to only four borer species, although he states that several species attack the crop. The ICRISAT Sorghum Insect Identification Handbook (Teetes et al. 1983) illustrates eleven stem-feeding pests, nine of which are lepidopterans; one dipteran, the shoot fly, *Atherigona soccata* (Rondani); and a coleopteran, the sugarcane rootstock weevil, *Anacentrinus deplanatus* (Casey).

Seshu Reddy (1983) published the most comprehensive list of lepidopterous stem borers known to attack sorghum. It includes: *Acigona ignefusalis* Hampson, *Busseola fusca* Fuller, *B. segeta* Bowden, *Chilo agamemnon* Bleszynski, C. *diffusilineus* J. de Joannis, C. *infuscatellus* Snellen, C. *orichalcociliellus* Strand, C. *partellus* Swinhoe, *Diatraea grandiosella* Dyar, *D. lineolata* Walker, D. *saccharalis* F., *Elasmopalpus lignosellus* Zeller, *Eldana saccharina* Walker, *Ematheudes* spp, *Maliarpha separatella* Ragonot, *Ostrinia nubilalis* Hubner, *Proceras venosatus* Walker, *Sesamia botanephaga* Tarns & Bowden, S. *cretica* Lederer, S. *calamistis* Hampson, S. *inferens* Walker, S. *penniseti* Tarns & Bowden, and S. *poephaga* Tarns & Bowden.

Undoubtedly, a few additional species could be added to this list; for example, it seems surprising that *Ostrinia furnacalis,* a devastating stem borer of maize in southeast Asia, is not on the list of known stem borers of sorghum. To summarize briefly: much of the available literature tends to give the impression that stem borers are not a significant hazard to sorghum. This impression is mistaken, especially in subtropical and tropical environments where sorghum is grown.

The type and amount of damage done by stem borers to the sorghum crop, of course, varies with species, season, and environmental influences on the crop and pest. All are known to attack leaf and stem tissues, resulting in deadhearts (loss of plant stand) or delayed maturity (from tillers produced), or cause reduced yield by affecting seed set and grain filling. In terms of potential world sorghum production, some borer species are relatively more important because of their distribution and abundance. However, at the individual farmer level, all are potentially or actually destructive. Farmers could avoid some of the production risks if adapted resistant varieties were available and adopted.

Infestation and Evaluation of HPR in Sorghum

The procedures useful for screening sorghum for resistance to pests depend on the biology of the pest, the type of damage caused, and the resulting injury to the plants. The identification of resistant genotypes for utilization per se, or for use in conversion or improvement programs, depends on uniform and timely infestation. For acceptable progress to be made, improvement programs require sufficient selection pressure; this implies the appropriate level of infestation in relation to the performance of the material being improved, and the selection intensity applied to the breeding population.

Screening and improvement of resistance for some insect pests and crop species has been accomplished using natural populations (Teetes 1980b). With some pests such as mites, aphids, and some dipteran pests, natural infestations are adequate for resistance screening and improvement because they have very high population size, short generation times, and can reproduce parthenogenetically. However, with lepidopterous pests, regardless of crop species, there are very few examples of successful development of resistance using natural infestation (Mihm 1984), because lepidopterous pests, including stem borers, have low population levels and long generation times, must mate to reproduce, and have the capability to actively respond to many environmental factors and plant characteristics.

Natural infestation with lepidopterous pests usually begins by adults searching for hosts suitable for oviposition. Avoidance of host plants for oviposition is a useful mechanism of resistance. However, identification of this type of resistance is complicated and difficult. Potential resistance of this type must be confirmed under a no-choice situation before utilization. Effort and resources would probably be better spent on more productive endeavors; entomologists could, for example, study the pest's biology and bionomics, improve techniques for mass rearing insects for artificial infestations, or refine biological or cultural control measures to prevent or minimize crop losses. Where resources and conditions do not yet permit controlled, timely, uniform artificial infestations, the entomologist should try to remove this limitation, using the most appropriate technology to fit existing conditions, but always trying to be innovative and striving for improvement. Much remains to be done in refining and more effectively utilizing artificial infestation to maximize progress in host plant resistance (HPR).

The program for screening and improving HPR in sorghum in the ICRISAT program at CIMMYT involves planting each genotype to be screened in four-row plots, 2 m long, in an unreplicated screening nursery. One row is infested with D. *saccharalis* (sugarcane borer, *or* SCB); the next is protected with granular insecticides; the next is infested with S. *frugiperda* (fall armyworm, or FAW, another key sorghum pest in the Central American region); the last is left unprotected. The protected row serves to indicate the genotype's agronomic characters without insect attack and also serves as the reference point for determining the amount of yield reduction and other effects of the insect damage. The row left unprotected serves as an indicator of natural infestation by other local pest species, and, more importantly, is a buffer row for the FAW-infested row.

Each plant in the borer-infested row is infested with 20 to 30 newly hatched SCB larvae, using the "bazooka" (Mihm 1983a). The larvae are mass-produced in the CIMMYT insect facility using the procedures described by Mihm (1983a). Screening is presently done with only one of the three *Diatraea* spp borers that occur and attack sorghum in Mexico and Central America. Mass production of *D. tineolata* is still too limited to allow large-scale screening, and, as *D. grandiosella* (southwestern corn borer, or SWCB) is found only in Mexico and not in other countries of the Central American region, the ICRISAT sorghum breeder has decided that resistance to SWCB is of low priority.

Screening and improvement of resistance to C. *partellus* is being conducted at ICRISAT Center near Hyderabad, India, under artificial infestation (Jotwani and Davies 1980; Leuschner 1984), using techniques developed at CIMMYT.

Screening and studies of the genetics and mechanisms of resistance to C. *partellus* are also being conducted at the International Centre of Insect Physiology and Ecology (ICIPE) near Nairobi, Kenya (Seshu Reddy 1983; Pathak and Olela 1983). These studies were done using natural infestations, but ICIPE has begun artificial rearing of C. *partellus* (Ochieng 1984). Artificial infestation on a small scale should be possible in the near future.

Studies on sorghum as a host of the SWCB to provide basic information on the damage it causes to the crop, using artificial infestations, have begun recently in the USA (Burton et al. 1982; Starks et al. 1982). Screening, evaluation, and inheritance of HPR in sorghum to ECB has been conducted for some time in the USA using artificial infestation, mostly with egg masses (Dicke et al. 1963; Ross et al. 1982; Guthrie et al. 1984a, 1984b; and Dharmalingam et al. 1984). Many ECB-resistant sorghums have been identified and are being used in production.

Damage is usually rated at about weekly intervals after infestation, until larval feeding has terminated. The sorghum breeder uses the 1 -to-5 scale preferred at ICRISAT, similar to those reported by House (1981). Many maize entomologists working with stem borers, and sorghum entomologists from the USA, prefer to use a 1 -to-9 scale similar to that devised by Guthrie et al. (1960), where 1 = no damage or a few pinholes to 9 = most leaves with elongated feeding lesions.

Many other damage variables have been studied to assess resistance/susceptibility to stem borers in sorghum. House (1981) lists 1 -to-5 scales for both deadhearts and tunneling at harvest, to assess resistance to shoot flies and four species of stem borers. Pathak and Olela (1983) recorded percentage deadhearts, percentage tunnel length, number of larvae per plant, effective tillers per hill, and yield to assess C. *partellus* damage.

For ECB, characters measured have included: days to flowering; plant height; heads per plot;

number of seeds *per* head; seed weight; percentage broken stalks; percentage infested heads; percentage total breakage; length (cm) of stalk damage; percentage of larvae feeding on sheath, collar, head, stalk, midrib, and peduncle; and number of larvae per plant (Dicke et al. 1963; Ross et al. 1982; Guthrie et al. 1984b).

For SWCB, percentage plants tunneled, number of holes per plant, length of tunnel per plant, percentage heads tunneled, percentage stalks girdled/ percentage larval survival, and grain weight per plant have been recorded (Burton et al. 1982; Starks et al. 1982).

Thus there seems to be little consensus among entomologists as to which characters to measure in assessing total damage and resistance/susceptibility to sorghum stem borers. Establishment of standardized scales is also hampered by the diversity and variability of borer species and the damage they do under differing environmental conditions.

Plant selection is done in selected lines having acceptable ratings, and superior plants are advanced and rescreened with replication in the next generation. Periodically, to further confirm resistance levels and determine progress, promising lines along with susceptible checks are evaluated in yield trials where each genotype is grown under both artificial infestation and protection, as described by Guiragossian and Mihm (1983). Their results showed that although the most promising lines for SCB resistance—M66152 (NPEC-64735 x E-35-1)-7, 88-4 Poza Rica, and 787-3—are not highly resistant, they were far superior to the susceptible checks.

The ICRISAT program at CIMMYT is expected to continue screening and improving resistance to stem borers. Hopefully, more varieties and lines with resistance can be made available to the farmers of the Central American region.

In summary, stem borers are a threat to increased sorghum production; increased efforts in HPR, utilizing the techniques described above, can be expected to aid in the integrated management of sorghum pests.

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Methods of Rearing, Infestation, and Evaluation for *Chilo partellus* Resistance in Sorghum

S.L. Taneja and K. Leuschner*

Abstract

A detailed account of mass rearing of stem borer on artificial diet, field infestation, and evaluation for resistance to this pest in sorghum is given. Deadheart formation has been found to cause maximum grain yield loss and thus should be given maximum weightage in evaluating sorghum for stem borer resistance. An efficient and economical artificial diet for rearing of stem borer on a large scale by utilizing readily available indigenous ingredients has been developed. The moth emergence has been 70 to 75%, with a sex ratio of 1:1. The method of diet preparation, sterilization, rearing conditions, moth collection device, egg-laying cage, storage of eggs, and management of insectary have been discussed. Uniform field infestation by the laboratory-reared first instar larvae is done with a "bazooka" applicator, which drops equal numbers of larvae in each plant, along with a carrier. Out of about 12 000 germplasm lines screened, 61 have been found to be less susceptible to stem borer; these were tested for more than three seasons. Four lines, IS Nos. 5470, 5604, 8320, and 18573 have shown stable resistance over six environments. Factors affecting the initial establishment of the larvae have been found to be important in the development of resistant cultivars. There are marked differences between susceptible and resistant cultivars in larval success in reaching the whorl. Antibiosis and tolerance have been known to be the primary resistance mechanisms.

Resume

***Methodes d'elevage, d'Infestatlon et d'evaluation pour la resistance a* Chilo partellus *chez la sorgho**: *La communication presente une description detaillee de l'elevage de masse des borers des tiges alimentes sur milieu artificial, de {'infestation au champ et de l'evaluation de la resistance du sorgho a cet insecte. La formation des "coeurs morts" est la principale cause des partes du rendement en grain et devrait donc recevoir une ponderation maximum dans l'evaluation de la resistance. Les chercheurs ont mis au point un milieu artificial d'alimentation efficace et peu couteux pour l'elevage de masse en utilisant les ingredients disponibles localement. L 'emergence des adultes est de 70 a 75% avec un rapport des sexes de 1:1. La preparation du milieu, la sterilisation, les conditions d'elevage, l'appareil pour prelever les adultes, la cage pour la ponte, la conservation des oeufs et la gestion de la cellule des insectes, sont decrits. Les champs sont infestes artificiellement en inoculant les plantes avec des larves de premiere mue a l'aide d'un applicateur de style "bazooka". Celui-ci pose sur chaque plante le meme nombre de larves portees dans une matiere inerte pour assurer une distribution egale, permettant ainsi une infestation uniforme. Parmi les 12000 accessions sous etude, 61 se sont montrees moins sensibles et elles ont ete mises a l'essai pendant plus de trois campagnes. Quatres lignees IS: 5470, 5604, 8320 et 18573 ont fait preuve d'une resistance stable a six localisations. Il sera interessant de considerer les elements qui influencent l'etablissement des larves dans la creation de cultivars resistants. Les possibilites d'atteindre le verticille par les larves sont nettement differentes selon que le cultivar soit resistant ou sensible. L 'antibiose et la tolerance sont les plus importants mecanismes de resistance.*

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Introduction

Insect pests are one of the major yield-reducing factors in sorghum, which is attacked by nearly 150 insect species (Reddy and Davies 1979; Jotwani et al. 1980). A number of stem borer species are serious sorghum pests, attacking at various growth stages, and the species spectrum varies from region to region. *Chilo partellus* Swinhoe, commonly known as maize stem borer or spotted stalk borer, is one of the serious pests of sorghum in India (Jotwani and Young 1972) and the lowland areas of eastern Africa (Ingram 1958), and is potentially important in other areas of the semi-arid tropics. In West Africa and highland areas of East Africa, *Busseola fusca* is the predominant stem borer. Other borers attacking sorghum are *Sesamia inferens, S. calamistis, Diatraea* spp, and *Eldana saccharina,* which cause significant losses in some areas (Seshu Reddy 1982).

C. *partellus* attacks sorghum from 2 weeks after germination until crop harvest and affects all plant parts except the roots. The first symptom of attack is the irregular-shaped holes on the leaves, caused by the early instar larvae feeding in the whorl. The older larvae leave the whorl and bore into the stem base and reach the growing point. They cut the growing point and cause a characteristic "deadheart" symptom. In older plants, where internode elongation has started and the growing point has moved upwards, the larva feeds inside the stem, causing extensive tunneling. It also tunnels the peduncle (the internode between the stem and the earhead) and moves up to the earhead. It completes its life cycle (egg to adult) in about a month under optimum environmental conditions, and three to four generations are usually completed in a crop season.

Since sorghum is mainly grown by the resource-poor farmers in the semi-arid tropics, host-plant resistance offers a cheap and safe method of insect control. It is also an essential component in an integrated pest management program, well suited to the environmental conditions of the semi-arid tropics.

The earliest report on sorghum cultivars resistant to stem borer is by Trehan and Butani (1949). Pant et al. (1961) and Swarup and Chaugale (1962) reported certain sorghum varieties to be relatively less damaged by the stem borer. Starks and Doggett (1970) described the breeding methodology to incorporate resistance to stem borer. Ovipositional nonpreference is not a strong resistance mechanism against stem borer, but some cultivars have been reported to be less preferred by the moths for egg laying (Rana and Murty 1971; Lal and Pant 1980a; Singh and Rana 1984). The main mechanisms of resistance are antibiosis and tolerance (Pant et al. 1961; Kalode and Pant 1967; Jotwani et al. 1971; Jotwani 1976; Pathak and Olela 1983; Singh and Rana 1984). High mortality in the early larval stages (Jotwani et al. 1978) and low survival rate of the larvae (Lal and Pant 1980b) have been reported on resistant cultivars. Dabrowski and Kidiavai (1983) have reported that ovipositional nonpreference, reduced leaf feeding, low deadhead formation and stem tunneling, and tolerance to leaf and stem feeding contribute to stem borer resistance.

There are marked differences in the establishment of first instar larvae among resistant and susceptible cultivars (Chapman et al. 1983; Bernays et al. 1983). Surface waxes of the plant probably affect the movement of first instar larvae, and some wax components act as feeding deterrents (Woodhead 1982). Low sugar content (Swarup and Chaugale 1962), amino acids, total sugars, tannins, total phenols, neutral detergent fiber (NDF), acid detergent fiber (ADF), lignins (Khurana and Verma 1982, 1983), and high silica content (Narwal 1973) have all been reported to be associated with stem borer resistance.

A systematic screening of the world sorghum collection against this pest was started in 1962 in India under the cooperative efforts of the Accelerated Hybrid Sorghum Project (ICAR), the Entomology Division of the Indian Agricultural Research Institute, and the Rockefeller Foundation (Singh et al. 1968; Anonymous 1971, 1978). Since then, this work has been continued by the All India Coordinated Sorghum Improvement Project (AICSIP). At the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), where most of the world germplasm collection is being assembled and maintained, the main thrust of the sorghum entomology group is to (i) develop a reliable screening technique, (ii) identify strong and stable pest resistance sources, and (iii) incorporate pest resistance into elite backgrounds. This paper reports the results obtained so far in relation to the sorghum stem borer, C. *partellus.*

Selection Criteria

The symptoms of stem borer attack on sorghum are leaf feeding, deadheart formation, and stem and peduncle tunneling. Not all these symptoms are related to yield loss. Leaf injury, which is the first larval feeding symptom, can only be related to yield loss in severe cases. Brar (1972) also reported that leaf injury caused by stem borer attack varies over time because the plant recovers by producing new leaves. At ICRISAT, it has been found that stem and peduncle tunneling are not correlated with grain yield, since even up to 60% tunneling in any part of the stem (bottom, middle, or top) did not reduce the grain yield of the susceptible hybrid CSH 1 (Table 1), although quantity and quality of fodder may be adversely affected. Similar observations have also been reported by Pathak and Olela (1983), who found no correlation between stem length tunneled by the stem borer and grain yield per plant.

Peduncle damage could be critical in situations of high wind velocities, which would break the peduncles. The most critical damage is the formation of deadhearts which kills the main shoot. Two years' data from yield loss trials conducted at Hissar, where various crop development stages were protected, indicated that the most critical stage was between 15 and 30 days after crop emergence (Table 2), when maximum deadheart formation takes place and crop protection is therefore essential. Deadheart formation had highly significant and negative correlation with the grain yield of CSH 1 (r = -0.90). Singh et al. (1968) also concluded that deadheart formation was the most stable criterion for differentiating degrees of resistance.

Screening Techniques

For a good host-plant resistance program it is essential to develop an efficient and reliable screening technique that ensures the desired level of insect pressure uniformly, at the most susceptible stage of the crop. These requirements can be met either by selecting a location where the pest occurs regularly ("hot spot") or by testing the material under artificial infestation with laboratory-reared insects. Hisar (Haryana) in north India has been identified as a hot spot for the sorghum stem borer, where severe infestations of this pest occur

Table 1. Effect of stem borer attack on head and grain yield of sorghum hybrid CSH 1 at Hissar, Haryana, India, 1982.

Category	Mean stem tunneling (%)	Mean head weight (g)	Mean grain weight (g)	Ratio of grain to head weight (%)
No damage	0.0	61.6	527	85.3
Stem tunneling				
Up to 10%	6.1	62.3	53.2	84.2
10-20%	14.1	64.0	53.8	83.1
20-30%	26.3	84.6	69.0	81.5
30-40%	34.2	79.2	65.0	81.8
40-50%	43.6	69.2	55.2	79.3
50-60%	52.8	88.3	71.6	80.6
SE	±1.34	±10.49	±9.56	±2.70
CV (%)	12	29	32	7
Stem tunneling				
at bottom	7.3	68.0	56.6	83.4
at middle	6.2	51.9	43.2	82.0
at top (peduncle)	30.9	102.2	86.1	83.6
at bottom and middle	14.4	63.4	54.9	85.0
at bottom and top	31.5	93.6	76.3	81.9
at middle and top	30.9	85.4	68.7	79.8
at bottom, middle and top	38.8	74.2	60.2	80.8
SE	±4.8	±11.3	±10.47	±3.11
CV (%)	31	27	31	7

Table 2. Effect of protection regimes on stem borer infestation and yield loss in sorghum (CSH 1) at Hissar, India, 1982 and 1983.

	Deadheart (%)		No. harvestable heads/plot'		Grain yield (kg/plot)	
treatment	1982	1983	1982	1983	1982	1983
T : Carbofuran at sowing and 15, 30, and 45 DAE[2]	10.5	9.5	63.7	102.7	37.0	27.2
T : Carbofuran at sowing and 15 and 30 DAE	8.2	12.4	67.0	99.3	34.1	23.8
T : Carbofuran at sowing and 15 DAE	20.3	21.8	56.7	100.0	29.3	19.7
T : Carbofuran at sowing	49.0	60.1	45.7	34.5	20.5	8.9
T : Untreated control	62.2	60.1	33.7	16.5	10.7	4.6
SE	±2.98	±3.79	±2.9	±9.22	±1.26	±1.29
CV(%)	17	23	9	26	8	15

1. Plot size: 8 rows, 4 m long. Observations made only on middle 4 rows.
2. Carbofuran : at sowing time, applied in soil; after crop emergence, applied in the whorl. DAE : Days after emergence.

regularly. Population dynamics studies through light trap catches of moths and pest incidence on monthly planted crops have indicated that this pest is most active from early July to the beginning of October, with a peak in September (Fig. 1 and Table 3). Thus the crop sown between the first and third week of July is under sufficient insect pressure. At ICRISAT Center, however, stem borer infestation is low and irregular. Hence attempts have been made to rear this insect on an artificial diet in the laboratory and release appropriate numbers at the appropriate stage of crop growth to obtain uniform infestation.

Table 3. Stem borer incidence on sorghum hybric CSH 1, planted in different months (1983) at Hissar, India.

Month of planting	Borer damage (% plants)	Dead heart (%)
April	26.7	11.5
May	34.3	18.4
June	36.0	13.8
July	87.5	65.4
August	99.8	36.6
SE	±3.86	±2.20
CV(%)	14	15

Mass Rearing and Field Infestation

Rearing of the insect on artificial diet in the laboratory has been reported successful for many lepidopterous stem borers such as *Sesamia inferens* (Chatterji et al. 1969), *Diatraea saccharalis* (Miskimen 1965; Hensley and Hammond 1968; Dinther and Van Goozens 1970), *Busseola fusca* (Van Rensberg and Walter 1983), *Chilo suppressalis* (Ishii 1971; Kamano 1973), and also for C. *partellus* (Chatterji et al. 1968; Dang et al. 1970; Lakshminarayana and Soto 1971; Siddiqui and Chatterji 1972; Siddiqui et al. 1977; Sharma and Sarup 1978; Seshu Reddy and Davies 1979).

Various diets reported in the literature have been tested and the most satisfactory for rearing C. *partellus* at ICRISAT is given in Table 4. All the ingredients of the diet are easily available in the local market, except for sorghum leaf powder. For sorghum leaf powder, the leaves of susceptible cultivar (CSH 1) are collected from a 35- to 40-day-old crop. They are washed, dried, ground to a fine powder, and autoclaved for 15 min at 120°C and 15 lb pressure. Average moth emergence from this diet has been found to be 70 to 75%, with the maximum output up to 90%. The sex ratio is also close to 1:1 and 90 to 95% of the moths emerge 25 to 35 days after egg inoculation in the diet.

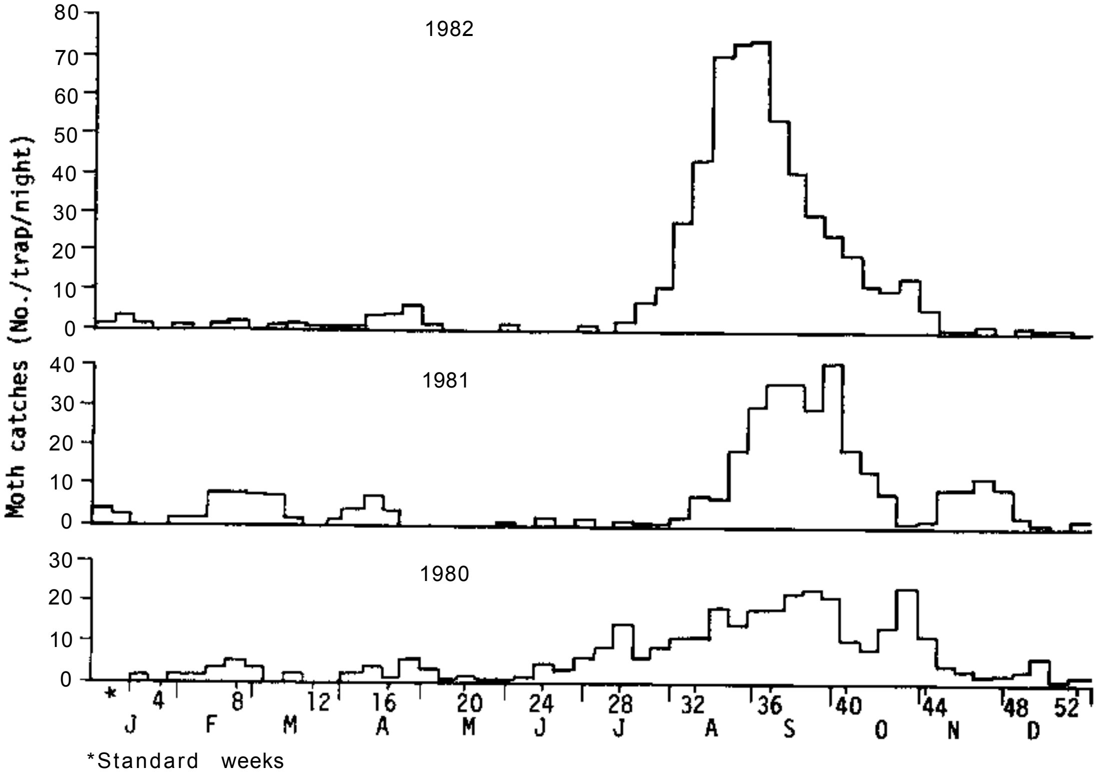

Figure 1. Seasonal activity of *Chilo partellus* based on light trap catches of moths at Hisar (1980-82).

Table 4. Artificial diet used for mass rearing of sorghum stem borer, *Chilo partellus,* at ICRISAT Center, India.

Ingredient	Quantity
Fraction A	
Water	2000 ml
Kabuli gram[2] flour	438.4 g
Brewer's yeast	32.0 g
Sorbic acid	4.0 g
Vitamin E (Viteolin capsules)	4.6 g
Methyl parahydroxy benzoate	6.4 g
Ascorbic acid	10.4 g
Sorghum leaf powder	160.0 g
Fraction B	
Agar-agar	40.8 g
Water	1600 ml
Formaldehyde (40%)	3.2 g

1. Amount used to prepare 15 jars of 300 g diet each.
2. A cultivar of chickpea *(Cicer arietinum).*

Method of Preparation

All the ingredients of fraction A (Table 4) except the sorghum leaf powder are blended for 1 min. Sorghum leaf powder is soaked in 2 liters of warm water (70° C) and blended with fraction A ingredients for 3 min. Agar-agar is boiled in 1.6 liters of water (fraction B) and cooled to 40° C before adding to the blender containing fraction A ingredients. Formaldehyde is finally added and all the constituents are blended for 3 min. The diet is then poured into plastic jars and cooled. Each jar contains about 300 g diet, which is sufficient for 100 larvae to develop successfully.

Egg Sterilization

To avoid any external contamination, eggs are sterilized during the black-head stage (1 day before hatching) in 10% formaldehyde for 2 min and then washed thoroughly with distilled water before being placed on the diet.

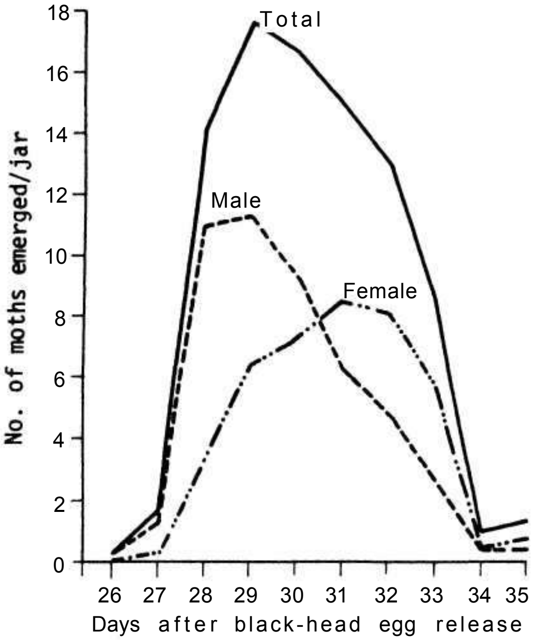

Figure 2. Stem borer moth-emergence rates from artificial diet at ICRISAT Center (1982/83).

Rearing Room

After the diet has cooled down to room temperature, approximately 100 black-head stage eggs are placed in each jar. The jars are kept in the rearing room in the dark for 2 days. First instar larvae have a strong photopositive behavior and settle better on the diet in darkness. In the rearing room, temperature is maintained at 28+1 °C, relative humidity at 60 to 70%, and light is provided for 12 h.

Larval and pupal stages of the insects are completed in the same jar where the eggs are placed. In this controlled environment, the larval period lasts 22 to 28 days and the pupal period 5 to 6 days. First moths (males) emerge 25 to 26 days after egg inoculation and continue to emerge up to the 35th day. Females start emerging 2 to 3 days later than the males (Fig. 2).

Moth Collection Device

Moths are collected with the help of a vacuum cleaner attached to a pipe with various outlets (Fig. 3). A bifurcating tube is fixed to the outlet, which

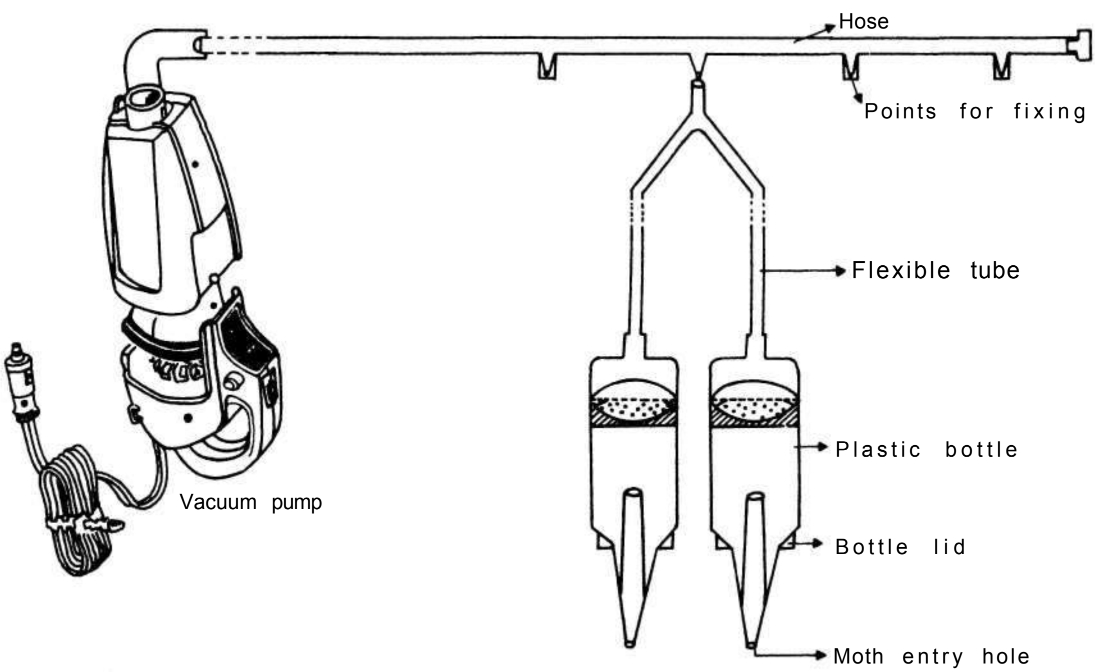

Figure 3. Sketch of stem borer moth-collection device employed at ICRISAT Center.

terminates at the moth-collecting plastic bottles. The plastic bottle can be replaced with a fresh one when a specified number of moths is collected. The suction of air can be regulated to allow smooth collection of moths without damaging them. With the help of two collection bottles, male and female moths are collected separately (males being smaller in size with dark forewings and smaller pointed abdomen) and transferred to the egg-laying cage.

Egg-laying Cage

The egg-laying cage consists of an open cylinder (25 cm high and 25 cm diameter) made of galvanized iron wire mesh. A thin georgette cloth is wrapped around this cylinder and uniform holes (6 mm) are made in it at regular intervals. White butter paper is wrapped around this cage at the time of moth release. Two saucers covered with mosquito net are fitted on both the ends. Female moths after mating lay eggs on the butter paper through the holes. The butter paper with egg masses is replaced every day with fresh paper. A female lays an average of 9 to 10 egg masses in a period of 4 days, the maximum being laid on the second day. We found that 50 moth pairs per cage were optimum for reasonable egg laying. Maximum eggs are laid when moths are fed on water only (Fig. 4).

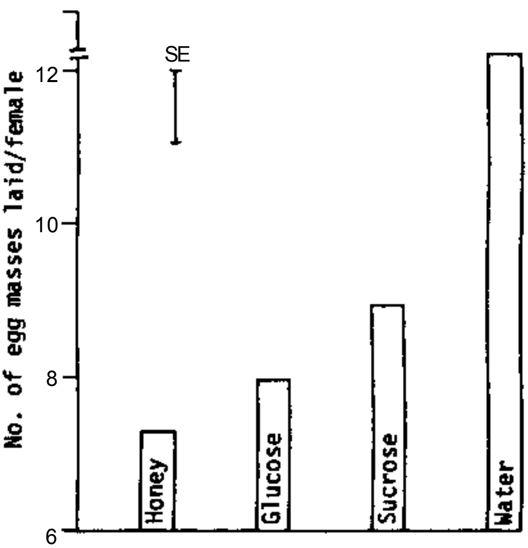

Figure 4. Effect of food on egg production by stem borer moths in the laboratory, 1CRISAT Center.

Storage of Eggs

High humidity (80-90%) is needed for normal embryonic development, and hatching was drastically decreased when humidity was down to 50% (Fig. 5). For normal incubation, eggs are stored at 26±1°C and high humidity (>80%). Under these conditions, the embryo matures to the black-head stage within 4 days. For long-term storage, black-head stage eggs can be kept at 10°C with high humidity for up to 10 days without reducing the hatchability (Fig. 6).

Field Infestation

Preparing the Applicator

For field infestation the "bazooka applicator" developed by Mihm and colleagues at the Centro Internacional de Mejoramiento de Maiz y Trigo (CIMMYT) in 1976 (CIMMYT 1977) for infesting maize with corn earworm has been modified to suit our requirements. This method requires a carrier plus larvae mixture. Various carriers have been tried by different workers, such as corn grits (Mihm 1982), com meal (Hall et al. 1980), and finger millet (Seshu Reddy and Davies 1979). We also tested different carriers to increase the efficiency and uniformity in larval distribution and found that small poppy seeds *(Papaver* sp.) locally known as *kash kash* were better than all other carriers tested, including finger millet, reducing larval mortality during dropping and giving more uniform numbers of larvae per stroke (Fig. 7).

For field infestation, first instar larvae are mixed with the carrier; 85 g of the carrier is placed in a plastic jar with a tight-fitting lid, along with 500 black-head stage egg masses. The plastic jar is kept at 26° C and 80% relative humidity overnight. Light is switched on at 0600 h to stimulate hatching; by 0900 h, most of the eggs are hatched. The larvae are then gently mixed with the carrier and transferred into the plastic bottle of the bazooka with the help of a funnel, and the bottle is attached to the applicator, ready for use in the field.

Infesting the Plant

The most critical damage, causing maximum grain yield reduction, is deadheart formation. This symptom can be obtained only if relatively young plants are infested. To identify the most critical stage of

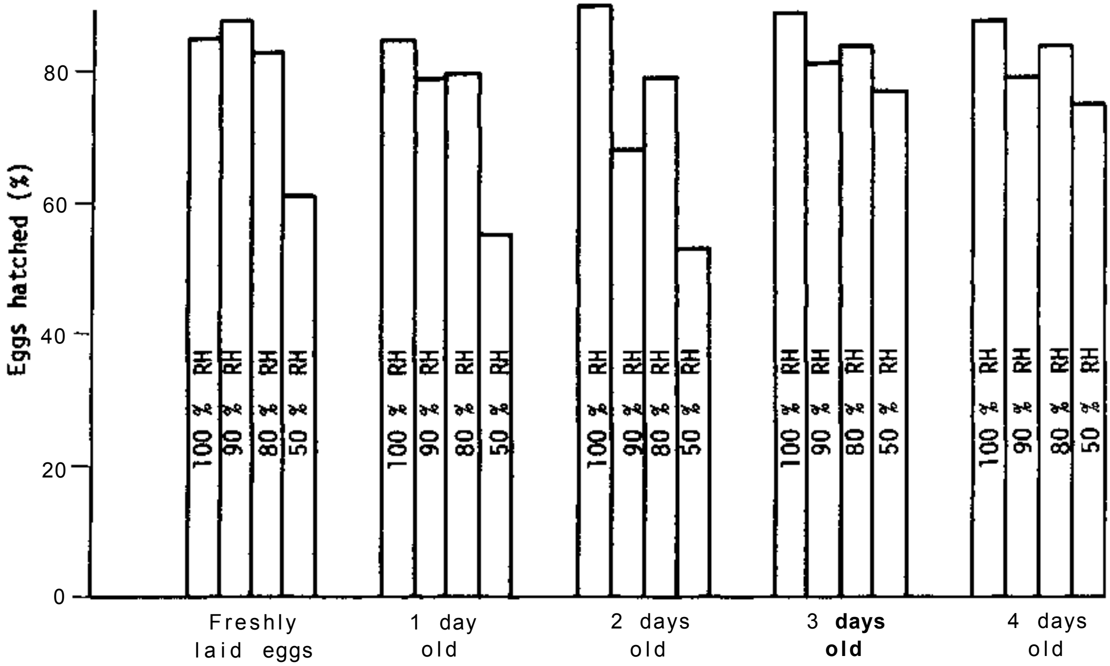

Figure 5. Effect of relative humidity (RH) regime on hatching of stem borer eggs in the laboratory, ICRISAT Center.

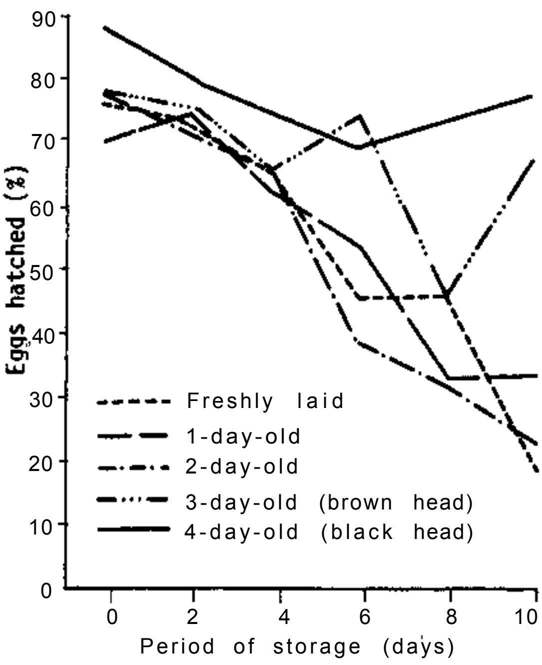

Figure 6. Effect of egg age and duration of storage (at 10°C) on hatchability of stem borer eggs, ICRISAT Center.

infestation for causing the maximum deadhearts, we experimented with infesting plants of different ages, 14 to 29 days old. Deadheart formation decreased progressively as infestation was delayed (Fig. 8). Another factor that interferes with stem borer testing, particularly during the *rabi*^post-rainy) season, is crop damage by shoot fly, which attacks 1 - to 4-week-old seedlings. To find a selective insecticide that would suppress shoot fly, but with no residual effects on stem borer establishment, different insecticides have been tested. Soil application of carbofuran at sowing, which is a common practice on research farms, had detrimental effects on stem borer establishment. Synthetic pyrethroid (fenvalerate) and endosulfan seem to be of some promise, having the least effect on stem borer (Fig. 9)

Management

Efficient planning is required to produce sufficient numbers of insects to infest the test material uniformly at the proper growth stage. At ICRISAT, screening for stem borer resistance is carried out in two seasons, rainy and postrainy. For the rainy season, planting is generally done in mid-June and for the post-rainy season, at the end of September. Fig. 10 indicates a schedule for diet preparation, sowing of the crop, and period of infestation.

Sanitation

Diseases (fungal, bacterial, viral, and microsporidian) in the insect culture may limit mass production. These are common hazards and can occur sooner or later if proper hygienic conditions are not maintained. Precautions that help to minimize disease outbreak in the insect culture followed at ICRISAT are: sterilization of all the plastic and glassware and appliances; surface sterilization of eggs; destruction of jars showing any disease or mite symptoms; regular disinfection of racks and floor, restricted entry of persons to the laboratory, and maintenance of personal hygiene by the persons working in the laboratory.

Identification of Resistance Sources

A number of sorghum germplasm lines and their derivatives have been reported to be resistant to

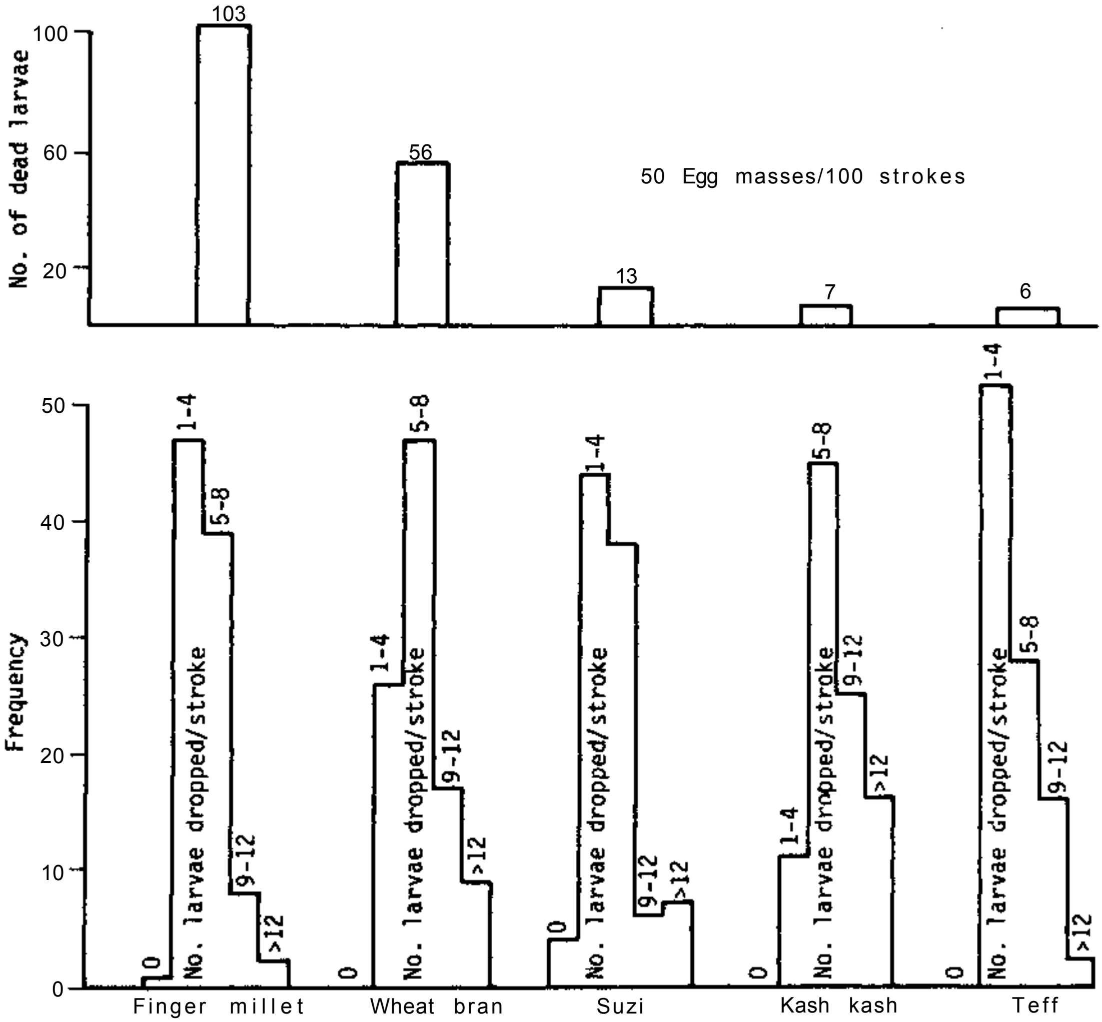

Figure 7. Evaluation of carrier for distribution of stem-borer larvae through 'bazooka' applicator, ICRISAT Center.

stem borer by various workers in India and elsewhere (Singh et al. 1968; Jotwani et al. 1974; Kundu and Jotwani 1977; Jotwani et al. 1979; Singh et al. 1980; Jotwani 1982; Dalvi et al. 1983; Singh et al. 1983; Sharma et al. 1983). At ICRISAT Center the initial stem borer resistance work using artificial infestation started in 1979 (Seshu Reddy and Davies 1979). Later on, testing of the material was also started at Hissar, where the natural stem borer infestation was found to be quite high and regular. Out of nearly 12 000 germplasm lines tested for more than three seasons, 61 have been found less susceptible (Table 5). In addition, out of nearly 3800 lines tested over two seasons, 36 have been

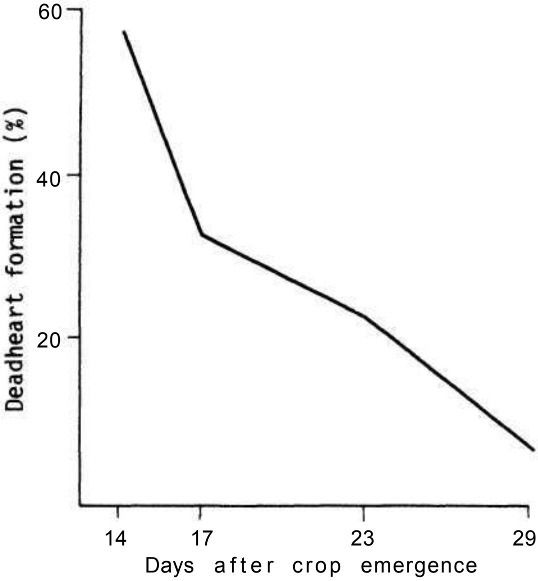

Figure 8. Deadheart formation in susceptible sorghum CSH 1 with larval infestation at 14, 17, 23, and 29 days after seedling emergence.

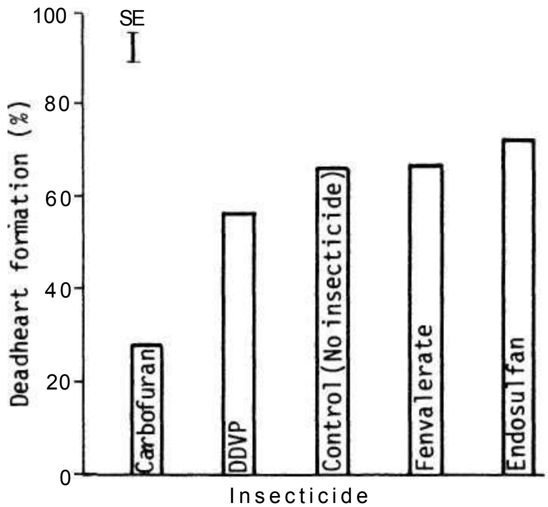

Figure 9. Residual effect of four insecticides used for shoot-fly control on stem borer larvae measured indirectly through deadheart formation (%) on sorghum cv CSH 1.

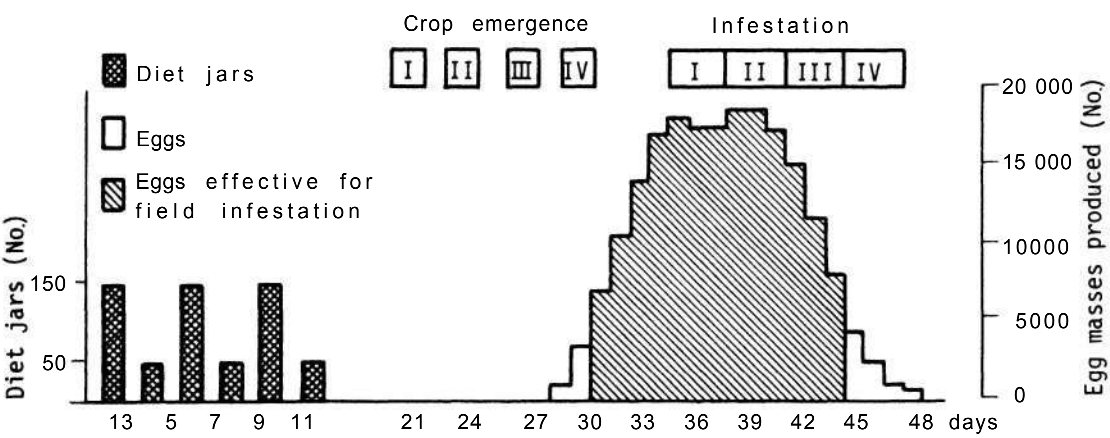

Figure 10. Scheme for mass rearing of stem borer and field infestation of sorghum at ICRISAT Center.

Table 5. Sorghum germplasm lines identified as less susceptible to stem borer at ICRISAT Center. India/

Pedigree	Origin	Stem borer incidence (%)
IS 1044	India	32.9
1082	India	45.3
1119	India	42.4
2122	USA	35.8
2123	USA	30.6
2146	USA	46.1
2168	USA	50.4
2195	India	43.8
2205	India	40.6
2263	Sudan	38.1
2269	USA	48.6
2291	Sudan	31.7
2309	Sudan	33.8
2312	Sudan	33.3
4273	India	63.9
4546	India	43.9
4637	India	41.4
4756	India	38.1
4776	India	38.0
4881	India	41.0
4981	India	48.3
5075	India	49.5
5253	India	53.4
5429	India	41.1
5469	India	28.3
5470	India	35.5
5480	India	37.9
5538	India	33.1
5566	India	32.9
5571	India	35.3
5585	India	35.2
5604	India	23.3
5622	India	41.0
7224	Nigeria	44.4
8320	India	33.6
8811	Uganda	56.4
10711	USA	38.7
12308	Zimbabwe	38.0
13100	India	36.8
13674	Uganda	33.9
17742	India	44.6
17745	India	44.4
17747	India	51.4
17750	India	47.5
1 7948	India	43.6
17966	India	45.4
18333	India	48.1
18366	India	53.7
18551	Ethiopia	36.0
18573	Nigeria	24.0
18577	Nigeria	34.9
18578	Nigeria	40.6
18579	Nigeria	34.6
18580	Nigeria	49.8
18584	Nigeria	40.5
18585	Nigeria	48.8
18662	India	39.0
18677	India	45.8
20643	USA	47.6
SB 8530	Not known	39.0
PB 8253	Not known	59.4
CSH 1 (control)		70.3

Continued

Table 5. Continued

1. Mean of six replicated trials.

selected for confirmation. Out of 2000 additional lines tested at Hissar for one season, 460 lines have been retained for retesting.

Stability in Resistance

Stability analysis (Finlay and Wilkinson 1963) of 62 lines (61 less susceptible lines and one susceptible control, CSH 1) over six locations indicated that the most stable lines were IS nos. 5470, 5604, 8320, and 18573; 28 lines showed less than 40% stem-borer incidence, with a moderate level of stability (Fig. 11).

Diversity

Of the less susceptible lines, 59 (Table 5) are of fairly diverse geographic origin: 36 of them are from India; 8 from Nigeria, 7 from the USA, 4 from Sudan, 2 from Uganda, and 1 each from Ethiopia and Zimbabwe. As far as taxonomic diversity is concerned, most of them belong to *Durra* sorghums (84%), while very few belong to *Durra membraceum* (10%), *bicolor* (4%) and *guinea bicolor* (2%). Although the geographic and taxonomic diversity in the stem borer resistant sources will be of great

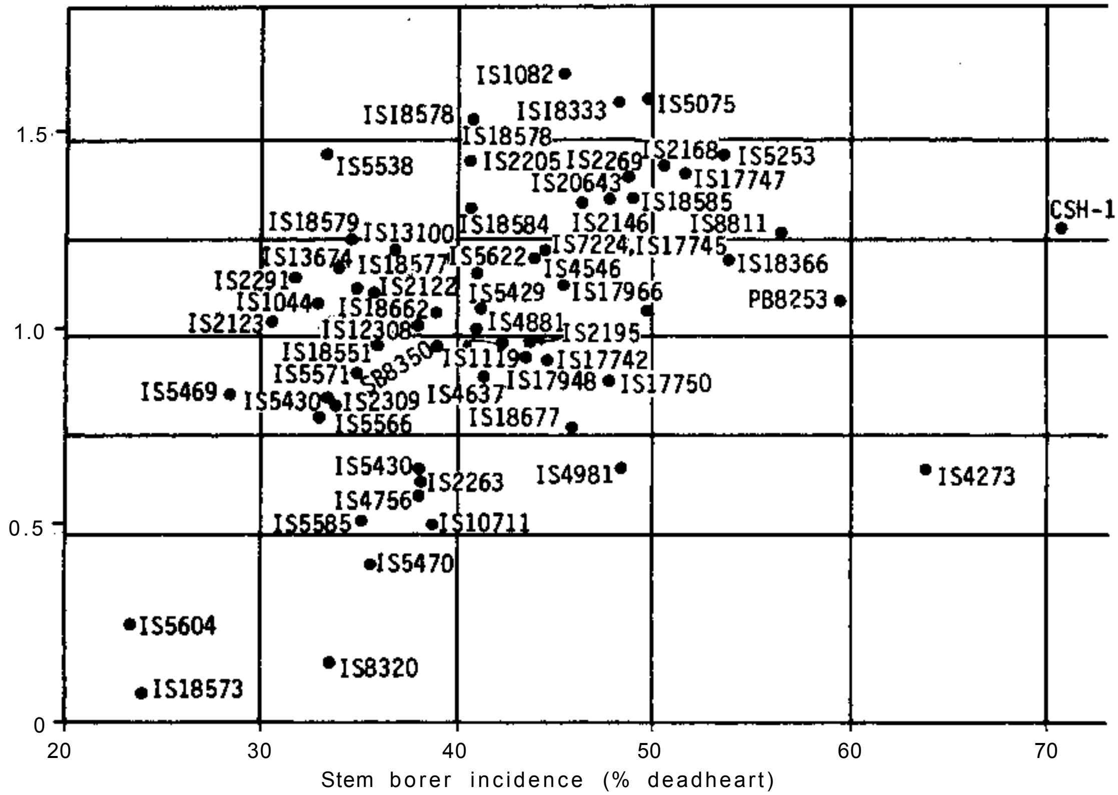

Figure 11. Stability analysis of sorghum lines less susceptible to stem borer (six seasons).

value in breeding cultivars with borer resistance, the presence of genetic diversity has yet to be established.

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Screening for Sorghum Stem Borer Resistance

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Abstract

Promising sources of resistance to spotted stem borer (Chilo partellus) *have been identified through systematic screening of the world sorghum germplasm collection. The best of these have been incorporated into the breeding program under the All India Coordinated Sorghum Improvement Project. Moderate levels of resistance have been found in two recently released hybrids, CSH 7(R) and CSH 8(R), as well as in varieties CSV nos. 3, 4, 5, 6, 7, and 8, and SPV nos. 17, 19, 29, and 58. Several other high-yielding varieties with high levels of stem borer resistance are in the advanced stage of testing. The mechanisms of resistance to sorghum stem borer are complex, and resistance is governed by several genes. The scheme for breeding to strengthen this resistance is described.*

Resume

***Criblage des sorghos pour la resistance aux borers das tiges** : Des sources prometteuses de resistance au borer ponctue des tiges* (Chilo partellus) *ont ete identifiees au cours du criblage systematique de la collection mondiale des ressources genetiques de sorgho. Les meilleures sources ont ete incorporees dans le programme de selection dans le cadre du Projet coordonne indien pour l'amelioration du sorgho. Deux hybrides, CSH 7(R) et CSH 8(R) vulgarises recemment revelent des niveaux acceptables de resistance aussi trouves chez les varietes CSV 3, 4, 5, 6, 7 et 8 ainsi que chez les varietes SPV 17, 19, 29 et 58. Plusieurs autres varietes a haut rendement avec niveaux eleves de resistance sont aux stades avances d'essai. Les mecanismes de resistance au borer sont complexes et la resistance est controlee par plusieurs genes. La strategie de selection pour renforcer ce caractere est decrite.*

Introduction

Sorghum *{Sorghum bicolor)* is an important food and fodder crop in the semi-arid areas of Asia and Africa. Insect pests are one of the main constraints to higher yields. The spotted stem borer, *Chilo partellus* (Swinhoe), has been recorded as a serious pest not only from the Indian subcontinent but also from a number of African countries, Indonesia, Malaysia, Taiwan, and Sri Lanka (Young and Teetes 1977). Avoidable grain losses of 55 to 83% on CSH 1 and CSV 1 were recorded by Jotwani et al. (1971).

Pest-resistant varieties are one of the important components of an integrated pest control strategy. Chemical control has its own limitations—e.g., high cost, potential insect resistance to insecticides, chemical residues and environmental pollution, and destruction of beneficial insects. Among the methods of insect pest control known and recommended, host-plant resistance has recently received more attention in India in relation to various crops under the All India Coordinated Schemes.

The spotted stem borer is one of the important pests of sorghum all over India. Because of the low commercial value of sorghum and the fact that it is grown by subsistence farmers in a low-input agricultural situation, it is necessary to screen and develop varieties resistant to the spotted stem borer.

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Biology and Population Dynamics

The sorghum stem borer, *C. partellus,* has been recorded as a pest of sorghum throughout India, but is more serious in the northern and central regions.

The adult *Chilo* moths are medium-sized, straw or light brown in color, with numerous shiny brown spots on wing margins, the hind wings being papery thin and white. The moths are nocturnal in habit and usually live for about 2 to 4 days. Mating generally takes place during the early hours of the day and egg laying during the evening hours. The female moth deposits patches of 50 to 150 flattened, overlapping, dirty yellowish white eggs on the undersurfaces of the leaves near the midrib or on tender stalks.

Depending on the prevailing weather conditions, larvae hatch within 3 to 8 days and immediately crawl up into the leaf whorls, where they feed and remain up to the second instar. In the third or fourth instar, most of them migrate to neighboring plants by suspending themselves on silken threads and being easily blown away by the wind. The few remaining on the original plants bore into the stem. The larval stage may last for 15 to 30 days. The full-grown larva, dirty white in color, measures about 20 to 25 mm in length. Normally larvae molt five times.

Pupation takes place inside the stem, and lasts from 6 to 12 days. Under optimum conditions the entire life cycle may be completed within 30 to 40 days. During the *entire* crop season, three to four overlapping generations of the spotted stem borer occur in the field.

There is some evidence of the existence of biotypes or races of the sorghum stem borer. In north India this pest undergoes diapause because of low winter temperatures, while in the southern states the pest remains active throughout the year. In central India, there are reports of two distinct strains, one undergoing diapause during the winter season, the other remaining active throughout the year.

During the last few years, there has been a sudden change in the pattern of damage by the stem borer during the advanced stage of the crop. In the past, the pest usually remained confined to the stem region of the plant and damage to earheads was insignificant. However, there are now reports of severe damage to earhead peduncles, which prevents grain formation. It is suspected that this unusual type of damage is being caused by a new race or biotype of the stem borer.

Damage Symptoms

Four distinct symptoms reveal damage caused by the sorghum stem borer:

1. "Windowpane" formation, which results from the larvae feeding inside the whorl, as is evident from the unfolding central leaves showing small or large holes on the lamina.
2. Deadheart formation, where the growing point is destroyed by the larvae, causing the central leaves to dry up and killing the main shoot. The plant may produce tillers to compensate for this damage.
3. Stem tunneling, where the internodes of the stem are tunneled by the larvae feeding inside.
4. Peduncle damage, in which the peduncle is tunneled and, due to the weight of the head, may break. Early peduncle damage may result in chaffy or partially filled heads.

Reported incidence of stem borer ranges from 10 to 75% and in severe cases resowing of the crop becomes inevitable (Rahman 1944; Trehan and Butani 1949; Pradhan and Prasad 1955). Sharma et al. (1983) reported 80 to 100% infestation by spotted stem borer at Hissar, Haryana, in northern India.

Control Measures

Newly developed hybrids and varieties are generally more susceptible to insect attack than traditional landraces. Intensive research work was initiated to develop effective control measures for the pest complex of sorghum. Initially, most research was done on chemical control but simultaneously, long-term programs were undertaken to develop other methods in which costly inputs in the form of insecticides may be avoided. The importance of developing such methods in the case of sorghum, which is mostly grown by small farmers under rainfed conditions, is evident.

The importance of adopting host-plant resistance as a major crop protection component against sorghum pests was stressed by Dahms as early as 1943:

> The use of resistant varieties to lessen injury from insects that attack sorghums would appear to deserve more attention, because the control of insects on a crop of low value per acre precludes the use of insecticides.

Furthermore there is a possibility that growing of resistant varieties would reduce the insect population.

In India an active program was initiated for developing high-yielding sorghum varieties resistant to stem borer. This includes the development of screening methodologies and the understanding of the biology and bionomics of the stem borer in relation to the phenology of the crop (Chapman et al. 1983; Bernays et al. 1983). Results and progress of this work are summarized in this paper.

Screening for Resistance

Screening Methodology

Under the All India Coordinated Sorghum Improvement Project, the available world germplasm of sorghum was screened during the course of two projects, i.e., Investigations on insect pests of sorghum and millets (1965-70) (Pradhan 1971) and Investigations on insect pests of sorghum and millets with special reference to host plant resistance (1972-77) (Jotwani 1978).

The preliminary screening was done in single-row unreplicated plots under natural infestation conditions. Selected lines were screened in replicated trials by artificially infesting the plants with egg masses of the borer at two stages of plant growth. The parameters for assessing the damage were (a) leaf injury and (b) stem tunneling caused by the borer. The lines were graded for leaf injury at different stages of plant growth by adopting a score ranging from 0 (no damage) to 9 (very severe damage). At harvest, randomly selected stalks were split open to measure the tunneled length in relation to the total length of the plant to give an index for stem tunneling. A known susceptible control was included for comparison.

Screening Results

Based on this screening procedure Pradhan (1971), Jotwani (1978), Jotwani and Davies (1980), and Jotwani and Agarwal (1982) screened 6243 lines available in the world germplasm collection and finally selected 26 lines (IS nos. 1044, 1056, 1115, 1151, 4424, 4552, 4651, 4689, 4747, 4764, 4776, 4782, 4827, 4841, 4875, 4934, 4994, 5030, 5031, 5470, 5837, 6041, 3096, 7273, 8314, and 9136) as promising sources of resistance.

Singh et al. (1983) screened 70 recently released varieties, hybrids, and experimental varieties under artificial infestation during the rainy season (July-October). Significant differences were observed among the varieties for leaf-feeding injury, percent deadheads, number of holes, and percent tunneling. The mean leaf-feeding injury rating was 0.21, with a range of 0-1.67. No leaf-feeding injury was observed on E 302, E 303, E 304, E 701, and SPV 105. Significantly fewer holes were observed in CSV 8(R), SPV 110, SPV 232, E 303, E 304, E 701, and P 37 compared with the resistant check IS 1151 (Aispuri).

Peduncle damage (tunneling) ranged from 0 to 37% in the trial. No peduncle tunneling was recorded in the resistant check IS 2313; SPV nos.35, 103, 107, 140, 192; R 133; and CSV 8(R).

Another major screening program for stem borer resistance is at ICRISAT. Sharma et al. (1983) screened 14 000 germplasm lines under natural and artificial infestation conditions at ICRISAT, Patancheru (Andhra Pradesh), and Hissar (Haryana). Lines with low percentages of dead-hearts and stem tunneling were identified as IS nos. 1044, 2123, 2137, 2168, 2205, 2309, 5538, 5566, 5571, 5585, 5604, 5622, 7224, 19551, 18577, 18578, 18584, and 18662.

Mechanisms of Resistance

Nonpreference

Observations indicate that nonpreference may be a factor involved in resistance to the stem borer. Lal and Pant (1980) reported that gravid female moths of the sorghum stem borer preferred to lay more egg masses on susceptible varieties of maize and sorghum than on resistant ones. Dabrowski and Kidiavai (1983) observed that of 100 lines tested under field conditions, 11 were nonpreferred for oviposition: E 302, E 303, and IS nos. 1044, 1151, 2162, 4660, 17739, 18328, 18349, 19479, and 18489.

Antibiosis

Jotwani et al. (1971) reported prolongation of larval period and higher mortality of borer larvae on three resistant lines of sorghum—IS nos. 1151, 4764, and 4776—as compared with the susceptible hybrid CSH 1.

Jotwani et al. (1978) studied the development of the stem borer larvae on resistant and susceptible lines of sorghum. They observed higher larval mortality on resistant lines IS nos. 1151, 4283, 4764, 4776, 5016, 5072, 5200, 5604, and 5629, than on the susceptible control, CSH 1. The larval period was also prolonged and less pupation took place on resistant cultivars than on CSH 1.

Lal and Sukhani (1979) studied the biology of the borer on four resistant lines (E 302, E 303, D 124, and IS 4308) and two susceptible controls (CSH 1 and CSV 1). They observed that larval survival in leaf whorls and stalks varied from 62.5 to 70% on susceptible controls, as compared with 22.5 to 37.5% on resistant lines. E 303 and D 124 showed relatively higher levels of antibiosis.

Dabrowski and Kidiavai (1983) also reported less feeding of first instar larvae on E 302, E 303, and IS nos. 1044, 2162, 2209, 18349, and 18427. IS nos. 2162, 2262, 18328, 18349, also expressed less deadheart formation. In IS nos. 4660, 18327, and 18479, reduced tunneling, which may be due to antibiosis, was observed.

Very little work has been done on the biophysical and biochemical basis of borer resistance. Bernays et al. (1983) observed that the wax bloom on cv 1151 interfered with the movement of the newly hatched larvae.

Swarup and Chaugale (1962) found that hydrocyanic acid (HCN) content of the sorghum plants was not related to the incidence of stem borer in different varieties. However, Woodhead et al. (1980) reported that HCN deterred feeding of *Locusta migratoria* on young sorghum plants. Similarly.the presence of high HCN also reduced feeding of first instar larvae of C. *partellus.*

Tolerance

Jotwani (1978) reported significantly lower yield loss to stem borer in selections 124, 175, 177, 446, 447, 731, 780, 827, and 829 than in CSH 1. It was observed that in spite of severe leaf injury and stem tunneling, the final plant stand was very good and most of the plants had normal-sized earheads, which can be classified as a tolerance mechanism. Similar results were obtained by Dabrowski and Kidiavai (1983) with IS 2205.

Recovery Resistance

In a trial conducted during the rainy season of 1979, a derivative selected from a cross between (IS 3684 x Aispuri) x (IS 3922 x Karad local) was observed to produce healthy tillers after the main shoot was killed by borers. The cross produced two to six productive tillers which matured almost simultaneously, and the grain yield was significantly higher than in undamaged plants (Table 1). This could be called recovery resistance, an important escape mechanism in local landraces.

Breeding for Resistance

Attempts have been made to utilize some of the above mentioned resistance sources in the breeding program. Figure 1 presents a flow diagram of the steps taken for the development of resistant varieties. In collaboration with breeders, several crosses were made. Initial selections were made for favorable agronomic traits. Selections for both

Table 1. Yield data of derivative (IS 3687 x Aispuri) x (IS 3922 x Karad local) in plants damaged and undamaged by stem borer.

Observation	Undamaged plants with single earhead	Damaged plants with productive heads	
		2 to 3	6
Av. wt of earhead (s)/plant (g)	120.00	150.50	212.00
Av, wt of grain/plant (g)	101.00	137.00	192.00
Av. wt of fodder/plant (g)	312.00	357.00	430.00

Source: Kishore and Jotwani (1979).

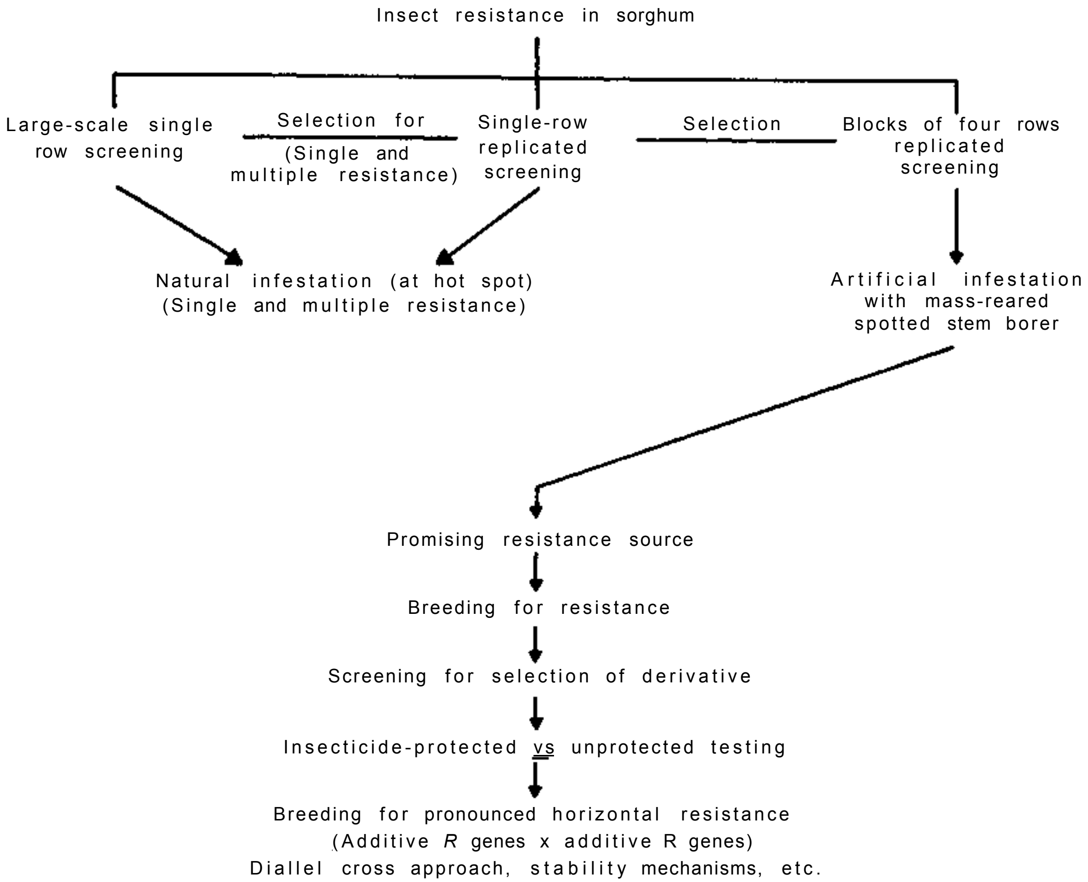

Figure 1. Scheme followed in developing a sorghum variety resistant to spotted stem borer.

borer resistanee and yield were made from the F_4 generation onwards. The promising lines were then tested in Initial evaluation trials and later in coordinated varietal trials at different locations in the All India Coordinated Sorghum Improvement Project.

The program has yielded two highly promising derivatives, E 302 and E 303. During the rainy season, 1974, these two derivatives and their parents were screened again to determine the heritability of borer resistance. The entries were sown in five-row plots with four replications. Leaf injury scores and percent stem tunneling are presented in Table 2.

The level of borer resistance in derivatives E 302 and E 303 was lower than that in the resistant parent BP 53, but significantly higher than in the susceptible parents. The data confirm that the resistant parent is a good combiner for donating borer resistance characters. This character was maintained at a sufficiently high level throughout subsequent generations, which was also confirmed by Dabrowski and Kidiavai (1983) in Kenya. Under heavy natural stem borer infestation at Delhi, the fodder and grain yields from these two derivatives were compared with the susceptible controls, CSH 1 and CSV 1 (Jotwani et al. 1974) (Table 3).

In addition, a number of other derivatives from the two borer-resistant line's M 35-1 and BP 53 have been rigorously screened at Delhi and Udaipur under high natural borer pressure.

Kundu and Jotwani (1977) then screened two derivatives (447 and VZM-2B) for their susceptibility *to* stem borer under heavy natural population pressure (Table 4).

These observations clearly indicate that both lines possess fairly high degrees of resistance. In addition, they have the desirable agronomic characters of early to medium maturity and pearly white grain.

Table 2. Leaf injury and stem tunneling by spotted stem borer in high-yielding, borer-resistant derivatives and their parents.

Sorghum entry	Av. leaf injury		Av. stem tunneling (%)
	25 DAG	60 DAG	
E 302 (CK 60B x BP 53) S x R	1.5	3.0	22.6
E 303 (IS 3954 x BP 53) S x R	2.2	3.2	17.2
BP 53 (IS 1056) R	2.0	2.5	9.0
IS 3954 (S)	3.0	7.5	40.1
CK 60B (S)	3.0	6.5	36.6

Source : Jotwani (1978).
1. Leaf injury grade : 0 = no damage; 9 = severe damage; DAG = Days after germination; S = susceptible; R = resistant.

Satisfactory progress was made in developing varieties resistant to stem borer by Kishore and Jotwani (1982)(Table 5). Among the resistant derivatives, the average leaf injury ranged from 1.5 to 3 as compared with 5.5 in the susceptible check, CSH 1. Average percentage stem length tunneled ranged from 6 to 19.2, as against 46.5 in the susceptible check.

Further, Jotwani (1981, 1982) and Kishore et al. (1983) tested nine selected lines for 2 years. The average leaf injury from stem borer in the test material ranged from 1 to 3 in 1980 and from 2 to 3 in 1981, while CSH 1 showed 6.5 and 6 in the respective years (Table 6). All resistant lines recorded significantly lower stem tunneling than CSH 1, indicating moderate levels of resistance.

Dalvi et al. (1983) screened 32 breeders lines in the rainy and 30 in the postrainy season at Rahuri (Maharashtra) during 1978-79. E 302 and E 303 performed best in terms of resistance in both seasons.

Singh et al. (1980) studied the stability of promising derivatives obtained from IS 2954 x BP 53 and IS 3922 x Aispuri (temperate x tropical) crosses. In the majority of the cases it was observed that temperate varieties are susceptible, while tropical varieties are fairly resistant to the stem borer.

Seventeen promising derivatives (D nos.108, 124, 167, 168, 169, 172, 175, 259, 300, 350, 358, 365, 366, 367, 369, 468, and 832) were screened for eight seasons for borer resistance. Stability of resistance was found to be a linear function of insect infestation derived by regressing the individual varietal performance on the susceptibility index. Six selected derivatives, D 168, D 172, D 259, D 358, D 367, and D 369, were observed to be

Table 3. Screening promising borer-resistant lines of sorghum for grain and fodder yields under heavy natural infestation of stem borer, Delhi, India.

Entry	Average yield			
	1972		1973	
	Grain (kg/ha)	Fodder (t/ha)	Grain (kg/ha)	Fodder (t/ha)
E 302	2672	19.2	3166	35.1
E 303	2688	15.2	3388	32.1
CSH 1	1590	6.6		
CSV 1			1442	13.8

Source : Jotwani et at. (1974).

Table 4. Evaluation of two promising sorghum derivatives for resistance to spotted stem borer.

Entry	Av. deadhead (%)	Av. stem tunneling (%)	Visual grading	1000-grain wt (g)	Plant maturity (days)	Av. plant height (cm)
447 (IS 2954 x BP 53) (E 304) S x R	5.27	11.80	2.60	29	114	148
VZM 2B (R)	4.72	5.20	0.0	35	124	178
SPV 1 (S) Control	44.00	35.59	5.98	35	116	146

Source: Kundu and Jotwani (1977).
1. Visual grading : O = no damage; 9 = severe damage; S = susceptible; R = resistant.

highly resistant and relatively stable over seasons. Four agronomically desirable lines, namely D 124, D 167, D 175, and D 832, also showed moderate levels of resistance.

Mutation Breeding

For improving stem borer resistance by mutation breeding a small program was initiated in 1974. A stem borer resistant variety (E 302) was treated with 0.005 and 0.01% NMU (N-nitroso Methyl Urea), and 20 and 25 k rad Gamma rays from ^{60}Co Gamma cell.

In M_2 families average borer damage grade was 2.3 as compared to 2.5 in the control. In M_3 populations the average grading in selected lines was 1.7, versus 2.8 in the control.

A striking mutation showing 11.5 cm broad lamina was isolated from the irradiated population of E 302. Percentages of plants bearing earheads on the 70th day after germination were significantly higher (56%) in the Gamma-treated M2 population of E 302. This indicated that early-maturing ten-

Table 5. High-yielding sorghum derivatives showing resistance to stem borer.

Derivative	Stem borer damage		Agronomic character		
	Av. leaf injury	Av. stem tunneling (%)	Days to 50% flowering	Grain yield (kg/ha)	Av. plant height (cm)
E 501	1.50	7.54	71	5239	154.25
E 502	2.00	8.14	78	5186	156.75
E 503	1.50	16.85	82	4022	130.85
E 504	2.00	12.50	78	4465	158.54
E 505	2.00	9.59	83	5078	156.35
E 303	2.50	6.00	68	5172	165.30
E 304	2.50	17.25	63	4080	135.65
E 333	2.50	18.00	70	4000	126.35
E 601	2.00	10.68	74	5200	108.90
E 634	3.00	12.65	72	4386	130.54
SPV 17	3.00	18.28	69	3695	120.40
SPV 19	2.00	16.86	71	3800	115.66
SPV 58	2.50	19.23	70	3785	117.58
CSH 1 (Susceptible control)	5.50	46.50	64	1898	114.20
CD at 5%	0.71	4.9		450	

Source : Kishore and Jotwani (1982).
1. Leaf injury grade . O = no damage; 9 = severe damage.

Table 6. Sorghum cultivars showing resistance to spotted stem borer.

	Av. leaf injury		Av. stem tunneling (%)		Av. grain yield (kg/ha)	
Entry	1980	1981	1980	1981	1980	1981
SPV 17	3.0	3.0	9.63	8.55	4125	4245
SPV 19	2.5	2.0	6.98	9.46	4000	4105
SPV 29	3.0	2.5	10.90	10.25	3800	3821
SPV 58	2.0	2.5	8.50	7.14	3465	4000
SPV 61	3.0	3.0	14.72	14.24	3260	3315
E 303	1.5	2.0	4.08	5.19	4495	4515
P 37	1.5	3.0	6.30	7.04	4246	4350
P 151	1.0	2.0	5.56	8.33	4423	4480
U 358	2.5	2.5	12.62	15.65	3125	3085
CSH 1 (Susceptible control)	6.5	6.0	40.66	42.71	2458	2285
CD at 5%	0.8	1.0	2.5	5.1	170	190

Sources : Jotwani (1981, 1982); Kishore et al. (1983).
1. Leaf injury grade : O = no damage; 9 = severe damage.

dency was also induced (Jotwani et al. 1977; Rao et al. 1978). During the 1983 rainy season, plant height stabilized at 1 m and plants bore good earheads.

Genetics of Resistance

Rana and Murty (1971) reported that resistance to stem borer is polygenically inherited. They found that leaf resistance to primary damage (visual grading for leaf damage) was governed by additive gene action and secondary damage (stem tunneling) was governed by additive x nonadditive type gene action.

Kulkarni and Murty (1981) studied the diallel analysis data for stem borer resistance in the F_2 and F3 generations by using six resistant varieties, CSV 3, CSV 5, SR 18, IS 4660, IS 5490, and VZM 2. Resistance was influenced by both additive and nonadditive gene action. In the F3 generation, additive gene action was reported to predominate. The best combiners were IS 4664, CSV 3, and SR 18.

Pathak and Olela (1983) studied the genetic analysis of sorghum resistance to stem borer in a 6 x 6 diallel cross. The results indicated that resistance to the stem borer is polygenically inherited in F1 hybrids. Resistance is partially dominant over susceptibility. Deadhearts were governed by both additive and nonadditive types of gene action, and percentage stem tunneling was governed predominantly by additive gene action. Stem tunneling in resistant and susceptible cultivars varied from 14% (IS 2146) to 61% (IS 18363), which may indicate antibiosis as a factor of resistance. Locally adapted cultivar Serena possesses tolerance, as it recorded maximum yield in spite of maximum percentage of stem tunneling. The authors concluded that resistance in sorghum to stem borer is of a horizontal nature. Resistance is polygenically inherited and the gene action is mainly additive.

Host-plant Resistance and Insecticidal Control

Trials were undertaken in different years to determine whether the level of resistance to stem borer in different selected derivatives was high enough or whether additional insecticidal protection was needed (Jotwani 1978; Jotwani et al. 1978). The experiment was conducted in a split-plot design with resistance forming the main treatments and insecticidal control forming the subtreatments. The protection in subplots was provided by applying 4% endosulfan to the plant whorls, 8 and 10 kg/ha on the 20th and 35th day after germination, respectively.

Table 7. Relative performance of five promising sorghum cultivars under insecticide-protected and unprotected conditions, 1978 rainy season.

Entry	Pedigree	Av. stem tunneling (%) Protected	Av. stem tunneling (%) Unprotected	Av. grain yield (kg/ha) Protected	Av. grain yield (kg/ha) Unprotected	Grain yield increase with insecticide (%)
P 37	CK 60B x IS 4906 (Dwarf sel.)	11.30 (19.44)	17.24 (23.90)	4109	3786	8.61
U 358	CK 60B x BP-53	9.87 (14.92)	13.92 (20.80)	2644	2613	1.19
E 302	CK 60B x BP-53	16.70 (24.11)	21.97 (27.68)	2484	2331	6.56
E 303	IS 3954 x BP-53	7.49 (15.86)	15.36 (21.88)	2590	2324	11.44
P151	IS 2954 x BP-53	4.32 (11.37)	5.87 (13.59)	4840	4482	7.99
CSV 1	(Control)	12.83 (22.30)	38.33 (38.22)	3121	2173	42.63
SE		±(2.07)		±95		
CD at 5% level		(6.37)		292		

Source : Srivastava and Kundu (1984).

1. Figures in parentheses are transformed values = Arc $\sin\sqrt{\text{Percentage}}$.

Table 8. Relative performance of sorghum cultivars under insecticide-protected and unprotected conditions, 1979 rainy season.

Entry	Pedigree	Av. stem tunneling due to borer (%) Protected	Av. stem tunneling due to borer (%) Unprotected	Av. grain yield (kg/ha) Protected	Av. grain yield (kg/ha) Unprotected	Grain yield increase with insecticide (%)
P 37	CK 60B x IS 4906	2.10 (5.75)'	5.10 (12.83)	6004	5459	9.98
U 358	CK 60B x BP-53	0.69 (3.01)	6.87 (13.55)	3203	2964	8.06
E 302	CK 60B x BP-53	1.69 (6.42)	8.04 (16.22)	4548	4123	10.31
E 303	IS 3954 x BP-53	2.13 (6.52)	7.34 (14.67)	4097	3917	4.60
P151	IS 2954 x BP-53	2.04 (7.97)	7.55 (15.69)	4317	3976	8.58
E 304	IS 2954 x BP-53 (Sel.)	3.46 (10.42)	6.47 (15.37)	4318	3828	12.80
E 333	147 x IS 4664	2.34 (5.84)	5.89 (11.81)	2381	2145	11.00
CSV 1	(Control)	2.83 (8.27)	18.01 (24.36)	4159	2772	50.04
SEm		±(4.87)		±163		
CD at 5% level		(14.12)		474		

Source : Srivastava and Kundu (1984).

1. Figures in parentheses are transformed values = Arc $\sin\sqrt{\text{Percentage}}$.

Table 9. Stemborer damage and grain yield of selected resistant varieties of sorghum with and without the application of insecticides.

	Av. stem tunneling (%)				Av. grain yield (kg/ha)				Grain yield increase with insecticide (%)	
	1978		1979		1978		1979		1978	1979
Entry	A[1]	B	A	B	A	B	A	B		
E 601	11.85	9.32	14.00	12.51	4584	4812	4739	4958	6.88	4.62
E 602	13.20	10.62	15.35	13.44	4380	4615	4687	4900	7.19	4.54
E 603	13.92	11.19	15.70	14.26	4285	4562	4623	4768	6.46	3.13
E 604	16.47	13.71	16.74	15.13	4165	4400	4495	4592	5.64	2.15
E 605	19.53	16.55	17.48	16.28	4120	4392	4425	4542	6.60	2.64
E 606	17.46	16.51	16.39	13.05	4150	4300	4366	4496	3.61	2.97
E 607	19.48	13.38	17.48	13.93	4090	4225	4440	4533	3.30	2.09
E 608	21.97	19.76	18.73	14.88	4015	4196	4332	4465	4.50	3.07
E 609	23.02	15.98	22.11	20.31	3964	4285	4305	4420	8.09	2.67
E 610	22.12	19.33	22.22	21.15	3992	4194	3923	4276	5.06	8.99
E 611	23.63	19.75	20.31	18.23	3848	4200	4022	4215	9.14	4.79
E 612	23.58	21.41	20.46	17.95	3900	4175	3851	4262	7.05	10.67
CSH 1	45.40	29.47	41.55	28.43	2710	4020	2885	4060	48.33	40.72
Mean	20.89	16.69	19.89	16.87	4342	4012	4238	4498		
SEm	1.22		±0.72		± 107		±,238			
CD at 5% level	:3.48		2.04		305		649			

Source : Kishore (1984).
1. A = Unprotected ; B = insecticide - protected.

At harvest, the total length of the stem and the stem borer tunneling were measured in 25% of harvested stems. The grain yield was recorded and the percent increase in yield due to insecticidal treatments was calculated by the formula T-C/C x 100, where T stands for insecticidal treatment and C for untreated control (Pradhan 1969). Results of the experiments conducted are presented in Table 7. Under moderate stem-borer infestation, only small yield differences could be found between unprotected and protected plots in the resistant derivatives, ranging from 1.19 to 8.6% yield increase. These results indicate that the resistance levels are adequate and no additional protection is required.

In 1979, results obtained were similar (Table 8). In both the trials the susceptible control CSV 1 gave high yields under insecticide protection, but these yields dropped by 43 and 50% in the unprotected plots. Among the resistant derivatives, however, differences between protected and unprotected plots were very low (1 to 13%). Thus under rainfed subsistence farming with little or no insecticide inputs, resistant varieties offer a clear advantage.

Kishore (1984) studied the combination of host-plant resistance and chemical controi in 12 resistant varieties during the rainy season in 1978 and 1979. In both the years, with or without chemical protection, minimum stem tunneling was recorded in E 601 (Table 9). In both the years E 601 also gave the maximum yield with or without protection. The increase in grain yield due to insecticidal treatment among resistant varieties ranged from 135 kg to 302 kg in 1978 and 93 to 411 kg/ha in 1979 as against 1310 and 1175 kg/ha in susceptible hybrid CSH 1.

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Improving Host-Plant Resistance to Fall Armyworm and Sugarcane Borer in Sorghum

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Abstract

Yield losses in tropical sorghum due to the fall armyworm, Spodoptera frugiperda *(J.E. Smith), and the sugarcane borer,* Diatraea saccharalis *(Fabricius), can be quite high in the Americas. A program is under way at CIMMYT (Centro Internacional de Mejoramiento de Maiz y Trigo) in Mexico to breed for host-plant resistance to these insect pests, using uniform and timely artificial infestation in order to develop sorghum lines with heritable resistance for use by small farmers. The screening method used can identify genetic differences in reaction to fall armyworm and sugarcane borer in the field. Field observations indicate that tolerance is the main type of resistance; however, tow levels of antibiosis or nonpreference were also observed. Progress in the ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) sorghum breeding program has been made with the assistance of the CIMMYT maize program and insect-rearing laboratory, using CIMMYT's techniques for improving resistance to fall armyworm and sugarcane borer. The indications are that continued progress is possible from selection through screening and recombination among tolerant genotypes.*

Resume

Amelioration de la resistance de la plante-hote a la chenille legionnaire et au borer amerlcaln de la canne a sucre chez le sorgho*: En Amerique, les pertes du rendement dues a la chenille legionnaire* Spodoptera frugiperda *(J.E. Smith) et au borer americain de la canne a sucre* Diatraea saccharalis *(Fabricius) sont parfois assez elevees. Le Centre international pour /'amelioration du mais et du ble (CIMMYT) au Mexique a entrepris un programme de selection pour la resistance de la plante-hote a ces ravageurs. Ce programme vise a la creation des lignees de sorgho ayant une resistance hereditaire qui seront destinees au petit paysannat. L'infestation artificielle sous conditions controlees permet d'identifier, au champ, les differences genetiques dans la reaction du materiel vegetal a ces deux insectes. Les observations au champ revelent que la tolerance constitue la principale forme de resistance; on a egalement constate une faible incidence d'antibiose et de non preference pour la ponte. Le programme pour la selection du sorgho de l'ICRISA T au Mexique regoit le concours du programme pour le mais du CIMMYT et de son laboratoire d'elevage et fait appel aux techniques perfectionnees par le CIMMYT pour l'amelioration de la resistance a ces parasites. Le criblage et la recombinaison des genotypes tolerants assureront le progres dans ce domaine.*

Among the many insect pests in Latin America, the fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), and the sugarcane borer (SCB), *Diatraea saccharalis* (Fabricius), have been identified by entomologists as being major pests of sorghum, maize, and other graminaceous crops. In order to identify and develop resistant varieties for small farmers, CIMMYT, (Centro Internacional de Mejoramiento de Maiz y Trigo) established an insect-rearing laboratory to undertake an intensive

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Improvement program using uniform and timely artificial infestation with major insect pests in maize and sorghum. Genetic resistance would help to complement other methods of insect control.

For the past 4 years, an ICRISAT plant breeder stationed at CIMMYT, working in collaboration with their entomologist and using their well-established insect-rearing laboratory, has been screening diverse grain sorghum lines for genetic resistance to FAW and SCB. A series of experiments was conducted at Poza Rica station to evaluate the potential for improving resistance in sorghum.

Three basic questions were addressed: (1) does the screening technique allow confident identification of genetic differences in reaction to FAW and SCB? (2) What type of resistance (antibiosis, nonpreference, or tolerance) is available in sorghum? (3) What are the major problems and some of the new research avenues to be considered rn the near future?

Materials and Methods

We began screening 200 diverse sorghum lines to identify plants resistant to FAW and SCB. Individual plant selections are made at harvest time, each season from the infested rows and advanced for further infestation and selection.

The field procedure for screening is as follows: (1) Each line is planted in four rows, 2 m long. (2) The first 2 m row of each family is protected using granular insecticide. The second row is infested with the larvae of FAW. The third row is left for natural infestation to occur and the fourth row is infested with SCB. (3) The mass-reared larvae are mixed with corncob grits and calibrated using a "bazooka" to drop about 15 larvae per shot. (4) Each plant is infested with FAW larvae at the 4- to 5-leaf stage, with the larvae placed in the whorl. Two consecutive shots of 15 larvae each are used to establish a more uniform infestation. (5) A scale of 1 to 5 is most frequently used to rate damage, where 1 is slight and 5 is severe damage. Ratings are normally made at about weekly intervals, starting 1 week after infestation and continuing until the larvae have ceased damaging the plants.

In addition to categorizing the amount and type of damage caused by FAW and SCB to maize and sorghum plants, CIMMYT (Mihm 1983) has been using the yield differential technique (Hershey 1978) to investigate further the tolerance type of resistance. In this technique, yield comparisons are made between paired infested and protected plots. Selections include progenies which are able to yield reasonably well in spite of the FAW and SCB damage sustained. Results from using this technique to date (Hershey 1978; Smith 1982) have not been as encouraging as had been hoped. Nonetheless, slow but steady progress in developing resistance is apparent.

Nine sorghum genotypes deriving from the screening nursery were evaluated in a replicated trial using six-row plots 5 m long, to show differences in susceptibility or tolerance to FAW and SCB.

Results and Discussion

The results of the replicated yield trial (Table 1) using nine different sorghum genotypes identified from previous screening nurseries, clearly indicate that there is no immunity in sorghum to FAW and SCB damage. Nonetheless, materials that underwent individual plant selection from infested rows show progress in resistance. For example (Table 1), QL-3 is susceptible to both FAW and SCB, while 787-3 and M 66152 showed some tolerance to both insect pests.

The first objective mentioned was to determine whether the screening method used enables identification of genotypic differences in the reaction to FAW and SCB with a high degree of confidence under field conditions. Evidence from the replicated yield trial (Table 1) indicates that such differences can be identified with reasonable accuracy.

The second objective was to determine what type of resistance (antibiosis, nonpreference, or tolerance) is available in sorghum in relation to FAW and SCB. Guiragossian et al. (1981) evaluated 200 diverse genotypes with a range of hydrocyanic acid (HCN) contents, by infesting them with FAW and SCB. HCN levels were determined at different stages and correlated to seedling damage 2 weeks after infestation and at harvest time. The results indicated that resistance was not associated with the presence of glucosides that would degrade and produce HCN, and suggested that there was no relationship between HCN and resistance to these pests in sorghum. Field observations indicate that tolerance is the main type of resistance in these lines because they were able to produce grain yield despite artificial infestation and damage at the seedling stage, when compared to their protected counterparts. Field observations also indicated low levels of antibiosis or nonpreference for oviposition.

Table 1. Time to 50% flowering, plant height, and grain yield of different sorghum genotypes infested with fall armyworm (F) and sugarcane borer (S) compared with insecticide-protected control (P).

Entry No.	Pedigree		Av. time to 50% flowering (days)	Av. plant height (cm)	Av. grain yield (kg/ha)	Yield reduction (%)
		P	73	132	2487	
1	MB1R-21-7-1BK	F	77	120	1322	47
		S	75	120	980	61
		P	79	160	4345	
2	743-5	F	82	140	1554	64
		S	80	135	925	79
		P	80	120	3097	
3	896-1	F	82	113	1947	37
		S	80	105	1130	64
		P	73	125	3737	
4	787-3	F	76	123	1984	47
		S	76	118	2254	40
		P	84	170	3929	
5	(GPR 148xE35-1)-4	F	86	170	2114	46
	x(CS3541 dial)-51-3	S	86	150	642	84
		P	80	202	3739	
6	M66152	F	82	197	2114	44
	(NPEC 64735 x E35-1)-7	S	82	183	1762	53
		P	78	143	2212	
7	QL-3	F	83	134	495	78
		S	83	136	478	78
		P	73	117	3697	
8	TAM 428	F	76	113	2067	44
		S	76	108	1530	59
		P	82	155	3889	
9	88-4	F	82	148	2309	41
		S	82	147	1995	49

The third objective was to identify problems and to determine what new research avenues should be considered in the near future. Two major problems are faced in this project. One is the lack of a sorghum entomologist who would closely work with the breeder; the second is the lack of sufficient larvae to infest the F_2 segregating generations or a genetic male-sterile population.

Smith (1982) reported that among the several maize populations studied, heritable variation for resistance to FAW is available, and that, in general, additive variation is more important than dominance or epistatic variation. After screening approximately 1000 lines from different sources and observing their reactions to FAW and SCB, we believe that differences in reaction to FAW and SCB exist and are heritable.

The experiments confirmed that such variation existed not only for resistance as measured by leaf-feeding damage ratings, but also for resistance measured in terms of the actual yield responses of materials under FAW and SCB infestation. If the ICRISAT program at CIMMYT does not receive further help from ICRISAT Center or INTSORMIL, the research emphasis will be directed toward evaluating F2 generation individual-plant selections generated from crosses between genotypes identified as being tolerant in the screening nursery. Each plant in the F2 generation will receive 30 larvae; at harvest, the best plants will be selected and advanced to F3; then individual F_4 plants will be infested to accumulate the additive genes for resistance. For this we have to sacrifice screening new genotypes. There is also a need to screen the world sorghum collection.

Sorghum genotypes identified as the most tolerant to FAW and SCB are: M 66152 (NPEC-64735 X E 35-1)-7, TAM 428, 88-4 Poza Rica, 787-3, and 896-1.

Summary

Yield losses in tropical sorghum due to the fall armyworm and sugarcane borer can be quite high in the Americas. A program is under way at CIMMYT in Mexico to breed for resistance to FAW and SCB, using artificial, uniform, and timely infestation to develop materials with genetic resistance for use by small farmers. The results indicate that the screening method can be used to identify genetic differences in reaction to FAW and SCB in the field. The field observations indicate that tolerance is the main type of resistance in these lines; however, low levels of antibiosis or nonpreference are noticeable. ICRISAT's sorghum breeding program has made progress using CIMMYT's technique in improving FAW and SCB resistance, and indications are that continued progress from selection through screening and recombination among tolerant genotypes is possible.

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Integrated Approach to the Control of Sorghum Stem Borers

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Abstract

The distribution and importance of 27 lepidopterous stem borers of sorghum are reviewed, and existing control practices discussed with a view to developing an integrated approach. The components of integrated management of stem borers and the effect of various cultural control operations are discussed. A large number of sources of resistance to stem borers and the progress made in developing high-yielding varieties of sorghum are reported. Although several effective natural enemies affecting stem borer populations have been identified, no systematic program to utilize these has yet been undertaken. Pheromone and light traps have been used to monitor the field population of stem borers. Several insecticides have been found effective in controlling stem borers, and their potential in traditional agriculture is discussed.

Resume

Approche Integree de la lutte contre des borers des tiges du sorgho*: L 'auteur etudie la repartition et l'importance de 27 lepidopteres borers des tiges du sorgho ainsi que les pratiques existantes de lutte en vue de formuler une approche integree. Les composants de la lutte integree des borers et l'effet des differentes operations culturales de lutte sont expliques. On signale l'existence d'un grand nombre de sources de resistance. Le progres fait dans la creation de varietes a haut rendement est documente. Malgre l'identification de plusieurs ennemis naturals des borers, un programme systematique pour utiliser cette ressource fait encore defaut. Des pieges lumineux et a pheromone sont utilises pour suivre les insectes au champ. Le potentiel de certains insecticides consideres efficaces, est examine dans le cadre de l'agriculture traditionnelle.*

Introduction

A complex of lepidopterous stem borers occurs regularly in sorghum, causing severe damage and thus constituting a major constraint to sorghum production in many countries. These stem borers occur in diverse ecological conditions under which sorghum is grown. A wide range of stem borer species infesting sorghum, their other host plants, and their distribution are listed in Table 1.

In Asia, the most important stem borers of sorghum are *Chilo partellus, Sesamia inferens,* and *Proceras venosatus.* In Africa, *Busseola fusca,* several species of *Chilo* and *Sesamia,* and *Eldana saccharina* are destructive and widely distributed. Until a few years ago, *E. saccharina* was only of economic importance in West Africa as an occasional pest of maize and sugarcane, but in recent years its importance on sugarcane, maize, sorghum, and other cereals is increasingly evident in several areas of Africa south of the Sahara. In Burundi, *E. saccharina* is the most important stem borer of sorghum, followed by *B. fusca* and *Sesamia* spp (Kabiro 1982). In the Americas, *Diatraea* spp and *Elasmopalpus lignosellus* are serious and very widely distributed pests. Although different species of stem borers are recorded from different regions, the species infesting sorghum and maize are for the most part the same.

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Table 1. Lepidopterous stem borers of sorghum, their hosts, and distribution.

Stem borer	Host plants	Distribution	Reference
A. Pyralidae			
Acigona ignefusalis Hampson	Sorghum, bulrush millet, maize, sugarcane, many grasses	West Africa	7,21
Chilo agamemnon Bleszynski (Oriental corn borer)	Sorghum, maize, sugarcane, *Vossia cuspidata*	Israel, Egypt	3, 13, 17
Chilo diffusilineus J de Joannis	Sorghum, maize, rice, bulrush millet, many grasses	West Africa	3,4,21
Chilo infuscatellus Snellen	Sorghum, maize, surgarcane, Italian millet	USSR, India, Afghanistan, Central Asia	16
Chilo orichalcociliellus Strand (Coastal stalk borer)	Sorghum, maize	Congo, Kenya, Tanzania, South Africa, Madagascar	3, 10, 13 15,21
Chilo partellus (Swinhoe) (Sorghum stem borer)	Sorghum, maize, finger millet, foxtail millet, bulrush millet, rice, wheat, sugarcane, wild species of sorghum, many grasses	Indian subcontinent, eastern and southern Africa	3,9,10 15,21,22
Chilo sacchariphagus sacchariphagus (Bojer) *{Proceras venosatus* [Walker]) (Striped sorghum borer)	Sorghum, sugarcane	China	1
Chilo suppressalis (Walker) (Rice stem borer)	Rice, maize, sorghum, wheat, sugarcane, cotton, grasses	Taiwan, Spain	12
Diatraea grandiosella (Dyar) (Southwestern corn borer)	Sorghum, maize, sugarcane, grasses	North, Central, and South America	10,22
Diatraea lineolata (Walker) (Neotropical corn stalk borer)	Sorghum, maize, sugarcane, rice, teosinte, grasses	North, Central, and South America	22
Diatraea saccharalis (Fabricius) (Sugarcane borer-Americas)	Sorghum, maize, rice, sugarcane, wheat, grasses	North, Central, and South America	22
Elasmopalpus lignosellus (Zeller) (Lesser corn stalk borer)	Sorghum, maize, rice, sugarcane, teosinte, peanuts, soybean	North, Central, and South America	6,22
Eldana saccharina Walker (Sugarcane borer-Africa)	Sorghum, maize, bulrush millet, finger millet, sugarcane, rice, cassava, several grasses	Most areas of Africa south of the Sahara	7,9,13 15,21,22
Ematheudes sp. nr. *helioderma*	Sorghum, finger millet, *Rottboellia compressa*	Uganda	9
Maliarpha separatella Ragonot (Rice stem borer)	Primarily rice, sorghum, grasses	Africa, India (recorded infesting sorghum only in Punjab, India) Burma, China	7,8,20
Ostrinia furnaca/is (Gn.)	Sorghum, maize	Japan	19
Ostrinia nubilalis Hubner (European com borer)	Sorghum, maize, wheat, potatoes, wild hops, wild hemp, *Capsicum annuum, Phaseolus vulgaris*	Europe, USA, Canada, China, Egypt USSR	14, 18
B. Noctuidae			
Busseola fusca Fuller (Maize stalk borer)	Sorghum, maize, bulrush millet, sugarcane, and several grasses	Widely distributed in Africa, south of the Sahara	7,9,10 13, 15, 21, 22

Continued

Table 1 *Continued*

Stem borer	Host plants	Distribution	Reference
Busseo/a segeta Bowden	Sorghum, maize, finger millet, sugarcane and several grasses	Uganda, Tanzania	9, 15
Sesamia albivena (Hampson)	Sorghum	Burundi	11
Sesamia botanephaga Tarns & Bowden	Sorghum, maize, rice, finger millet, sugarcane, and many grasses	West Africa, Kenya, Uganda, Sudan, France, Spain	5,9
Sesamia calamistis Hampson (African pink stalk borer)	Sorghum, maize, bulrush millet finger millet, rice, sugarcane, and many grasses	Widely distributed in Africa	7,9,15,21,22
Sesamia cretica Lederer	Sorghum, maize, sugarcane, bulrush millet, and grasses	Mediterranean Europe, Middle East, North Africa, Sudan, Somalia	2,10,1 5,18,23
Sesamia inferens (Walker) (Pink borer)	Sorghum, maize, rice, foxtail millet, wheat, bulrush millet finger millet barley, sugarcane, and grasses	Indian subcontinent, China, southeast and east Asia	10,22
Sesamia nonagrioides Lefebvre	Sorghum, maize, ornamental plant (*Stre/itzia reginae)*	France, Spain, Italy	2,7
Sesamia penniseti Tarns & Bowden	Sorghum, maize, bulrush millet, sugarcane	West Africa, Uganda	7,15
Sesamia poephaga Tarns & Bowden	Sorghum, maize, bulrush millet, sugarcane	West Africa, Sudan	7,9,15

1. References : 1 = Anonymous (1977); 2 = Badalato (1976); 3 = Bleszynski (1970); 4 = Bonzi (1982); 5 = Bowden (1976); 6 = Busoli et al. (1977); 7 = Harris (1962); 8 = Ho and Seshu Reddy (1983); 9 = Ingram (1958), 10 = Jepson (1954); 11 = Kabiro (1982); 12 = Kung (1976); 13 = Mohyuddin and Greathead (1970); 14 = Nagy(1977);15 = Nye(1960);16 = Pletnev(1975);17 = Saadetal.(1971);18 = Saadany and Hosny(1973); 19 = Saito (1981); 20 = Sandhu and Ramesh Chander (1975); 21 = Seshu Reddy (1983); 22 = Teetes et al. (1983); 23 = Temerak(1983).

In considering the pest management strategies for control of the sorghum stem borer complex, it is essential to develop methods that are cheap, effective, and simple, involving a minimum use of insecticides. The strategy of integrated pest management (IPM) is of special importance for sorghum, which is a crop grown by resource-poor farmers. IPM fits well into the economy of sorghum cultivation under subsistence farming conditions. Some useful information has now become available on different methods of controlling the stem borer complex. The aim of this paper is to review different methods of stem borer control and to evaluate their potential for developing an integrated control approach.

Components of IPM for Sorghum Stem Borers

In order to develop an IPM program it is necessary to determine economic injury levels. Clearly, as a first step, there is an urgent need for more comprehensive data on crop losses due to stem borers.

Crop Loss Assessment

Losses due to stem borers are generally difficult to assess precisely. The number of pest species involved, the different types of damage, the plant developmental stages attacked, and often the associated presence of other insects and microorganisms have made it difficult to determine their separate effects on yield. Davies and Seshu Reddy (1980) noted that attempts to correlate borer damage with grain yields have, on the whole, given very contradictory results due to plant-to-plant variation. Their work showed that the timing of attack is critical and that the exact location of damage in the stem may be important. However, methods of assessing the degree of infestation by lepidopterous stem borers and relating this *to* crop loss have been described by Jepson (1954), Chiarappa (1971), Judenko (1973), and Walker (1981, 1983).

Cultural Control Practices

Cultural control may be defined as the tactical use of regular farm practices to delay or reduce insect pest attack. It involves the manipulation of the environment to make it less favorable for the insect pests and more favorable for crop growth and natural enemies of the pests. Cultural control practices have great appeal as components of IPM for developing countries. Lawani (1982) reviewed in detail the effects of various agronomic practices on cereal stem borer populations. Cultural practices that may affect sorghum stem borer population include: tillage, sanitation, crop rotation, time of planting, density, fertilizer and water management, and various traditional practices.

Tillage and Mulching

During the off-season, tillage will destroy stubble, weeds, and volunteer hosts that may harbor the stem borers. Du Plessis and Lea (1943) found that only partial control *of Busseola fusca* was achieved by plowing. In Uganda, Mohyuddin and Greathead (1970) observed that untreated crop residues were often used to mulch the next crop. In each case the levels of stem borer infestation were far higher than those normal for the area. All and Gallaher (1977) and Cheshire and All (1979) have studied the effects of no-tillage, conventional tillage, and mulched conventional tillage on the infestation of maize by the lesser corn stalk borer *Elasmopalpus lignosellus.* All and Gallaher (1977) found that infestations were greatly reduced in no-tillage cropping, and the damage to seedlings was less in an untreated no-tillage system than in insecticide-treated conventional tillage systems. They also noted that no-tillage may produce changes in the microenvironment that discourage oviposition and larval survival.

Time of Planting

Adjustment of planting dates could be an effective control method for sorghum stem borers. Early planting is an important factor in the control of the southwestern corn borer, *Diatraea grandiose/la.* However, in areas where *Ostrinia nubilalis* has only one generation a year, early-planted maize has a higher level of infestation than late-planted maize in the USA (U.S. National Academy of Sciences 1969). In Libya, Ahmed (1978) found that maize sown during June and July was severely damaged by *Sesamia cretica,* whereas that sown in mid-May was not heavily infested. On the contrary, Al-Dabbas and Al-Shekli (1978), in Iraq, found that the infestation levels of S. *cretica* varied from 1% for maize planted on 15 July to 15% for maize planted on 15 May. In Tanzania, Swaine (1957) found that later sowings of maize largely escaped damage by *Busseola fusca,* compared with earlier sowings. Similarly, in northern Indian states, the stem borer, *Chilo partellus,* causes more damage in the early-sown than the late-sown crop. Appropriate planting dates to avoid stem borer infestations in different areas should be determined by detailed investigations of the seasonal incidence and period of peak activity of the stem borers.

Spacing

Close spacing may either favor some pest species or may increase the effectiveness of the natural enemies in reducing the pest populations. For example, Chiang and Hudson (1972) observed that an increase in the density of maize led to an increase in the population of *Ostrinia nubilalis.*

Fertilizer Management

The U.S. National Academy of Sciences (1969) reported that the use of fertilizers to enhance plant nutrition often influenced the longevity and fecundity of insects and mites and the damage they cause. Singh and Shekhawat (1964) found that the percentage of maize plants infested by *Chilo par-*

tellus and *Sesamia inferens* was least witn no nitrogen and increased as the level of nitrogen increased. Similarly, Singh et al. (1968) and Singh and Singh (1969) noted that increased nitrogen levels increased infestation levels of C. *partellus.* In Uganda, Starks et al. (1971) found more C. *zonellus (partellus)* per grain sorghum plot when nitrogen and phosphorus fertilizers were used; although the fertilizers contributed to increased grain yield, the stem borers prevented the maximum response to soil fertility. However, the use of fertilizers is relatively limited in developing countries and therefore is unlikely to be a major factor in IPM.

Water Management

Soil moisture can be an important factor in stem borer infestation. All and Gallaher (1977) reported that increased soil moisture was important in deterring infestations of *Elasmopalpus lignosellus,* so that irrigation could be used as a control method for this borer. Reynolds et al. (1959) found that well-timed irrigation decimated populations of *E. lignosellus* on sorghums in southern California. However, sorghum in traditional agriculture is mostly grown as a rainfed crop where water resources are scarce.

Sanitation

This practice involves the removal or destruction of crop residues to eliminate the pest or deny it food and shelter. In Tanzania, Duerden (1953) found that nearly complete eradication of *B. fusca* and C. *zonellus (partellus)* on sorghum and maize was achieved by burning stubble and crop residues. In East Africa, Ingram (1958) and Nye (1960) reported that the destruction of all crop residues and wild species of sorghum around cultivated areas would considerably reduce stem borer attack at the beginning of the growing season. Mohyuddin and Greathead (1970) stated that ratooning of sorghum is a dangerous source of stem borer infestation for other crops.

Bowden (1976) found that destruction of first crop trash of maize had no effect on second crop attack by *Sesamia botanephaga* because of migration from the alternative grass hosts. Adesiyun and Ajayi (1980) suggested partial burning of sorghum stalks, which can kill 95% of the larvae of *B. fusca* without any damage to the stalks.

The diapausing larvae inside the stems kept for fodder purposes can be easily killed by chopping and storing the stems as small pieces. In India, Taley and Thakare (1980) found that the traditional storage of sorghum stalks for fodder was conducive to the carryover of C. *partellus* and recommended the practice of chopping stalks to help control the pest. In contrast, Adenuga (1977) found that removal of stalks and stubble after each harvest did not reduce the populations of *B. fusca, S. calamistis, Acigona ignefusalis,* and *Eldana saccharina,* nor did it alter the alternation between low and high populations in early and late maize crops.

However, the wide-scale practice of chopping and storing the sorghum stalks in small pieces, partial burning of the stalks, and destruction of stalks and stubble could be very effective in reducing borer populations.

Removal of Deadhearts

The removal and destruction of deadhearts can prove successful only if carried out by farmers over large areas. However, it may be more effective to remove and destroy central shoots showing early "pinhole" damage symptoms. These invariably contain a large number of young stem-borer larvae, which will disperse to adjacent plants at a later stage.

Removal of Volunteer and Alternative Host Plants

Most stem borers are harbored by wild graminaceous host plants in addition to their cultivated hosts. In Botswana, Roome (1976) found that sudangrass was often heavily infested with C. *partellus* and possibly played an important part in the carryover of the pest from one season to the next. Therefore, wherever possible, volunteer cereal host plants, wild sorghums, and other wild host plants should be removed, together with their stubble, and destroyed, as otherwise they will form an important source of carryover at the beginning of the growing season. Again this operation could be effective only if practiced by farmers over large areas.

Crop Rotation

Crop rotation is a classical cultural practice which denies access of the pest to its host. Since stem borers have a wide host range, rotation to nonhost crops forms an important cultural control method. A sequence of closely related crops such as maize and sorghum should be avoided. In Texas, rotation with nonhost crops has been recommended for the *Diatraea* complex (Anonymous 1979).

Intercropping

In intercropping, modification of the microenvironment and differences in nutrient uptake by the intercrops may influence plant infestation, and the development and movement of insect pests. Amoako-Atta et al. (1983) reported that the incidence of C. *partellus, B. fusca, E. saccharina,* and S. *calamistis* on maize and sorghum monocrops and the maize/sorghum dicrop was earlier and increased over time, whereas intercropping these two cereals with cowpea caused a significant delay in borer colonization and establishment. These studies suggest that intercropping has great potential as a cultural method of controlling stem borers. Almost without exception, traditional agriculture has incorporated intercropping as a major feature.

Traditional Methods

In some tropical countries, traditional methods of pest control are practiced in which various plants, herbs, and other substances are used to kill or repel insects or other animals. In their survey in Kenya, Goldman and Omolo (1983) found that a brew made by the traditional herbalists was used against sorghum and maize stem borers.

There is an urgent need to explore this further, and study the potential of plants and/or natural products for stem borer control.

The foregoing information demonstrates that cultural control operations have an enormous potential for reducing stem borer populations, if carried out simultaneously by many farmers over a large area.

Host-plant Resistance to Stem Borers

Cultivation of insect-resistant varieties of crops is the most valuable and practical solution to insect pest problems and fits ideally into an IPM program in traditional agriculture. Plant resistance is very important, particularly for stem borers, since they attack all growth stages of the plant and usually have more than one generation in each cropping season. More than one species of stem borer (e.g. *C. partellus, B. fusca, S. calamistis,* and *E. saccharina)* were often seen infesting the same plant.

Sorghum resistance to C. *partellus* was first reported by Trehan and Butani (1949). In India and East Africa, a systematic screening program for identifying sources of resistance to the stem borer, C. *partellus,* was undertaken and has yielded some highly promising resistant lines (Seshu Reddy 1982). In general, however, these lines are tall, and therefore susceptible to lodging, are photosensitive, late-maturing, and low-yielding. At ICRISAT, India, a few selected lines are being utilized systematically in the breeding programs in an attempt to transfer the resistance to high-yielding cultivars.

In India, some satisfactory progress has been made in developing varieties showing resistance to C. *partellus* as well as desirable agronomic characters of high yield, early maturity, and medium height. These varieties include E nos.501, 502, 503, 504, 601, 602, 603, and 604 (Jotwani 1982). Starks and Doggett (1970) in Uganda, made significant advances in both breeding methodologies and the incorporation of resistance to *C. partellus.* However, efforts to increase the level of resistance should continue.

Except for *C. partellus,* the identification of sources of resistance against stem borer species and their incorporation in breeding programs have been limited. However, Barry (1980) reported that rating systems were developed for host resistance programs and 306 sorghum lines were tentatively selected from about 4000 lines for possible resistance to *B. fusca.* Studies conducted in Kenya at the International Centre of Insect Physiology and Ecology (ICIPE), showed that under natural levels of infestation by the stem borer complex (C. *partellus, B. fusca, S. calamistis, E. saccharina)* where damage exceeded 95%, some sorghum lines obtained from ICRISAT (India), Texas (USA), and Kenya showed resistance potential. Some of the most promising lines include IS nos. 1044, 1096, 1151, 2123, 3962, 4213, 4405, 4881, 5613, 10364, 10370, 10711, 12447, 18323, 18326, 18427, 18479, 18517, 18523, 18676, L 1 (A and B Tx2756), L 2 (Tx 2780) L 3 (Sorghum-118), and S 178 (Seshu Reddy 1984). There appears to be cross resistance to the stem borer complex.

Also, some of these sorghum lines (including IS nos. 1096, 2123, 3962, 5613, and 10711) have resistance potential to sorghum shoot fly, *Atherigona soccata.* However, none of the lines evaluated exhibited immunity to the stem borer complex or to the shoot fly.

Work on the identification of new sources of sorghum resistant to stem borers should continue and also immediate efforts should be made to incorporate already identified resistance sources into elite agronomic backgrounds. Research is also needed to identify sources of multiple resistance not only to stem borers and shoot fly but also to sorghum midge and earhead bugs, and later to incorporate them into the new high-yielding cultivars. More information on mechanisms of resistance, including physical and chemical factors, and the genetics of traits contributing to resistance, needs to be obtained.

Biological Control

Biological control is a very important component of IPM, particularly in developing countries, as it is cheap, effective, nondisruptive of the ecosystem, and relatively permanent. Considerable information is available on the natural enemies of sorghum stem borers (FAO 1980).

Mohyuddin and Greathead (1970) recommended *Apanteles flavipes, A. chilonis, Bracon chinensis, B. onukii,* and *Sturmiopsis inferens* for trials in East Africa as they have a wide distribution, high biotic potential, and a wide host range. Further, these authors also recommended parasites from East Africa, which include *A. sesamiae, Pediobius furvus, Dentichasmias busseolae, Hyperchalcidia soudanensis,* and *Procerochasmias glaucopterus* for trials in other countries. However, when *A. fiavipes, B. chinensis, Isotoma javensis, Trichogramma australiacum, T. chilotraeae, T. fasciatum,* 7. *flandersi,* and 7. *semifumatum* (all from India) were released in Uganda, no recoveries were made, except for *A. flavipes,* which was recovered twice at Kawanda, but failed to become established (Ingram 1983).

In India, a project on the control of *C. parteilus* has been started by releasing Barbados, Colombia, and Philippines strains of *Trichogramma exiguum,* an egg parasite, in different ecological areas. 7. *exiguum* has now become established on C. *parteilus* in the Delhi and Nagpur areas (Jotwani 1982).

Ingram (1983) reported that in Mauritius, *Sesamia calamistis,* a major pest of maize, has been controlled by using *Apanteles sesamiae* from Kenya and in Madagascar by using *Pediobius furvus* from Uganda. In Kenya, *Trichogramma* sp was found parasitizing more than 60% eggs of C. *parteilus,* while *Dentichasmias busseolae,* a solitary pupal endoparasite of C. *parteilus,* caused 25% parasitism under natural conditions.

Very little information is available on stem borer predators, other than from occasional references. Black ants *(Camponotus rufoglaucus),* ladybird beetles *(Cheilomenes* spp), earwigs *(Diaperasticus erythrocephala),* and spiders were found feeding on the major stem borers of sorghum in Kenya.

Sharma and Sarup (1979) recorded ten species of spiders from the leaf whorls of maize plants infested with C. *parteilus* and suggested the potential use of spiders for integrated control of C. *parteilus.* Temerak (1983) found several soil-inhabiting arthropod predators of the pupae of *Sesamia cretica.* These comprised 16 species of spiders (Lycosidae) and a centipede (Lethobiidae); 64% pupae were destroyed by the predatory ant, *Paratrechina* sp.

Fungal, bacterial, and viral diseases of stem borers are known to exist in many countries, but their value in biological control is not yet known.

Sinha and Prasad (1975) suggested that either the spore suspension or the crude toxin of the fungus, *Fusarium aleyrodis* could be used in the biological control of C. *zonellus (parteilus).*

Although some very useful information is available on the natural enemies of the stem borer complex, it is evident that a systematic program on biological control has not been undertaken. Critical studies are therefore required of stem borers and their natural enemies on wild host plants during the dry season and in relation to crop infestations. Surveys of natural enemies should be undertaken and their relative efficiency assessed. Possible changes in agronomic practice to enhance the effectiveness of natural enemies should be studied and efficient and healthy parasites, free from hyperparasites or diseases, introduced. Mass rearing and release of effective native natural enemies could also be undertaken.

Use of Sex Pheromones

Sex pheromones are chemical messengers secreted by one sex, usually the female, which elicit a definite behavioral response to attract members of the opposite sex for mating. The sex pheromones could provide a relatively inexpensive method of insect control as they have a high biological activity and negligible toxic effects on plants and animals. The pheromones can be used for population monitoring and control by mass trapping and mating disruption.

Walker (1981) suggested that pheromone traps might be useful as a method of estimating first and second generation populations of stem borers on maize. Campion and Nesbitt (1983) reviewed the progress made in identifying sex pheromones of lepidopterous stem borers and their potential use in crop protection. They discussed the sex pheromones and attractants that have been identified for the sorghum stem borers, including *Busseola fusca, C, partellus, Ostrinia nubilalis, E. saccharina, Sesamia inferens, S. cretica,* and *Diatraea saccharalis.*

The use of pheromones has shown promise against the stem borers when used in limited areas; however, large-scale trials on farmers' fields will have to be undertaken to assess the effectiveness of this method.

Use of Light Traps

Light traps could be used to monitor the field populations of insect pests, and as data accumulate, it would be possible to correlate seasonal incidence and possibly abundance with climatic factors.

Mass trapping using light traps has been adopted in China to provide the basis of forecasting systems for a variety of insect pests (Chiang 1977). In Kenya, Ho and Seshu Reddy (1983) observed that the rice stem borer, *Maliarpha separatella* showed the strongest attraction to light traps, followed by C. *partellus, E. saccharina, S. calamistis,* and 8. *fusca.*

However, there is need to collect more data on the type of traps and optimum light intensity before recommending this method of stem borer control to sorghum growers.

Chemical Control

Pesticides pose a threat to subsistence farming in developing countries because of high cost, free availability, lack of adequate protection for the user, absence of safety warnings, improper storage, excessive and wasteful use leading to environmental pollution and development of pest resistance, and residues in food. Even in the developed countries where insecticides in spray and granular formulations have been used successfully, chemical control has proved quite expensive and not particularly effective against heavy infestations (Painter 1958). However, despite all these dangers some significant work has been done on the chemical control of stem borers.

In India, a number of insecticides have proved effective in the control of C. *partellus.* In earlier trials, it was found that granules applied to leaf whorls were more effective than dust and spray formulations applied to the foliage. In subsequent trials it was found that insecticidal dusts containing 4% endosulfan, 5% carbaryl, 0.65% lindane, 5% malathion, or 2% phenthoate when applied to leaf whorls at reduced dosages of 8 to 10 kg/ha, gave effective control of the borer (Jotwani 1982, 1983). However, in South Africa, chemical control of C. *partellus* was found to be ineffective (Rensburg and Hamburg 1975). Kundu et al. (1977) recommended judicious use of insecticides as one of several management practices for the control of C. *partellus.*

Very little work has been done on the chemical control of *Sesamia* spp on sorghum and maize. Satisfactory control of S. *cretica* on maize was obtained by Al-Dabbas and Al-Salih (1978) in Iraq with a single application of granular carbofuran (3%), diazinon (10%) or chlorfenvinphos (10%).

Adeymi et al. (1966) found that two applications of carbaryl at 1.5 kg/ha either as spray or as dust gave the best control of S. *calamistis, B. fusca,* and *E. saccharina* on maize in Nigeria. Similarly, Saad et al. (1971) found that two applications of carbaryl and cytrolane gave satisfactory control of S. *cretica, Chilo agamemnon,* and *Ostrinia nubilalis* on maize. In Nigeria, Barry and Andrews (1971) obtained satisfactory control of *B. fusca* with a special type of pistol-grip sprayer which delivered 1 ml spray of carbaryl W.P. per sorghum leaf whorl.

Egwuatu and Ita (1982) found that a single dose of carbofuran (Furadan 5G) at 1.5 kg a.i./ha applied in the planting hole reduced the incidence of spittle bug *(Locris maculata)* and stem borers *(B. fusca* and S. *calamistis)* on maize, compared with split application of the same dose applied at planting and 40 days after planting. They also noted that the yields of fresh maize cobs increased significantly in the treated plots. In contrast, in South Africa, Rensburg and Malan (1982) reported that when 10% carbofuran granules were applied in the furrows along with sorghum seeds, significant reductions of the infestations by various pests, including *B. fusca,* resulted, but caused phytotoxicity in some plots.

In China, application of granules containing 0.25% demeton (systox) gave 80% control of the striped sorghum borer, *Proceras venosatus* (Anonymous 1977). In Peru, granular formulations of methomyl (lannate) and carbofuran when applied in soil at 1 to 2 kg/ha gave respectively 90 and 50% mortality of *Diatraea saccharalis* attacking sorghum (Ruiz Medina and Korytkowski 1975).

Proper timing and efficient methods of application of insecticides are very important for effective stem borer control. To achieve these, studies of life tables, periods of peak activity, and monitoring techniques should be carried out.

If all the factors are considered, including the socioeconomic status of the farmers, the development of selective and cheap insecticides for the chemical control of narrow target insect populations should form only one of the components of IPM, and these insecticides should be used only if absolutely necessary.

Conclusion

Given the present status of knowledge on the control of the sorghum stem borer complex, it is evident that the damage could be checked effectively. However, work on the stem borers needs to be intensified to establish the economic status of the different species by determining the incidence and losses caused in different areas. More emphasis should be laid on cultural methods of control to be carried out as campaigns in groups *of* villages, blocks, or divisions.

More work should be done to identify sources of resistance to as many major pests as possible and improve the level of resistance in high-yielding sorghum cultivars, as it is undoubtedly a major factor to be favored by resource-poor farmers in the developing countries. More attention should also be paid to developing biological control methods, as they have tremendous potential in traditional agriculture and can integrate very well with host-plant resistance and cultural control methods.

For an effective implementation of IPM programs there should be team spirit and motivation among the agriculturalists and experts, including entomologists, pathologists, agronomists, breeders, geneticists, physiologists, and socioeconomists. Training of research and technical personnel involved with the IPM programs should also receive serious consideration. There is a need for more international cooperation among researchers in solving the problems of sorghum growers. Also it is essential to have very good working relationships with farmers, who are ultimately responsible for implementing the IPM programs.

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Panicle-feeding Insects

IPM of Fall Armyworm and Panicle Caterpillars in Sorghum

B.R. Wiseman*

Abstract

A brief review is presented of the biology-ecology, population monitoring, and control tactics for the fall armyworm, Spodoptera frugiperda *(J.E. Smith); the corn earworm,* Heliothis zea *(Boddie); and the sorghum webworm,* Celama sorghiella *(Riley), as related to grain sorghum production. The integrated insect pest management approaches relating to these insects as occasional sorghum pests are discussed.*

Resume

***La lutte Integree contra la chenille laglonnalra at les chanllles des panlcules de sorgho** : La communication porte sur la biologie et l'ecologie, le suivi des populations et les methodes de lutte contre la chenille legionnaire* Spodoptera frugiperda *(J.E. Smith), le ver americain de la capsule du cotonnier* Heliothis zea *(Boddie) et le ver a soie* Celama sorghiella *(Riley) dans le cadre de la production de sorgho. La lutte integree contre ces insectes en tant que ravageurs occasionnels de sorgho est examinee.*

The fall armyworm (FAW), *Spodoptera frugiperda* (J.E. Smith), the corn earworm (CEW), *Heliothis zea* (Boddie), and other panicle-feeding caterpillars that compete directly with the producer for his food and feed grain are occasionally of utmost importance to sorghum production. Integrated pest management (IPM) strategies available for use against these species and others under consideration are discussed herein. Highlights will include discussions of the economic importance of the pest species, their biology-ecology and population monitoring, and biological, cultural, plant resistance, and insecticidal methods of density suppression.

Economic Importance

The FAW and the CEW and, to a lesser extent, the sorghum webworm, *Celama sorghiella* (Riley) are usually considered occasional pests of grain sorghum by Young and Teetes (1977) and Teetes (1980), although CEW density may surge after insecticide application for key pests and CEW may thus respond as a secondary pest. These authors reported that FAW and CEW larvae may commonly feed within the plant whorl and may cause extensive ragging of sorghum leaves. Damage to the plant at this stage of growth rarely justifies control, except when high densities infest plants. However, in the southern, and particularly the southeastern, portion of the USA and other humid regions, these pests would be considered key pests (Teetes 1980).

Biology-Ecology

Fall Armyworm

Sparks (1979) reported that FAW has been a sporadically occurring but devastating insect pest of

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several agricultural crops since colonial times in the USA. Mitchell (1979) reported that the annual economic crop losses caused by FAW to all crops in the USA exceed $300 million. During years when particularly severe infestations occur, such as those in 1975, 1976, and 1977, economic losses attributed to damage by this pest may exceed $500 million annually. However, losses due to the FAW and other panicle caterpillars in sorghum do not approach the magnitude of the loss that these insect pests inflict on other crops.

Luginbill (1928) reported that the FAW originated from the tropical-subtropical Western Hemisphere. The FAW is one of the most unusual lepidopterous insect pests attacking sorghum in that it does not diapause in temperate North America, unlike both the CEW and the sorghum webworm, which have a diapause mechanism and overwinter in temperate North America. The FAW survives the winter in south Florida and Texas each year and in the spring begins the annual northward migration. The greenish-gray FAW eggs are deposited en masse and are often covered with down from the moth. The young larvae have jet-black heads and white bodies. The larger larvae are dark brown to greenish in color, with a prominent white inverted Y on the front of the head. The adults are about 1.8 cm in length. The body is ash gray. The forewings of the male FAW are mottled in appearance, with an irregular white spot near the extreme tip of the wing. The FAW life cycle has been extensively studied by Walton and Luginbill (1917), Luginbill (1928), and Vickery (1929). However, Sparks (1979) provided a concise description of the life history with a thorough up-to-date report on the unique behavioral aspects of the FAW:

> The FAW adult is nocturnal in habit. At dusk, adults initiate movement near host plants that are suitable for feeding, oviposition, and mating. Early evening movement of adults near corn is generally with the wind and the elevation of adult flight extends from a few feet up to 9.1 m above the plant canopy. This "with-the-wind" movement of males and females is followed by an "against-the-wind" or "oblique-to-the-wind" movement at dark or shortly thereafter when the adults are flying more slowly or hovering and feeding.
>
> After the general feeding period, which extends from shortly after dark to up to 2 h after sunset, depending upon temperature and time of year, virgin females initiate calling. Calling females sit on plants near the top, extend their ovipositors, and emit the sex pheromone to indicate that they are available to mate. Males travelling at oblique angles to the wind and just above the crop canopy have been observed to respond to a calling female from a distance of 9.1-12.1 m. Temperature and wind velocity greatly affect the distance from which males respond. Generally, from 2 to several males respond to the call of a female. Since FAW females mate only once a night, some very stringent tussles occur among males. Rejected males revert to their oblique-to-the-wind movement. This male action-reaction explains the occasional observation of as many as 50 males flying in groups. Generally, virgin females mate early in the night; females that have previously mated once mate somewhat later, and multiple-mated females mate last. Mating is greatest prior to midnight, depending on temperature and time of season, but some mating may occur throughout the night.
>
> Oviposition by females follows soon after mating and may overlap with the early evening feeding period. Oviposition certainly overlaps the mating period. In corn fields where FAW densities are low, females normally oviposit on the under side of the plant leaves. When FAW density is high, oviposition is rather indiscriminate over the corn plant, on other objects including practically any type of plant and foliage, on windowpanes, and on flags, carts, and sheds of golf courses. Eggs are laid in clusters and protected by a dense covering of scales. Egg masses contain from a few to hundreds of eggs that hatch in 2-4 days when mean temperatures are 21.1-26.7°C.

As FAW larvae hatch from eggs, they eat the shells and then begin feeding on the host plant. They continue to devour foliage until they have completed six instars, after which they pupate (Luginbill 1928). Luginbill (1928) reported that Samuel Blum produced evidence that indicated FAW larvae needed an average of 13806 mm^2 of crabgrass per larva to develop through six instars. The intake per instar averaged 0.1, 0.6, 1.1, 4.7, 16.3, and 77.2% for instars 1 to 6, respectively. The first three larval instars are quite small in size and require less than 2% of the total foliage consumed by all instars. However, R.A. Vickery found that a single FAW larva may consume about 2840 mm^2 of corn foliage (Luginbill 1928). This might explain the statement, "those worms just ate my crop overnight."

The sixth-instar larva drops to the ground and pupates about 2.5 to 7.5 cm below the soil surface, depending upon soil texture, moisture, and temperature. According to Vickery (1928), the pupal period varies from 7 to 37 days, again depending on a mean soil temperature ranging from 15 to 28.9°C.

When adult FAW emerge from pupal cases, they find their way to the soil surface, where they cling to plants or plant debris and inflate their wings (Sparks 1979). This behavior was observed in the field from 2 to 3 h after sunset until about midnight. Sparks also suggested that teneral adults do not mate the first night. Single FAW males and virgin females that appear to be newly emerged (no loss of scales, reluctance to fly) have been collected while feeding well after midnight; thus, the adults probably feed the first night of their lives.

Corn Earworm

The CEW egg is about half the size of the head of a common pin, shaped like a ball, and has numerous ridges. The neonate larva is creamy white with a black head. The larger larvae vary in color and may be solid green, cream or yellow, slate or black, or pinkish. The fully grown larvae drop to the ground and pupate. The entire life cycle requires about 21 to 30 days (Barber 1936).

The CEW adult is about 1.88 cm long and has a wingspan of about 3.8 cm. The coloration is dull, from a light olive green to a rather dark reddish brown. The moth appears above ground early in the evening, and as soon as its wings are dry, it is ready to begin its activities (Barber 1936; Blanchard and Douglas 1953).

Lingren et al. (1982) reported that initial nocturnal activity of the CEW began 1 h after sundown with a flight that was generally oriented downwind. This behavioral movement lasted about 10 min, and then large numbers of moths of both sexes were observed moving upwind and feeding on plant nectaries. Mating behavior may begin by ca. 4 h after sundown and may continue for several hours. Temperature and nocturnal duration tend to regulate the periods of mating. On cool nights, mating and behavioral activity occurs earlier in the evening than on warm nights (Lingren et al. 1982). Oviposition is usually interspersed with periods of feeding activity.

Sorghum Webworm

The adult sorghum webworm is a small, whitish moth of the family Noctuidae that has characteristic tufts of suberect scales on the upper surface of the forewing. The eggs are white, with a pale greenish yellow tinge. The newly hatched larva appears to be woolly and is pale greenish but turns darker in color to a cream-brown with light brown stripes soon after feeding begins. The body is rather slender, with hair along the lateral margins. At the anterior and posterior extremities, the hair length sometimes slightly exceeds the body length. The mature larva is marked with four longitudinal reddish to black dorsal stripes. The pupa is usually enclosed within a white silken cocoon. The sorghum webworm overwinters in the larval stage. Length of life cycle ranges from 18 to 30 days (Reinhard 1938).

Insect Migration

FAW outbreaks depend to a large extent upon the prevailing weather conditions during the winter where it is a permanent resident (Luginbill 1928). !n its southern habitat, this insect thrives best during periods of cool weather with an abundance of rainfall. Such conditions are favorable for the multiplication of food plants but are known to check the buildup of natural enemies (Luginbill 1928). Sparks (1979) speculated that the rate of movement of adult FAW is ca. 300 miles per generation. He further stated that there is convincing evidence implicating weather fronts as a primary mode for dispersal of this insect in the adult stage.

Raulston (1982) stated that the movement of *Heliothis* spp plays an important and complicating role in its population dynamics. He further stated that movement can be at several levels, ranging from trivial movements within a crop, through movement from crop to crop, to the long-range migration from one area to another.

Sorghum webworm moths have not been observed to make extended flights; however, Reinhard (1938) reported that they are fairly strong fliers and that they are capable of readily moving from field to field throughout the summer. The adults remain quite inactive during the day, but resume normal activity after dusk, and dispersal seems to occur then. Reinhard (1938) further pointed out that among the natural factors favoring a buildup of sorghum webworm, climatic conditions are of the greatest importance. During wet seasons when temperatures are usually moderate, multiplication proceeds at a maximum rate and extensive damage to grain sorghum usually results.

Population Monitoring

Monitoring insect densities has been accomplished by using a number of methods including actual counts, light traps, pheromone traps, and the more complex systems, such as predictive modeling. Mitchell (1979) and Hartstack et al. (1979) reported on methods to estimate FAW and CEW densities, respectively. Hartstack (1982) reported on the use of the MOTHZV model that was developed and is used in Texas to predict *Heliothis* spp adult emergence. However, this model has not been developed to the extent that it can predict actual numbers. Also, BUGNET, a computerized pest management delivery system, has been developed and used by the Texas Agricultural Extension Service and other research cooperators (Hartstack 1982). The MOTHZV model and BUGNET programs are currently being used by Texas producers for decision making in pest management. The sorghum webworm has not yet received the attention given to the CEW and FAW, probably because of the relatively greater importance of these latter two species to numerous other host crops besides sorghum.

Migrating insects, e.g., the CEW and, in particular, the FAW, are being studied by novel approaches, such as the use of radar to monitor nocturnal flight behavior and movement (Wolf et al. in press). From these efforts, an insect dispersion model for *Heliothis* spp is being developed that simulates the dispersal of an insect population. The model uses radar-derived flight behavior, population density updates based on daily pheromone trap catches, and relaxation of the wind field at the appropriate insect flight altitude to predict populations.

Economic threshold levels exist for all three insect pests, and most sources suggest that control measures should be taken when two small FAW or CEW, or five sorghum webworm larvae per panicle occur in maturing sorghum (TAES 1979; Teetes and Wiseman 1979; Young and Teetes 1977). Martin et al. (1980) reported action threshold levels for FAW on grain sorghum to be (1) 10% of the seed ling sorghum plants possessing egg masses (2) one larva per whorl, and (3) two larvae per panicle after flowering.

Biological Control

FAW is susceptible to at least 20 species of entomogenous pathogens, including viruses, fungi, protozoa, nematodes, and a bacterium (Gardner and Fuxa 1980; Gardner et al. 1984). Gardner and Fuxa (1980) reported that many of the pathogens occur naturally in FAW populations. Schwehr and Gardner (1982) reported finding five species of entomopathogens infecting FAW larvae in whorl-stage sorghum in 1979/80 They observed that 50% of the larvae were infected with nuclear polyhedrosis virus (NPV). Hamm(1980) found that *Entomophthora aulicae* infected 19 to 49% of FAW larvae attacking panicle-stage sorghum in 1978. Hamm and Hare (1982) found that it was possible to apply entomopathogens through an overhead irrigation system to initiate a microbial epizootic. Four microbial control agents were successfully evaluated: a fungus, two species of microsporidia, and the nuclear polyhedrosis virus. Therefore, some of these entomogenous pathogens have the potential for a significant role in the management of the FAW (Gardner et al. 1984). Potential strategies include the use of natural epizootics or the introduction of pathogens, applied as insecticidal agents, and use of pathogens in combination with other biological or chemical control agents.

Ashley (1979) reported finding some 53 species of FAW parasites representing 43 genera and 10 families. He also stated that parasite distribution indicated that importations of natural enemies from Central and South America into Florida and Texas could significantly reduce overwintering FAW densities. *Apanteles marginiventris* (Cresson) and *Chelonus texanus* (Cresson) were the most frequently recovered parasites. Lewis and Nordlund (1980) discussed the strategies for employing entomophages as pest control agents against the FAW. Their approaches included importation of new parasites, propagation and release of parasites throughout the overwintering zones, and habitat management.

Pair and Gross (1984) reported *Diapetimorpha introita* (Cresson) as a new pupal parasitoid of the FAW. This was the first record of a pupal parasitoid of this host insect. Of the FAW pupae found in *the* field, 13.5% were parasitized by *D. introita* and 73.3% of all exposed pupae were either parasitized by this parasitoid or destroyed by predators.

Microbials for *Heliothis* spp, including CEW, suppression have been in use for some time. Bell (1982) and McKinley (1982) reported that all of the major groups of entomopathogens show some potential for use in *Heliothis* spp management. Bell stated that using gustatory-stimulant adjuvants can increase the effectiveness of the microbials and can result in the control of high densities of CEW. But Bell (1982) stated that the current use of microbial-induced epizootics as single-factor methods for control is negligible. However, Hamm (1980) found that a natural epizootic of E. *aulicae in* sorghum infected 48 to 100% of CEW larvae.

King et al. (1982) reported on the prospects for using parasitoids and predators for managing CEW and other *Heliothis* spp. In the USA, they showed that at least 8 parasitoids and 11 different predator species readily attack *Heliothis* spp. However, they further pointed out that consistent control of these pests by augmentative releases of predators and/or parasitoids, at a cost competitive with the use of insecticides, is dependent on (1) elucidation of factors affecting host searching, and (2) development of mass-production procedures using artificial diets.

Reinhard (1938) reported five parasitic Hymenoptera and one parasitic fly attacking the sorghum webworm. Hamm (1980) found that a fungus, *E. aulicae,* caused 74 to 95% mortality of the larvae collected from the panicles of sorghum.

Cultural Methods

Luginbill (1928) reported that large numbers of FAW could be eliminated by keeping the fields and area grass-free. Also, early planting and proper crop management would reduce the chances of severe late-season infestations inflicting economic losses. Knipling (1980) stated that cultural measures may be the most important of the suppressive measures available. He also noted that crops such as sweet corn and field corn are the major hosts for oviposition by overwintering FAW. Teetes and Wiseman (1979) stated that manipulation of CEW by cultural, biological, or chemical means in one crop host in the agroecosystem could mitigate infestations in other crops. Earlier, Lopez and Teetes (1976) reported that biological control agents in cotton and sorghum were similar in species composition and that this similarity becomes progressively more intimate during the season. Certainly, early plantings are an effective cultural practice for reducing the possibility of sorghum webworm density increase (Reinhard 1938; Hobbs et al. 1979). Gardner and Duncan (1983) showed that the natural incidence of sorghum pests in late plantings of sorghum and ratoon sorghum had much higher densities than early-planted sorghum. Thus, no additional control expense occurs when early plantings are used in the management of these pests.

Plant Resistance

Wiseman and Davis (1979) reviewed the history and current knowledge of plant resistance to FAW. They reported that the genetic variability within sorghum makes it an attractive candidate for successful plant resistance programs.

Plant resistance remains a mainstay of integrated insect pest management approaches in sorghum (Wiseman and Morrison 1981). It is the one tactic that can be used either alone or in combination with any control or suppressive tactic available to date. One of the generally recommended methods for limiting FAW, CEW, and sorghum webworm losses is to plant open or loose-headed sorghums (Young and Teetes 1977; Teetes and Wiseman 1979; Wiseman and Morrison 1981). Hobbs et al. (1979) reported that as sorghum panicles increased in compactness, sorghum webworm densities also increased.

Very limited grain sorghum resistance research has been done for these three insect species. Wiseman and Gourley (1982) developed a system for evaluating seedling resistance to FAW. They found that 1821 c.m. was the least damaged of all the lines tested. Oliver and Tipton (1972) found differences in CEW feeding responses to mature seeds incorporated into a pinto bean diet. Wiseman et al. (in press) found similar differences with FAW on sorghum seeds incorporated into a pinto bean diet. They also found that differences between cultivars could be detected at the milk stage as well as later stages of kernel development. Their data indicated that some of the sorghum cultivars were not adequate as a diet for FAW development. Thus, if the results can be correlated to field responses, we will have a real demonstration of tremendous impact on at least two sorghum insects in the integrated suppression approaches using resistant cultivars.

Insecticidal Suppression

Gardner et al. (1981) and Young (1979) described some of the conventional approaches for insect suppression and noted some pesticides that are effective in controlling FAW, CEW, and sorghum webworm. Conventional equipment used in making ground applications includes tractor-mounted broadcast booms, high-clearance sprayers, and granular formulation applicators. Other methods of control include aerial applications of granular formulations. One of the more innovative methods of insecticidal application was reported by Young (1980), where he used a center-pivot irrigation system for the application of pesticides through the irrigation water. Control was achieved with 0.25 and 075 cm (2700 and 8100 gal.) water/acre.[1] The cost of applying insecticides in irrigation water was less than $0.50/0.25 cm of water/acre as compared with $2.25 to $3.00/acre for aerial applications and $2.30 to $5.00/acre for applications with ground equipment (Young 1981). FAW resistance to insecticides has been demonstrated for carbaryl and trichlorfon (Young 1979).

When control measures were applied to flowering sorghum for the sorghum midge, *Contarinia sorghicola* (Coq.)., good to excellent control of panicle-feeding lepidopterous pests resulted *for* 1 to 2 weeks (Gardner, personal communication).

Discussion

In general, most of the descriptive information presented and the approaches for integrated pest management discussed have been recommended and developed for crops other than grain sorghum. But for the most part, the integrated insect-pest management approaches used for occasional sorghum pests, such as FAW, CEW, and sorghum webworm will be dictated by those strategies developed and implemented for the sorghum midge, *Contarinia sorghicola* (Coq.), and the greenbug, *Schizaphis graminum* (Rondani). However, most general practices available to manage the sorghum midge and the greenbug also are practical approaches applicable to FAW, CEW, and sorghum webworm management.

The greenbug and sorghum midge are key sorghum pests for which good economic threshold levels and insect-resistant cultivars are available to the grower. Therefore, most growers should plant pest-resistant cultivars wherever the sorghum midge and/or greenbug are key pests. Thus, the remaining components for integrating management of lepidopterous pests are cultural, biological, and insecticidal control. Control measures are readily available for use in the management of the sorghum midge or greenbug.

Renewed emphasis is being placed on the development of plant cultivars that are resistant to attack by insects. The incorporation of known genetically controlled factors that influence lepidopterous larval feeding, such as loose-head characters, into midge- and greenbug-resistant cultivars could also provide the desired resistance to lepidopterous pests. Since the lepidopterous larval pests under discussion are occasional pests, low levels of resistance, coupled with cultural and biological control components, could provide effective control.

Therefore, the research and approaches developed for integrated pest management for crops other than grain sorghum are applicable to the aforementioned occasional pests. They could be readily used with components now used in managing the primary grain sorghum insects. Favorable results could be expected until specific research is completed that deals directly with these occasional lepidopterous pests of sorghum. However, control strategies developed and used to limit losses by occasional insect pests of sorghum should be integrated with approaches used for managing key pests to form a complete management package.

1. One gallon = 4.55 liters; 1 acre = 0.4 ha.

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The Sorghum Midge: A Review of Published Information, 1895-1983

K.M. Harris*

Abstract

Major published sources of information on the sorghum midge, Contarinia sorghicola *(Coquillett), are reviewed for the period 1895-1983, with summaries of the present state of knowledge on history, host plants, recognition of damage, crop losses, distribution, biology, ecology, parasites/predators/ pathogens, chemical control, cultural control, and the development of resistant varieties.*

Resume

La cecldomyle du sorgho—une recapitulation de la documentation da 1895 a 1983*: La documentation publiee entre 1895 et 1983 sur la cecidomyie du sorgho,* Contarinia sorghicola *(Coquillett), est passee en revue. Des syntheses sont presentees sur l'etat actual des connaissances concernant l'historique, les plantes-hotes, la reconnaissance des degats, les pertes de recoltes, la repartition, la biologie, l'ecologie, les parasites/predateurs/pathogenes, les luttes chimique et culturate et la creation des varietes resistantes.*

Introduction

In October 1895 D.W. Coquillett of the U.S. Department of Agriculture received damaged seed-heads of sorghum from Dillburg and Montgomery, Alabama, and, on examining them, found that the grain had been destroyed by the larvae of a cecidomyiid. The next specimens he saw were received on 26 September 1898, from R.H. Price of College Station, Texas. This time he obtained adult midges from the damaged heads and in 1899 he published his formal description of *Contarinia sorghicola* (Coquillett), the sorghum midge.

The sorghum midge is now known to be one of the most widely distributed and important pests of sorghum. Wherever sorghums are grown between latitudes 40°N and 40°S the developing grain may be attacked and destroyed by larvae of this midge. Crop losses are measured in millions of dollars, and there is now a considerable literature of research papers and other publications on this pest. Barnes (1956) provided the first detailed review of the literature on a world basis and subsequent reviews have been published by Harris (1969, 1976), Young (1970), and Young and Teetes (1977). A bibliography for the period 1898-1975, published by Wiseman et al. (1976) contains 185 references and the *CAB Annotated Bibliography E 104* for the period 1973-1983 contains 119 abstracts of research papers (CAB 1983). Current research papers are recorded in *Sorghum and millets abstracts* (published by the Commonwealth Agricultural Bureaux) and in *SMIC Newsletter* (published by ICRISAT).

History

After its discovery in the USA in 1895, the sorghum midge was initially considered to be a native American species that was later spread to Hawaii (1906), St. Vincent (1910), Australia (1928), and Africa

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(1930), possibly with Improved American cultlvars, and up until 1964 it was thought that distinct species occurred on sorghum in India and in South America. Detailed taxonomic research has shown, however, that this interpretation was incorrect, and dissections of spikelets taken from herbarium specimens in the collections of the Royal Botanic Garden, Kew, and the British Museum (Natural History) have shown that C. *sorghicola* was present in many countries long before it was described in America (Harris 1964 and Table 1).

It now seems certain that C. *sorghicola* is an African species that evolved on *Sorghum* in Ethiopia and adjacent areas, where it occurs on both cultivated and wild sorghums. Sorghum was first cultivated in this part of Africa from about 4000 B.C. and as the crop was transported first into Asia and later into the Americas, sorghum midge must have been transported with it, probably as diapausing larvae in dry seed-heads. The recent detection of many new sources of resistance to midge in sorghums collected from Ethiopia, Uganda, and the Sudan (Johnson and Teetes 1980) tends to confirm that the pest originated in that part of Africa.

The earliest published account of sorghum midge and the damage that it causes to grain sorghums is in a paper presented to the Queensland Natural History Society, Australia, by Tryon (1895), which is the same year that it was discovered in the USA.

Host Plants

Despite published statements to the contrary, sorghum midge can only develop on the genus *Sorghum* and is probably restricted to *Sorghum,* section *Sorghum,* which includes its cultivated and wild host plants S. *bicolor, S. dochna,* S. *sudanense, S. arundinaceum,* and S. *verticilliflorum.* This restricted host range has been confirmed by studies of survey material from Australia, where the indigenous grasses *Sorghum plumosum,* S. *intrans,* and S. *stipoideum,* which are assigned to *Sorghum* section *Parasorghum,* are not hosts of C. *sorghicola* but are attacked by morphologically distinct species of *Contarinia* (Harris 1979). All reports of C. *sorghicola* on graminaceous genera other than *Sorghum* (i.e. *Andropogon, Brachiaria, Schizachyrium, Trioza)* are based on misidentifications of the gall midges.

Table 1. First records of sorghum midge.

Field records		Kew Herbarium specimens	
		1860	Mozambique
		1869	Sudan
USA	1895	1886	Puerto Rico
Hawaii	1906	1898	Burma
St. Vincent	1910		
Australia	1928	1912	Australia
		1914	Congo
Nigeria	1929	1917	Nigeria
Sudan	1930		
Uganda	1951	1926	Uganda
South Africa	1958	1932	South Africa

Recognition of Damage

Midge larvae feed inside sorghum spikelets on the ovaries, which shrivel and fail to develop into grain. Low levels of attack are difficult to detect but in severe infestations, the heads look blasted and sterile and may produce no grain at all. The presence of midge can often be confirmed by squeezing spikelets firmly between thumb and forefinger, which crushes the larvae and pupae, producing bright orange-red droplets of body fluids at the tips of the spikelets. Careful dissection of spikelets under a microscope will also reveal larvae and pupae and during active infestations it may be possible to see adults in the field, either emerging from infested seed-heads or ovipositing on flowering heads. Empty pupal cases often remain at the tips of spikelets for some time after adults have emerged, and are a useful indication of midge activity. Infested heads kept in polyethylene bags for a week or so usually produce adults. Larvae enter diapause ail through the season.

Crop Losses and Distribution

The most accurate assessments of crop loss have been made in the USA where the midge is considered to be the most damaging of all sorghum insects (Wiseman and Morrison 1981). Recurrent annual losses are estimated at 4% of the grain sorghum crop, and in Texas alone estimates of losses have exceeded 10 million dollars per annum on several occasions (Wiseman et al. 1976). A similar level of overall loss was estimated in Nigeria in 1958 (Harris 1961) and recurrent losses of 5 to

10% of the crop are probably typical of most major sorghum-growing areas. Local losses in tropical Africa and Asia may exceed 50% and complete loss of some crops is not uncommon.

Midge is ranked as a major pest of grain sorghums in the USA, Mexico, Argentina, Brazil, West Africa, India, and northern Australia and has now been recorded from most sorghum-growing countries in Africa, Asia, the Pacific, and the Americas. Its northern limit includes southern France, Italy, Japan, and the USA and its southern limit runs through Argentina, South Africa, and Australia. In countries within these limits where it has not been formally recorded it seems probable that it is present but unrecognized.

Biology and Ecology

Adults are small, with a wing length of only about 3 mm, and are therefore relatively inconspicuous. They mostly emerge 1 to 2 h after sunrise from pupae in damaged spikelets, either in seed-heads on plants or from crop debris. Adults mate within an hour of emergence and, after resting for about half an hour, the females fly in search of flowering sorghum heads. Once a suitable head has been found, eggs are deposited on the young ovaries within the glumes through the midge's long, fine telescopic ovipositor. For some hours each female probes suitable spikelets and carefully places about 50 to 100 eggs. Peak egg laying usually occurs before midday and most females finish laying and die before sunset. Eggs hatch about 4 days later, and larvae feed for about 1 to 2 weeks at the expense of the ovary, which shrivels and fails to develop. Attacked spikelets therefore remain tightly closed and have a flat, empty appearance, which is sometimes wrongly attributed to poor fertilization, genetic sterility, unfavorable weather, or attack by head bugs or other pests.

During the growing season a new generation of adult midges is produced about every 2 to 3 weeks, but towards the end of the season, larvae spin small silk cocoons inside attacked spikelets and can then survive in diapause for at least 3 years.

Diapause usually ends as humidity rises during subsequent rains and emergence of the first generation of adults in the new season generally coincides with the first appearance of flowering heads in cultivated and wild sorghum. Populations then build up through the season and tend to cause most damage to late-flowering crops.

Many detailed accounts of the biology and ecology of the species in North and South America, Africa, India, and Australia have been published and are mostly covered by the literature reviews referred to earlier in this paper, but new information is still appearing. Recent papers that merit particular attention include Summers et al. (1976) on the development of higher levels of midge infestation on low plant populations in California; Baxendale and Teetes (1981) on the production of single-sex progeny by mated females in Texas; Barwad (1981) on the presence of diapause larvae in pedicellate spikelets in India; and Mogal et al. (1980) on high larval mortality resulting from exposure of crop residues to the sun in India.

Parasites, Predators, and Pathogens

The main parasites of sorghum midge are the parasitic Hymenoptera *Eupelmus popa* Girault and *Tetrastichus diplosidis* Crawford [= *Aprostocetus diplosidis].* Other species of *Tetrastichus* may also attack the midge in some areas but this genus is taxonomically difficult and accurate identification of the species involved is not always possible. There is little evidence that these parasites have appreciable controlling effects on midge populations but better understanding of their interactions with the midge and with sorghum would be useful in developing integrated pest management programs. Recent research in Georgia, USA, has shown that *T. diplosidis* is strongly attracted to sorghum spikelets from a distance of about 3 m (McMillian and Wiseman 1979) and research in Brazil has shown that overall parasitization of midge by *Tetrastichus* species and *E. popa* was 17.6% on sorghum variety AF 28 compared with 8.7% on the hybrid RS 1090 (Lara 1974). It would be useful to know the causes of such a difference.

Many predators have been recorded on adult midges, including spiders, ants, anthocorids, mirids, and coccinellids but little detailed work has been done on them and there seem to be no published records of pathogens attacking sorghum midge.

Biological control of the sorghum midge has not been attempted, possibly because the main hymenopterous parasites have already been transported around the world with the crop, but research on parasite/predator/pathogen complexes, especially in Africa, might produce useful results.

Control Methods

Chemical Control

Chemical control aims at killing emerging and ovipositing females and has to be critically timed. Spray or dust formulations are used either as a single application at about 50% anthesis or as two or more applications made at 5-day intervals during the flowering period. The economic threshold is 1 to 2 ovipositing females per flowering head in the USA (Wiseman and Morrison 1981).

Many active ingredients have been tested, especially in North and South America, India, and Australia, and various degrees of control have been reported from the use of carbaryl, carbofuran, carbophenothion, chlorfenvinphos, chlorpyrifos, diazinon, dichlorvos, dimethoate, endosulfan, ethion, fenitrothion, fensulfothion, fenvalerate, HCH, leptophos, malathion, methamidiphos, methidathion, methyl-demeton, monocrotophos, naled, parathion, permethrin, phenthoate, phosalone, phosphamidon, tetrachlorvinphos, and trichlorphon. Results from experiments vary considerably and control of midge does not necessarily result in increased grain yields, partly because of phytotoxicity. Recommendations for chemical control must therefore be based on local experience and information.

Cultural Control

Cultural methods of control can be used against midge and are certainly effective, as has been demonstrated in Texas (Young and Teetes 1977). The severity of midge attack on any particular sorghum crop is mainly determined by the extent to which midge populations have built up on earlier flowering sorghums in the vicinity. Long flowering periods of wild and cultivated sorghums favor rapid increases of midge, with consequent risk of substantial grain losses, especially on late-flowering varieties. Adult midges seldom fly far upwind and usually drift only short distances downwind, so the problem of population buildup is essentially a local one, which can be tackled by individual farmers where agricultural holdings exceed about 500 ha or on a village basis where agricultural holdings are fragmented. The main requirements are:

a. Reduce the carryover of diapause larvae from one season to the next by destroying old seedheads and trash during the winter or dry season either by burning or burying.

b. Cut down self-sown or ratoon plants that come into flower early in the season and, where possible, cut forage and silage crops before they flower.

c. Eliminate wild sorghum grasses from farm areas.

d. Sow early, if possible, to produce early-flowering crops, and arrange sowing dates so that all crops come into flower at about the same time. If this is not possible, sow late-flowering crops upwind of earlier-flowering ones.

It is possible to estimate a date of flowering up to which crops are unlikely to be at risk to midge and after which chemical protection may be needed. This is now standard practice in pest management on grain sorghums in the USA (Wiseman and Morrison 1981).

Resistant Varieties

The development of resistant varieties offers the best hope of midge control on a long-term basis and considerable progress has been made during the past decade, especially in North and South America and India. Recent progress has been reviewed by Teetes (1980), Johnson and Teetes (1980), and Jotwani and Davies (1980), within the wider context of plant breeding for resistance to arthropod pests of sorghum. New sources of resistance have been identified, especially in sorghum lines collected in Ethiopia, the Sudan, and East Africa and screened in the USA (Johnson and Teetes 1980).

In the USA, research is directed towards the development of commercially acceptable midge-resistant sorghum hybrids and towards the elucidation of resistance mechanisms. SGIRL-MR 1, the first commercial midge-resistant sorghum, which was released by the Southern Grain Insects Research Laboratory, Tifton, Georgia, in 1971, has proved very promising under artificial infestation in India (Jotwani and Davies 1980), indicating the potential for wider application of local breeding programs and supporting the hypothesis that the sorghum midge is a single, widespread, genetically uniform species.

Conclusions

Enough technical information is available to support general planning of pest management systems to reduce crop losses caused by the sorghum midge. Cultural methods of control should be given first priority where they can be operated and general use of chemical control seems unlikely and inadvisable. Selective use of chemicals on late-flowering crops may be necessary, at least until adequate midge resistance can be bred into commercial varieties, but the main improvements in control must come from the identification and use of sources of resistance. Further research on mechanisms of resistance and on parasite/predator/pathogen complexes might produce useful results and current research on pheromones in *Contarinia* may provide better monitoring of pest incidence. Continuing and increasing international cooperation in research, development, and information exchange is especially necessary when dealing with such a widely distributed pest species.

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Sorghum Midge Biology, Population Dynamics, and Integrated Pest Management

George L. Teetes*

Abstract

The agroecosystem is the basic unit of consideration in the integrated pest management approach. The target crop within this ecological system and its level of susceptibility to insect pest species is of fundamental importance, and can be altered genetically through breeding for pest resistance. The relative level of pest resistance as influenced by pest density demands a knowledge of pest density/plant damage (yield) relationships. An understanding of these relationships leads to the determination of economic injury levels and subsequently to the establishment of dynamic economic threshold levels. Comparing the economic injury level of insect-resistant cultivars with that of susceptible cultivars defines the resistance level and provides the base-line data on which to quantify the effects of other direct control tactics and natural pest density suppressing agents.

Insect-resistant sorghums are used as a model to examine the unique value of host-plant resistance as a component in an integrated pest management strategy, the role it plays, and how it influences other direct control and support tactics.

Resume

***La cecidomyle du sorgho—biologie, dynamique das populations et lutte Integree**: L 'unite' de base a considerer dans toute approche de la lutte integree est l'agroecosysteme. La culture visee dans ce systeme est d'importance fondamentale ainsi que son niveau de sensibilite aux insectes nuisibles qu'on peut modifier par la selection pour la resistance a ces insectes. La connaissance du rapport entre la densite parasitaire et les degats en termes de rendement, permet d'etablir le niveau relatif de la resistance en fonction de la densite parasitaire. On peut ainsi determiner le seuil de nuisibilite economique et ulterieurement les seuils economiques dynamiques. La comparaison des seuils de nuisibilite economiques des cultivars resistants et sensibles fournira les donnees de base a partir desquelles on peut quantifier les effets des autres methodes de lutte y compris ceux des agents naturels qui limitent la densite des ravageurs.*

Les sorghos resistants ont servi de modele dans revaluation de la resistance de la plante-hdte en tant que composant de la lutte integree, et dans la determination du role de cette resistance et de son influence sur d'autres mesures directes et d'accompagnement pour lutter contre ces ravageurs.

Plant resistance to insects is a viable component in integrated pest management (IPM) strategies, and the tactic has wide applicability and function. The use of insect-resistant cultivars is the epitome of applied ecology, which is the essence of IPM. The basic unit of consideration in IPM is the agroecosystem of which the target crop is of main importance; it includes the biotic and abiotic forces that improve or constrain crop production. The inherent susceptibility of the target crop to production-constraining forces, such as insect pests, is of fundamental importance. Most IPM direct control tactics function to rapidly reduce insect pest density (insecticidal control), lower the general equili-

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brium position of the pest (biological control), or provide temporal or spatial separation of the crop and the pest (cultural control). Plant resistance to insects functions at the most intimate level of the crop-pest association. This close union of plant and pest provides an avenue of weakness that can be exploited, as the pest is certainly vulnerable to a change in its host association. Through plant resistance it is possible to intrinsically alter the plant-pest association.

In practical terms, what is of concern is the damage or yield loss that results from plant-pest associations. In this regard, plant resistance is a functional control tactic that acts to reduce pest density and/or increase the plant's damage-tolerance level, depending on the resistance mechanism(s). Fortunately, genetic variability in a crop species is usually sufficient to allow for the identification of genetically governed resistance traits that can be incorporated into useful cultivars. Also, the compatible, complementary role that plant resistance to insects plays with other direct control tactics is in concert with the objectives of the IPM concept in theory and practice.

However, despite the obvious potential utility of insect-resistant cultivars—either alone or most commonly in combination with other IPM tactics—in providing crop protection that is biologically, ecologically, economically, and socially feasible, their use in the mechanized farming of North America seems to remain unexploited. Except for a limited number of dramatically successful cases, i.e., aphid-resistant alfalfa and Hessian fly-resistant wheat, the use of insect-resistant cultivars by farmers has been limited, at best. Considering the recent greatly increased volume of literature published on plant resistance to insects, it is surprising and discouraging to find that the actual use of insect-resistant cultivars in agricultural production is quite limited. There are a number of identifiable reasons for this limited impact.

1. *Failure of entomologists and plant breeders to utilize insect-resistant germplasm:* Identifying resistance sources is fairly commonplace and relatively simple; however, incorporating resistance genes into agronomically acceptable cultivars is a much more difficult issue.

2. *Failure of farmers to accept and use insect-resistant cultivars:* Farmer acceptance and continued use of insect-resistant cultivars have been conservative at best. The reasons for this reluctance are many, partly sociological, based on unfounded, preconceived opinions of the performance of insect-resistant cultivars.

3. *The insecticide crutch:* Insecticides remain a major insect-control method because they are easy to use, usually effective, economical, and have rapid curative action. Their ecological disruptiveness and biological and sociological adverse effects are well documented. In theory, their use in IPM strategies demands selectivity by chemistry or application procedure based on real need judged by the use of economic threshold levels. In practice, however, insecticides provide relatively cheap crop protection insurance and a crutch on which to rely when traditional insect-susceptible varieties are grown. Insecticides provide an escape from the pressure to develop and use insect-resistant cultivars because they provide an easy alternative.

4. *Tendency to separate crop production and crop protection:* Traditionally, crop production and crop protection have been separated. IPM has provided some thrust toward considering the two from a cropping systems approach. Also, it has tended to weaken the barrier that has so long existed among agricultural disciplines. An understanding of the role, function, and performance of insect-resistant cultivars is much more likely to be achieved as crop production and crop protection specialists unite in their objective of producing more, more consistently, at less expense.

5. *Failure to produce adequate information about the pest and the resistant cultivar:* This constraint to deploying insect-resistant cultivars has research and extension implications. Reluctance to change or to adopt a new strategy inevitably stems from inadequate knowledge or assurance that the new approach will succeed. Perhaps it is here that we as entomologists working with plant resistance to insects have failed. A procedure that dramatically and spectacularly controls insect pests is rapidly and readily accepted. But insect-resistant cultivars mostly have quite subtle effects on insect pests. In deployment, this is a disadvantage, but the ecological advantages are real. Consequently, plant resistance to insects has unique applicability and function in IPM.

This paper deals with the program of identifying and developing sorghums resistant to the sorghum midge, *Contarinia sorghicola* (Coquillett), and the data collection necessary to provide extension personnel and farmers a package of information on the expected performance of the resistant cultivar in agricultural production and its response to or effect on the pest.

Biological Facts about the Sorghum Midge

The female midge deposits eggs in flowering spikelets of grasses of the genus *Sorghum.* The number of eggs laid varies considerably, but usually is about 150 per female. The immature stages develop cryptically within spikelets and larval feeding inhibits kernel formation. Depending on environmental conditions, a generation is completed in 14 to 22 days. At favorable temperatures, mean development time from egg to adult is 16 days, allowing for numerous generations per season, which accounts for the build up of extremely high midge densities, especially when the sorghum flowering period is extended by successive planting dates. A single feeding larva is sufficient to destroy a kernel. When midge densities are high, grain losses can approach 100%.

The adult midge is short-lived. Males begin to die 5 h after emergence and 50% are dead within 9 h. Females usually live for 12 h, but rarely over 24 h if mated. Consequently, a new brood of midges occurs each day.

Adult midge emergence from infested spikelets is influenced by time of day, temperature, and moisture (Fisher and Teetes 1982; Fisher et al. 1982). No midges emerge at night and males begin to emerge at dawn, with peak abundance between 0700 and 0900 h. Adult females begin to emerge from infested spikelets 2 to 3 h after male emergence begins and maximum female emergence occurs between 0900 and 1100 h. By 1630 h, midge emergence is virtually complete for a given day.

Males begin to emerge at lower temperatures (10-16°C) than females (20-22°C) and peak emergence of males occurs at lower temperatures (24-28°C) than females (26-32°C). Cool temperatures (23°C) delay midge emergence. Males hover around the panicle from which they emerge and mate with females as soon as they emerge. After mating, females leave the panicle from which they emerged and disperse to flowering sorghum panicles. Abundance of ovipositing females in flowering sorghum is directly related to prior emergence patterns from infested panicles. The greatest number of ovipositing females occurs at 1130 h, 2 h after maximum female emergence from infested panicles, and the least between 1830 and 0630 h. Ovipositing female midges are present in flowering sorghum at temperatures between 21 and 41 °C, the greatest proportion being present between 34 and 38°C.

More midges emerge at high relative humidity (RH)(90%) than at lower RH (10 and 50%)(Fisher and Teetes 1982). Males emerge earlier than females when the relative humidity and vapor pressure deficit (VPD) are higher. Artificial wetting of panicles or heavy rainfall reduces adult emergence, but high RH before and after the rainfall increases it.

Environmental factors influence midge emergence and oviposition and are reflected in hourly, daily, and seasonal density fluctuations. While sunlight appears to be involved in the initiation of daily male emergence, temperature is the driving force behind adult midge emergence and establishes the upper and lower limits to its rate and magnitude as modified by RH, VPD, and rainfall. These influences affect the accuracy of sampling procedures.

In temperate regions, a varying proportion of sorghum midge larvae in each generation constructs silken cocoons and enters diapause within spikelets of the host plant. Typically, these spikelets fall to the ground and become covered with litter or are disked into the soil along with plant residues. Emergence times and yearly emergence distributions of overwintered sorghum midges is a function of soil temperature and moisture (Baxendale and Teetes 1983a). However, diapausing larvae usually require about 7.5 months to complete the sequence of physiological changes (diapause development) and then to commence post-diapause development. Based on laboratory experiments, larvae in diapause for at least 7.5 months when exposed to moist conditions, terminate diapause and emerge as adults when temperatures are in the range of 15 to 35°C; however 20 to 30°C is optimal for emergence, which occurs in 12 to 13 days if moisture is continuously available.

Adult midges initiate emergence after accumulating 431 centigrade heat units (based on mean daily 10-cm soil temperatures starting 1 April) above a threshold temperature of 14.8°C; 679 and 977 heat units are required for 50 and 95% emergence, respectively (Baxendale and Teetes 1983b).

The time that midges enter diapause one year has little effect on the timing or distribution of emergence the following spring. Midges do not terminate diapause and emerge as adults during the same year they entered diapause. Almost 25% of the midges entering diapause during a season emerge not in the subsequent spring but in the second spring, and almost 3% do not emerge until the third spring, but times and distribution of emergence are similar for all years.

Based on laboratory and field data, two separate temperature-dependent models have been formulated to describe adult spring emergence from overwintering and development of nondiapausing generations of the sorghum midge (Baxendale et al. 1984a, 1984b). Stochastic, two-component, temperature-based models were developed to predict the emergence of adult midges in the field. The first component of each model uses a poikilotherm rate equation to predict emergence rates as a function of temperature. The second model component distributes emerging adults over normalized time using a temperature-independent cumulative Weibull distribution. When coupled, the components form temperature-dependent simulation models that describe the emergence of overwintered midges and generation development over calendar time. Model simulations have been field-validated and compare favorably with observed field emergence and development of midges from sorghum.

Population Dynamics

Fundamental to the development of a comprehensive pest management system for the sorghum midge is the construction of a seasonal dynamics model around which grower-oriented management strategies can be designed. Sorghum midges overwinter subterraneanly as diapausing larvae within spikelets of sorghum. In the spring, adults emerge from the soil and oviposit the season's first generation in nearby flowering johnsongrass, *Sorghum halepense* L. This wild host maintains the first two spring generations until flowering sorghum, *Sorghum bicolor* L (Moench), becomes available. Once early-planted sorghum begins to flower, most midges disperse to sorghum, where economic densities can be reached in a single additional

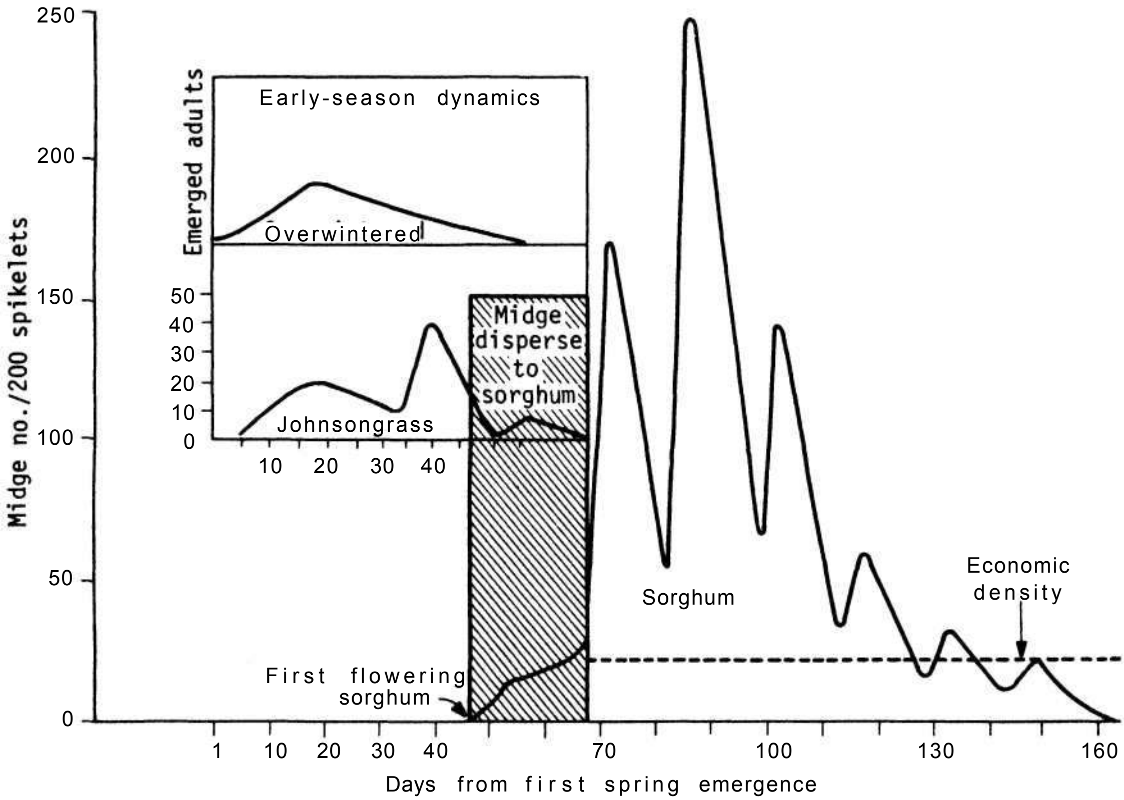

Figure 1. Seasonal dynamics of sorghum in Central Texas, USA.

generation (Baxendale et al. 1984b). Sorghum flowering after this time is subject to severe midge damage. Very late in the season, sorghum midge densities generally decline to noneconomic levels. A diagrammatic representation of the seasonal dynamics of the sorghum midge in Central Texas is presented in Figure 1.

Management Strategies

Cultural Control

The most effective method presently available of reducing losses by sorghum midge is avoidance by the cultural practice of uniform, regional planting of sorghum early in the growing season. However, such planting is not always possible. Planting periods may be delayed or extended due to drought or by frequent spring rains. Elimination of major wild maintenance hosts such as johnsongrass has potential midge suppression effect, but control of this grass has been impractical because of its abundance in cultivated and noncultivated areas.

Biological Control

Natural enemies of sorghum midge include most general predators found in a sorghum field (Walter 1941). Among those reported are several species of ants which prey on midge pupae and adults (Newell and Barber 1913; Taley and Garg 1976). Midge adults are also attacked by various hemipterans, chrysopid and coccinellid larvae and adults, several species of *Odonata* and two predacious fly species. Various spiders and mites have also been reported to prey on midge adults (Dean 1910; Walter 1941; Harding 1965). Several parasitoids of sorghum midge have been recorded. These include four eupelmids, several eulophids, and several unidentified *Tetrastichus* species (Crawford 1907; Callan 1941; Passlow 1958; Priore and Viggiani 1965; Wiseman and McMillian 1970). A ceratopogonid fly and a braconid wasp are also reported to parasitize sorghum midge (Seshu Reddy and Davies 1979).

Lippincott and Teetes (1983) found four hymenopterous parasitoids of the sorghum midge in Central Texas and studied their nature of parasitism and biology. *Eupeimus popa* Girault and *Aprostocetus diplosidis* Crawford were ectoparasitic on the midge host in sorghum spikelets, while *Tetrastichus* near *venustus* Gahan fed both externally and internally. Mode of feeding by *T.* near *blastophagi* was not determined. Members of the parasitoid complex oviposited and developed to adults in spikelets containing 1- to 18-day-old immature midges, which corresponded to the larval and pupal stages of midges. Most parasitoids developed from midges parasitized as midstage larvae.

Developmental time from egg to adult emergence ranged from 7 to 32 days for the parasitoid complex. Emergence of most adults of the individual parasitoid species ranged from 15 to 19 days. This developmental time corresponded to that of the midge hosts, which emerged as adults in 15 to 18 days after oviposition. £ *popa* was most abundant during spring and early summer in both johnsongrass and sorghum (Baxendale et al. 1983). *A. diplosidis* reached its highest density in late summer and fall. *T. venustus* was primarily a midseason parasitoid and T. *blastophagi* densities were relatively high during the spring and summer months. *T. blastophagi* preferred sorghum midges infesting johnsongrass, while *T. venustus* and *A. diplosidis* preferred midges infesting sorghum. Over the course of the season, 20.0 and 8.2% of sorghum midges were parasitized in johnsongrass and sorghum, respectively. Parasitism did not appear to provide significant sorghum midge density suppression.

Chemical Control

When weather conditions at planting time result in staggered planting dates, the only control measure available to protect the later plantings has been the use of insecticides to kill females prior to oviposition. Current recommendations suggest that applications begin when 25 to 30% of the panicles are at anthesis ("flowering" or "yellow bloom") and there is an average of one adult female midge per panicle. Additional applications might be needed at 3- to 5-day intervals during the remainder of the flowering period in order to maintain adequate control.

However, attempting to kill females with the contact insecticides now labelled for use in sorghum is difficult. The short life cycle of the sorghum midge, the occurrence of broods and overlapping generations, and the relatively brief time span over which females infest a field require that in many instances one must scout fields frequently and be prepared to control a new brood of females daily throughout a bloom period which may last for 2 weeks or more. Multiple applications are also costly, and such additional expense can negate the traditional advantage of sorghum over competitive crops; namely, the smaller investment required per unit area for sorghum production. Moreover, most insecticides currently labeled for use in sorghum are organophosphates, which are highly toxic to a broad spectrum of insect species, including beneficials. The application of such insecticides to sorghum fields can disrupt insect control by beneficial insects in adjacent crops, especially cotton, due to drift from the treated field and destruction of a potential sanctuary for beneficials.

Host-plant Resistance

Host-plant resistance had been investigated as a potential means of controlling the sorghum midge by Ball and Hastings (1912) as early as 1908. They, as well as other researchers in subsequent years (Gable et al. 1928; Walter 1941, 1953; Passlow 1965; Harris 1969), were unsuccessful in their attempts to detect resistant lines. Bowden and Neve (1953) reported that "Nunaba" varieties possessing long papery glumes were resistant to the sorghum midge. However, in field tests in Australia, Passlow (1965) concluded that such varieties were no more resistant than others tested.

Nevertheless, plant resistance to Other sorghum insect pests had been demonstrated, and efforts to identify lines resistant to the sorghum midge persisted in Georgia during the 1950s (Painter 1958) and 1960s (Wiseman et al. 1974). Wiseman and McMillian (1968) reported the detection of plant resistance to the sorghum midge in the 1960s. Added impetus for the search for midge-resistant sorghum lines resulted from the successful development of sorghums resistant to another serious insect pest, the greenbug, *Schizaphis graminum* (Rondani), in the early 1970s (Teetes 1975) and from the availability of a greatly expanded collection of germplasm available for screening from the Texas Sorghum Conversion Project initiated in 1963 (Stephens et al. 1967; Johnson et al. 1971). By 1975, several lines resistant to sorghum midge had been identified.

Wiseman et al. (1973) reported the discovery of a midge-resistant line, SGIRL-MR 1, which they had selected from ODC 19, a line of South African origin. That same year, Johnson et al. (1973) listed eight converted exotic sorghums, adapted to temperate areas, which exhibited midge resistance. Two years later, Rossetto et al. (1975) reported that a line they designated as "AF 28" (PI 383856) showed a high level of midge resistance in field trials in Brazil.

Mechanisms of Resistance

Related to mechanisms and causes of resistance to the sorghum midge, Bowden (1965) and Harris (1969, 1970) reported that Nunaba varieties are resistant because the glumes are long and they do not open during anthesis. The same phenomenon was reported for IS 2663 and IS 2660 sorghum lines by Bergquist et al. (1974). Another source of resistance, AF 28, was studied by Rossetto et al. (1975). The line retained its resistance under artificial infestation at high midge densities in a no-choice test. Studying the response of eight lines of sorghum to midge infestation, Overman (1975) observed that although AF 28 was the most visited by the midge females, it was the least infested with eggs and consequently, the least damaged. On the other hand, the line SGIRL-MR 1 was least visited, but more highly infested and damaged. A negative correlation between tannin content and midge damage was reported by Santos and Carmo (1974), but later Martins (1977) failed to confirm this relationship.

More detailed studies of sorghum midge and resistant sorghum interactions involving the mechanisms of resistance were reported by Rossetto (1977) and Wuensche (1980). Studying about 20 lines reported in the literature as midge-resistant, Rossetto (1977) observed, under field conditions, that at low midge density all were about equally resistant when compared with the susceptible control. However, at high infestation densities, a range of responses was observed. The same author studied the types of resistance of these sources in a free-choice test and by artificially introducing a known number of eggs into the flowering spikelets. He concluded that, in general, nonpreference for oviposition was present to a varying degree in almost all resistant sources, the most resistant being AF 28, which showed the highest level of nonpreference.

Besides nonpreference for oviposition, the lines SC 175-9, SC 175-14, and SC 239-14 exhibited some degree of resistance to larvae. In Texas, Wuensche (1980) reported that comparisons of adult emergence from six sorghum midge-resistant lines failed to show any difference in the level of resistance. However, nonpreference by ovipositing females was shown for the following lines in increasing order: SGIRL-MR 1, AF 28, TAM 428, SC 423, and TAM 2566. In addition, significant differences were observed between the number of egg-infested spikelets and the number of adults emerging 17 days later, as well as differences in larvae size. Wuensche (1980) evaluated yield, adult emergence, and caryopsis development. He failed to identify tolerance as an important mechanism. In conclusion, some data are in agreement that adult nonpreference and resistance to the larvae seem to be the major mechanisms of resistance in the currently known resistant sorghum lines.

Genetics of Resistance

Regarding the genetics of resistance of sorghum to the sorghum midge, little has been done. The resistant characters seem to be recessive traits (Widstrom et al. 1972; Bergquist et al. 1974; Rossetto 1983) but the number of genes involved is still to be determined. Widstrom et al. (1972) and Teetes and Johnson (1978) speculated that resistance is polygenic. Rossetto (1983) reported that at least two recessive pairs of major genes are responsible for the resistance of AF 28 to the sorghum midge, but other genes with minor effects might be present. Therefore, it is possible that different sources of resistance have different mechanisms with different genetic inheritances and they can be combined to improve the resistance level of the present cultivars.

Midge-resistant Cultivars in IPM

The discovery of sorghum midge-resistant germplasm provided a unique opportunity to add another significant management component (Teetes 1980, 1982). The three major resistant sources, SGIRL-MR 1, TAM 2566, and AF 28 are highly resistant to sorghum midge, but are of poor agronomic quality. Significant improvement in agronomic features has been required. Also, based on experience with the discovery, improvement, and use of greenbug-resistant sorghum hybrids, much must be learned about the responses of plant to pest and pest to plant. The original lines are very resistant and show high levels of antibiosis and nonpreference; however, significant changes in these lines occur as parent lines are improved for use in acceptable, adapted hybrids.

Midge Response to Resistant Sorghum

Most literature to date on pest-to-plant responses and the mechanisms of resistance to the sorghum midge has dealt with the pest response to resistant lines and not hybrids. It is very important to identify levels of resistance and resistance mechanisms of improved hybrids, because they will be used by farmers as an IPM tactic. An understanding of the interactions between the sorghum midge and the agronomically improved resistant hybrids and the determination of resistance mechanisms are both important. First, this knowledge assists in predicting biotype development and provides the basis for combination of different gene sources into a single hybrid to increase the level and duration of the resistance. Secondly, a knowledge of plant-pest relationships is required to describe the performance of the resistant cultivars in agricultural production.

Fewer ovipositing female sorghum midges visit flowering panicles of resistant grain sorghum hybrids (ATx2755 x RTx2767 and ATx2761 x RTx2767) than of susceptible hybrids (ATx2752 x RTx430 and ATx3042 x RTx2737) and only on a few occasions. These differences in adult abundance occur erratically and do not follow any apparent pattern. It is doubtful that the resistance of these hybrids could be attributed to an effect on the number of ovipositing midges.

Determination of the number of progeny produced per female that oviposited in panicle spikelets of susceptible and resistant hybrids is complicated by competition between midges at high population densities. Melton and Teetes (1984) used an interference index to compensate for this competition. Midges infesting resistant hybrids produce 50 to 60% fewer progeny per female than those infesting susceptible hybrids, regardless of midge density. This percentage reduction, however, is ineffectual in preventing economic damage to resistant hybrids when midge densities reach high levels. There is a slight, but statistically nonsignificant, increase in the developmental time of midges infesting resistant sorghum hybrids. These results suggest that the effects of midge-resistant sorghums would be cumulative in reducing midge density over time.

Nonpreference for adult midge visitation is a minor resistance mechanism in sorghum hybrids. The ovipositional behavior of sorghum midge on resistant sorghums, however, appears to be a significant mechanism. The searching time (interval between two oviposition attempts) is shorter for females on a resistant hybrid (5.9 s) than on a susceptible one (7.2 s)(Waquil et al. 1984); however, the number of flowers searched by each female on a resistant or susceptible hybrid during this interval of time is about *the* same. Considerable variability occurs in the number of flowers searched. About 50% of the observed females probe the first flower searched, 21% fail to probe the first flower but probe the second one. A small number of the females search up to 10 flowers before probing a spikelet of either a resistant or susceptible hybrid. However, probing time is shorter for females on a susceptible hybrid, and the success of oviposition (oviposition efficiency), is much greater (about four times) than on a resistant hybrid.

Thus egg laying in spikelets of a resistant hybrid is much less efficient than in spikelets of a susceptible hybrid. Although females search spikelets of resistant hybrids more rapidly than those of the susceptible ones, females spend a longer period of time probing spikelets of a resistant hybrid than those of a susceptible one.

The reduction in ovipositional efficiency on resistant hybrids compared with those on susceptible sorghums may be related to spikelet morphology. Midge-resistant hybrids have small glumes and anther extrusion is less than that in a susceptible hybrid.

The percentage of midges in diapause generally increases as the season progresses. The seasonal mean shows there is a trend toward more diapausing larvae in resistant than in susceptible sorghums (Hallman and Teetes 1984). However, differences in percentage of midges in diapause in resistant and susceptible hybrids are not significant and indicate that resistance does not affect the mechanism inducing the sorghum midge to enter diapause.

Plant Response to Sorghum Midge

Economic threshold levels (ETL) for the sorghum midge in susceptible grain sorghum currently are based on ovipositing adult female midge number per flowering sorghum panicle. In Texas, the level is one (Hoelscher and Teetes 1981); in Mississippi, two to three (Pitre et al. 1975); in Australia, over six (Passlow 1973); and in Argentina, one per two panicles (Limonti and Villata 1980). These levels were largely empirically derived. Economic threshold levels have not been available for sorghum midge attacking resistant sorghum hybrids.

Incorporating the use of midge-resistant sorghums in a pest management strategy requires that we determine the relationship of ovipositing midge densities to subsequent damage in midge-resistant hybrids as well as susceptible ones. These data are required to establish economic threshold levels, as midge-resistance levels are not sufficiently high to provide immunity.

Two published works have dealt with the relationship between adult midge infestation levels and damage to susceptible sorghum. Montoya (1965) placed 2, 4, 6, and 8 midges per caged panicle on RS 610 hybrid sorghum and the mean number of damaged spikelets per ovipositing midge was 34, 38, 31, and 31, respectively. Karanjkar and Chundurwar (1978) placed 2, 4, 8, 12, 16, 20, and 24 midges per caged panicle on CSH 1 hybrid sorghum and the mean number of spikelets damaged per ovipositing midge was 30, 20, 13, 10, 8, 9, and 9 respectively.

Hallman et al. (1984) used three methods to investigate the relationship between adult sorghum midge density and yield loss in susceptible (ATx2752 x RTx430) and resistant (ATx2755 x RTx2767 and ATx2761 x RTx2767) sorghum hybrids. Using natural infestation and a sequential model, similar results were obtained: 1.5 g of grain lost (42 to 48 damaged spikelets) per ovipositing midge for the susceptible and 0.32 g (9 damaged spikelets) for the resistant hybrids.

A technique using caged midges resulted in less loss per midge than the other two methods: 0.54 g (16 damaged spikelets) for the susceptible and 0.15 g (4 to 6 damaged spikelets) for the resistant hybrids. This was due to reduced oviposition by midges in cages. However, the relative differences in midge damage to resistant and susceptible sorghum hybrids were similar in all three methods used. Resistant hybrids suffered about one-fifth as much damage as the susceptible hybrids because of a reduction in oviposition (45%), in the proportion of egg-infested spikelets that failed to produce kernels (52%), and in yield loss per developing midge (13%). Under the conditions of these experiments, a static economic threshold level of one adult midge per flowering panicle of susceptible sorghum and five per panicle of resistant sorghum was indicated. This fivefold increase in the economic threshold level for resistant hybrids is of major significance to integrated pest management strategies (Fig. 2).

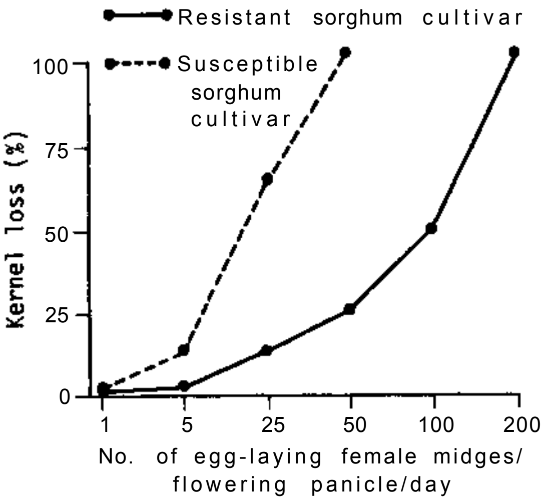

Figure 2. Kernel damage in relation to midge density in susceptible and resistant sorghum hybrids.

The density-damage relationship developed by Hallman et al. (1984) is being used to develop economic threshold levels (ETL) using the following equation:

$$ETL = \frac{Cost \times 30239}{Price \times panicle\ population}$$

where "cost" is the cost of control per acre (0.4 ha), "price" is the expected price of sorghum per cwt (45.4 kg) and "panicle population" is the number of panicles per acre. The constant 30239 is a conversion factor which represents the number of ovipositing midge needed to completely destroy 1 cwt of sorghum.

Dynamic ETLs for a midge-susceptible sorghum at varying prices per cwt versus various control costs per acre at a panicle population level of 60 000 panicles per acre are illustrated in Table 1. The ETL ranges from 0.2 to 1.2 adult midges per panicle. The ETL for a resistant sorghum ranges from 1 to 6 midges per panicle (Table 2). However, these ETLs assume that all of the panicles are in anthesis, the stage at which midge attacks sorghum. Also, they are based on the total number of ovipositing midges per panicle. However, results

Table 1. Economic threshold levels for sorghum midge attacking susceptible grain sorghum hybrids. (Calculated for various grain prices, based on number of adult midges/flowering panicle; 60 000 panicles/acre).

	Economic threshold level (no. adult midges/flowering panicle)						
Control cost	Grain price (U.S.$/cwt):[1]						
(U.S.$/acre)	4.00	4.50	5.00	5.50	6.00	6.50	7.00
3.00	*0.4*	0.3	0.3	0 3	0.2	0.2	0.2
3.50	0.4	0.4	0.3	0.3	0.3	0.3	0.2
4.00	0.5	0.4	0.4	0.4	0.3	0.3	0.3
4.50	0.6	0.5	0.4	0.4	0.4	0.3	0.3
5.00	0.6	0.6	0.5	0.5	0.4	0.4	0.4
5.50	0.7	0.6	0.5	0.5	0.5	0.4	0.4
6.00	0.7	0.7	0.6	0.5	0.5	0.5	0.4
6.50	0.8	0.7	0.6	0.6	0.5	0.5	0.5
7.00	0.9	0.8	0.7	0.6	0.6	0.5	0.5
7.50	0.9	0.8	0.7	0.7	0.6	0.6	0.5
8.00	1.0	0.9	0.8	0.7	0.7	0.6	0.6
8.50	1.1	0.9	0.8	0.8	0.7	0.7	0.6
9.00	1.1	1.0	0.9	0.8	0.7	0.7	0.6
9.50	1.2	1.1	0.9	0.9	0.8	0.7	0.7
10.00	1.2	1.1	1.0	0.9	0.8	0.8	0.7

1. Acre = 0.4 ha; cwt = 45.4 kg.

Table 2. Economic threshold levels for sorghum midge attacking resistant hybrids. (Calculated for various grain prices, and based on no. of adult midges/flowering panicle; 60 000 panicles/acre).

	Economic threshold level (no. adult midges/flowering panicle)						
Control cost (U.S.$/acre)[1]	Grain price (U.S.$/cwt):[1] 4.00	4.50	5.00	5.50	6.00	6.50	7.00
3.00	2.0	1.5	1.5	1.5	1.0	*1.0*	1.0
3.50	2.0	2.0	1.5	1.5	1.5	1.5	1.0
4.00	2.5	2.0	2.0	2.0	1.5	1.5	1.5
4.50	3.0	2.5	2.0	2.0	2.0	1.5	1.5
5.00	3.0	3.0	2.5	2.5	2.0	2.0	2.0
5.50	3.5	3.0	2.5	2.5	2.5	2.0	2.0
6.00	3.5	3.5	3.0	2.5	2.5	2.5	2.0
6.50	4.0	3.5	3.0	3.0	2.5	2.5	2.5
7.00	4.5	4.0	3.5	3.0	3.0	2.5	2.5
7.50	4.5	4.0	3.5	3.5	3.0	3.0	2.5
8.00	5.0	4.5	4.0	3.5	3.5	3.0	3.0
8.50	5.5	4.5	4.0	4.0	3.5	3.5	3.0
9.00	5.5	5.0	4.5	4.0	3.5	3.5	3.0
9.50	6.0	5.5	4.5	4.5	4.0	3.5	3.5
10.00	6.0	5.5	5.0	4.5	4.0	4.0	3.5

1. Acre = 0.4 ha; cwt - 45.4 kg.

of two sampling methods show that usually not all of the midges are found when sampling; some go undetected because of their small size and color proximity to old anthers.

ETLs will be affected by the sampling techniques. For example, if one-half of the insects present are sampled by one technique and all of the insects present are sampled by another, ETLs using the first technique will be double the ETLs using the second, although the insect infestation levels are the same.

Sampling sorghum midge on grain sorghum is further complicated by the fact that density levels of egg-laying females fluctuate widely within a day, and when damaging levels are observed in the field it is too late to protect those spikelets in anthesis. Fisher et al. (1982) found 8 midges per panicle at 0730 h, 67 per panicle at 1100 h, and 14 per panicle at 1900 h. Midges live less than 1 day, so that the midges infesting a field the day after sampling constitute a completely new brood and may be at a different level.

Midge-resistant Sorghum and Insecticidal Control. Determining density-damage relationships enabled the establishment of economic threshold levels. These studies, plus numerous field observations confirmed that midge densities in some areas at certain times reached such high levels that even resistant hybrids were economically damaged. Consequently, it became important to determine the combined midge-control effects of midge-resistant hybrids and insecticides.

At a midge density of 53 adults per panicle, both resistant and susceptible hybrids gave significantly higher yields when treated with insecticide than when untreated (Becerra et al. 1984).

The resistant hybrid yielded about 4000 kg/ha with, and 2517 kg/ha without, diazinon; five applications at 3-day intervals gave 64% more grain, and three applications at 5-day intervals gave 59% more, than the untreated control. However, differences between the 3- and 5-day treatments were not significant.

With the susceptible hybrid again, insecticide treatment gave significantly higher yields than no treatment. Although the hybrid tended to yield more (494 kg/ha) when treated five times at 3-day intervals rather than three times at 5-day intervals, the difference was not statistically significant. The increase in yield was 674 and 542% for the 3-day and 5-day application intervals, respectively.

Even though the susceptible and resistant hybrids have comparable yield potential, the resistant hybrid yielded more than the susceptible one when yields following each treatment were compared. In fact, the resistant hybrid treated three times every 5 days yielded more than the susceptible hybrid did, treated five times every 3 days. Compared by treatment, the resistant hybrid yielded 569,42, and 65% more than the susceptible hybrid following no treatment, 3-day and 5-day treatments, respectively.

In another trial, yields of a resistant hybrid were not significantly different among treatments, even though 8 and 21 % more grain was produced following treatment at 3- and 5-day intervals, respectively, when mean midge density was 7 per panicle.

However, insecticide applications at 3- and 5-day intervals to the susceptible hybrid significantly improved the yield, by 73% and 63% respectively. The untreated resistant hybrid yielded twice as much as the untreated susceptible hybrid. When treated five times at 3-day intervals, the resistant hybrid yielded 25% more than the susceptible hybrid, but at the 5-day interval this difference rose to 49%.

Data from these experiments supported the established economic threshold level for midge-resistant hybrids of five adults per panicle during flowering. The data also indicated that at moderate to high midge densities, midge-resistant hybrids receive as much protection from insecticide applied three times at 5-day intervals as susceptible hybrids would, treated five times at 3-day intervals. This longer application interval would save two insecticide applications, which is economically and environmentally beneficial. The complementary relationship between midge-resistant sorghum hybrids and judicious insecticide use is compatible with other control tactics such as early uniform regional planting and johnsongrass destruction. Integrated, these tactics form a sound pest management strategy for the sorghum midge.

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Importance de la cécidomyie en tant que facteur limitant la production du sorgho au Burkina Faso et au Mali

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Résumé

La présence de la cécidomyie responsable de la stérilité des épillets de sorgho a été constatée au Burkina Faso et au Mali depuis les années soixante. Sa distribution saisonnière et géographique ainsi que l'importance des dégâts ont été étudiées. Les principaux foyers d'activité ont été identifiés. Certains facteurs favorables et défavorables à la multiplication du ravageur sont présentés.

La recherche des variétés résistantes ou tolérantes à la cécidomyie dans les collections locales s'avère prometteuse d'après les résultats déjà obtenus.

Dans les localités données, la mise au point de méthodes de lutte judicieuses et adaptées contre ce ravageur est nécessaire pour préserver les récoltes de sorgho devenues aléatoires en raison de la pluviométrie défavorable dans le Sahel.

Introduction

Le Burkina Faso et le Mali sont certainement les plus gros producteurs de sorgho grain des pays du Sahel de l'Afrique de l'Ouest. Dans ces pays le petit mil et le sorgho constituent la base de l'alimentation humaine. (Voir Annexe 1 pour les productions annuelles de sorgho de quelques pays sahéliens).

Le sorgho y est partout cultivé, même au nord du 14e parallèle où le petit mil prédomine, lorsque l'humidité et la qualité du sol le permettent. Les sorghos traditionnels sont le plus souvent cultivés suivant les méthodes ancestrales. Ils sont adaptés à leurs différentes régions d'origine où la saison pluvieuse s'étale sur 2 à 6 mois pour une pluviométrie de 400 à 1200 mm (Fig. 1). Cependant les variétés locales, améliorées, sont de plus en plus cultivées d'après les méthodes agronomiques mises au point par la recherche agronomique et les organismes de développement.

Au Mali, le sorgho est produit essentiellement en culture pluviale, et à une moindre échelle, en culture de décrue.

Dans les régions les mieux arrosées, plusieurs sorghos de qualités et de cycles différents sont couramment cultivés. Les sorghos à grains blancs, durs et vitreux sont utilisés dans l'alimentation humaine pour la fabrication de *tô*, plat national, ou de *couscous.*

Au Burkina Faso, les sorghos dits rouges parce qu'ils ont un grain brun, tendre et très farineux, sont utilisés dans la fabrication de la bière traditionnelle, le *dolo* largement consommé dans les villes et villages. Ces sorghos ont un cycle plus court que celui des sorghos blancs.

La diversité des variétés, des écotypes et des cycles de cette céréale d'origine africaine, ainsi que les pratiques culturales à travers les zones de production constituent des facteurs favorables au développement et à l'action des ennemis de cette culture, dont la cécidomyie du sorgho.

Les travaux réalisés ou en cours au Burkina Faso et au Mali ont pour objet de définir l'aire de distribution du ravageur, les principaux foyers d'activité et les éléments de biologie et d'écologie nécessaires pour situer l'importance écono-

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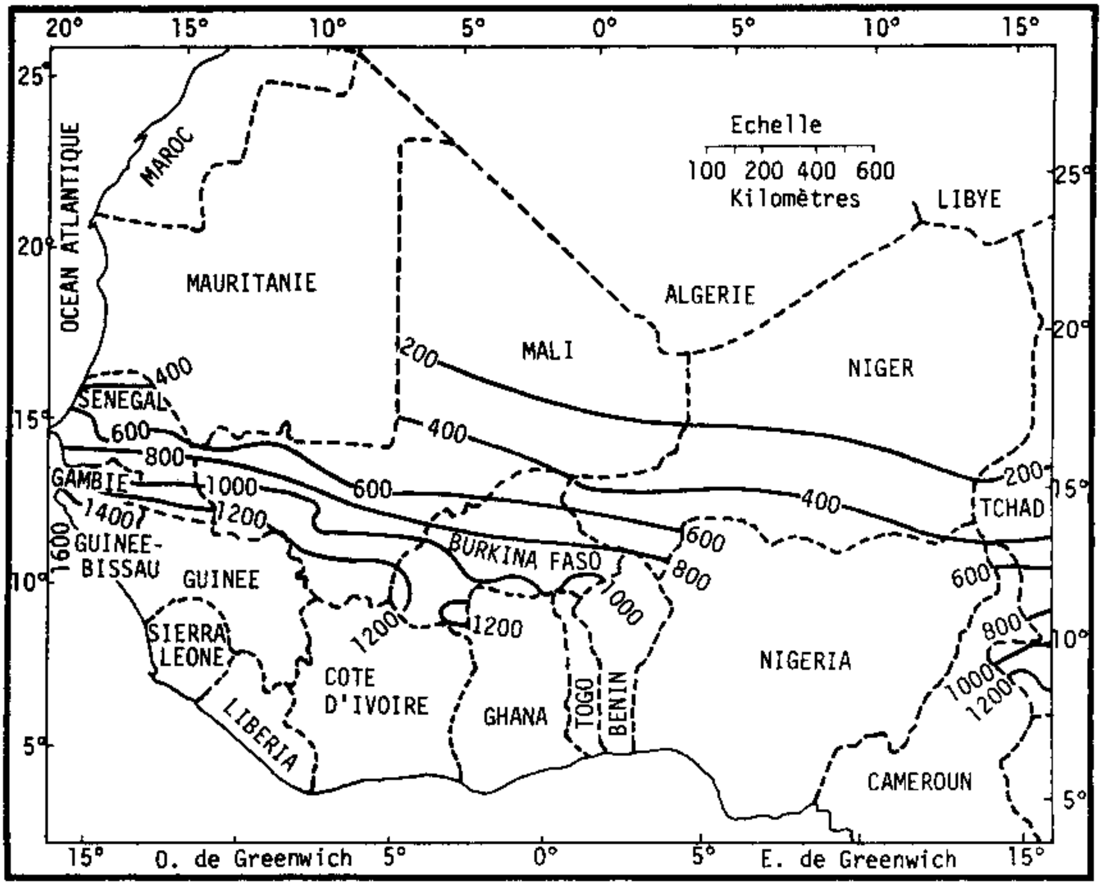

Figure 1. Les isohyètes (mm) de la pluviosité annuelle en Afrique de l'Ouest.

mique de ce ravageur dans les conditions naturelles afin d'envisager les possibilités de lutte.

Distribution saisonnière

Des semis échelonnés mensuels de sorgho effectués en station dans un bas-fond irrigué ont permis de suivre durant une année l'activité de la cécidomyie au Burkina Faso à Farako-Bâ (Bonzi, 1980; Dakouo 1981). Pendant l'hivernage les premières attaques surviennent en juin et se poursuivent après l'arrêt des pluies jusqu'en décembre. Le maximum des attaques enregistrées se situe en octobre avec 60% des épillets attaqués.

Au Mali, les études faites à Sotuba et à Samanko par piégeages des adultes au Piège malais et aux assiettes colorées, montrent que les populations de *Contarinia sorghicola* augmentent fortement à partir d'août et septembre. Les variétés de sorghos à cycle long sont également les plus attaquées. Les premiers adultes de cécidomyies sont capturés en début de saison des pluies en mai et les derniers au mois de décembre.

Distribution géographique et importance des dégâts

Les enquêtes sur l'importance de la cécidomyie du sorgho en milieu paysan dans les conditions naturelles ont été menées aussi bien au Burkina Faso qu'au Mali.

Les zones de répartition de l'insecte dans l'ensemble des deux pays et certains foyers importants ont pu être identifiés. Dans les stations de recherches agronomiques des études complémentaires ont été conduites.

Burkina Faso

Si en Afrique de l'Ouest ce ravageur a été découvert en 1929 au Nigeria, au Ghana en 1951 et en Gambie en 1956, c'est seulement en 1960 que ses dégâts ont attiré l'attention au Burkina Faso avant que l'insecte lui même soit mis en cause en 1964 dans les stations de recherche agronomique. Les résultats des prospections effectuées par plusieurs chercheurs à travers le pays (Bonzi 1979, 1980; Nwanze 1980; Dakouo 1981) ont montré que la cécidomyie du sorgho est présente dans le pays partout où est cultivée sa plante-hôte principale, le sorgho. Cependant il existe des zones particulières où les attaques de l'insecte sont sensiblement plus concentrées tandis qu'ailleurs, par contre, le ravageur semble absent (Tab. 1).

Les principaux foyers d'infestation enregistrés se situent approximativement entre les 11°N et 13°N notamment dans les régions de Fada-N'gourma, Koupéla-Tenkodogo, Ouagadougou, Koudougou-Réo et Bobo-Dioulasso (Fig. 2). On y a enregistré entre 20 et 100% de grains détruits par la cécidomyie, elle-même parasitée à 30% par des hyménoptères.

Par contre dans les zones situées en dehors des latitudes 11°N et 13°N, l'absence ou le faible taux d'attaque de sorgho peut s'expliquer par :

1. La brièveté du cycle des sorghos au nord de la latitude 13°N, correspondant à une courte saison des pluies, moins de 3 mois, à une faible pluviométrie (moins de 600 mm), et aux superficies réduites cultivées en sorgho.
2. La longueur très importante du cycle de certaines variétés de sorgho des Provinces du Poni (Gaoua) et de Comoé (Banfora). Ces sorghos fleurissent très tard après les périodes de pullulation de *C. sorghicola* en fin octobre début novembre, au début de la saison froide. Il faut signaler cependant que ces sorghos à long cycle sont de moins en moins cultivés en raison des risques de sécheresse.

Dans les stations et les points d'appui de la recherche agronomique, la cécidomyie du sorgho occasionne toujours plus de dégâts que dans les champs paysans des régions avoisinantes. La diversité des origines, des cycles et des variétés des sorghos expérimentés dans ces sites favorise et maintient la multiplication du ravageur.

Mali

Au Mali, en 1965 M. Bono dans la "Note technique sur la stérilité des sorghos autour de Bamako au cours de la dernière campagne", n'explique pas l'origine exacte de cette stérilité qu'il a observée, mais remarque après enquête qu'elle affecte les sorghos "non originaires de cercle de Bamako". Selon l'auteur, les panicules *stériles* :

- "provenaient de semences "tout venant" achetées au marché de Bamako dans sept cas sur dix;
- dans les trois autres cas elles pouvaient être dues à des semis trop tardifs et à l'emploi d'une population à trop long cycle."

Il est très probable à notre avis que ce soit là une manifestation bien remarquée des attaques de *C. sorghicola* d'autant que l'auteur exclut l'action des facteurs sol et sécheresse.

Plus tard J. Brenière a observé à Sotuba au cours d'une mission en octobre 1967 des adultes femelles de *C. sorghicola* en train de pondre sur des panicules de sorgho en cours de floraison.

A l'heure actuelle, même si les prospections réalisées à ce jour ne permettent pas encore de situer l'importance économique réelle du ravageur, sa répartition est cependant connue.

Elle correspond aux aires de culture du sorgho situées dans les parties sud et ouest du pays à l'exclusion de la région sahélienne au nord d'une ligne Kayes-Ségou (Fig.3).

Les prospections effectuées en saison humide 1983 ont été perturbées par la sécheresse très marquée qui a affecté l'ensemble du pays. L'epiaison, la floraison et la maturation, quand elles ont eu lieu, se sont déroulées dans des conditions difficiles.

Tableau 1. Infestation d'échantillons de 1000 épillets prélevés en champ paysan au Burkina Faso, 1970.

Type de sorgho	Localité et date de prélèvement	Epillets avec larves ou pupes de *C. sorghicola* (%)	Parasitisme (%)	Stade phénologique
Blanc	Kombissiri 18 oct.	58,6	13,6	Grains pâteux
Rouge	Tenkodogo 19 oct.	80,6	29,1	Début maturité
Blanc	Fada N'gourma 19 oct.	23,2	16,3	Grains laiteux
Blanc	Saria 20 oct.	5,2	1,9	Grains laiteux
Blanc	Koudougou-Réo 20 oct.	30,2	2,9	Grains laiteux
Rouge	Réo 20 oct.	6,0	5,0	Grains laiteux

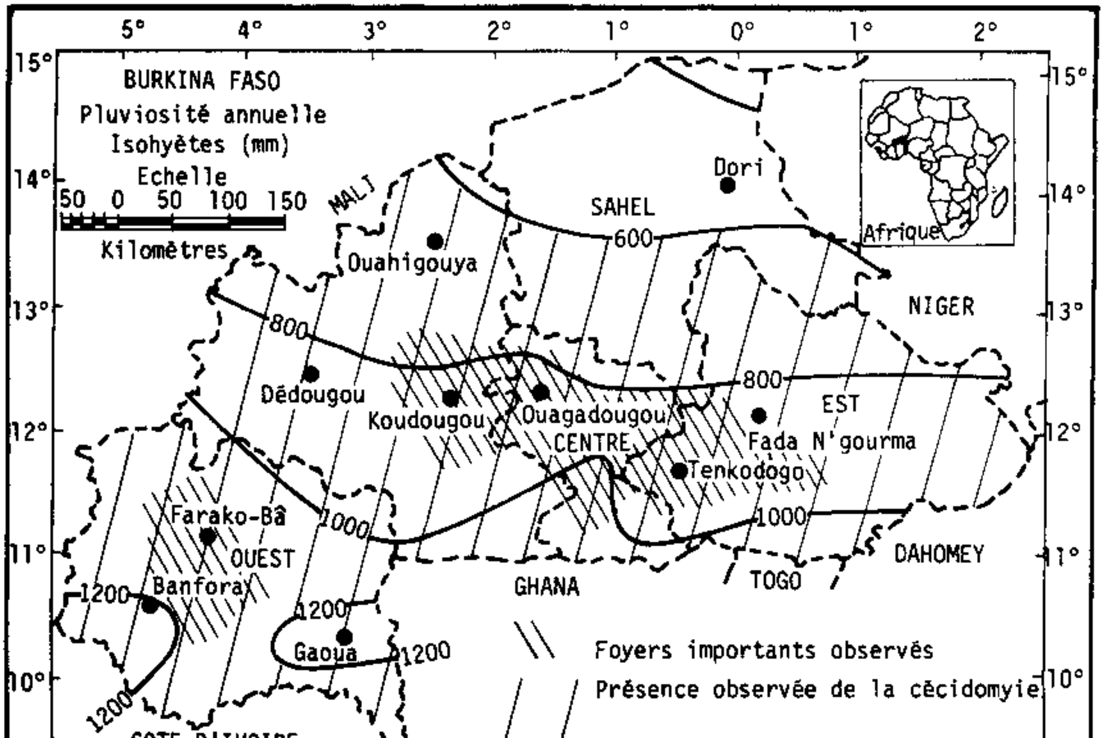

Figure 2. Distribution de la cécidomyie au Burkina Faso 1979-1981. (Source : Virmani et al. 1980 pour les données pluviométriques).

A la Station de recherche agronomique de Sotuba, pour les variétés tardives fleurissant en fin octobre, les infestations se sont situées entre 10% et 90%.

Autour de la ville de Bamako, l'on a enregistré de 3 à 10% de grains infestés dans des champs paysans. Plus loin, à Bankoumana en zone de l'Opération Haute-Vallée (OHV), 0 à 4% des épillets sont détruits.

Les observations et investigations qui ont été faites (Bono 1965; Bonzi et Doumbia 1983) permettent de résumer la situation comme suit :

- fortes infestations (plus de 50%) dans les stations de recherche pour les variétés tardives fleurissant après la mi-octobre;

- infestations modérées (10%) autour des grands centres urbains et le long de certains grands axes de communication;

- infestations faibles (autour de 5%) dans les champs paysans en dehors des foyers localisés qui restent à identifier;

- pas d'infestations constatées dans la partie nord du pays dont les conditions climatiques difficiles sont plutôt défavorables au développement du ravageur sur le sorgho en culture pluviale ou en culture de décrue autour de grandes mares, des lacs ou le long du fleuve Niger.

Facteurs de multiplication du ravageur

Les plantes-hôtes secondaires

En dehors du sorgho grain, d'autres espèces de sorgho cultivées ou non contribuent avec quelques graminées sauvages à la multiplication et à la survie de population de *C. sorghicola* : *Sorghum halepense*, *Sorghum* spp (Tab. 2).

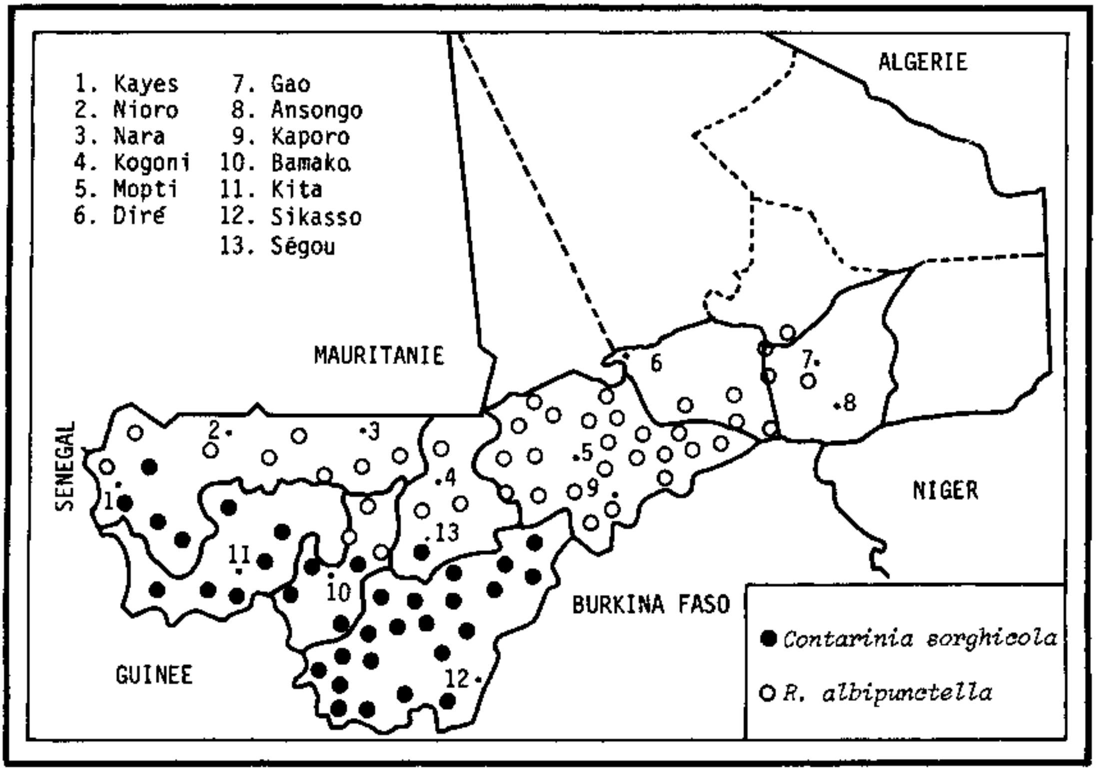

Figure 3. Distribution de *Contarinia sorghicola* et *Raghuva albipunctuella* dans les régions agricoles du Mali en 1983.

Tableau 2. Quelques plantes-hôtes non cultivées de cécidomyies à Sotuba au Mali, 1983.

Plantes-hôtes (graminées)	*Contarinia sorghicola*	*Contarinia* sp	*Lasioptera* sp	*Lestodiplosis* sp
Sorghum halepense	*			
Setaria barbata		*		
Pennisetum typhoides		*		
Vetiveria nigritana		*		
Panicum subalbidum			*	
Pennisetum pedicellatum				*

*Présence de cécidomyie sur la plante correspondante.

Ces sorghos sauvages se rencontrent couramment autour des grandes agglomérations, en bordure des routes principales près des villes, et parfois le long des cours d'eau.

Le sorgho sucré, *Sorghum mellitum* est cultivé en milieu paysan traditionnel. Ses tiges à moelle très sucrée sont consommées sous forme de friandise comme celles de la canne à sucre.

Ce sorgho est surtout très cultivé dans la région de Bamako et vendu en ville à partir de fin août. On le récolte dès l'épiaison.

Le sorgho de bouche est une variété précoce dont les grains se mangent à l'état frais à la fin du stade grain laiteux. Il mûrit au mois de septembre. Il est répandu dans la région de Ouagadougou.

Des élevages au laboratoire ont permis de recenser un certain nombre de graminées non cultivées servant de plantes-hôtes à diverses cécidomyies identifiées ou non.

Jusqu'ici les plantes-hôtes non cultivées en dehors du genre sorghum sur lesquelles *C. sorghicola* a été identifié sont encore rares. Cependant les recherches se poursuivent compte tenu de l'importance que ces plantes ont dans le cycle du ravageur.

Dates de semis et longueur des cycles du sorgho

L'ensemble des essais conduits en station ou en milieu paysan a partout confirmé le fait que pour une même variété de sorgho les semis les plus tardifs sont les plus attaqués à la floraison. Pour plusieurs variétés de cycles différents, celles qui fleurissent le plus tard sont les plus attaquées.

Dans un même champ l'étalement de la période de floraison d'une variété expose davantage les dernières panicules aux attaques de la cécidomyie au moment de l'anthèse (Tab. 3).

Facteurs limitant l'activité du ravageur

La sécheresse

En dehors de la saison sèche et froide de novembre à février puis sèche et chaude de février à mai, qui vient d'être évoquée, la sécheresse due à l'arrêt précoce des pluies comme en 1983 ou à leur mauvaise répartition affecte lar-

Tableau 3. Infestation de sorgho local suivant l'étalement de la floraison à Farako-Bâ, 1976.

	Jours depuis début floraison								
	J[1]	J+2	J+4	J+6	J+8	J+10	J+12	J+14	J+16
Épillets infestés (%)[2]	0	0	0	0,4	1,2	4,7	14,2	14,8	19,2

1. Date de début floraison.
2. Examen des épillets pour la présence des cécidomyies a été fait par l'écrasement 12 jours après la floraison. Une liquide rouge exsude des épillets infestés soit par les larves sôit par les pupes de la cécidomyie.

gement le développement de *C. sorghicola*.

Il a été noté en octobre 1983 dans la région de Bamako et ailleurs au Mali, que le faible pourcentage d'attaques des variétés tardives ne pouvait s'expliquer que par les difficultés de développement rencontrées à la fois par le ravageur et sa plante-hôte à cause de l'arrêt précoce des pluies.

Les ennemis naturels

Les ennemis de la cécidomyie les plus communs sont :

1. Les parasites : Ce sont des microhyménoptères dont les plus communs identifiés au Burkina Faso sont : *Aprostocetus diplosidis* Graw; *Eupelmus popa* Gir. Les autres parasites sont des familles des Trichogrammidae, des Proctotropidae et des Mymaridae. D'après les élevages, le taux de parasitisme peut atteindre et même dépasser 30% après le mois d'octobre. Mais ce taux devient important à un moment où le plus gros des dégâts est déjà fait et son intérêt réside dans la réduction des populations hivernantes.

2. Les prédateurs : Les plus nombreux sont les petites punaises noires, *Orius* sp dont les larves et les adultes se nourrissent des adultes de cécidomyie. Plusieurs espèces d'araignées carnassières capturent facilement les cécidomyies dans leurs toiles tendus autour des panicules. Les mêmes ennemis de la cécidomyie se retrouvent au Mali.

Recherche de variétés résistantes

Les essais réalisés dans des conditions de forte infestation avec des sorghos issus des collections locales montrent qu'il existe des variétés prometteuses dans la recherche de variétés tolérantes ou résistantes.

Burkina Faso

Les variétés locales les moins sensibles à *C. sorghicola* après plusieurs années d'observations sont : N°323 Tonnetolo-pen à grains petits, durs et à bonne vitrosité, N°170 Guerson et N°174 Yara. Les grains de ces deux dernières variétés sont enveloppés par les glumes à maturité. Toutes ces variétés ont une panicule lâche. Le taux d'infestation enregistré après les comptages par écrasement et par dissection est inférieur à 5% et généralement voisin de 1% pour le N°323.

Si pour les variétés N°170 et 174 la présence des glumes enveloppantes peut constituer un obstacle aux attaques de la cécidomyie, le mécanisme exact de la faible ou la non infestation des trois variétés n'est pas encore élucidé surtout en ce qui concerne la variété N°323.

Mali

Des études menées à Sotuba (Doumbia 1983) sur plus de 800 variétés de sorgho, dont des variétés locales, ont révélé le bon comportement de quelques variétés parmi les plus tardives. Elles fleurissent entre le 20 et le 30 septembre. Ces variétés prometteuses sont :

(CSM 63 x CSM 445) x SA7706-2	(panicule lâche)
HT-nain-20	(panicule lâche)
HT-nain-2	(panicule lâche)
HT-nain-8	(panicule lâche)
81 pop MB-16-3	(panicule semi-compacte)
81 pop CE 90-74-1	(panicule compacte)
81 pop CE 90-74-2	(panicule compacte)

La recherche de variétés résistantes ou tolérantes surtout d'origine locale se poursuit.

Discussion et conclusion

La cécidomyie est l'un des principaux insectes les plus potentiellement dangereux pour la culture du sorgho au Burkina Faso et au Mali. Dans les conditions climatiques normales avec une pluviométrie suffisante et bien répartie, des foyers de forte multiplication et d'infestation existent dans les zones rurales de même que des zones pratiquement indemnes de cécidomyies.

Depuis une dizaine d'années la hantise de la sécheresse qui se manifeste chaque année avec plus ou moins d'acuité çà et là, incite les paysans à introduire dans leurs localités des variétés à cycle plus court et les chercheurs à s'orienter vers l'obtention de variétés à rendement stable, mieux adaptées à une plus faible pluviométrie. A ces qualités il faut associer la résistance ou tolérance variétale à la cécidomyie. Les migrations et échanges de variétés que connaissent actuellement les régions soudanienne et sahélienne facilitent le maintien ou la multiplication de la cécidomyie.

Nos enquêtes auprès des paysans ont révélé que ceux-ci ne soupçonnent pas l'existence de la cécidomyie responsable de la perte des grains de sorgho.

Les dégâts sont attribués soit, à une coïncidence malheureuse entre la floraison du sorgho et l'effet de soleil, de la lune ou de la pluie soit, à la sécheresse, ou à d'autres facteurs.

Pour toutes ces raisons et malgré le niveau relativement faible des infestations en milieu paysan (0 à 10% attribuées à la cécidomyie du sorgho), cet insecte demeure un des ravageurs potentiels principaux les plus intimement inféodés au sorgho au Burkina Faso et au Mali. La tâche la plus urgente consiste à situer avec le plus de précision possible partout où le problème est posé, l'importance économique réelle de la cécidomyie du sorgho.

Les possibilités de solutions résident, là où cela est nécessaire, dans un recensement et une analyse approfondie au niveau local des connaissances pratiques de nos paysans en ce qui concerne la production et l'utilisation du sorgho et de ses sous-produits, et, au niveau régional sahélien, en une concertation multi et inter disciplinaire en vue de la mise au point de méthodes de lutte conséquentes, conformes aux réalités du terrain et utilisant judicieusement les données bio-écologiques et agroclimatiques disponibles.

Remerciements

Nous prions K.M. Harris, Taxonomiste au Commonwealth Institute of Entomology et A. Sow, Botaniste à Sotuba qui ont assuré l'identification respectivement des cécidomyies et de leurs plantes-hôtes, de trouver ici l'expression de nos sincères remerciements.

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Annexe 1. Production de sorgho dans quelques pays sahéliens.

Pays	Production totale de sorgho grain (t/ha)						
	1973	1974	1975	1976	1977	1978	1979
Burkina Faso	481 000		738 000		660 000		
Mali			277 100	315 500	440 000	358 100	395 900
Mauritanie	25 000	40 000	32 000	21 000	30 000	43 000	21 200
Niger	126 000		254 000	286 500	336 100	371 200	
Sénégal (sorgho + mil)	510 792	795 045	620 966	553 780			

Sources : Divisions Analyses des Statistiques (ESP), FAO, Haute-Volta. Rapport d'enquête agricole 1979, 1980, Fév. 1983, Mali. Quatrième plan de développement économique et social, Déc. 1981, Mauritanie. Direction de l'Agriculture, MDR, Niger.

Sorghum Midge as a Limiting Factor in Sorghum Production in Burkina Faso and Mali

S.M. Bonzi and Y.O. Doumbia*

Abstract

The sorghum midge, responsible for the lack of grain development in sorghum florets, has been observed in Burkina Faso and Mali since the 1960s. Its seasonal and geographic distribution and the extent of damage caused by this insect have been studied, and areas of severe midge incidence identified. Factors favorable and unfavorable to multiplication of the pest are reported. Present results show that identification of resistant or tolerant varieties from local collections is promising. In several locations appropriate pest control methods need to be designed to protect the sorghum crop against midge.

Introduction

Burkina Faso and Mali are the largest producers of grain sorghum among the West African Sahelian countries, where pearl millet and sorghum form the staple diet. (See Annexure 1 for annual sorghum production in some Sahelian countries).

Sorghum is cultivated throughout these countries (even in regions north of 14°N where pearl millet is predominant) if soil moisture is sufficient.

Local sorghum landraces are still most commonly grown in traditional farming systems. They are well adapted to regions with a rainfall period of 2 to 6 months and 400 to 1200 mm annually (Fig. 1). However, local improved varieties are increasingly cultivated in farming systems developed by local research stations and developmental organizations.

In Mali, sorghum is grown mainly as a rainfed crop, and to a lesser extent, as a receding flood crop.

A number of sorghum varieties of different durations and different grain quality are commonly cultivated. Varieties with white, hard, flinty grains are used directly for human consumption, for making *to,* the national diet, or *couscous.* In Burkina Faso, the red sorghums, named for their brown, tender, and mealy grain, are used for making *dolo,* the traditional beer that is commonly brewed in towns and villages. These sorghums have a shorter duration than the white sorghums.

The sorghum midge, *Contarinia sorghicola* (Coquillett), is one of the major insect pests in the more humid parts of Mali and Burkina Faso. Surveys have been carried out to determine the distribution and severity of the midge fly in both countries. Biological and ecological data are being collected to back up the survey results and to develop an effective control program.

Seasonal Distribution

In Burkina Faso, the midge population development over time was observed on sorghum by planting at monthly intervals under irrigated conditions at Farako-Ba Research Station. The results show that the sorghum midge is present from June to December. The maximum population and consequent damage was recorded in October, with 60% chaffy (no grain development) florets (Bonzi 1980; Dakouo 1981).

In Mali, studies carried out at Sotuba and Samanko by capturing the adults with a Malay trap and colored plates, indicate that the sorghum midge populations peak from August to September.

* Integrated Pest Control Project, Subprogram Mali, Bamako, Republic of Mali.
Note: This is an edited English translation of the original French paper immediately preceding.

International Crops Research Institute for the Semi-Arid Tropics. 1985. Proceedings of the International Sorghum Entomology Workshop, 15-21 July 1984, Texas A&M University, College Station, TX, USA. Patancheru, A.P. 502 324, India: ICRISAT.

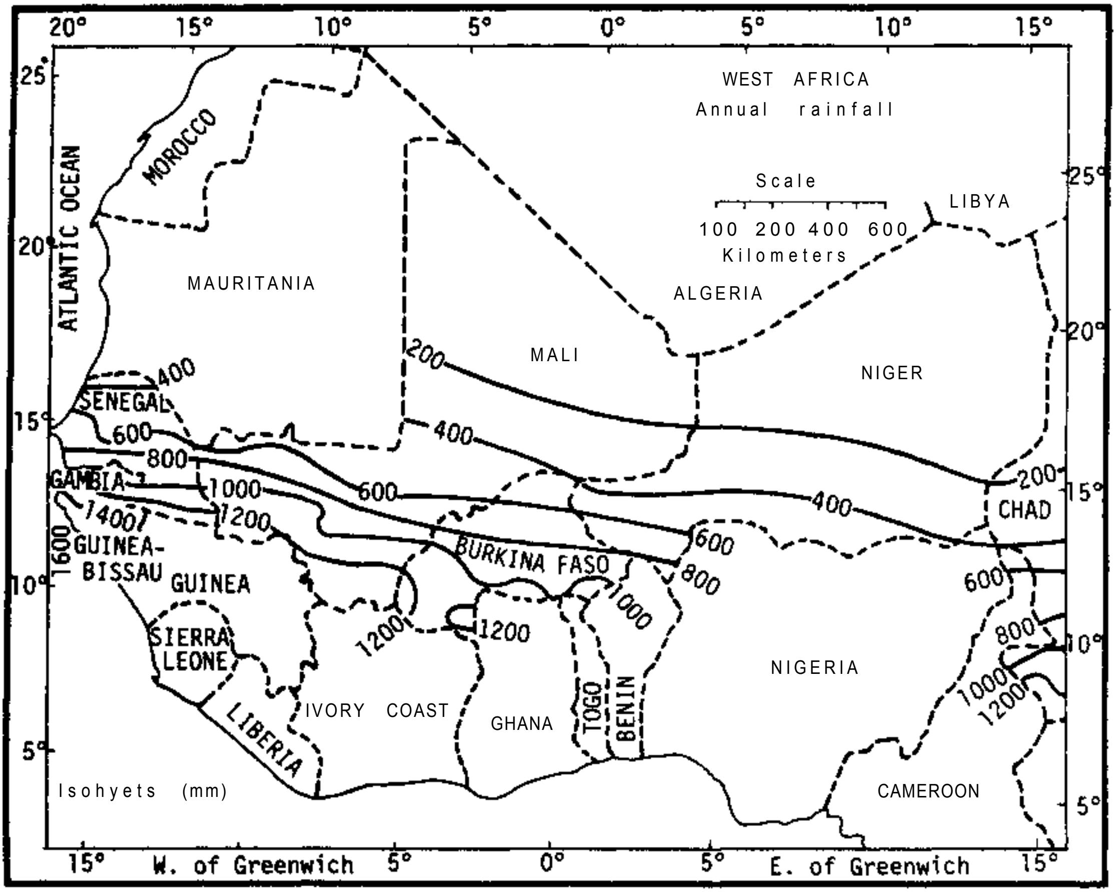

Figure 1. West Africa showing annual rainfall isohyets (mm).

Long-duration sorghum varieties are more attacked. The first adult midges are captured early in the rainy season in May and the last ones in December.

Geographic Distribution and Extent of Damage

The sorghum midge incidence in rural areas under natural conditions was surveyed in Burkina Faso and in Mali, and the areas of distribution of the insect in the two countries identified. Complementary studies were conducted in the agronomic research stations.

Burkina Faso

Although in West Africa this pest was discovered in 1929 in Nigeria, 1951 in Ghana, and 1956 in Gambia, it was only in 1960 that it was identified as a sorghum insect pest in Burkina Faso. The results of surveys carried out by several researchers throughout the country (Bonzi 1979, 1980; Nwanze 1980; Dakouo 1981) have shown that the sorghum midge occurs all over the country in areas where sorghum, its principal host, is cultivated. However, there are particular regions where its incidence is considerably higher and others where it seems to be absent (Table 1).

The main areas of infestation recorded are situated approximately between latitudes 11°N and 13°N, especially in the Fada-N'gourma, Koupela-Tenkodogo, Ouagadougou, Koudougou-Reo, and Bobo-Dioulasso regions (Fig. 2), where 20 to 100% of grain was destroyed by midge. The parasitization rate of midge in these areas by hymenopteran parasites was up to 30%.

Table 1. Midge infestation on 1000 spikelet samples collected from farmers' fields in Burkina Faso, 1979.

Sorghum type	Location and date of collection	Spikelets with midge larvae or pupae (%)	Parasitic infestation on midge (%)	Phenological stage
White	Kombissiri 18 Oct	58.6	13.6	Soft dough
Red	Tenkodogo 19 Oct	80.6	29.1	Hard dough
White	Fada N'gourma 19 Oct	23.2	16.3	Milk
White	Saria 20 Oct	5.2	1.9	Milk
White	Koudougou-Reo 20 Oct	30.2	2.9	Milk
Red	Reo 20 Oct	6.0	5.0	Milk

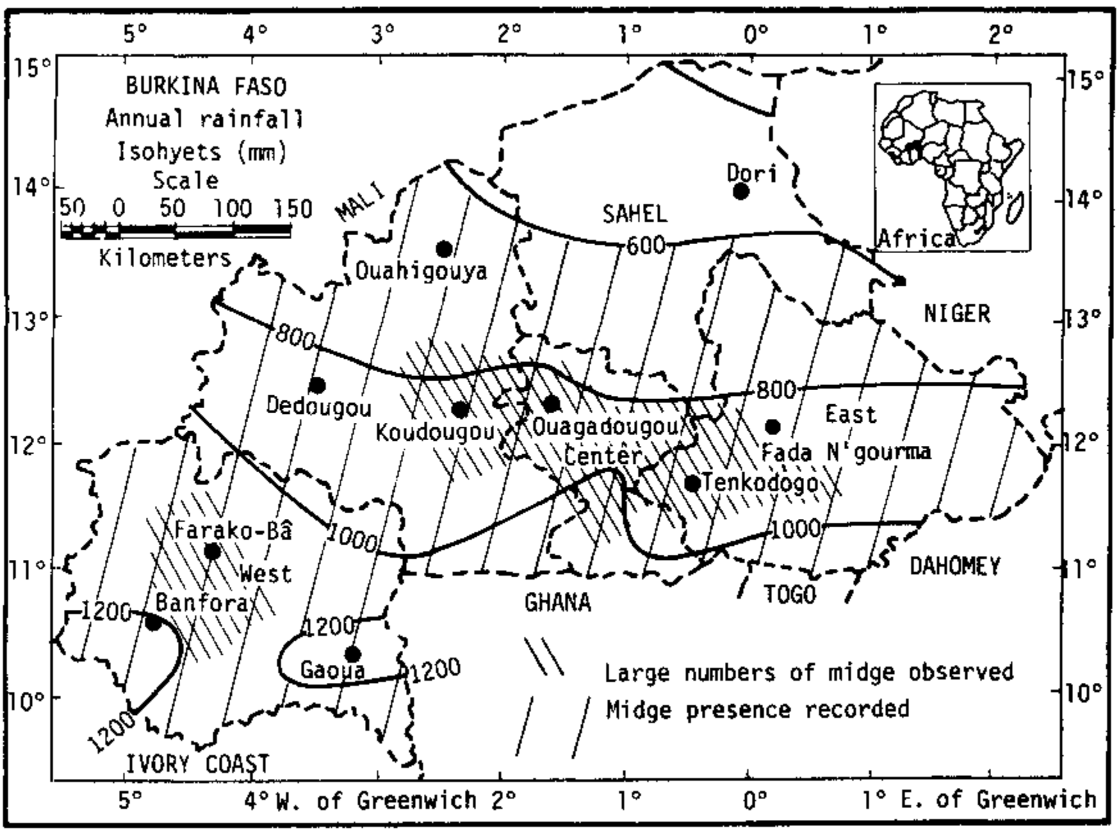

Figure 2. Sorghum midge distribution in Burkina Faso, 1979-1981. (Source: Virmani et al. 1980 for rainfall data.)

On the other hand, in the areas situated outside the 11 °N and 13°N latitudes, the absence or low incidence of attack can be explained by:

1. The short duration of the sorghums north of 13°N latitude, corresponding to a short rainy season (less than 3 months), low rainfall (less than 600 mm), and to smaller areas under sorghum cultivation.

2. The very long duration of most sorghum varieties in the Poni (Gaoua) and Comoe (Banfora) provinces. These sorghums flower very late, after the main midge infestation periods, in late October or early November at the onset of the cold season.

But the present trend is to reduce cultivation of these long-duration sorghums in seasons of drought.

The sorghum midge always causes more damage on research stations than on farmers' fields. The diversity of the origins, durations, and varieties of sorghums tested on research stations favors the multiplication of the pest.

Mali

In Mali, in 1965, M. Bono in his "Technical note on sorghum sterility around Bamako during the last season," did not explain the exact origin of this sterility observed by him, but mentioned that it mainly affected sorghums which were imported to Bamako. According to the author, the sterile heads:

- "were obtained from 'ungraded' seed bought at the Bamako market in seven out of ten cases;
- in the other three cases, sterility could be due to very late plantings, and the use of an excessively long-duration variety."

In our opinion, it is very likely that this is an indication of C. *sorghicola* infestation, especially as the author rules out the action of soil and drought.

Later, during a mission at Sotuba in October 1967, J. Breniere observed female C. *sorghicola* adults laying eggs on sorghum panicles during flowering.

The distribution of this pest is now known, though its actual economic importance cannot yet be evaluated since surveys are still going on.

The pest occurs in the sorghum-growing areas in the southern and western parts of the country, with the exception of the Sahelian region north of the Kayes-Segou line (Fig. 3)

The surveys carried out during the 1983 rainy season were disturbed by the severe drought which affected the entire country. Heading, flowering, and maturation took place, if at all, under stress conditions.

At the Sotuba Agronomic Research Station, the infestations ranged between 10 and 90% for late varieties flowering in late October.

Around the city of Bamako, 3 to 10% infested grain was recorded on farmers' fields. Further away, at Bankoumana in the Upper Valley Operation (Operation Haute Vallee—OHV) region, 0 to 4% spikelets were destroyed.

On the basis of the observations and investigations made earlier (Bono 1965; Bonzi and Doumbia 1983) the situation can be summarized as follows:

- heavy infestation (more than 50%) occurred at research stations on late varieties flowering after mid-October;

- moderate infestations (10%) were observed around the major urban centers and along certain major roads;

- low infestation (around 5%) occurred on farmers' fields outside the two areas mentioned above;

- no infestation was recorded in the northern part of the country, where the difficult climatic conditions are rather unfavorable for the development of the pest on rainfed sorghum or on receding flood sorghum crops around large ponds, lakes, or along the Niger river.

Factors Influencing Pest Increase

Secondary Host Plants

Apart from grain sorghum, *Sorghum mellitum* (grown for its sugar content) and a few wild relatives, such as *Sorghum halepense* and *Sorghum* spp, contribute to the multiplication and survival of C. *sorghicola* (Table 2).

These wild sorghum grasses are commonly found in the vicinity of large settlements on the borders of main roads near towns, and sometimes along waterways. So far, the noncultivated host plants other than sorghums on which C. *sorghicola*

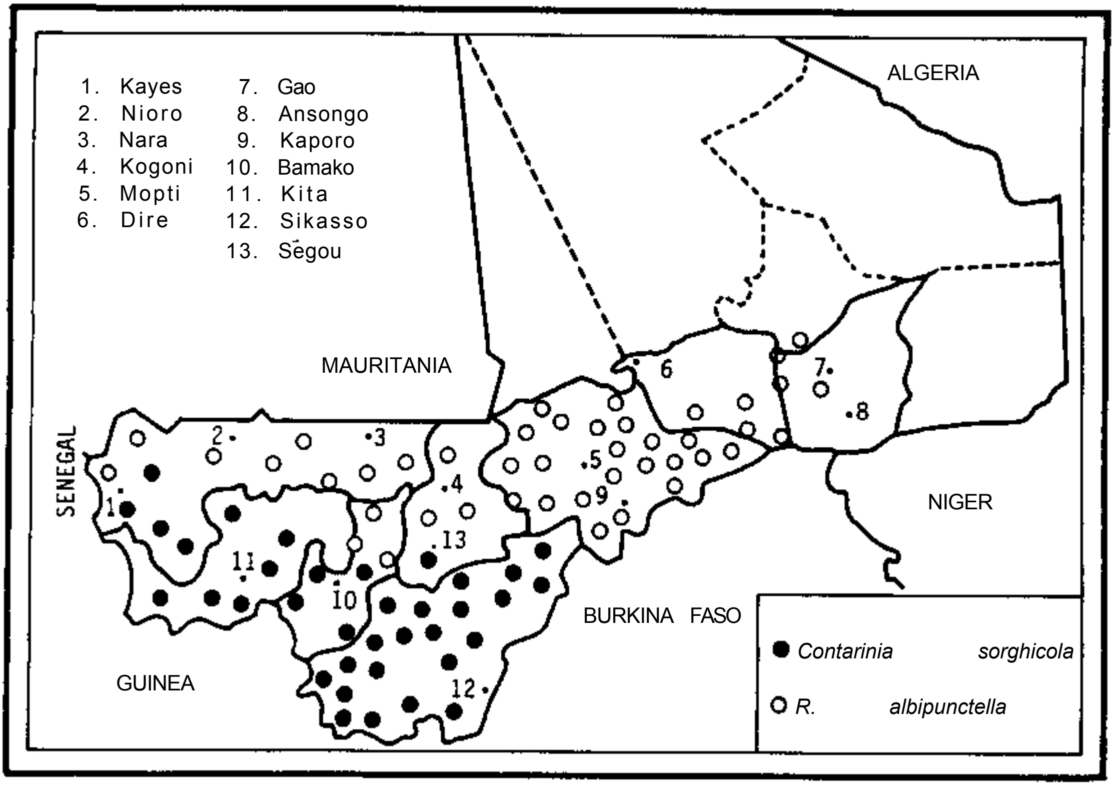

Figure 3. Distribution of *Contarinia sorghicola* and *Raghuva albipunctella* in the agricultural areas of Mali 1983.

has been identified are still rare. However, research is in progress, given the importance of these plants in the pest's life cycle.

The sweet sorghum, *Sorghum mellitum* is cultivated in traditional rural areas and is widely grown around Bamako. Like sugarcane, the sweet pith of the stalks is consumed as a delicacy.

The edible sorghum is an early variety which matures in September. Its grain is eaten fresh, at the end of the milk stage. It is one of the early hosts, on which the midge population can build up and later carry over to later maturing sorghums.

Table 2. *C. sorghicola* and other unidentified midge species found on wild grasses in Sotuba, Mali, 1983.

Host plants (grasses)	*Contarinia sorghicola*	*Contarinia* sp	*Lasioptera* sp	*Lestodiplosis* sp
Sorghum halepense	*			
Setaria barbata		*		
Pennisetum typhoides		*		
Vetiveria nigritana		*		
Panicum subaibidum			*	
Pennisetum pedicel latum				*

* Asterisk indicates midge presence on corresponding host plant.

Planting Dates and Duration for Sorghum

By and large, the on-station or on-farm experiments have confirmed everywhere that early-planted sorghums are less attacked than later planted ones. This also held true In a trial with varieties of different maturity durations in which the late-flowering sorghums were most damaged (Table 3).

Factors Limiting the Activity of the Pest

Drought

Early termination of the rains, as in 1983, or bad rainfall distribution, can considerably affect the sorghum midge population development.

In October 1983, in Bamako and other regions of Mali, late varieties were less attacked, which was due to early termination of the rains.

Natural Enemies

The most common enemies of the midge are:

1. Parasites: The most common ones identified in Burkina Faso and Mali are the Hymenoptera, *Aprostocetus diplosidis* Craw, and *Eupelmus popa* Gir. The other parasites belong to the Trichogrammidae, Proctotropidae, and Mymaridae families. Depending on the populations, the level of parasitic infestation can reach and even exceed 30% after October. This level is reached only when maximum damage is already done but it may help to reduce the diapausing carryover population.

2. Predators: The small black bugs *Orius* sp are the most numerous predators. The larvae and adults feed on adult midges. Many species of predacious spiders easily capture midges in their webs spun around the panicles.

Identification of Resistant Varieties

Screening trials with local sorghum collections conducted in Burkina Faso and Mali under heavy midge infestation pressure gave promising results in the identification of tolerant and resistant varieties.

Burkina Faso

After many years of obervations, the following local varieties were found to be least susceptible to C. *sorghicola:* No. 323 Tonnetolo-pen, with small, hard and very flinty grains; No. 170 Guerson; and No. 174 Yara. All three varieties have an open (loose) panicle, and No.170 Guerson and No.174 Yara have protective glumes covering the grains. The infestation level recorded after crushing and dissection was below 5% for No. 170 and 174 and around 1% for No. 323. Although No. 170 and No. 174 are long-glume types which may be less preferred for oviposition, the exact resistance mechanism is still unclear, especially in variety No. 323.

Mali

Studies at Sotuba (Doumbia 1983) on more than 800 sorghum cultivars including local ones, identi-

Table 3. Midge infestation on local sorghums according to flowering at Farako Ba 1976.

	Days from first flowering								
	D[1]	D + 2	D + 4	D + 6	D + 8	D + 10	D + 12	D + 14	D + 16
Infested spikefets (%)[2]	0	0	0	0.4	1.2	4.7	14.2	14.8	19.2

1. Day of first flowering.
2. Midge presence checked 12 days after flowering by crushing the florets. Red fluid exudes from florets where midge larvae or pupae are present.

fied some very late varieties, (flowering between 20 and 30 September) moderately resistant against midge. These are:

(CSM 63 x CSM 445) x SA 7706-2	(open panicle)
HT-dwarf 20	(open panicle)
HT-dwarf-2	(open panicle)
HT-dwarf-8	(open panicle)
81 pop MB-16-3	(semi-compact panicle)
81 pop CE 90-74-1	(compact panicle)
81 pop CE 90-74-2	(compact panicle)

Further identification of resistant or tolerant varieties, particularly local ones, is under way.

Discussion and Conclusion

The sorghum midge is at present one of the major pests of sorghum and has the potential to become the key pest in Burkina Faso and Mali. So far, there are still some areas practically free of midge, although climatic conditions are favorable for population buildup.

Over the last 10 years, where drought occurred with varying intensity every year, some farmers introduced short-duration varieties believed to be less drought-susceptible. Breeders generally believe that shorter duration varieties are more stable yielders and better adapted to the erratic rainfall patterns in West Africa. Varietal resistance or tolerance to midge should be associated with these qualities.

Our surveys among the farmers have indicated that they have no idea about the role of the midge in grain loss. Damage is attributed either to an unfortunate coincidence between sorghum flowering and the effect of the sun, the moon, or rain, or to drought and other factors.

Although midge damage at present is only about 10% at most, this insect may become the most important pest in the near future in Burkina Faso and Mali. The most urgent task ahead is therefore to identify, as precisely as possible, the real economic importance of the sorghum midge in all areas where the pest occurs. In addition, as many factors as possible associated with the development and buildup of midge populations should be identified so that an integrated control method can be devised for use across the Sahelian countries.

Acknowledgment

Our sincere thanks to K.M. Harris, Taxonomist at the Commonwealth Institute of Entomology, and A. Sow, botanist at Sotuba, who have helped to identify the midge species and their host plants.

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Annexure 1. Sorghum production in some Sahelian countries.

Country	Total grain sorghum production (t/ha)						
	1973	1974	1975	1976	1977	1978	1979
Burkina Faso	481 000		738 000		660 000		
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Mauritania	25 000	40 000	32 000	21 000	30 000	43 000	21 200
Niger	126 000		254 000	286 500	336 100	371 200	
Senegal (Sorghum and millet)	510 792	795 045	620 966	553 780			

Sources: Statistical Analysis Division (ESP), FAO, Upper Volta, Agricultural Survey Report 1979, 1980, Feb 1983, Mali. Fourth Plan on Economic and Social Development, Dec 1981, Mauritania. Directorate of Agriculture, (MDR), Niger.

Screening Sorghums for Midge Resistance

K.A. Kulkarni*

Abstract

Studies were conducted at the Regional Research Station, Dharwad, India, on seasonal incidence and biology of the midge in relation to host-plant resistance. Midge incidence was lowest on the crop sown on 1 June; highest on that sown on 15 August. Meteorological observations during the flowering period indicated that higher precipitation during the later part of the season predisposes the later sown crop to midge attack. Highest midge attack coincided with a minimum temperature of 18.5°C, maximum temperature of 27.7°C, and relative humidity of 76%.

The egg, larval, and pupal stages of the midge lasted 3,9, and 7 days, respectively, and the total life cycle occupied 19 days under Dharwad conditions.

Although no cultivar proved fully immune to midge, some kafir and zerazera cultivars recorded a low incidence of the pest. The best resistance sources so far identified are DJ 6514, TAM 2566, AF 28, IS 12666C, and SGIRL-MR 1. Of the genetic stock, PVK62, PVK 48, PM 7178, PM 4972, and PM 5068 were highly promising. Studies on the mechanism of resistance to midge in DJ 6514 revealed that antibiosis was involved.

Resume

***Crlblage des sorghos resistants a la cecldomyie**: La station regionale de recherches de Dharwar en Inde a entrepris des etudes sur l'incidence saisonniere et la biologie de la cecidomyie liees a la resistance de la plante-hote. L'incidence atteint le maximum chez le semis du 15 aout et descend au minimum chez celui du 1 juin. Les observations meteorologiques pendant la floraison indiquent que la pluviometrie plus elevee pendant la derniere partie de la saison rend le semis tardif plus sensible a l'attaque. L'incidence la plus elevee coincide avec une temperature minimale de 18,5°C, une temperature maximale de 27,7° C et une humidite relative de 76%.*

Les stades ova/re, larvaire et de nymphose durent respectivement 3, 9 et 7 jours et le cycle de vie dure 19 jours sous les conditions a Dharwar.

On n'a encore repere un cultivar completement immune a la cecidomyie; cependant /'incidence est faible chez certains cultivars Kafir et Zera Zera. Les meilleures sources de resistance identifiees jusqu'a present sont : DJ 6514, TAM 2566, AF 28, IS 12666C et SGIRL-MR 1. Les accessions suivantes prises du stock genetique semblent tres prometteuses : PVK 62, PVK 48, PM 7178, PM 4972 et PM 5068. Les etudes sur le mecanisme de resistance chez DJ 6514 revelent qu'il s'agit de l'antibiose.

Introduction

The sorghum midge *(Contarinia sorghicola* [Coquillett]) is a pest of sorghum throughout the world. Among the 150 species of insect pests reported on sorghum, midge is one of the most important, and distributed worldwide (Harris 1976; Davies 1982). In India, the insect has attained the status of a key pest in recent years. The first midge report in India came from Fletcher (1914), who found the insect in Pune. It was considered a minor pest until sorghum hybrids and high-yielding varieties were introduced. The midge built up on the earlier-maturing new cultivars and was carried over to the late-flowering local cultivars, which suffered heavy midge-damage. Under these conditions, the midge population steadily increased and became a major problem in Maharashtra and Karnataka states.

Although a good deal of research has been done

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International Crops Research Institute for the Semi-Arid Tropics. 1985. Proceedings of the International Sorghum Entomology Workshop, 15-21 July 1984, Texas A&M University, College Station, TX, USA. Patancheru, A.P. 502324, India: ICRISAT.

on chemical control of the midge (Taley and Garg 1984), this method is not widely adopted in India because of the low cash value of sorghum and the problems of insecticide distribution in rural India. Some information is also available on parasites and predators attacking the different life stages of midge (Sharma 1984); however, their effect in controlling the midge population has not been evaluated yet.

Plant resistance as a method of pest control offers many advantages, and for some insect species it is the only way of effective control (Painter 1951).

Therefore, Frankel and Bennett (1970) reported that host-plant resistance should form the basis for plant protection in the future. Teetes (1982) has also emphasized the important role of resistant cultivars in an integrated pest management (IPM) program.

With these points in view, screening of sorghum for midge resistance was undertaken at the Regional Research Station in Dharwad, India, together with the necessary backup studies on the biology and population dynamics of the pest and resistance mechanisms in sorghum. The results are reported in this paper.

Seasonal Midge Incidence

The seasonal fluctuations of sorghum midge were studied to establish the best time for screening by sowing susceptible hybrid CSH 1 at fortnightly intervals from 1 June to 15 September during the rainy season 1973 to 1975. Each sowing was done in a randomized block design, five-row plots 3.0 x 2.5 m, with three replications. Observations were taken by counting the chaffy florets and healthy grains on three spikelets (selected from the top, middle, and bottom portion of the head) on ten

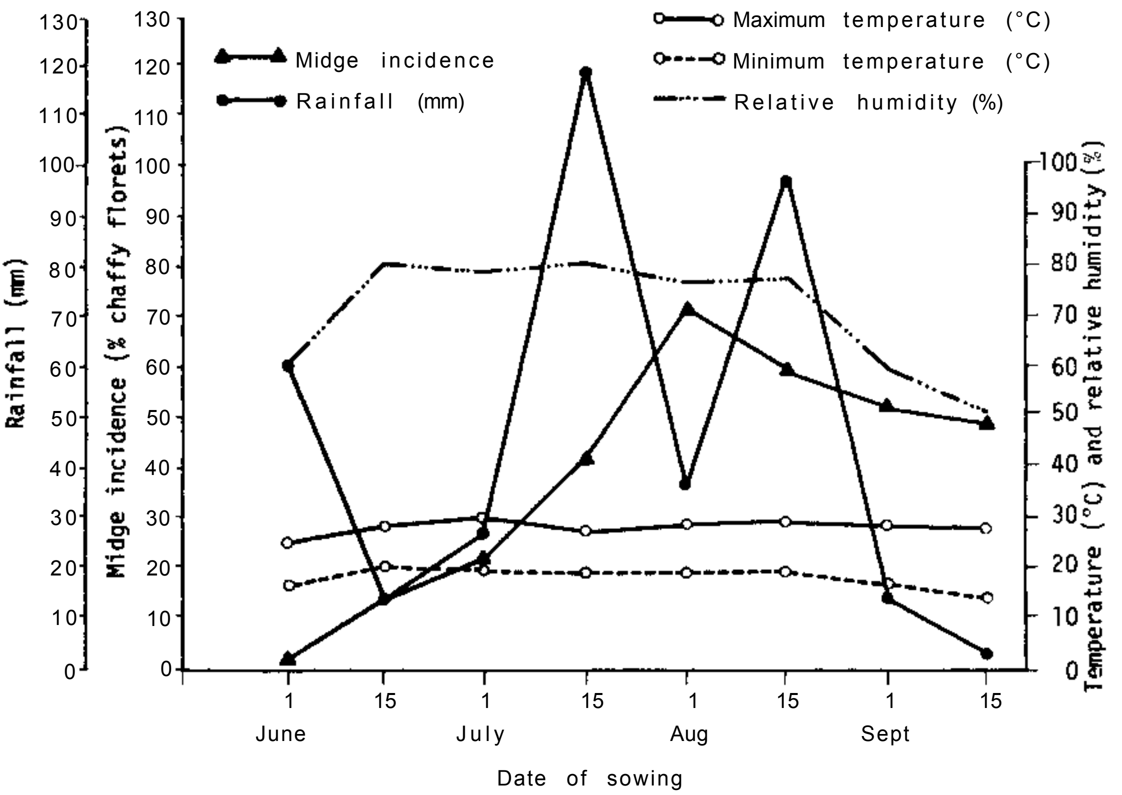

Figure 1. Seasonal incidence of sorghum midge on susceptible sorghum hybrid CSH 1 sown at 2-week intervals In relation to rainfall, temperature, and relative humidity, 1 June to 15 September, at Dharwad, India (average of 3 years, 1973-1975 rainy seasons).

random heads per plot. Temperature, relative humidity, and rainfall data were collected from the Agrimet Observatory at the Regional Research Station for interpretation of the population changes in relation to weather conditions and related midge damage.

The results showed that grain damage increased from 1.76% on the crop sown on 1 June to a maximum of 70.72% on that sown on 1 August (Fig. 1). The highest midge incidence coincided with minimum temperature of 18.5°C, maximum temperature of 27.7°C, and relative humidity of 76%. The higher rainfall (119.4 mm) during the later part of the season may have increased adult emergence and consequent grain damage on the crop sown on 1 August. Therefore, to avoid midge damage, the best period for sowing in southern Karnataka is October to February (Gowda and Thontadarya 1977); in the northern region, May to June (Thimmaiah et al. 1973). Similarly at Delhi, India, Jotwani et al. (1972) reported that July sowings suffer less midge damage than later sowings. Wiseman and Mcmillian (1968) reported that April sowings result in less midge damage at Tifton, Georgia, USA.

Biology

The biology of the sorghum midge has been studied by Dean (1910), Randolph and Montoya (1964), Passlow (1965), Coutin (1970), Taley et al. (1971), and Madansure and Chundurwar (1978) in different parts of the world.

In order to understand the host-plant x midge interaction in India better, a biological study was undertaken during 1975 rainy season at Dharwad. Cv CSH 5 was sown in plots 3.0 x 2.75 m on 1 June. The field design and treatments were the same as earlier described. Plants were covered with a cage (as described under screening technique) to prevent natural egg laying at the boot stage. At 50% anthesis of the head, freshly emerged adults were confined to the screening cage at the rate of ten midge adult pairs per head for 24 h. Subsequently, 100 spikelets were sampled daily from the infested heads and examined for the development of different life stages and the duration of each stage from egg to adult was recorded.

Mating was observed 1 h after emergence and lasted for about 20 to 30 s. Generally males searched for females and in one or two cases more than one male attended one female. In certain cases, a male was observed waiting for the emergence of the female.

Maximum egg laying took place between 0800 and 1030 h. Eggs were laid between the glumes inside the florets. Freshly laid eggs were yellowish orange and turned dark orange before hatching. The incubation period varied from 2 to 4 days, with an average of 3.1 days (Table 1).

Soon after hatching, the larva started feeding on the ovary. Newly hatched larvae were white, later becoming slightly pinkish with a yellow tinge; full-grown larvae were deep orange. The larval stage lasted for 9.5 days.

Before pupation the length of the larva decreased and it became somewhat globular and dull in color. The pupa formed was orange in color. The pupal stage lasted 7.1 days.

The emerging adult ruptured the thoracic and

Table 1. Biology of sorghum midge at Dharwad, India, rainy season 1975.

Date of egg laying	Incubation period (days)	Larval period (days)	Pupal period (days)	Total life period (days)
8 Sept 1975	3	9	7	19
8 Sept 1975	3	9	8	20
9 Sept 1975	4	10	7	21
9 Sept 1975	3	10	6	19
9 Sept 1975	3	10	8	21
9 Sept 1975	4	9	7	20
10 Sept 1975	3	10	7	20
10 Sept 1975	2	10	8	20
10 Sept 1975	3	9	7	19
10 Sept 1975	3	9	6	18
Range	2-4	9-10	6-8	18-21
Average	3.1	9.5	7.1	19.7

head region of the pupal case by pushing its head upwards. Antennae emerged first, after which the rest of the adult body followed. The newly emerged adult was pale white, but within a minute became yellowish brown. The pupal cases remained attached to the tips of the florets. Mass emergence of adults was observed during the morning between 0630 and to 1130 h, in September and October. Males emerged earlier than females. The total life cycle from egg to adult was completed in 19.7 days.

A certain proportion of the larval population entered into diapause in every generation, remaining in the chaffy floret and carrying over to the next season to form the primary source of subsequent infestation.

Two larval parasites, *Tetrastichus diplosidis* Craw. and *Eupelmus popa* Gir., have been found in large numbers at Dharwad.

Host-plant Resistance

Resistance against midge has been reported from several countries. Bowden and Neve (1953) reported natural resistance to sorghum midge attack in "Nunaba" varieties of *Sorghum membranaceum,* a species cultivated in West Africa. Mechanical resistance due to glume hardness has been reported but this did not hold under no-choice conditions (Harris 1961). Geering (1953) found no true resistance to midge in Uganda. Johnson and Teetes (1979) reported less damage due to midge in converted lines in the USA. In India, several sorghum cuitivars have been reported resistant to midge (Jotwani 1978; Kulkarni et al. 1978; Sharma et al. 1983). Other sorghum lines resistant to sorghum midge have been reported from different parts of the world (Anonymous 1971; Wiseman et al. 1973, 1974; Rossetto et al. 1975; Faris et al. 1976; Bhuti and Kulkarni 1982; Sharma 1984).

Screening Techniques

The screening of sorghum cuitivars for midge resistance was done under both artificial and natural infestation.

For artificial infestation a headcage has been designed, consisting of a cylindrical wire frame (65 cm high and 30 cm in diameter), covered with a fine muslin cloth bag with a 15-cm strip of thin transparent polyvinyl chloride sheet around the center for observation. Each cage was supported on a bamboo pole 203 cm long. The cage covered the sorghum head fully and the cloth bag was tied on the top and around the peduncle. Ten pairs of adult midges were released in each headcage and left for 48 h to oviposit. Damage due to midge was recorded at harvest. Three spikelets each from the top, middle, and bottom portion of the head were selected. The number of developed grains and chaffy florets were counted on ten heads selected at random per genotype, and the data averaged for analysis.

For screening under natural infestation no special screening method was developed, except that the material was planted at the beginning of August to ensure flowering during the peak midge density period in late October-November.

Screening for Resistance

Screening of Germplasm

Sixty-five sorghum genotypes (received from ICRISAT) belonging to different working groups of sorghum such as sudanense, bicolor, roxburghii, conspicuum, zerazera, roxburghii-shallu, margaritiferum, durra, kafir, nervosum-kaoliang, and other genetic stocks were screened under natural infestation during peak midge activity in the 1979 and 1980 rainy seasons (Table 2).

Based on the damage data, resistance was not confined to any one sorghum group. However, sorghum belonging to the kafir and zerazera groups recorded a lower range of midge incidence. Johnson and Teetes (1979) also reported resistance in the zerazera group.

•During the 1975 rainy season, fourteen midge-resistant entries were screened under both natural and artificial conditions. Under artificial infestation, midge incidence ranged from 19.5% in DJ 6514 to 83.8% in CSH 1; under natural screening, from 10.8% on TAM 2566 to 81.7% on IS 1151. Under both natural and artificial conditions, DJ 6514 exhibited stable, high levels of resistance (Table 3).

Screening of Advanced Breeding Material

During 1980, 1981, and 1982, 31 advanced yield trial lines from different centers of the All India Coordinated Sorghum Improvement Project (AICSIP) were screened for midge resistance (Table 4). Average damage from midge ranged from 11.6% in

Table 2. Reaction of sorghum entries originating from different groups to midge, rainy season, 1979 and 1980.

Group/entry	Midge damage (% chaffy florets)		
	1979	1980	Mean
Sudanense			
IS 651	89 5	30.0	59.7
IS 703	75.2	78.6	76.9
IS 705	63.2	20.3	41.7
IS 3192	38.6	19.6	29.1
Guinea Roxburghii			
IS 642	33.4	24.5	28.9
IS 1182	32.6	37.4	35.0
IS 3696	22.8	22.0	22.4
IS 9407	98.5	42.1	70.3
Roxburghii Shallu			
IS 452	31.9	62.7	47.3
IS 458	23.2	28.0	25.6
Conspicuum			
IS 6810	14.9	16.4	15.6
IS 7402	66.8	23.8	45.3
Margaritiferum			
IS 7818 (white)	42.4	41.0	41.7
IS 8064 (red)	25.2	22.6	23.9
Zerazera			
IS 3541	22.7	28.0	25.3
Bicolor			
IS 13	43.9	43.8	43.8
IS 601	54.3	22.0	38.1
IS 640	22.0	31.0	26.5
IS 719	45.8	24.0	34.9
IS 2095	78.5	31.8	55.1
IS 11085	85.2	57.0	71.1
Kafir			
IS 156	24.3	16.1	20.2
IS 9327	28.5	33.6	31.0
IS 9333	18.7	11.8	15.2
IS 9530	18.5	17.9	18.2
Kaoliang			
IS 3604	22.1	14.1	18.1
IS 3980	36.1	19.9	28.0
Hegari			
IS 127	24.1	25.0	24.5
Durra			
NJ 1944	18.0	74.2	46.1
NJ 1948	44.2	23.6	33.9
PJ 22K	11.8	36.6	24.2
PJ 24K	81.8	17.5	49.6
H 109	36.2	28.2	32.2
IS 2209	27.6	24.9	26.2
NJ 1989/2	33.7	18.4	26.0
Philippines (white)	22.7	21.6	22.1

Continued

Table 2. *Continued*

Group/entry	Midge damage (% chaffy florets) 1979	1980	Mean
Atquabace	52.7		32.6
Ziendouha	26.4	14.2	20.3
E 15-1	36.1	23.2	29.6
Genetic stock			
EN 33374	26.1	41.5	33.8
IS 1121C	30.1	15.6	22.8
IS 8052	53.7	39.4	46.5
BG 10	87.2	58.2	72.7
IS 84	34.5	27.4	30.9
IS 154	22.5	32.3	27.4
IS 3687	26.5	45.7	36.1
E 15-2	74.3	39.7	57.0
E 1772-2	70.7	44.3	57.5
E 1793	39.4	39.2	39.3
E 63-3	13.8	24.0	18.9
E 1971-1	15.6	32.6	24.1
Sanaa-3	22.8	33.0	27.9
S 302	23.5	28.1	25.8
Pickett-3	28.5	15.3	21.9
Pickett-4-8	22.0	17.4	19.7
R 16	36.0	70.6	53.3
IS 6418C	57.9	66.8	62.3
CSH 5	74.5	68.2	71.3
SE	±4.3	±3.8	
CV(%)	21	19	

Table 3. Reaction of sorghum entries to midge under artificial and natural infestation, Dharwad, India, rainy season 1975.

Entry	Midge damage (% chaffy florets) Artificial infestation	Natural infestation
CSH 1	83.8 (67.5)[1]	78.6 (62.9)
EC 92-794	38.6 (38.2)	30.1 (33.2)
575-1	52.7 (46.6)	40.6 (36.1)
IS 1151	82.6 (66.7)	81.7 (63.6)
572-2	46.8 (43.2)	19.4 (25.5)
DJ 6514	19.5 (26.0)	17.5 (24.5)
1510	37.1 (38.5)	18.0 (24.8)
SGIRL-MR 1	55.1 (48.6)	25.7 (30.4)
575-3	76.1 (61.3)	77.3 (61.9)
TAM 2566	32.5 (34.2)	10.8 (32.2)
AF 28	27.3 (27.9)	28.5 (32.2)
EC 92792	29.9 (32.5)	37.1 (36.9)
IS 12573	15.5 (22.8)	13.7 (21.4)
4 Glue	26.5 (13.7)	11.0 (19.1)
SEm	±5.1	±4.2
CV(%)		29

1. Figures in parentheses indicate arcsine transformed values.

DJ 6514 (resistant control) to 65.9% in SPH 176. In general, the resistance level was very low; however, SPV 350 (17.8%) showed a comparatively high level of resistance under natural screening conditions.

Screening of crosses derived from resistant sources and developed at different centers of the AICSIP and ICRISAT during the 1982 rainy season indicated that PVK 62 (12.3%), PVK 48 (13.4%), PM 7178 (14.9%), PM 4972 (16.2%), and PM 5068 (18.0%) were quite promising (Table 5).

Mechanisms of Resistance

Rossetto (1977), Jotwani (1978), and Page (1979) have reported antibiosis to be a mechanism of resistance to sorghum midge. Varying contents of tannin in the grain are a probable biochemical factor imparting resistance (Santos et al. 1974). Agrawal and House (1982) reported that several

Table 4. Reaction of advanced sorghum yield trial material to midge, Dharwad, India, rainy season 1980-1982.

Entry	Midge damage (% chaffy florets)			
	1980	1981	1982	Mean
SPV 5913	*19.3*	749		47.1
SPV 104	39.6	79.8	52.9	57.4
SPV 105	43.8	81.0	37.1	53.9
SPV 107	32.6	73.5	28.7	44.9
SPV 125	23.1	49.9	31.8	34.9
SPV 221	31.0	64.8	55.3	50.3
SPV 224	36.2	60.2		48.1
SPV 232	43.1	83.3		63.2
SPV 245	16.1	62.0	26.1	34.7
SPV 247	32.4	38.8	32.7	34.7
SPV 313		58.3	39.8	49.0
SPV 346	18.4	76.6	28.8	41.2
SPV 350	16.8	18.8		17.8
SPV 351	13.0	49.9	21.7	28.2
SPV 354	29.5	60.7	38.1	42.7
SPV 386		65.9	27.5	46.8
SPV 394		31.9	46.9	39.4
SPV 396		34.3	37.4	35.8
SPH 139	37.6	72.7	—	55.1
SPH 159		71.8	42.6	57.2
SPH 176		86.6	45.3	65.9
SPH 196		41.8	33.1	37.4
SPH 221		37.5	32.0	34.7
CSH 5		45.6	38.2	41.9
CSH 6		32.4	24.4	28.4
CSH 9		55.5	22.9	39.2
IS 2312	66.9	62.4	28.9	52.7
DJ 6514	11.8	12.7	10.3	11.6
CSH 1	41.4	50.6	57.9	49.9
SE	±4.7	±3.8	±3.7	
CV (%)	26	24	29	

non-cleistogamous sorghum lines also exhibited resistance to midge.

To understand the underlying mechanisms of resistance in material we found resistant, a special experiment was conducted to study the life cycle duration and emergence of adult midge flies on resistant cultivars, using the headcage method (Table 6). On cv DJ 6514, the life cycle lasted for 27.28 days and only 5 midges emerged, while on IS 18830 the life cycle was completed in 16 to 27 days and 140 midges emerged. The resistance mechanism involved in DJ 6514 may be antibiosis, since examination of the sorghum heads showed the presence of many eggs.

Midge resistance alone is useful under conditions when this insect is the only problem; however, under most circumstances, more than one pest attacks sorghum and therefore multiple resistance is needed. Work has been initiated in this direction (Kulkarni et al. 1982; ICRISAT 1983). DJ 6514, for example, possesses resistance to midge and stem borer and has good resistance levels to some diseases also (Anahosur and Hegde 1980).

Thus it is evident that sources of midge resistance, such as DJ 6514, AF 28, TAM 2566, and IS 12666C are available for further breeding work.

Table 5. Reaction of sorghum derivatives to sorghum midge at Dharwad, India, rainy season 1982.

Entry	Days to 50% flowering	Midge damage (%)	Visual damage score (0-9)[1]
PM 4972	60	16.2 (21.8)	2.0
PM 4977	64	23.2 (28.8)	2.3
PM 4981	68	23.5 (28.9)	3.3
PM 4987	63	24.9 (29.2)	2.3
PM 5068	65	18.0 (25.0)	2.7
PM 5094	66	22.5 (28.0)	2.7
PM 6910	63	25.9 (30.5)	3.0
PM 7178	61	14.9 (20.8)	1.7
PM 7347	72	19.9 (26.4)	2.0
PM 7348	70	22.0 (27.8)	3.0
PVK 46	68	17.8 (24.6)	2.0
PVK 47	68	17.3 (24.6)	2.0
PVK 48	64	13.4 (21.2)	2.7
PVK 62	70	12.3 (20.1)	2.3
SPV 90	73	27.2 (30.8)	3.3
SPV 313	65	32.0 (33.9)	3.7
SPV 314	67	24.3 (28.8)	2.0
SPV 315	70	40.2 (39.3)	5.7
SPV 553	75	53.1 (34.9)	3.7
SPV 554	66	23.6 (29.0)	2.7
K 82-301	75	39.0 (38.6)	5.7
CSH 1	65	46.2 (42.8)	5.7
CSH 5	70	33.1 (34.9)	4.0
SEm		±3.2	
CV(%)		23	

1. 0 = no damage; 9 = severe damage.

Table 6. Life cycle of midge on seven sorghum entries, Dharwad, India, rainy season 1983.

Entry	Total life cycle (days)	No. adult midges emerged
DJ 6514	27-29	5
IS 12666C	19-24	11
IS 18330	16-27	140
TAM 2566	22-24	5
AF 28	14-23	12
SPV 351	16-26	70
SPV 422	16-20	80

Further, PVK 62, PVK 48, PM 7178, PM 4972, and PM 5068 are lines developed from resistant sources which have desirable agronomic traits.

Future Work

Future research should study:

1. The nature and inheritance of resistance.
2. The biochemical factors contributing to midge resistance.
3. The population dynamics of the midge fly. (Attractant pheromone traps should be developed for this purpose).
4. Development of sorghum lines with multiple resistance to pests and diseases.

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Screening for Sorghum Midge Resistance and Resistance Mechanisms

H.C. Sharma*

Abstract

Sorghum midge, Contarinia sorghicola *Coq., is the most important pest of sorghum worldwide. The use of resistant cuitivars is one effective way of keeping this pest in check. Adjusting planting dates, screening at "hot spots," increasing midge population/damage through infester rows inoculated with sorghum heads carrying diapausing midge larvae, use of overhead sprinklers to maintain high humidity during the postrainy season, planting at low densities and on two dates, have been suggested for field screening. A no-choice headcage screening technique has been developed. The midge-resistant cuitivars have been grouped in different categories under no-choice screening using cluster analysis. Over 10000 germplasm lines have been screened and 21 sources of resistance identified. Mechanisms of resistance have been studied, and ovipositional nonpreference by midge, fast ovary growth in sorghum panicle, and short floral parts are associated with midge resistance. Current knowledge of resistance needs is discussed.*

Résumé

Criblage pour la résistance à la cécidomyie et les mécanismes de résistance : *La cécidomyie,* Contarinia sorghicola *Coq., est le plus important ravageur du sorgho dans le monde. L'exploitation de cultivars résistants constitue un moyen efficace pour limiter son incidence. Les techniques recommandées pour le criblage au champ sont : l'adaptation des dates de semis, l'utilisation des foyers d'infestation du ravageur, l'augmentation des populations et des dégâts du ravageur par la mise en place des rangs où les panicules inoculées de larves diapausantes permettent de propager l'infestation, l'aspersion d'en-haut des plantes pour maintenir l'humidité à un niveau élevé pendant la saison sèche, le semis à faible densité et à deux intervalles. On a mis au point une technique de criblage en cage avec choix unique d'un seul cultivar. Les cultivars résistants ont été groupés d'après l'analyse des composantes des résultats de ce criblage. Parmi les 10 000 accessions mises à l'essai, on a identifié 21 sources de résistance. L'étude des mécanismes de résistance révèlent que la non préférence pour la ponte, la croissance rapide de l'ovaire chez le sorgho et les parties florales peu longues sont liées à la résistance. L'état actuel des connaissances sur les besoins en sources de résistance est examiné.*

Introduction

The sorghum midge, *Contarinia sorghicola* Coq. is the most destructive pest of grain sorghum. It is a serious problem in Asia, Africa, Australia, Europe, and America, and worldwide there seems to be no other single species with such widespread and Damaging effects on sorghum yields (Harris 1976).

Cultural practices, chemical control, and resistant varieties are currently recommended for the control of sorghum midge. Chemical control is normally costly and numerous applications are required, as infestation is often prolonged. The prospects for successful application of cultural and chemical control measures against sorghum midge in the semi-arid tropics are limited. It is practically impossible to plant at times when midge incidence can be completely avoided, but timely

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and early planting, in many areas, can help reduce midge attack. Normally, farmers plant with the first good showers of rains; however, because all the farmers in an area cannot plant simultaneously, midge populations build up on successively planted crops. Use of resistant or less susceptible cultivars is one important means of keeping midge populations below the economic threshold levels. Planting of resistant cultivars (e.g. DJ 6514) over large areas, can be expected to reduce midge populations by 100x over a susceptible cultivar (CSH 1)(Sharma 1984). Planting of resistant cultivars is especially useful under the subsistence farming conditions of the semi-arid tropics, because it does not involve extra costs to the farmer. In addition, it is compatible with other methods of pest control.

Reference to midge resistance in sorghum was first made by Ball and Hastings in 1912, though Gable et al. (1928) failed to find resistance to sorghum midge. Later, Evelyn (1951) found varietal resistance to midge in sorghums grown in the Gezira (Sudan). Bowden and Neve (1953) in the Gold Coast reported cv Nunaba to be resistant to midge attack. Screening efforts in several countries in recent years have indicated the existence of a number of resistant or less susceptible sorghum lines (Sharma and Davies 1981).

Resistance Screening Techniques

Testing cultivars with a standard level of infestation is a useful tool for locating resistant parents in a pest resistance breeding program. A major difficulty in locating source material with stable resistance against sorghum midge has been the lack of an appropriate and repeatable screening technique. Optimum levels of midge populations are difficult to maintain under natural conditions because of: (1) staggered flowering of sorghum cultivars, (2) day-to-day variation in midge populations, (3) competition with other insects such as head bugs, (4) parasitization and predation by natural enemies, and (5) sensitivity of midge flies to temperature and humidity.

Most of the cultivars selected as less susceptible under natural conditions are very early or late-flowering genotypes which escape midge damage. In a breeding trial at ICRISAT subcenter, at Dharwad (Karnataka, India), the percentage of cultivars selected as less susceptible decreased sharply

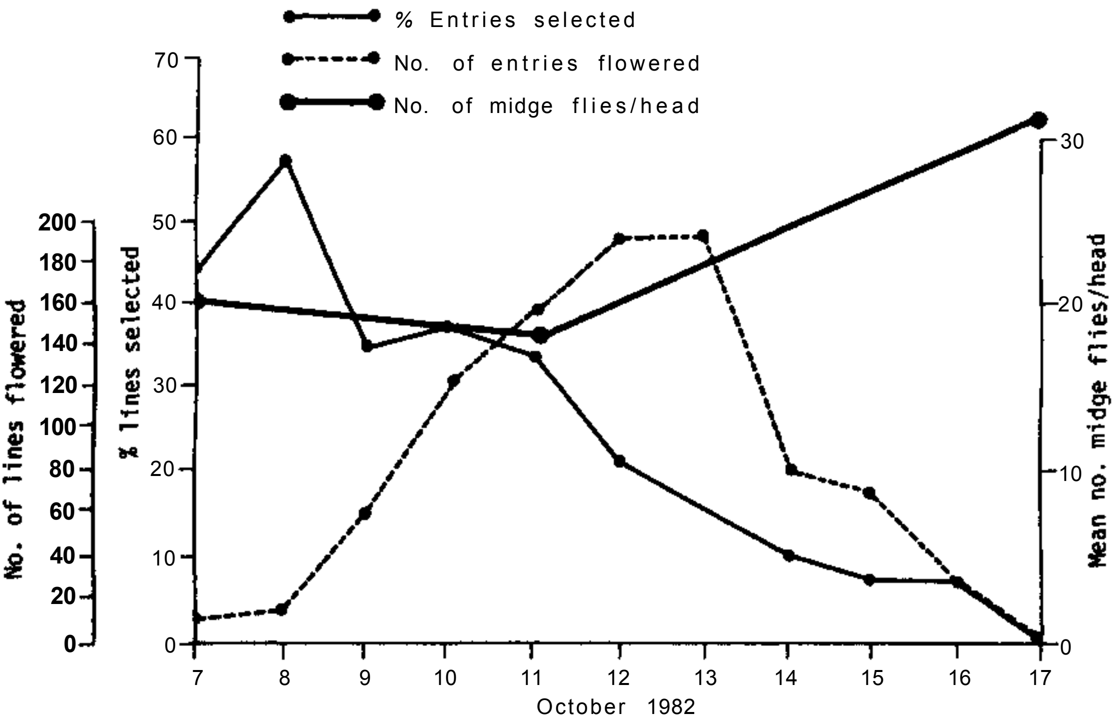

Figure 1. Selection of sorghum entries for midge resistance under natural conditions.

with the increase of midge population over the season (Fig. 1) A large proportion of lines selected as less susceptible at the beginning of the season probably consist to a large extent of early escapes. Because of these problems, the midge resistance observed in one season quite often breaks down in the following seasons, or at other locations.

Hot Spots

The use of "hot spot" areas where the midge is endemic is one of the effective ways of screening for midge resistance. Dharwad, Bhavanisagar, Pantnagar, and Hissar have been identified as hot spots to screen for midge resistance in India.

Field-screening Techniques

Planting Dates

For successful screening of cultivars for pest resistance under natural conditions, a knowledge of the population dynamics of the insect in question is most important. It is crucial to adjust the sowing dates so that the most susceptible stage of the crop coincides with the peak activity period of the insect. The development of appropriate population monitoring techniques is therefore an important component of an insect resistance screening program. Midge populations have been monitored for 4 years through fortnightly plantings of susceptible cv CSH 1 and resistant TAM 2566 at ICRISAT Center near Hyderabad, India, and Dharwad (Sharma et al. 1983b). Plantings made during the third week of July have been found to suffer maximum midge damage during the rainy season. At ICRISAT Center, a major midge population peak has been observed during October and a smaller one during March (Fig. 2).

Midge Population Management for Resistance Screening

Early planting of susceptible sorghum has been suggested to increase the midge population and consequent damage (Wiseman and McMillian 1971). Midge damage can be increased significantly under field conditions through a number of field operations (Sharma et al. 1984a). Infester rows of two susceptible cultivars (CSH 1 and CSH 5 in 1:1 ratio, flowering at 55 and 65 days respectively) are planted 20 days earlier than the test material. At the flag-leaf stage, sorghum heads (kept wet for 15 days) carrying diapausing midge larvae are spread in the infester rows to increase midge damage (Fig. 3).

The use of overhead sprinklers during the post-rainy season (to increase the relative humidity) also increases midge damage (Table 1) and improves the efficiency of selecting for midge resistance (Fig. 4). Less persistent contact insecticides such as carbaryl and malathion may be sprayed to control head bugs and midge parasites

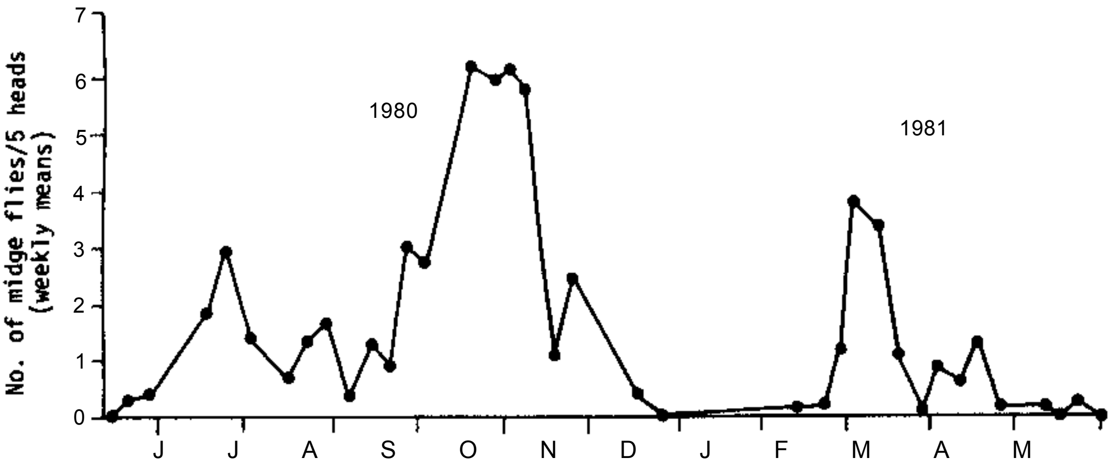

Figure 2. Population dynamics of sorghum midge *(Contarinia sorghicola)* at ICRISAT Center, Patancheru, India, 1980/81. (Number of midge flies/5 earheads, in weekly means.)

at post-anthesis to milk stage. The midge larvae feeding inside the glumes are not affected by the insecticides. The material should be planted on two planting dates to avoid escapes (Fig. 4) and at low planting densities to avoid insect population dilution (Fig. 5). This approach has been found useful for initial large-scale screening of germplasm and breeding cultivars.

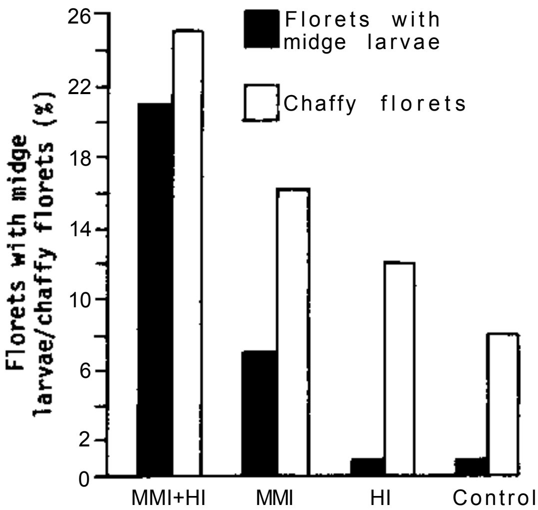

Figure 3. Midge population management for resistance screening of sorghum using (1) mixed-maturity infester rows (MMI) plus head inoculation (HI), (2) MMI only, and (3) HI only on sorghum hybrid CSH 1 (based on observation of 2000 florets from 25 heads), ICRISAT Center, Patancheru, India, postrainy season 1981/82.

Headcage Screening

Caging of midge flies with sorghum earheads is more useful than natural infestation in identifying stable sources of resistance and reducing the chances of escape and preferential behavior (Rossetto et al. 1975b; Jotwani 1978; Page 1979). Using this technique, a *more uniform relation can be* maintained between the number of florets at the susceptible stage and midge flies. The use of large field cages has also been suggested (Wuensche et al. 1978) to confine midges with resistant cultivars for studying the impact of larger plantings of resistant cultivars on the midge population.

A headcage technique to screen for midge resistance under no-choice conditions has been developed and standardized at ICRISAT Center (Sharma et al. 1984b). A wire cage (16 cm diameter, 20 cm long) is tied around the sorghum earhead and covered with a cloth bag (blue colored bags give best results) (Fig. 6). Forty midge flies collected in the morning hours (0900-1100h) (Table 2) are released into the headcage at top to half-anthesis (Fig. 7) stage for 2 consecutive days. Maximum and uniform midge damage results. Five to ten heads of each cultivar should be infested.

This technique is quite simple, easy to operate, and can be used on a fairly large scale to confirm resistance in field-selected cultivars. Changing weather conditions influencing the midge activity

Table 1. Effect of overhead sprinkler irrigation on midge damage in sorghum (postrainy season 1980/81).

Sorghum cultivar	Midge damage (% chaffy florets)	
	With sprinkler	Without sprinkler
AF 28	32.1 (5.57)[1]	21.6(4.59)
SGIRL-MR 1	47.3 (6.84)	35.2 (5.85)
IS 12573C	61.2(7.78)	44.7 (6.59)
DJ 6514	16.0(3.97)	18.7(4.19)
CSH 1	49.0 (6.98)	48.7 (6.90)
Main effect means	(6.23)	(5.63)
SE for main effect means	± (0.202)	
SE for cultivars at the same level of main treatment		±(0.145)

1. Figures in parentheses are square root transformations.
The differences are significant for the irrigation and cultivars and the interaction is nonsignificant.

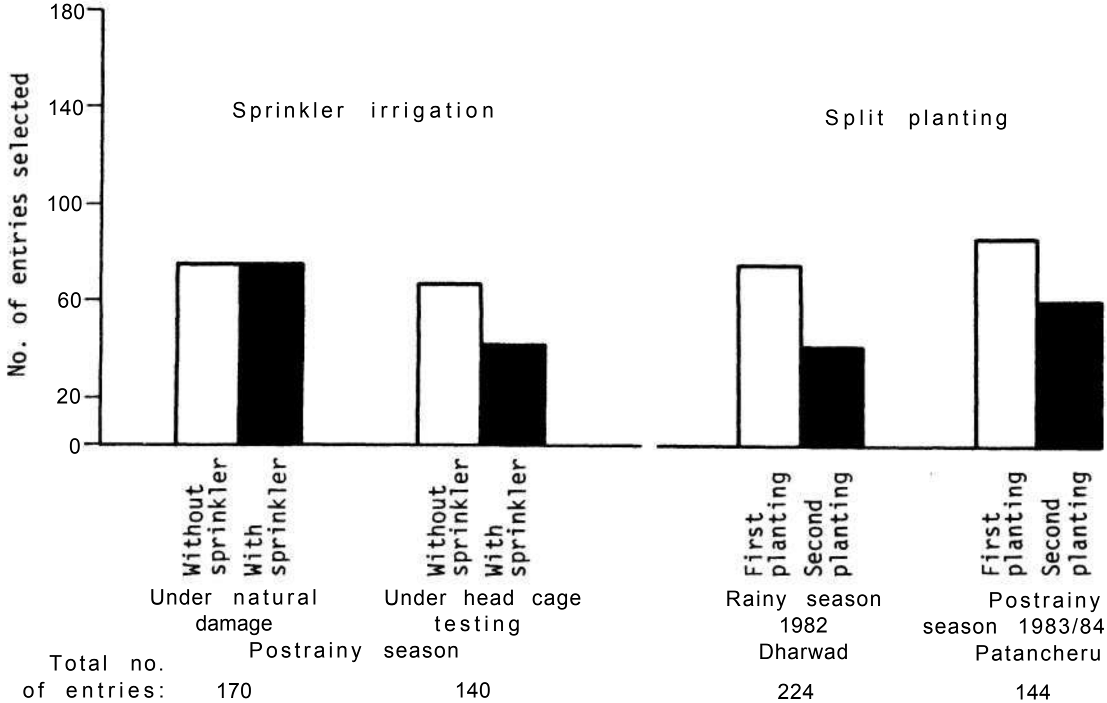

Figure 4. Effect of sprinkler irrigation and split plantings upon selection for midge resistance.

can affect the results in the headcage to some extent over time. But in general it is a rigorous test of resistance in that a number of cultivars selected as resistant under natural conditions have been found to be susceptible under the headcage test (Table 3) (Sharma et al. 1984c). Only three cultivars—DJ 6514, TAM 2566, and IS 12666C-showed stable and repeatable levels of resistance over four seasons when tested under the headcage. The cultivars mentioned in Table 3 can be grouped into different susceptibility categories and, based upon cluster analysis, were placed in nine groups. DJ 6514 and TAM 2566 were placed in the first group of highly resistant cultivars (Fig. 8). These observa-

Table 2. Effect of time of midge collection and infestation on percent florets with midge larvae and chaffy florets (five replications).

	% florets with midge larvae			% chaffy florets		
Time of collection	1980/81 postrainy season	1982 rainy season	1982/83 postrainy season	1980/81 postrainy season	1982 rainy season	1982/83 postrainy season
0830 h	11.0(3.39)**	47.8 (43.67)*	81.6(64.61)*	39.8 (39.08)*	67.0(55.16)*	87.8 (69.67)*
1030 h	8.0 (2.98)	36.2 (36.94)	44.0(41.54)	34.2 (35.70)	58.4 (49.93)	53.2 (46.86)
1230 h	7.0 (2.83)	37.2 (37.39)	10.0(18.01)	29.8 (32.86)	74.0 (59.80)	27.6(31.69)
1430 h	0.8(1.25)	17.4 (23.86)	7.4(15.36)	21.8(27.57)	66.4 (55.24)	39.4 (38.86)
SE	± (0.28)	± (2.89)	±(1.67)	± (2.32)	± (3.67)	±(1.14)

** $\sqrt{N+1}$ transformations * Angular transformations.

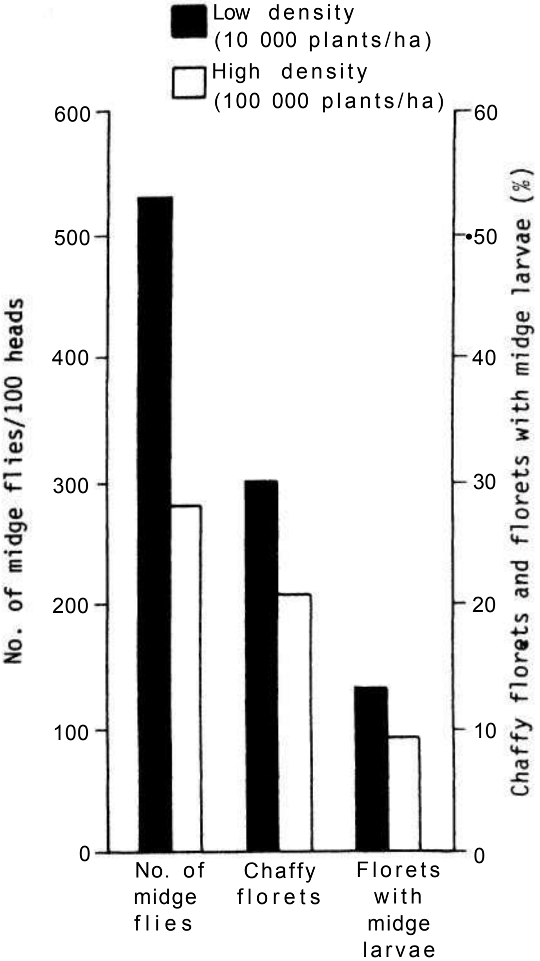

Figure 5. Effect of plant density upon midge population and damage in sorghum.

tions indicate that there is a distinct possibility of increasing the levels of midge resistance by hybridization among cultivars belonging to diverse groups.

Screening for Resistance

A number of cultivars have been reported to be resistant to sorghum midge (Table 4). We have screened over 10 000 germplasm lines and more than 100 reported sources of resistance. The cultivars selected under natural conditions were tested under no-choice conditions in the headcage over many seasons and locations. Cultivars selected as midge-resistant were tested at several locations through the international sorghum midge nursery. Figure 9 shows a flow diagram of ICRISAT's midge resistance screening and breeding program. The cultivars showing repeatable levels of resistance are shown in Table 5.

Resistance Mechanisms

The identification of resistance mechanisms and a proper understanding of the inheritance of resis-

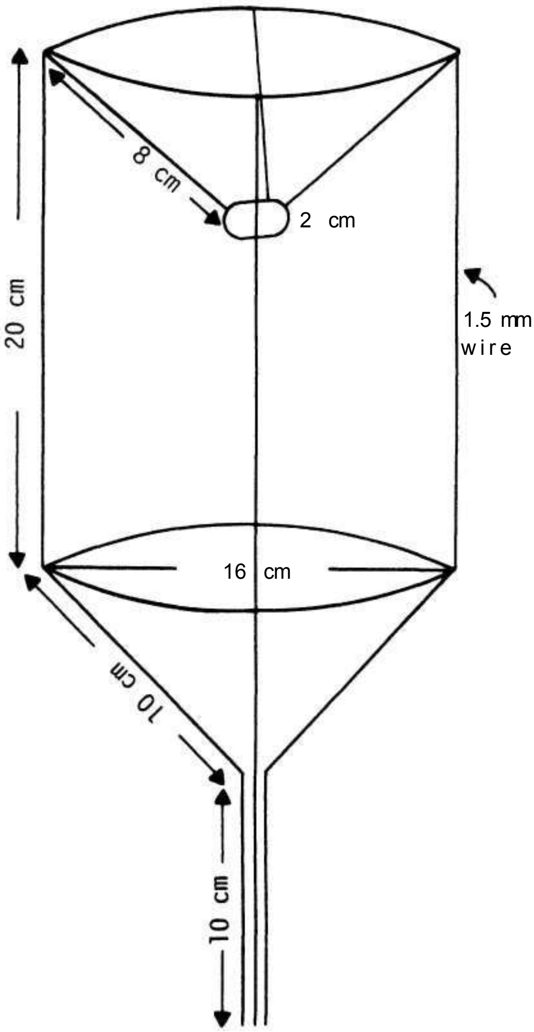

Figure 6. Headcage for midge resistance screening of sorghum under no-choice conditions.

Table 3. Florets with midge larvae and chaffy florets in 21 sorghum cultivars under headcage in four seasons.

Sorghum cultivar	% florets with midge larvae				% chaffy florets			
	1980 rainy season	1980/81 postrainy season	1981 rainy season	1981/82 postrainy season	1980 rainy season	1980/81 postrainy season	1981 rainy season	1981/82 postrainy season
DJ 6514	21.0	11.5	18.5	2.3	60.0	20.0	36.5	19.0
TAM 2566	16.0	16.0	25.0	18.7	21.0	53.3	38.0	27.0
IS 12666C	33.0	20.0	30.5	24.3	52.5	36.5	73.0	35.0
IS 12573C	16.0	46.5	17.0	36.3	55.5	80.0	55.5	63.0
IS 2579C	27.5	45.5	34.0	53.7	70.0	72.5	74.0	64.7
IS 12664C	30.5	30.5	46.5	55.0	33.0	41.5	86.0	63.0
IS 1151	22.5	35.0	45.0	66.3	51.5	60.5	91.0	79.3
IS 12612C	26.0	48.0	57.0	39.3	48.5	44.5	65.0	60.3
EC 92792	40.0	29.5	60.0	42.7	33.5	57.5	66.5	59.7
IS 12611	31.5	36.0	56.0	61.0	48.0	54.0	74.0	71.7
SGIRL-MR 1	34.0	44.5	64.0	45.3	57.0	57.0	80.0	64.3
IS 2327	46.0	51.0	54.0	46.0	32.0	69.0	76.5	59.0
IS 1510	36.0	45.0	55.0	70.3	80.0	55.0	83.5	84.7
EC 92793	43.0	38.0	70.5	56.7	52.0	55.0	79.0	66.0
ENTM 3	48.5	57.0	45.0	58.3	71.0	50.0	77.5	72.7
IS 12608C	36.0	45.5	71.0	58.3	35.5	80.0	94.0	70.3
IS 2328	67.0	62.0	24.0	58.3	63.0	70.5	93.0	67.7
EC 92794	47.0	45.5	69.5	51.7	54.0	54.5	83.0	75.0
IS 2816C	42.5	71.5	42.5	66.0	25.0	83.0	25.0	79.0
IS 6195	70.0	37.5	70.0	54.3	59.0	56.0	58.5	86.7
CSH 1	58.0	54.0	57.0	71.0	71.0	69.0	81.5	80.3
SE	± 8.72	± 9.13	± 6.65	± 9.22	± 12.97	± 10.40	± 9.08	±8.29

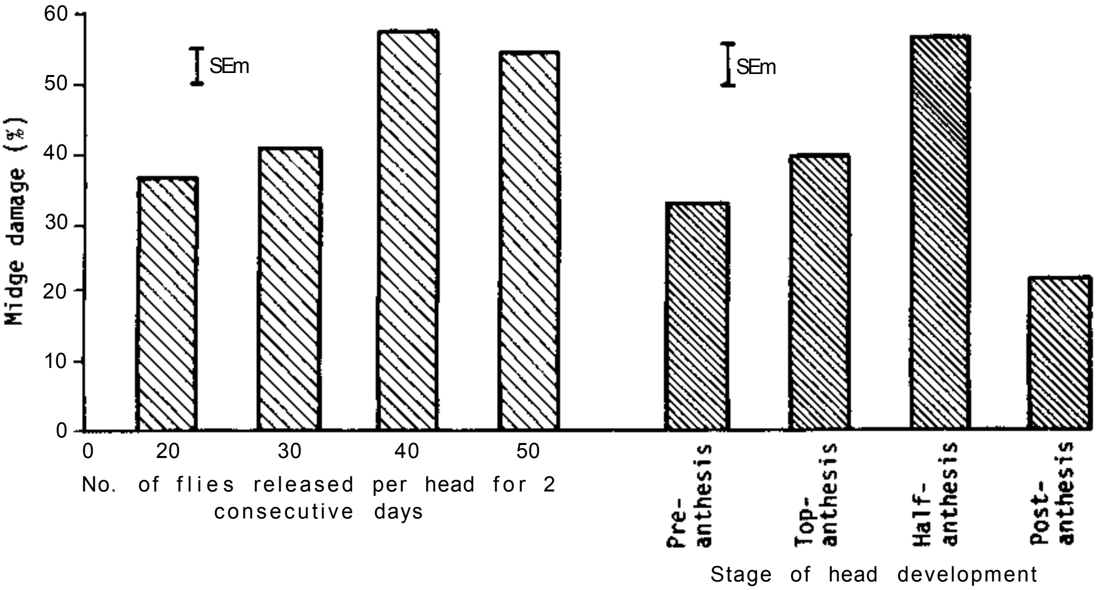

Figure 7. Midge damage in sorghum heads (cv CSH 1) at different levels of midge pressure and stages of head development under headcage conditions, ICRISAT Center, 1981/82.

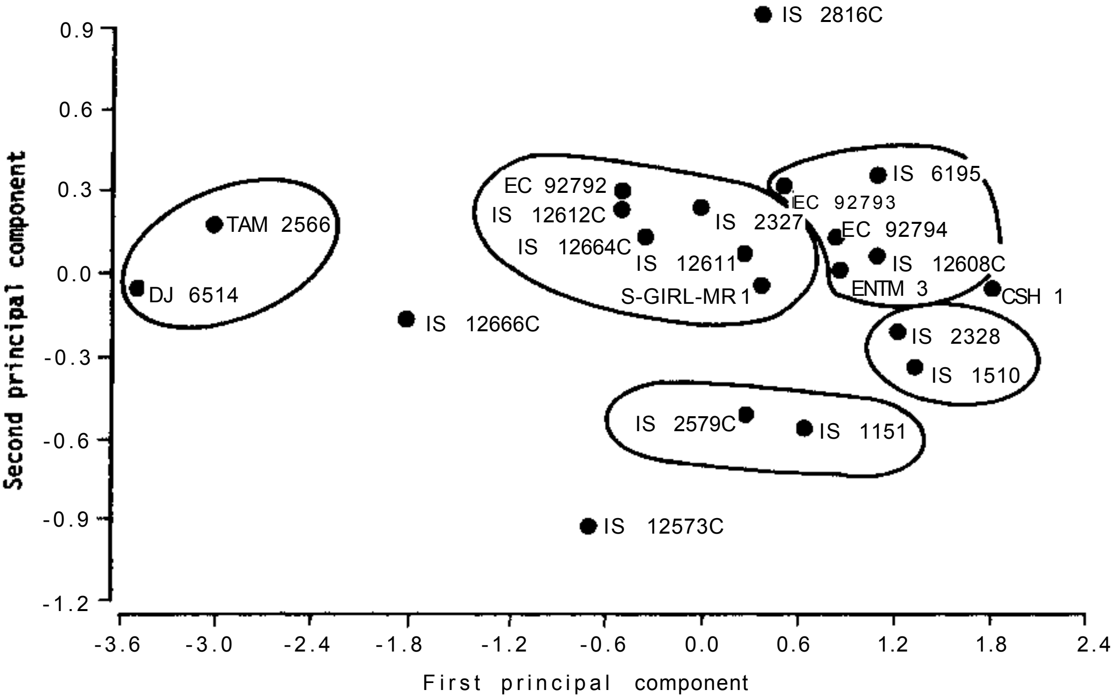

Figure 8. Cluster analysis of 21 sorghum cultivars for midge resistance.

Table 4. Sorghum lines promising/resistant against sorghum midge, *C. sorghicola.*

Sorghum line	Remarks	Reference
Nunaba	3% midge incidence	Bowden and Neve (1963)
ODC 19	0.2 flies/head compared with 52.2 flies on CI 938	Wiseman and McMillian (1968)
IS 413, IS 1002, IS 1004, IS 1021, IS 1064, IS 1079, IS 1087, IS 1151, IS 1457, IS 1462, IS 1472, IS 1474, IS 1501, IS 1510, IS 1542, IS 1568, IS 2160, IS 2205, IS 3472, IS 3950, IS 4307, IS 4308, IS 4316, IS 4411, IS 4429, IS 4477, IS 4511, IS 4528, IS 4544, IS 4569, IS 4653, IS 4757, IS 4761, IS 4782, IS 4808, IS 4832, IS 4859, IS 4868, IS 1870, IS 4876, IS 4955, IS 5230, IS 5384, IS 5389, IS 5452, IS 5475, IS 5656, IS 5940, IS 5977, IS 6146, IS 6163, IS 6170, IS 6179, IS 6195, IS 6206, and IS 6367	20% midge incidence	Pradhan(1971)
IS 2579C, IS 2816C, IS 3574C, IS 12612C, and IS 12666C,	< 4.5 damage rating	Johanson et al. (1973)
SGIRL-MR 1	< 5 damage rating	Wiseman et al. (1973c)
A 25, Grenador INTA mf; Linea 64/21 mf (RS2583); Linea 63/54 mf (RS 2324), Line 3017	< 5 damage rating	Wiseman et al. (1974a, 1974b)

Continued

Table 4 *Continued*

Sorghum line	Remarks	Reference
(SA-8774-2-2-109 Wh), 111567 (Arkansas)		
IS 2660, IS 2663	Closed glume character	Bergquist et al. (1974)
Hurein INTA	Tolerant to midge	Parodi et al.(1974)
AF 28	Resistant	Rossetto et al. (1975a, 1975b)
1809 cm, 2321 cm, and 2331 cm	Showed least damage	Wiseman et al. (1975)
DJ 6514	27.87% incidence	Shyamsundar et al. (1975)
E 92792 EC 92794 and SGIRL-MR 1	< 10% incidence	Raodeo and Karanjkar (1975)
E-248A, 1209 cm, 121 7 cm, 1731 cm, 1749 cm	Less susceptible	Wiseman et al. (1976)
ATX 398, TAM 2566, IS 2501C, IS 2508C, ATX 378 X	< 2.66 damage rating	Faris et al. (1976)
TAM 2566, SGIRL-MR 1		
IS 3472, IS 4411, IS 4870, IS 5940, IS 5977, IS 6170	< 1 midgefly emerged/ head	Gowda and Thontadaraya (1976)
AF 28, AF 11 7, SC 239-14, SC 175-9, SC 175-14, SC 574-6	Resistant	Rossetto (1977)
DJ 6514; SGIRL-MR 1, 573-3/F3, 575-2/F3	Resistant	Venugopal et al. (1977)
SPV 4, SPV 80, SPV 97, SPV 102	Less susceptible	Avadhani et al. (1977)
CO 4, CO 11, CO 18, K4K	< 10% incidence	Murthy and Subramaniam (1978)
DJ 6514		Kulkarni et al.(1978)
EC 92792, IS 1151, IS 1 501, IS 2205, IS 3272, IS 3472, IS 4076, IS 4114, IS 4416, IS 4808, IS 4955, IS 5977, IS 61 70, IS 61 74, IS 61 79, ODC 92793, SGIRL-MR 1	< 3 damage rating	Jotwani (1978)
IS 2626C, IS 3071C, IS 2757C	< 4.5 damage rating	Wuensche et al. (1978)
IS 2579C, IS 12612C, SGIRL-MR 1	Resistant	Jadhav and Jadhav (1978)
EA 73, EA 177, EA 261	26.02% damage vs 53.11% in control	Lara et al. (1979)
AF 28	Most stable line	Faris et al. (1979)
IS 2579C, IS 3071, IS 7142, IS 8263, IS 8337, IS 12593, IS 12676	Highly resistant	Johanson et al. (1979)
AF 28, DJ 6514, TAM 2566, IS 271, IS 2761, IS 3461, IS 7005, IS 7687, IS 8284, IS 8571 IS 8711, IS 8713, IS 8721, IS 8724, IS 9807, IS 10712, IS 11117, IS 12213, IS 12666C, IS 14864, IS 14871, IS 14876, IS 15107, IS 19474,CSH 1	Damage rating < 3 vs 5 in CSH 1	Sharma et al. (1983b)
E 73, EA 256, E 261, EA 361	Moderately resistant	Busoli and Ayala (1982)

tance is most important in a program aimed at incorporating resistance traits into agronomically elite material. Resistance to sorghum midge is mainly of two types: (a) anti-xenosis (nonpreference), and (b) antibiosis. The scope for tolerance mechanism is limited because of the nature of damage and inability of nondamaged grains to compensate for the damaged ones. A grain

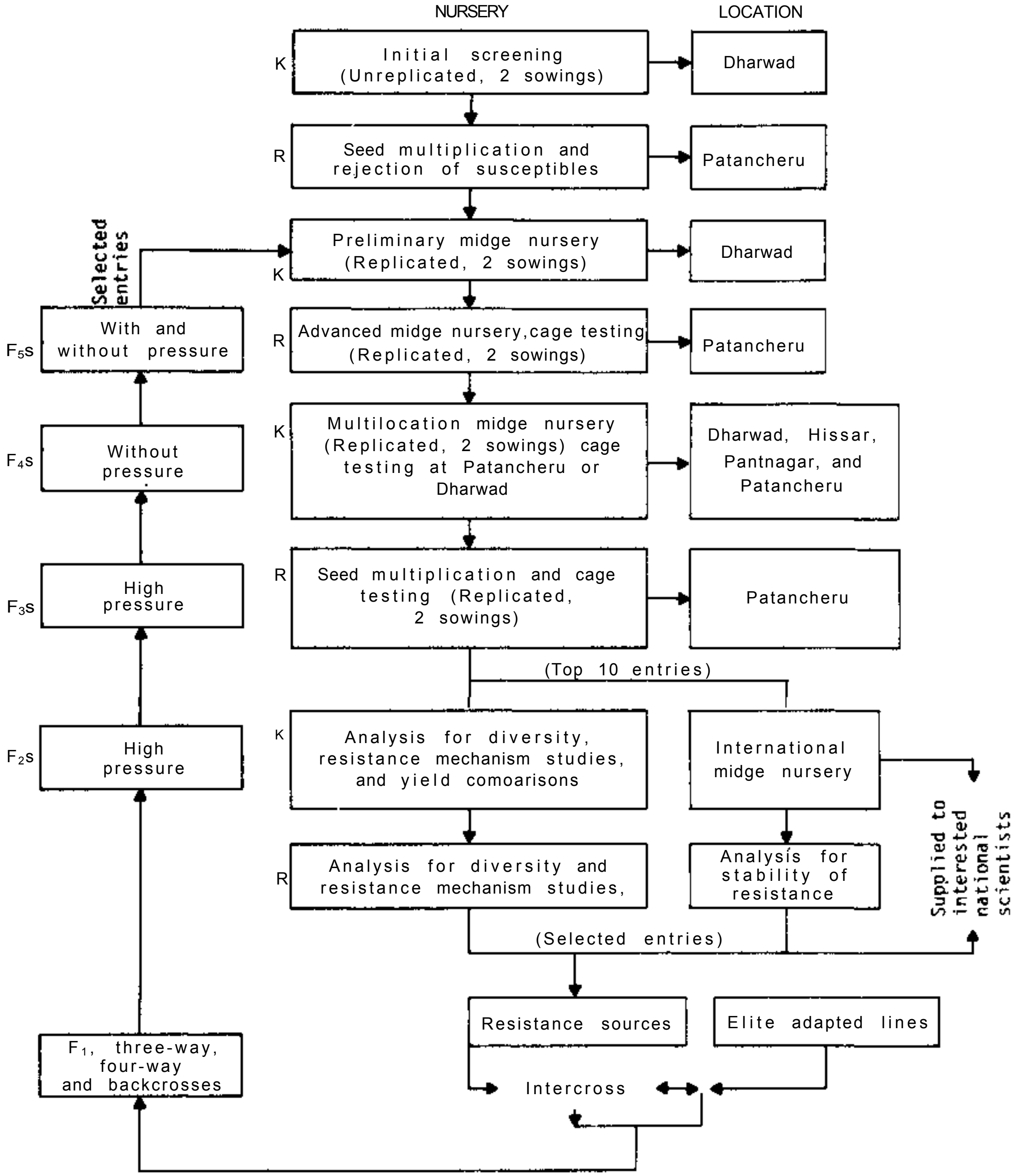

Figure 9. Flow diagram of midge resistance screening of sorghum at ICRISAT. K = *Kharif* (rainy season); R = *Rabi* (postrainy season).

Table 5. Damage ratings[1] of 29 sorghum cultivars under natural and no-choice conditions over four seasons or locations.

	Natural conditions					No-choice conditions (headcage testing)					
Sorghum cultivar	1982K[3] Dharwad	1983K Dharwad	1983K Hissar	1983K Patancheru	Mean	1982–83R Patancheru	1983K Patancheru	1983K Dharwad	1983–84R Patancheru	Mean	Level of resistance[2]
IS 61	2	2	2	2	2.2	3.5	4	3	3.3	3.4	S
IS 271	2	2	4	2	2.5	3	4	3	4.1	3.5	MR
IS 2549C	3	2	2	3	2.7	3.5	4	3	3.9	3.6	S
IS 2761	2	2	2	3	2.2	2.6	4	3	3.5	3.3	MR
IS 3073	3	3	3	3	3	2.4	4	3	3.6	3.2	MR
IS 3461	2	2	2	2	2	1	4	2	1.7	2.2	R
IS 7034	3	3	3	3	3	3.5	4	4	–	4.1	S
IS 8571	3	3	3	2	2.7	2	4	2	1.3	2.3	R
IS 8711	3	3	3	1	2.5	2.6	4	3.5	4.4	3.6	S
IS 8721	3	3	3	3	2.7	2.7	3	4	2.1	2.8	MR
IS 9807	2	2	2	1	1.7	2	3	2	2.9	2.5	R
IS 10712	2	2	2	2	2	2.2	3	2	3.1	2.6	MR
IS 12608C	2	3	3	4	3	5	4	3.5	4.0	4.1	S
IS 12664C	2	2	3	3	2.5	3.6	3	3	4.2	3.4	MR
IS 12666C	3	2	2	4	2.7	3	4	3	3.1	3.5	MR
IS 14889	2	2	2	2	2	4	4	2	4.1	3.5	MR
IS 15107	2	3	2	3	2.5	2.3	3	3	–	2.6	MR
IS 18733	3	3	3	3	3	3	–	3.5	2.7	3.4	MR
IS 18832	2	3	3	3	2.7	4	5	3	3.4	3.8	S
IS 18836	3	3	3	4	3.2	–	5	3	4.4	3.1	MR
IS 19474	2	2	2	2	2	2	3	2	2.5	2.4	R
IS 19512	2	2	2	2	2.2	2	2	2	2.2	2.0	R
IS 20506	3	2	2	5	3	2.7	4	2	4.8	3.4	MR
IS 21873	2	3	3	3	2.7	3	2	2	3.4	2.6	MR
DJ 6514	2	2	2	2	2	1	3	2	1.9	1.9	R
AF 28	2	2	2	1	1.7	1	3	1	1.3	1.6	R
TAM 2566	2	2	2	2	2	2.2	1	2.5	2.6	2.1	R
CSH 1	5	5	5	5	5	5	5	5	5	5.0	HS
Swarna	5	5	5	5	5	5	5	5	4.4	4.8	HS

1. Damage rating: 1 = 10% incidence; 10 percent chaffy florets
2 = 10–25% incidence; a few pupal cases on heads
3 = 25–40% incidence; most of the earheads with pupal cases showing considerable effect on seedset
4 = 40–60% incidence; large number of pupal cases and heads with 50% seedset
5 = 60% incidence; heads severely attacked.
2. R = resistant; MR = moderately resistant; S = susceptible; HS = highly susceptible.
3. K = *Kharif* (rainy season); R = *rabi* (postrainy season).

attacked by the midge larva is always a total loss (midge larvae continuously feed on the attacked grains for 10-12 days).

Nonpreference is one of the important components of resistance to sorghum midge. Wiseman and McMillian (1968) observed 0.2 midge flies per head on ODC 19 compared with 52.2 flies on CI 938. Under natural conditions, ten cultivars were less preferred by the midge flies (<4 midges/5 heads) as compared with CSH 1 (18.7 midges/5 heads) (Table 6). Among the less preferred cultivars, TAM 2566, IS 12666C, and SGIRL-MR 1 suffered lower midge damage (5-11% florets with midge larvae) under natural conditions. Under no-choice conditions (under headcage), only two cultivars (TAM 2566 and IS 12666C) were significantly less damaged (< 27% florets with midge larvae). DJ 6514 suffered the least damage (13.3% florets with midge larvae) under no-choice conditions.

In another study at ICRISAT Center, four cultivars were found to be less attractive than control cv CSH 1 to midge flies, of which SGIRL-MR 1 and IS 12573C suffered least damage under natural conditions. Under no-choice conditions, TAM 2566 and IS 12573C suffered least damage among the less preferred cultivars. DJ 6514 and AF 28 also suffered less damage under no-choice conditions, although they were quite attractive to the midge flies. These results indicate that some genotypes may be less susceptible because of ovipositional nonpreference while in other cultivars other mechanisms, such as, (1) morphological barriers to oviposition and (2) antibiosis, are important. Ovipositional nonpreference as a mechanism of resistance may not be useful under field conditions when the same cultivar is planted over large areas, since such cultivars can become susceptible under no-choice conditions (as indicated above)

Table 6. Florets with midge larvae and chaffy florets under headcage and natural conditions in 21 sorghum cultivars.

Sorghum cultivar	Headcage conditions: % florets with midge larvae	Headcage conditions: % Chaffy florets	Natural[2]: % Florets with midge larvae	Natural[2]: % chaffy florets	No. of midge flies/5 heads[2]
DJ 6514	13.3 (18.9)[3]	33.9 (34.0)[3]	5.0 (11.5)[3]	23.7 (28.6)[3]	7.3 (2.3)[4]
TAM 2566	18.9 (25.2)	34.9 (35.3)	7.0 (13.2)	17.3 (23.9)	2.8 (1.7)
IS 12666C	26.9 (30.9)	49.3 (44.0)	11.0 (17.7)	15.8 (22.9)	2.7 (1.5)
IS 12573C	28.9 (32.7)	63.5 (53.3)	3.5 (10.2)	28.2 (31.1)	1.2 (1.1)
IS 2579C	40.2 (40.0)	70.3 (56.0)	19.2 (21.3)	25.0 (29.4)	5.0 (2.0)
IS 12664C	40.6 (40.4)	55.9 (49.6)	20.3 (23.6)	20.7 (26.9)	2.8 (1.6)
IS 1151	42.2 (41.9)	54.6 (48.1)	9.7 (15.8)	14.2 (21.0)	9.5 (2.8)
IS 12612C	42.6 (40.3)	70.6 (59.0)	11.2 (17.1)	20.2 (25.6)	6.2 (2.4)
IS 92792	43.1 (40.9)	54.3 (47.8)	8.8 (15.4)	11.2 (20.6)	7.2 (2.4)
IS 12611	46.1 (43.6)	61.9 (52.9)	15.8 (21.7)	13.5 (21.2)	7.5 (2.7)
SGIRL-MR 1	46.9 (43.1)	64.6 (53.9)	8.2 (15.4)	13.7 (21.6)	3.0 (1.6)
IS 2327	49.3 (43.0)	59.1 (50.5)	23.8 (24.9)	18.7 (25.0)	9.3 (2.6)
IS 1510	51.6 (47.4)	75.8 (60.9)	9.5 (15.8)	23.3 (28.3)	3.3 (1.8)
EC 92793	52.1 (46.7)	63.0 (53.0)	8.7 (15.5)	14.3 (21.2)	8.7 (2.3)
ENTM. 3	52.2 (46.7)	67.8 (56.3)	20.2 (23.3)	27.7 (29.4)	6.8 (2.3)
IS 12608C	52.7 (48.3)	69.9 (58.6)	14.0 (18.2)	24.7 (28.3)	3.7 (1.8)
IS 2328	52.8 (46.9)	73.6 (59.6)	17.0 (20.2)	31.5 (32.6)	12.8 (3.3)
EC 92794	53.4 (46.9)	63.6 (55.9)	14.5 (18.8)	21.8 (27.2)	4.8 (2.0)
IS 2816C	55.6 (49.2)	53.0 (48.9)	11.2 (17.6)	22.0 (32.4)	2.3 (1.4)
IS 6195	57.9 (49.5)	65.1 (56.6)	16.2 (19.9)	30.3 (32.9)	6.0 (2.1)
CSH 1	60.0(51.8)	75.5 (62.3)	18.7 (25.5)	23.8 (28.5)	18.7 (4.1)
SE	±(5.26)	±(6.31)	±(3.64)	±(3.72)	±(0.47)

1. Based on four seasons' data. 2. Based upon 3 seasons' data.
3. Angular transformations. 4. Square root transformations.

Table 7. Factors influencing resistance to sorghum midge *(Contarinia sorghicola)*[1].

Cultivar	Eggs/100 florets	Larvae/ 100 florets	Adults emerged/ head	Measurements (length in ocular scale units)[2]							Total tannins (%)
				Glume (G)		Lema (L)					
				G_1	G_2	L_1	L_2	Palea	Anther	Style	
DJ 6514	50 (7.0)[3]	2(1.5)	13(3.5)	139	142	128	71	95	84	46	0.1
AF 28	45 (6.4)	49 (6.9)	24 (4.7)	138	139	130	110	99	90	29	26.3
TAM 2566	14(3.6)	22 (4.6)	48 (6.9)	122	125	115	99	83	83	40	11.1
IS 15107	13(3.6)	65(8.1)	79 (8.9)	156	151	136	107	98	106	46	13.9
Swarna	107(10.4)	106(10.3)	314(17.7)	188	192	163	136	105	108	63	0.4
CSH 1	122 (10.9)	138(11.7)	301 (17.1)	181	180	149	120	103	120	55	0.4
SE	±(1.9)	± (0.70)	± (1.20)	±(3.2)	±(2.4)	±(2.4)	±(2.4)	±(2.6)	±(3.1)	±(2.1)	-

1. Based on three seasons' experiments.
2. 40 ocular scale units = 1 mm.
3. Square root transformation.

and in the absence of a more favorable host (Harris 1961; Passlow 1965).

Antibiosis and morphological barriers to oviposition are important mechanisms of resistance to sorghum midge. Significantly fewer midge flies have been reported to emerge from the infested heads of resistant cultivars compared with the susceptible ones (Gowda and Thontadarya 1976; Rossetto 1977; Jotwani 1978; Page 1979; Sharma et al. 1983a). Oviposition, larval population, and adult emergence were observed in six cultivars for four seasons at ICRISAT Center (Table 7) under no-choice conditions. The heads were exposed to 60 midge flies for 1 day in the headcage. The resistant cultivars (DJ 6514, AF 28, TAM 2566, and IS 15107) had fewer eggs and larvae in the florets than the susceptible ones (CSH 1 and Swarna). Adult emergence in resistant cultivars was low (< 71 midge flies/head versus 404/head in the susceptible control) and delayed (20-27 days after oviposition compared with 15-24 days in the control) (Table 8).

The correlation and regression coefficients between the various parameters of insect host-plant relationship (oviposition, number of larvae, adults emerged, and percent damage) were significant (Sharma et al. 1983a). However, larvae and

Table 8. Adult midge emergence pattern in 11 sorghum cultivars under headcage conditions, 15 to 27 days after inoculation.

Sorghum cultivar	Midge emergence/head[1]													Total no. of flies
	15 days	16	17	18	19	20	21	22	23	24	25	26	27	
DJ 6514	-	-	-	-	-	-	-	-	-	-	-	2	1	3
AF 28	-	-	-	-	-	-	9	9	4	2	-	-		24
IS 12664C	-	-	-	-	-	-	6	8	14	11	6	4		49
TAM 2566	-	-	-	-	-	19	8	8	4	5	2	4		50
IS 15107	-	-	-	-	-	25	16	12	11	7	4	4		79
IS 12666C	-	-	16	16	12	15	9	7	5	3	1	3		86
IS 8721	-	-	-	-	27	16	7	10	9	10	6	4		89
IS 8544	-	-	16	25	26	46	23	23	4	10	2	3	1	179
IS 7034	14	29	48	39	31	32	38	16	-	-	-	-		247
CSH 1	21	38	49	63	41	34	33	20	9	6	-	-		314
Swarna	-	-	59	30	43	50	52	47	22	9	4	-		316

1. Based on three earheads inoculated with 60 midge flies under headcage.

adults accounted for only 53 and 40% of the eggs laid, respectively, indicating differential larval/pupal mortality in different cultivars.

Factors Associated with Midge Resistance

Morphological Factors

Ball and Hastings (1912) considered that short glumes contributed to midge resistance, while Geering (1953) suggested that the degree of apposition of glumes is a factor in midge resistance. Bowden and Neve (1953) observed that length and thickness of glumes (cleistogamous) in Nunaba variety contributed to resistance. However, Harris (1961) and Passlow (1965) found that resistance due to the nature of glumes was only apparent and Nunaba lost its resistance in the absence of a more favored host. Studies in recent years have shown the presence of resistance in noncleistogamous sorghums also (Pradhan 1971; Johnson et al. 1973; Jotwani 1978). Murty and Subramaniam (1978) reported that glume length, presence of awns, and rachis length were not related to resistance. They reported genotypes with compact heads to be resistant; those with semicompact heads, highly susceptible. Rossetto et al. (1975a) reported that closed spikelets apparently made oviposition difficult in AF 28. The same character found in IS 2260 and IS 2263 has also been suggested as being responsible for imparting resistance to midge (Bergquist et al. 1974).

The role of the rate of ovary development (growth rates based upon size, fresh weight and dry weight) and floral parts (glume G1 and G2, lemma L1 and L2, palea, lodicule, ovary, stigma, style, and pollen tubes) was studied in six cultivars over four seasons at ICRISAT Center. The rate of ovary development was higher in resistant cultivars than in the susceptible ones (Fig. 10; Table 9). Susceptibility to

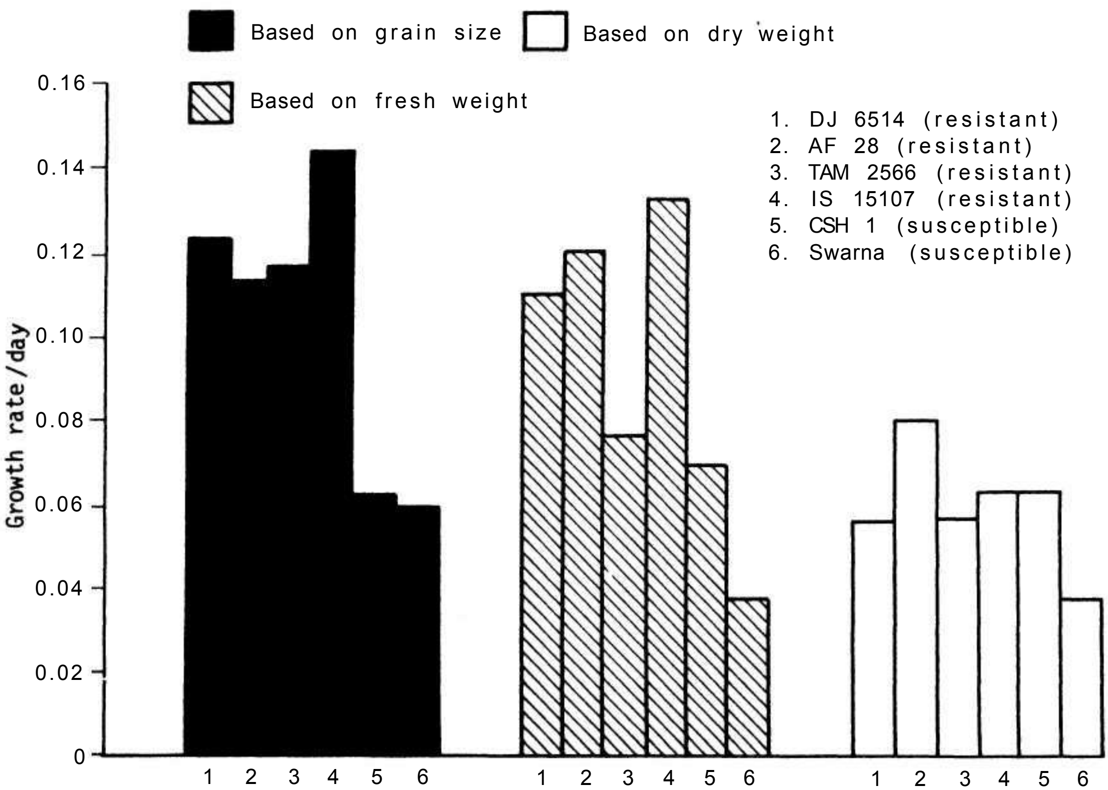

Figure 10. Grain growth rates of four midge-resistant and two susceptible cultivars, 3 to 7 days after anthesis.

midge was positively and significantly correlated with glume length G1 and G2, lemma length L1 and L2, palea length, anther length, and style length. The lodicule width was significantly correlated only with midge damage and oviposition. Ovary and anther width were negatively correlated with midge damage, though the correlation coefficients were low and nonsignificant.

These results indicate that the initial faster growth of the grain and short floral parts are associated with midge resistance. The negative relationship between midge resistance and ovary and anther width probably is due to the limited space available for oviposition and larval development. The same may be true for the initial faster ovary growth rates in the resistant cultivars.

Chemical Factors

Santos and Carmo (1974) and Santos et al. (1974) suggested that tannin content may be one of the factors imparting resistance to sorghum midge. Studies at ICRISAT Center have shown that midge-

Table 9. Correlation coefficients' between factors measuring midge resistance (% florets with midge larvae, % chaffy florets, % florets with eggs, No. eggs/100 florets, larvae/100 florets, and adult emergence) and ovary growth rates, floral characters, and chemical components. (Four seasons[1] data.)

Floral parameter	% florets with midge larvae	% chaffy florets	% florets \with eggs	No.eggs/ 100 florets	No.larvae/ 100 florets	Adult emergence/ head
Ovary growth rate-1[2]	-0.35	-0.36	-0.20	-0.21	-0.12	-0.25
Ovary growth rate-2	-0.50	-0.49	-0.36	-0.54	-0.33	-0.41
Ovary growth rate-3	-0.37	-0.24	-0.49	-0.53	-0.17	-0.31
Glume length - G_1	0.87	0.79	0.73	0.69	0.75	0.81
Glume length - G_2	0.89	0.80	0.77	0.73	0.74	0.81
Lema length - L_1	0.82	0.74	0.67	0.70	0.71	0.78
Lema length - L_2	0.78	0.79	0.59	0.60	0.88	0.85
Palea length	0.56	0.49	0.56	0.56	0.63	0.67
Lodicule length	0.68	0.59	0.58	0.51	0.50	0.60
Lodicule breadth	0.49	0.43	0.35	0.49	0.36	0.38
Ovary length	0.32	0.33	0.21	0.19	0.35	0.38
Ovary breadth	-0.16	-0.18	-0.15	-0.21	-0.13	-0.16
Anther length	0.89	0.82	0.72	0.65	0.84	0.89
Anther breadth	-0.16	0.17	-0.06	-0.14	-0.42	-0.29
Style length	0.80	0.63	0.68	0.68	0.50	0.59
Stigma length	0.26	0.24	0.32	0.26	0.25	0.31
Tannins 10 day grains	-0.51	-0.32	-0.62	-0.52	-0.33	-0.52
Tannins in mature grains	-0.47	-0.32	-0.47	-0.45	-0.23	-0.45
Sugars in 10 day grains	0.51	0.39	0.36	0.50	0.47	0.51
Sugars in matured grains	-0.53	-0.40	-0.40	-0.38	-0.32	-0.51
Proteins in 10 day grains	-0.15	-0.45	-0.39	-0.25	-0.15	-0.34
Proteins in matured grains	-0.31	-0.28	-0.17	0.26	-0.37	-0.16

1. Tabulated value of r at $P = 0.05$ is 0.40; at $P = 0.01$ is 0.51 at 22 df.

2. Ovary growth rate =

$$\frac{\text{Size/wt. of the ovary on 7th day after anthesis} - \text{Size/wt. of the ovary on 3rd day after anthesis}}{\text{Mean size/wt. of the ovary during the growing period} \times \text{Duration of the growing period}}$$

Growth rate 1 (between 3-7 days) based upon grain size; growth rate 2 (between 3-7 days) based upon fresh weight of the grain; growth rate 3 (between 3-7 days) based upon dry weight of the grain.

resistant genotypes are rich in tannin content (Table 9), though there are distinct exceptions, e.g., DJ 6514. The sugar and protein content does not show any relationship to midge resistance.

Inheritance of Resistance

Not much work has been done on the inheritance of resistance to sorghum midge. Widstrom et al. (1972) reported that resistance to midge shows highly additive gene effects. Dominance effects were only significant for the cross SGIRL-MR 1 x 130. Dominance conditions susceptibility to midge damage. Studies carried out on midge resistance at ICRISAT Center are reported in detail in another paper on breeding for midge resistance by Agrawal and Abraham (these Proceedings).

Looking Ahead

1. Screening for midge resistance can be carried out effectively through a combination of field and headcage screening techniques. Midge populations in the field are influenced by the prevailing weather conditions, which result *in* uncontrollable day-to-day variation in midge populations. Therefore, the cultivars selected under natural conditions will always have a certain number of escapes. To overcome this, multilocation and headcage screening are recommended. Testing over several locations and seasons is time-consuming, while the headcage technique is labor-intensive and also influenced by environmental conditions. Thus there is a need to develop simpler no-choice screening techniques, and to study marker characters such as short glumes to simplify the process of screening for midge resistance.

2. Half of the international sorghum germplasm collection has been screened for midge resistance and some cultivars showing repeatable resistance have been identified. However, the need to convert the photoperiod-sensitive cultivars into adapted backgrounds should not be overlooked. Search for newer sources of resistance is essential to diversify the sources of resistance.

3. Factors associated with midge resistance have been explored. Studies should be continued in greater detail on the mechanisms of resistance and on quantifying the contribution of different factors to midge resistance.

4. Efforts should be made to understand the inheritance of resistance to plan the appropriate resistance breeding strategy. Efforts to transfer the midge resistance into agronomically superior cultivars should be intensified, with greater emphasis on developing A and B lines with midge resistance for producing midge-resistant hybrids.

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Sorghum Midge: Host-Plant Resistance Mechanisms

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Abstract

The possible mechanisms of host-plant resistance to sorghum midge are reviewed. Nonpreference for oviposition is generally present in some resistant varieties, closed glumes probably being the most common cause for nonpreference. The closed-glume character seems to be a recessive trait, and both parent lines of a hybrid should carry it for the hybrid to express the trait The existence of the closed-glume character in AF 28(PI 383856), IS 2660, and IS 2663 makes it possible to introduce it into parent lines of a hybrid without losing heterozygosity. Resistance against the midge larva has been demonstrated in TAM 2566, SCO 175-14 and SCO 175-9, which are seloctions of IS 12666C. The tolerance mechanism has received the least attention from entomologists. Although it may not be of much value in itself, it could help increase the total resistance, if combined with nonpreference for oviposition and antibiosis against the larva to lower the infestation levels. Early flowering and short periods of anthesis are both mechanisms to evade midge attack in sorghum.

Résumé

***Le cécidomyie du sorgho—mécanismes de résistance de la plante-hôte :** Les mécanismes éventuels de la résistance de la plante-hôte à la cécidomyie sont étudiés. On trouve généralement pour certaines variétés résistantes une non préférence pour la ponte, celle-ci provient le plus vraisemblablement du caractère apprimé des glumes. Ce caractère semble être récessif et les deux lignées parentales d'un hybride devraient en être porteuses pour que l'hybride l'exprime.La présence de ce caractère chez AF 28 (PI 38385, IS 2660 et IS 2663) permet de l'introduire chez les lignées géniteurs d'un hybride sans perdant l'hétérozygosité. La résistance aux larves de la cécidomyie a été constatée chez TAM 2566, SCO 175-14 et SCO 175-9 qui sont des sélections faites à partir de IS 12666C. Le mécanisme de la tolérance a malheureusement retenu peu d'attention. Peu importante en soi, la tolérance peut toutefois renforcer la résistance totale lorsqu'elle est accompagnée de la non préférence pour la ponte et de l'antibiose contre les larves, en vue de réduire l'infestation. En outre, la floraison précoce et les courtes périodes de l'anthèse permettent d'éviter l'attaque de la cécidomyie.*

Sorghum Midge: Resistance Mechanisms

A better knowledge of the resistance mechanisms of the sorghum plant against midge fly attack would be useful for several reasons (Wuensche 1980; Melton 1982); it would help to:

1. Distinguish plants with true resistance from those that escape insect attack.
2. Provide a better understanding of the insect-host plant relationship.
3. Plan a breeding program towards obtaining higher and more stable levels of resistance by combining lines possessing different resistance mechanisms.
4. Obtain some indication of the stability of resistance.
5. Provide basic knowledge of midge biology, behavior, and physiology in relation to the sorghum plant.

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6. Determine how the resistance can be utilized in an integrated pest management scheme.

The mechanisms of resistance to sorghum midge discussed in this paper are based on the classification and definitions given by Painter (1951).

The possible mechanisms of resistance of sorghum to the midge are summarized in Table 1.

Nonpreference for Oviposition

This mechanism of resistance against sorghum midge has at least two components. A variety may be less preferred for oviposition by the females, which results in a lower number of flies per sorghum head. Secondly, a variety may be as attractive for females as a susceptible check, but less oviposition takes place on it. The degree of nonpreference is therefore a direct function of the numbers of adult midges present on the inflorescences and the number of eggs laid per midge. The number of midges ovipositing on one panicle, however, does not measure by itself the degree of nonpreference for oviposition. The degree of preference for oviposition in a sorghum line can be expressed by the mean number of eggs laid per flower, which could be approximately measured on a given day by the following formula:

$$\text{No. eggs/flower} = \frac{\text{No. midges present on one inflorescence} \times \text{No. of eggs laid per midge}}{\text{No. of flowers at anthesis per inflorescence}}$$

Nonpreference as a Function of Fly Number

Fewer midge females have been observed to oviposit on TAM 2566 than on the susceptible check (Table 2). This line sheds less pollen than the susceptible line Tx 7000 and its anthers are less extruded out of the spikelet, which could make it less attractive to midge adults (Wuensche 1980).

Johnson (1974), however, observed as many midges visiting TAM 2566 flowers as the flowers of a susceptible line Tx 2536. Melton (1982) observed that the numbers of midges visiting the flowers of

Table 1. Summary of possible mechanisms of resistance and pseudoresistance of sorghum to sorghum midge.

Mechanism	Midge stage affected	Expression	Reference
Nonpreference for oviposition	Resistance to adult	Fewer females ovipositing Fewer eggs oviposited/female	Teetes and Johnson (1978) Wuensche(1980) Harris (1961) Overman (1975) Rossetto(1977) Rossetto et al. (1984) Teetes and Johnson (1978)
Nonpreference for feeding	Resistance to larva	Larva or pupa lighter weight smaller size;	Rossetto (1977) Teetes and Johnson (1978)
Antibiosis	Resistance to larva	mortality higher Development period longer	Wuensche (1980)
Tolerance	Resistance to larva	Compensation in weight of undamaged kernels	Hamilton et al. (1982) Page (1979) Summers et al. (1976)
Evasion	Pseudoresistance to adult	Early maturity (in early plantings) Less time to complete anthesis	Painter (1951) Rossetto (1977) Wuensche (1980)

Table 2. Female midges collected by plastic bag sampling in inflorescences of susceptible and resistant sorghum cultivars.

Sorghum cultivar	No. of adults collected/day 1976	1977
TAM 2566 (R) (SC 175-9)	11.8	2.5
SC 423 (R)	50.3	11.3
TAM 428 (R) (SC 110-9)	44.7	19.0
Tx 7000 (S)	107.6	35.9

Source : Teetes and Johnson (1978).

two resistant and two susceptible sorghum hybrids varied significantly but the differences were not consistent. These observations were made under free-choice conditions. It remains to be seen whether the lower number of females visiting the inflorescences of a given cultivar could be maintained under a no-choice situation. Because of the inconsistency of the results and the possibility that the type of resistance may not hold under no-choice conditions, this component of nonpreference does not, at present, offer much promise.

Nonpreference as a Function of Egg Number

The inflorescences of the resistant variety AF 28 under field conditions were more attractive to female midge flies than susceptible varieties, but significantly fewer eggs were laid in flowers of AF 28 (Table 3)(Overman 1975). Under caged conditions, AF 28 and a susceptible variety (Sart) were equally attractive to midge females, but 17 times fewer eggs were laid in AF 28 flowers (Rossetto et al. 1984). Florets of resistant AF 28 and susceptible Sart were placed with midges in a transparent paper cage and the oviposition behavior of the female midges was observed under the stereomicroscope. The midges attempted to oviposit in both varieties but were more successful in introducing the ovipositor into the florets of the susceptible line. The AF 28 florets were more closed at the tip during anthesis than the Sart florets (Rossetto et al. 1984).

The glumes of resistant lines IS 2660 and IS 2663 remain closed throughout anthesis, while glumes of susceptible lines remain open (Bergquist et al. 1974). These authors considered this to be an exclusion mechanism and noticed that plants of the F_1 generation from the cross between open- and closed-glume lines expressed the open-glume character. The F_1 generation of a cross between AF 28 and Sart also showed susceptibility to the sorghum midge (Rossetto and Igue 1983). The closed-glume character seems to be a recessive one and both parent lines of a sorghum hybrid should carry it for the trait to be expressed in the hybrid. The existence of a number of sources with the closed-glume character (AF 28, IS 2660, IS 2663) makes it possible to incorporate this character into the male and female parents of a sorghum hybrid without losing heterozygosity.

Jadhav and Jadhav (1978) also observed that the glumes of less susceptible entries were short and compact and remained closed during anthesis. The resistance of the Nunaba variety is also due to an exclusion mechanism (Bowden and Neve 1953).

The advantage of the closed-glume character is that it reduces oviposition, reducing grain damage and insect population density simultaneously. It will probably be difficult for the midge to develop a biotype as efficient in inserting eggs into closed-glume as into open-glume sorghum types. Harris (1961) confirmed nonpreference for oviposition in Nunaba when midges had a choice of ovipositing in the susceptible Farafara variety; however, he observed that the midges were able to oviposit in Nunaba under no-choice conditions. Rossetto et al.

Table 3. Number of midges vising inflorescences, percentage of spikelets with eggs, and percentage of damaged spikelets in eight sorghum varieties.

Sorghum variety	No. of midges visiting inflorescences	Spikelets containing eggs (%)	Damaged spikelets (%)
SGIRL-MR 1	48.0	94	80.8
Granador	69.3	93	82.3
IS 8361	68.0	56	99.7
Tx 2536	114.2	96	98.6
BRP 3R	104.3	88	99.5
BRP 4B	73.9	84	97.5
AF 28	186.0	46	43.0
Leoti	96.0	100	100.0

Source: Overman (1975).

Table 4. Percentage of caged spikelets of TAM 2566 and Tx 7000 found to be infested with each life stage of the sorghum midge.

Midge life stage	Line		Difference in infestation between lines (%)
	Tx 7000 (Susceptible)	TAM 2566 (Resistant)	
Egg	22.2	7.8	64.8
Larva	10.3	5.1	50.9
Pupa	6.6	0.1	98.8
Adult	0.5	0.1	85.2

Source: Teetes and Johnson (1978).

(1975) observed that the variety AF 28 was resistant even under no-choice conditions under heavy artificial midge infestation.

Murthy and Subramaniam (1978) noticed that varieties with compact panicles were consistently less midge-infested than varieties with semicompact or open panicles. The compact panicles restrict free access of the midge to all spikelets for egg-laying and only the external florets were infested. Compact panicles would therefore confer some degree of nonpreference for oviposition; however, this trait has other disadvantages because it favors the development of molds and head caterpillar infestations (McMillian and Wiseman 1972). When equal numbers of midges were caged on spikelets of TAM 2566 and Tx 7000, fewer eggs were laid on the first, showing that this line is less preferred for oviposition (Teetes and Johnson 1978) (Table 4).

The number of eggs laid in flowers of excised inflorescences of seven previously selected sorghum lines under free-choice cage conditions is shown in Table 5 (Rossetto 1977). Nonpreference for oviposition is probably a mechanism commonly present in sorghum varieties resistant to the sorghum midge.

Resistance to the Midge Larva

Resistance against the midge larva is possibly due to antibiosis, leading to smaller size of larvae and pupae, extended developmental period, and/or higher mortality. Here it is difficult to make a distinction between nonpreference for feeding and antibiosis. Since the larva has no choice, I do not attempt to distinguish between these mechanisms but classify them both as resistance to the midge larva.

Table 5. Mean number of eggs of sorghum midge/floret and percentage of florets infested in excised inflorescences (free-choice cage experiment with seven sorghum lines).[1]

Sorghum entry	Eggs/flower	Infested florets (%)
AF 28 (PI 383856)	2.4a	46.3a
SC 574-6 (IS 8337C)	2.5a	65.0b
SC 239-14 (IS 3574C)	4.5ab	63.8ab
SC 175-14 (IS 12666C)	4.6ab	66.3b
SC 175-9 (IS 12666C)	7.9b	81.3bc
Granador	16.7c	86.3c
Sart	17.9c	85.0c
CV(%)	15.0	10.3

Source: Rossetto (1977).
1. Means in the same column not followed by a common letter differ significantly at $P \leqslant 0.05$ as determined by the Tukey test.

Table 6. Mean size of sorghum midge larvae found in spikelets of four sorghum lines.[1]

Sorghum line	Mean (mm)	
	Diameter	Length
Tx 7000	0.23a	0.47a
TAM 428 (IS 12610C)	0.15b	0.37b
SC 423 (IS 2579C)	0.12c	0.31c
TAM 2566 (IS 12666C)	0.09d	0.28c

Source : Wuensche (1980).
1. Means in the same column not followed by a common letter differ significantly at $P \leqslant 0.05$ as determined by Duncan's multiple range test.

Evidence for the existence of resistance against sorghum midge larvae was obtained by Wuensche (1980)(Table 6). He dissected caged and artificially infested flowers, by examining a certain number every day, 1 to 17 days after egg laying, for the presence of larvae. Teetes and Johnson (1978) also reported higher larval mortality in TAM 2566 than in Tx 7000.

Rossetto et al. (1984) artificially inserted 10 to 15 eggs into each of 170 individual flowers of midge-resistant AF 28 and susceptible Sart. There was no significant difference in the numbers of midges that emerged and developmental period (in days) between the two varieties. Approximately one midge emerged from each floret of either variety.

Rossetto (1977) artificially inserted approximately five eggs into flowers of several resistant sorghum lines, using ten flowers per line and three replications. A summary of the numbers of midges emerged from four of these lines and Sart (susceptible) is shown in Table 7.

Johnson (1977) reported that sorghum lines with the highest level of sorghum midge resistance have a testa. Kofoid et al. (1982) found that sorghum types with a testa also had a higher tannin content, which could be a factor of resistance against the larva. A correlation between tannins and resistance to sorghum midge was suggested by Santos and Carmo (1974); however, Martins (1977) working with the same sorghum lines previously selected for a range of tannin content, failed to obtain a correlation between numbers of midges emerged and the tannin content. The variety AF 28 included in this study is nonpreferred for oviposition and has a low tannin content. It is possible that resistance to midge is often associated with nonpreference for oviposition, and therefore no clear correlation between tannin content and resistance to midge larvae has been observed. This correlation should be expected only in situations where the resistance against the larva is being studied by excluding nonpreference for oviposition.

Tolerance

The resistant lines TAM 2566 and IS 2579C (SC 423) had a more rapid seed growth rate than the susceptible lines Tx 7000 (Johnson et al. 1977) (Table 8). This could be a tolerance mechanism, but the more vigorous growth of the seed could also be associated with physiological changes that could cause resistance to the larva. No evidence of tolerance was observed in these lines by Wuensche (1980).

Summers et al. (1976), working with the sorghum hybrid Amak-R 10 under different plant densities, observed that the yield per head in the high-density

Table 7. Mean number of adult midges emerged from 10 sorghum florets artificially infested with five eggs each (three replications).[7]

Sorghum line	Mean number of midges emerged from 10 sorghum florets	
	1976	1977
SC 175-14 (IS 12666C)	2.3ab	1.7a
SC 424-14 (IS 8100C)	3.0ab	2.3ab
SC 239-14 (IS 3574C)	2.0ab	3.7ab
SC 175-9 (IS 12666C)	1.0a	4.7ab
Sart	8.3b	6.7b

Source : Rossetto (1977).
1. Means in the same column not followed by a common letter differ significantly at $P \leqslant 0.05$ as determined by Tukey's test.

Table 8. Seed weight of four selected sorghum lines.

	Seed age (days)		
	5	10	15
Sorghum line	1000-seed weight		
TAM 2566 (SC 175-9)	0.485	1.335	4.154
IS 2579 (SC 423)	0.419	1.532	5.188
TAM 428 (SC 110-9)	0.379	0.922	4.108
Tx 7000	0.199	0.818	3.665

Source : Johnson et al. (1977).

plots (39 plants/m) decreased by 48 mg per head per midge, whereas in the low-density plots (13 plants/m) the decrease was only 25 mg per head per midge.

There may be a compensatory mechanism operating as suggested by Henzell and Gillieron (1973, cited by Page 1979), who said that sorghum yields after moderate midge attack may be higher than expected, because grain sorghum is able to compensate for loss of up to one-third of the florets by increase in grain size in the remainder of the panicle.

Hamilton et al. (1982) reported full grain compensation in the hybrid CSH 6 when the panicles lost up to 20% of their kernels at the base of the panicle or at random. So far, entomologists have paid little attention to the capacity of different sorghum cultivars to compensate for midge damage, and this mechanism remains to be studied. In itself it may have little potential, but it would be useful to associate it with nonpreference for oviposition and resistance to the larva.

Evasion

It is important to distinguish between host evasion of pest attack and escape in time. Escape, either in space or in time is a pseudoresistance, due to chance; it does not have a genetic basis and cannot be used by the plant breeder.

Host evasion of a pest is due to a plant character, has a genetic basis, and can consequently be used in a breeding program in order to lower the damage done by an insect.

At least two traits contribute to evasion in sorghum of the midge: earliness of flowering and short duration of anthesis. Early varieties when planted at the proper time can evade damage (Painter 1951). A sorghum line with a shorter period of anthesis would be exposed for a shorter period of time to oviposition by midges. Significant variation of the anthesis period has been observed among sorghum lines. A range between 5.0 days for SC 423-14 and 8.9 days for AF 117 was observed by Rossetto (1977) in the greenhouse, and a range between 5.2 days for SC 423 and 7.8 days for TAM 428 was observed by Wuensche (1980) in the field.

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Head Bugs: Methodology for Determining Economic Threshold Levels in Sorghum

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Abstract

The determination of economic injury levels based on insect density-damage relationships is crucial to crop loss assessment and integrated pest management strategies. Methodology for determining pest density-damage relationships for several hemipteran species infesting sorghum panicles is described, including artificial infestation procedures, cages and their construction, and required data collection and analysis. Based on regression analysis of bug density to damage parameters, dynamic economic injury levels were established for Oebalus pugnax *(F.),* Nezara viridula *(L.),* Chlorochroa ligata *(Say), and* Leptoglossus phyllopus *(L.) and are presented as a case study. The largest reductions in yield occurred when panicles were infested from milk stage to maturity (28 days). No yield reductions occurred when panicles were infested during hard dough, the last 10 days of grain development, at levels up to 16 bugs per panicle. Regression analyses indicated that percent yield reductions increased quadratically as the number of bugs increased per panicle. Equations [$E(Y)=bX^2$] were determined which estimated percent yield losses at different infestation levels for infestations from milk and soft-dough stages to maturity, and these were used to calculate economic injury levels for each species.*

Résumé

Punaises des panicules—méthodologie pour la détermination du seuil économique chez le sorgho : *La détermination des seuils de nuisibilité économique fondés sur le rapport densité parasitaire/dégâts est indispensable à l'évaluation des pertes de récolte et les stratégies de la lutte intégrée. La méthodologie pour déterminer le rapport densité parasitaire/dégâts est expliquée pour plusieurs espèces hémiptères qui infestent les panicules de sorgho. L'infestation artificielle, les cages et leur construction ainsi que la collecte des données et leur analyse sont décrites aussi. L'analyse de régression de la densité parasitaire par rapport aux paramètres de dégâts, a permis d'établir les seuils de nuisibilité économique pour* Oebalus pugnax *(F.),* Nezara viridula *(L.),* Chlorochroa ligata *(Say) et* Leptoglossus phyllopus *(L.), présentés ici en tant qu'une étude de cas. Les pertes de récolte sont les plus élevées lorsque l'infestation se produit à partir du stade laiteux jusqu'à la maturation (28 jours). Au stade pâteux (dur) pendant les 10 derniers jours du développement des grains, les pertes sont presques nulles à une densité parasitaire allant jusqu'à 16 punaises par panicule. L'analyse de régression indique que tout accroissement du nombre de punaises par panicule entraîne une augmentation quadratique du pourcentage des pertes de rendement. L'équation $E(Y)=bX^2$ permet de déterminer le pourcentage des pertes de rendement à différents niveaux d'infestation depuis les stades laiteux et pâteux (moelleux) jusqu'à la maturation. A partir de ces pourcentages, sont calculés les seuils de nuisibilité économique pour chaque espèce.*

Successful insect pest management in sorghum requires a good understanding of the pest complexes within each agroecosystem. Key, secondary, and occasional pest species must be distinguished, and information on their biology and ecology obtained in order to develop pest management strategies. Strategies for managing different pests must be compatible. The management

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approach is generally better than a dependence on pesticides for pest control and is usually also more economical.

Economic injury levels constitute a crucial component of a pest management system. They define the level of a pest population below which damage is tolerable and above which emergency pest control elements must be invoked or applied to avoid economic damage and an outbreak of the pest (U.S. National Academy of Sciences 1969). Damage is economic when its worth is greater than the cost of pest control. An economic injury level is the lowest level of pest density causing economic damage. A pest's economic injury level is usually higher than its economic threshold level, which is the level of an increasing pest density at which control measures are imposed to prevent a pest from reaching the economic injury level. Establishing economic injury levels is essential to integrated control or pest management programs and crucial to the efficient use of pesticides (Stern 1966; Stone and Pedigo 1972; Ogunlana and Pedigo 1974; Stewart and Khattat 1980). The determination of economic injury levels is usually based on damage-density relationships between crop and pest. Economic injury levels are known for few insect pests. This paper outlines the methodology for determining density-damage relationships from which economic injury levels are 'determined, to establish economic threshold levels for head bugs attacking the panicles of sorghum.

Species of true, or hemipterous, bugs that infest panicles of sorghum comprise a complex which varies geographically. At least 17 different species are known worldwide. Common species in North America include the rice stink bug, *Oe balus pugnax* (F.); southern green stink bug, *Nezara viridula* (L); conchuela stink bug, *Chiorochroa iigata* (Say); leaf-footed bug, *Leptoglossus phyllopus* (L); and a false chinch bug, *Nysius raphanus* (Howard). Adult bugs move from alternate host plants to sorghum during grain development, and large infestations occasionally occur (Hall and Teetes 1981). The earhead bug, *Calocoris angustatus* Leth., has long been considered to be a major pest of sorghum in southern India (Young and Teetes 1977) and the problem seems to be increasing with the introduction of high-yielding cultivars (Seshu Reddy 1982). Considerable damage caused by several species of head bugs has been observed in Africa (L.R. House and N.G.P. Rao, personal communication). Yet little is known of the biology, ecology, population dynamics, carryover, or even loss levels caused by the head bug complex.

Sorghum is a reported host plant of a number of species of panicle-feeding bugs, including the rice stink bug (Dahms 1942), southern green stink bug (Hoffman 1935), conchuela stink bug (Morrill 1907), leaf-footed bug (Forbes 1920), and sorghum earhead bug (Young and Teetes 1977). Other species infesting sorghum panicles in the USA are *Leptoglossus zonatus* L (Hayes 1922), Say stink bug, *Chiorochroa sayi* (Stal) (Russell 1952), brown stink bug, *Euschistus servus* (Say)(Wiseman and McMillian 1971), western brown stink bug, *E.impictiventus* (Say) (Russell 1952), *E. conspersus* Uhler (Toscano and Stern 1976), *Thyanta* spp (Esselbaugh 1948), and the false chinch bug (Wood and Starks 1972; Teetes et al. 1974). While the list is extensive, the species of panicle-feeding bugs in sorghum tend to vary across the USA, being abundant in some areas but not in others.

The earhead bug is a key pest of sorghum in India (Young and Teetes 1977), and *Eurygastor integriceps* Puton is an occasional pest of sorghum in the Near East (Anonymous 1980). Several species of panicle-feeding bugs have been reported as pests in Africa, including the Sudan millet bug, *Agonoscelis pu bescens* (Thnb.) (Whitfield 1929); *Mirperus* spp, and *Riptortus* spp (Bowden 1966); a cotton stainer, *Dysdercus superstitiosus* F (Geering 1953); *Dolycoris indicus* (Stal); and *Spilostethus* sp, *Eurystylus rufocunealis,* and *Creontiades pallidas.*

Alternate host plants play an important role in infestations of panicle-feeding bugs in sorghum. Bugs, principally adults, move from alternate hosts to sorghum during grain development. The number of bugs moving into sorghum may depend upon alternate hosts available during grain development, densities of bugs present on these alternate hosts, and specific bug preferences.

Research on damage caused by panicle-feeding bugs to sorghum is limited, but reports indicate that some species cause severe damage to sorghum seed. During August 1978, in Luna County, New Mexico, USA, damage to grain by bugs (primarily Say stink bug) was severe, and approximately 12 000 ha of sorghum were treated two or three times for control (Anonymous 1979). In 1922, *L. phyllopus* and *L. zonatus* were reported by Hayes as pests of developing sorghum grain. Dahms (1942) determined that 5 rice stink bugs per panicle caused some injury to sorghum seed, while 25 or more prevented production of normal seed. The false chinch bug reduced seed weight, number, and germination in tests conducted by Wood and Starks (1972). Teetes et al. (1974) showed that this species significantly reduced yield of grain when present in large numbers, and suggested 140 bugs per panicle as an economic threshold level.

During 1970, several species of panicle-feeding bugs, primarily leaf-footed bug and southern green stink bug, seriously damaged late-planted sorghum in Georgia (Wiseman and McMillian 1971). These authors reported that damaged seeds weighed only one-sixth as much as undamaged seeds. The sorghum earhead bug feeds on developing grain, apparently causing seed shrinkage and distortion, thereby reducing yield (Young and Teetes 1977). According to these authors, both adults and nymphs cause damage to grain.

Little research has been conducted on the nature and intensity of damage caused by panicle-feeding bugs. Bugs damage sorghum grain by injecting digestive enzymes into developing seed and sucking the partially digested material from the grain, reducing both yield and quality (Young and Teetes 1977). Forbes (1920) reported that the leaf-footed bug seriously damaged developing corn kernels during the milk stage, apparently poisoning seed tissues at feeding sites and distorting seed growth. According to Wood and Starks (1972), extensive feeding by the false chinch bug usually results in underdeveloped seeds that are smaller, softer, and lighter than undamaged seeds.

Dahms (1942) reported that infestations of the rice stink bug during the bloom stage of grain development caused the most damage to grain; more mature plants were injured less, and differences existed with respect to varieties of sorghum in injury and bug preference. During the bloom stage in rice, feeding by the rice stink bug has an effect on seed development resembling sterility (Odglen and Warren 1962). Kernel spot is a type of damage associated with feeding by bugs in some crops. Rice stink bugs cause pecky rice (Douglas 1939), which may result from introduced fungi (Odglen and Warren 1962), and several species of Hemiptera cause kernel spot of pecan, including the southern green stink bug, leaf-footed bug, and brown stink bug (Turner 1923). Bowden (1966) concluded that sorghum seeds with shrunken areas and/or necrotic spots surrounding small scars had been damaged by bugs. According to Young and Teetes (1977), sorghum seed infested by bugs is often infected with a fungus *(Alternaria* sp), giving a black appearance to the grain and further lowering seed quality.

Some phytophagous bugs, including the rice stink bug, southern green stink bug, conchuela stink bug, and leaf-footed bug, deposit a stylet sheath or tract at feeding sites. Stylet sheaths guide and protect the feeding stylets and reduce contact between mouthparts and plant tissues (Miles 1959). An external, volcano-shaped flange is initially secreted onto the plant surface at the feeding site (Miles 1959; Pollard 1977). As stylets are inserted, an internal feeding sheath is formed. Stylet sheaths, especially their external flanges, have been used as feeding indicators (Wiseman and McMillian 1971; Bowling 1979, 1980).

Economic injury levels are difficult to determine, especially when a pest causes indirect damage (Chant 1966; Stone and Pedigo 1972). Stern (1966) presented three empirical methods of establishing economic injury levels, each requiring visual examination of loss. Stone and Pedigo (1972) presented a deductive approach to establishing these levels for the green cloverworm in soybean, based on a linear model relating damage to density, integrated with cost, marketing, and yield data from economists and agronomists. Ogunlana and Pedigo (1974) established damage-density relationships of potato leafhopper in soybean and, following the approach used by Stone and Pedigo (1972), determined economic injury levels. These authors found yield to be linearly related to infestation densities.

Economic injury levels of tarnished plant bug in green bean were determined by Stewart and Khattat (1980) using wholesale bean prices, a range of control costs, and the regression equation,

$$E[Y] = a + bX$$

where E[Y] was the expected yield below which loss was greater than the cost of controlling tarnished plant bug, a was the expected yield of uninfested beans, b was the slope, and X the number of bugs per plant. These authors defined economic damage as (a-Y), and the economic injury level (EIL) per control cost as

$$EIL = \text{economic damage}/b \text{ (absolute value).}$$

Economic injury levels are dynamic, varying with a number of factors. Ogunlana and Pedigo (1974) found that these levels varied for potato leafhopper on soybean depending on the stage of plant growth attacked, value of the crop, cost of pest control, and the environment of the plant and insect.

Density-Damage Relationships

Bug Damage to Kernels

Panicle-feeding bugs feed primarily on seeds and, to a lesser extent, on the stem and rachis branches. Stink bugs have piercing-sucking mouthparts which they insert into plant tissues for feeding; enzymes are released at feeding sites and the partially digested material is ingested. Feeding on seeds reduces grain weight, size, quality, and germination. Non-seed feeding may reduce seed yield indirectly. The number of feeding punctures per seed and percentage of seeds punctured on infested panicles depend on the infestation period and number of bugs present. Bugs may puncture every seed on a panicle, and some seeds may have more than 10 feeding wounds each. Bugs deposit a volcano-shaped stylet sheath at feeding sites, which protects the mouth parts and which is often used as an indicator of feeding activity. Stylet sheaths are translucent and small, but staining techniques facilitate sheath detection and counting.

During years of abundant rainfall, grain molds may develop on infested panicles. Some molds give punctured seeds a black appearance and seed quality may further deteriorate. Extensive insect feeding usually results in underdeveloped seeds that are smaller, softer, and lighter weight than undamaged seeds. Such damaged seed reduces bushel weight and may be lost during harvest.

The seed development stage strongly influences the extent of damage caused by panicle-feeding bugs. Sorghum grain development begins shortly after a panicle is exserted from the boot, approximately 60 days after seedling emergence for commonly used U.S. hybrids. The entire grain developmental process takes about 36 days and progresses through an anthesis or flowering stage (about 8 days), a milk stage (about 8 days), a soft-dough stage (about 10 days), and a hard-dough stage (about 10 days) before reaching maturity. During the anthesis stage, flowering begins at the top of the panicle and progresses toward the base; the point when the top half of a panicle has flowered is called 50% flower. Panicles enter the milk stage, soft-dough stage, and hard-dough stage of grain development about 7, 15, and 25 days, respectively, after 50% flower.

Panicle-feeding bugs cause more damage to seeds early during grain development, and less damage as grain develops to the hard-dough stage. Bugs cause the most damage when infestations begin early during grain development and persist to grain maturity. Infestations of bugs during the anthesis stage of grain development cause reductions in the number of seeds *per* panicle, while later infestations cause reductions in the weight and size of seed.

In the sorghum field, panicles damaged by bugs can usually be distinguished by their number of smaller and sometimes shriveled seeds. Visible insect damage increases as infestation densities increase, and is more pronounced when infestations begin during the anthesis or milk stages.

Infestation Methods

Natural infestations of bug species seldom occur at desired densities or times, and usually individual sorghum panicles must be caged and artificially infested at certain constant bug densities of a given species at various stages of grain development for different durations.

Cages used to cover individual panicles can be of a sleeve type slipped over a panicle and fastened snugly around the peduncle (Fig. 1). A rectangular piece of light-weight nylon screen is sewn by machine to make a screen cylinder 31 cm tall and 15 cm in diameter. Each screen cylinder is slipped onto a simple frame made of three narrow acetate rings spaced equally along and attached between two wooden garden stakes (30.5 x 2.5 x 0.3 cm). Once inside the sleeve, the frame forms a structural liner.

Each end of the screen sleeve is fitted with a cloth-tube extension 18 cm in length (Fig. 1). Cloth tubes are made of a rectangular piece (47.0 x 17.8 cm) of cotton-polyester fabric and are attached to ends of the screen cage with staples. When the sleeve cage is placed over a panicle, the bottom cloth-extension is fastened around the peduncle with rubber bands. Cages are placed over plants during the boot stage of plant development and secured as panicles began to emerge. This technique facilitates cage placement and removal. The top opening of each cage is tied closed with one end of a piece of string about 1 m long.

Cage support is of a suspension type. In the field, an overhead wire is stretched over each row of plants to be caged, and attached to wooden posts. The free end of the string used to tie the cage top closed is looped over the overhead wire and tied with a slip-knot (Fig. 1). Cage weight is thus sup-

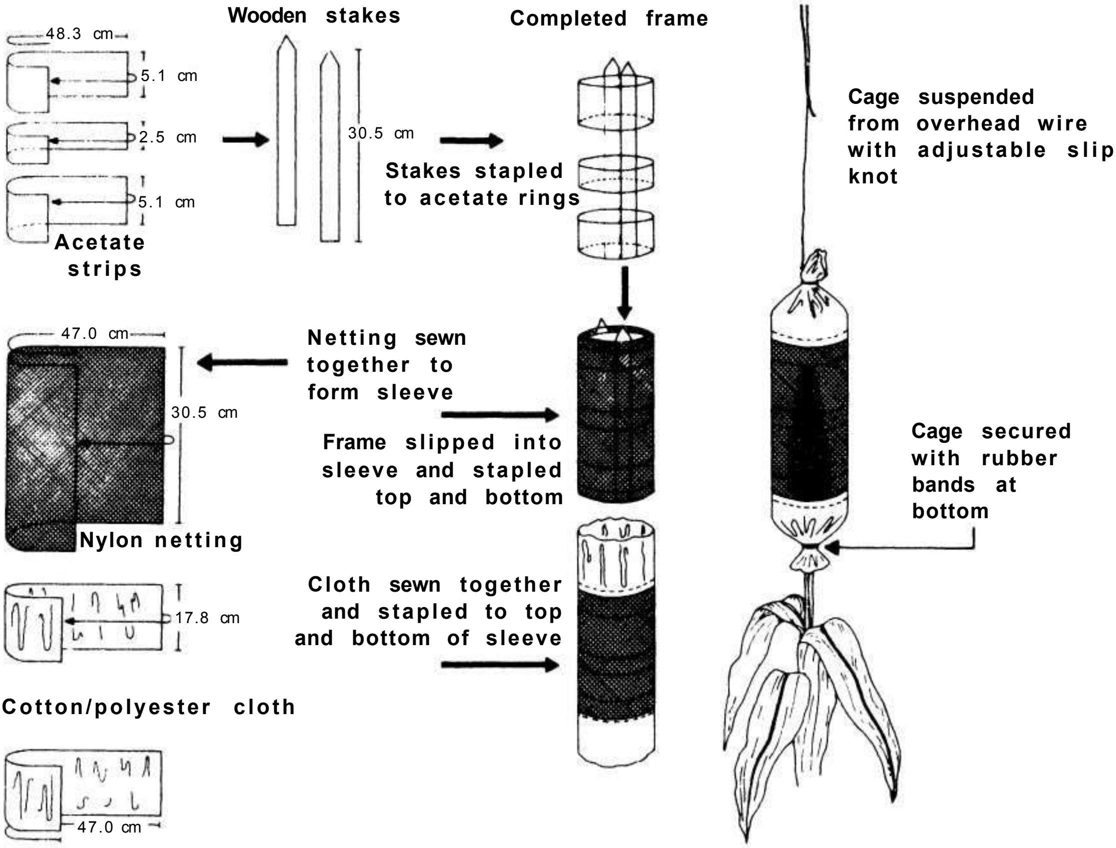

Figure 1. Nylon screen suspension cage for artificial infestation of sorghum panicles with head bugs.

ported by the wire rather than the plant, and one such wire can support several cages. To prevent the cage from touching the panicle, cage position is adjusted as plant height increases. Another, simpler cage construction is illustrated in Figure 2.

In order to assess damage to grain caused by a constant infestation density of bugs, panicles can be infested from the anthesis, milk, soft-dough, and hard-dough stages through maturity (36, 28, 20, and 10 days, respectively). Panicles can also be infested during individual stages of grain development in order to assess damage by bugs during each developmental stage. Panicles at the appropriate stage are selected and randomly infested at one of several infestation levels, such that a number of panicles are infested at each level of bug density during each infestation period.

Adult and/or nymphal (depending on species) bugs are placed on panicles in cages at the appropriate stage of grain development and are removed after the designated infestation period. Panicles should be checked every 2 days to maintain constant bug infestation densities. Panicles are harvested at maturity, weighed, and then hand-threshed. Data are collected on the prethreshed weight of panicles, gross seed weight per panicle, threshed weight of panicles, and 1000-seed weight. Gross seed weight and prethreshed weight of panicles are used to calculate threshing percentages or percent thresh (percent seed weight per panicle). One hundred seeds are selected from each of five panicles per infestation level, stained with an acid fuchsin dye, and examined for feeding damage. Seeds bearing stylet sheaths are classified as being damaged.

Data are also collected on the percentage of seeds punctured per panicle, the number of feeding punctures per seed, and the weight of damaged and undamaged seeds. Panicles from each infestation level should be selected and 100 seeds from

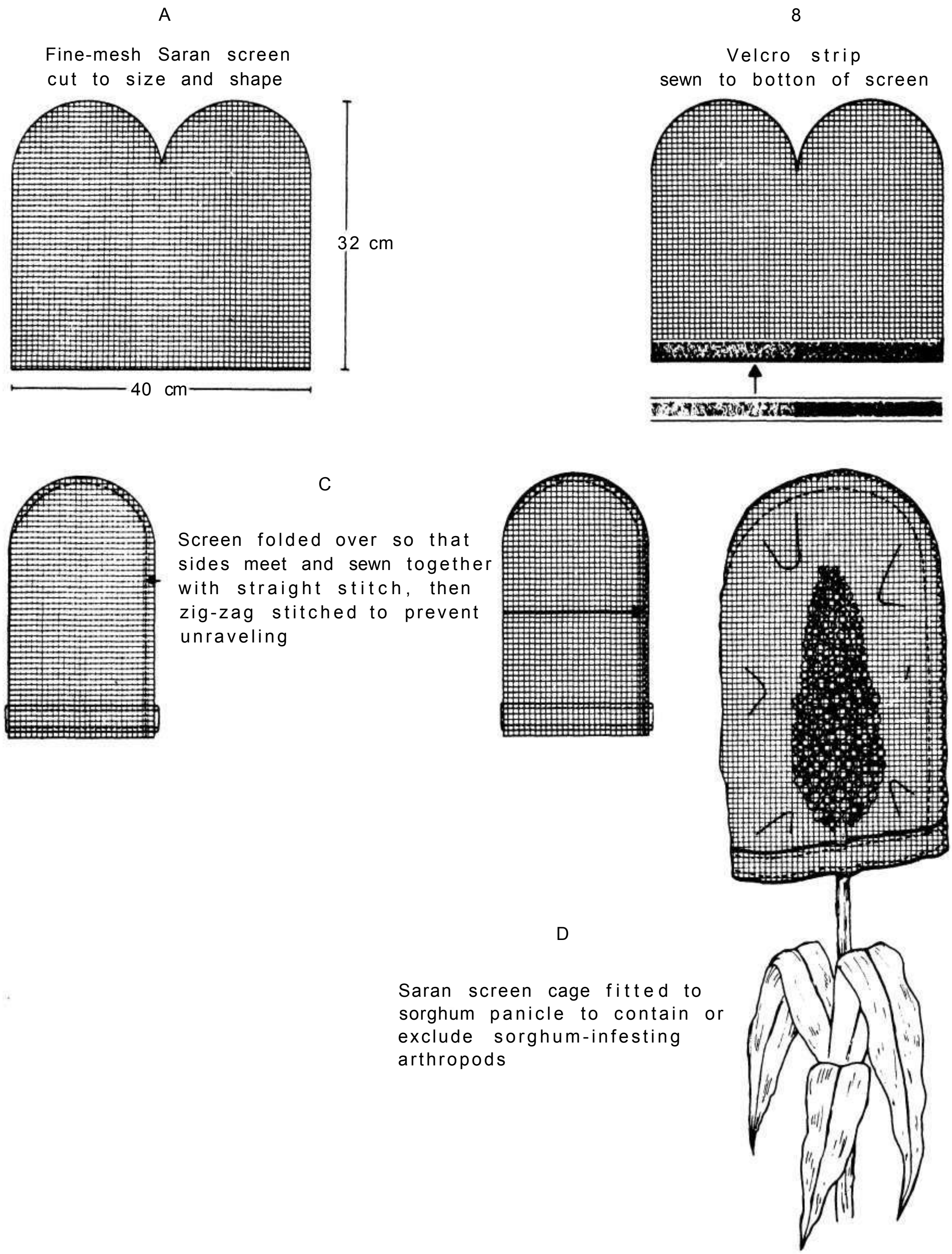

Figure 2. Fine-mesh Saran® screen cage fitted over sorghum panicle for artificial infestation with head bugs.

each panicle subjected to a germination trial (rolled-towel method; 8 h light at 30° C, 16 h dark at 20° C). Using acid fuchsin dye, the stem, 10 rachis branches, and glumes from 100 seeds should be stained and examined for feeding punctures. All data can be analyzed using one-way analysis of variance. Comparisons among infestation levels are made using Duncan's New Multiple Range Test.

Yield Loss-Density Relationships

Simple linear models have been used to predict crop yield at different pest densities in order to establish economic injury levels (Stone and Pedigo 1972; Ogunlana and Pedigo 1974; Stewart and Khattat 1980). Stone and Pedigo (1972) reported economic injury levels for the green cloverworm, *Plathypena scabra* (F.), in soybean based on a quadratic relationship between percent defoliation and percent yield loss, assuming percent defoliation per larva was a constant.

The relationship between percent yield loss and infestation levels per panicle can be determined. Data on gross seed weight per panicle can be adjusted for differences in the relative size of panicles within each test to compare yields more accurately:

adjusted gross seed weight = (gross seed weight/threshed panicle weight) x (mean threshed weight of panicles)

Percent yield losses based on mean adjusted gross seed weight of uninfested panicles are then calculated. Regression analyses are conducted, and a deterministic model chosen to relate percent yield loss to the number of bugs per panicle.

Economic Injury Level Determination: A Case Study

Based on results reported by Hall and Teetes (1980, 1982a, 1982b), and using the methodology previously described, Hall and Teetes (1982c) developed yield-loss : pest-density relations for

Table 1. Mean adjusted[1] gross seed weights of sorghum panicles infested from milk stage to maturity (M-M) and soft dough to maturity (S-M) with rice stinkbug, southern green stinkbug, conchuela stinkbug and leaf-footed bug.[2]

Bug density	Rice stinkbug		Southern green stinkbug		Conchuela stinkbug		Leaf-footed bug	
	M-M	S-M	M-M	S-M	M-M	S-M	M-M	S-M
				1978				
0	49.2a	40.6a	30.9a	30.0a	22.6a	18.3a	24.2a	21.5a
2	42.2ab	42.5a	29.9a	24.9a	20.5a	18.7a	19.7a	21.6a
4	40.4b	40.8a	18.3b	28.6a	13.9b	18.8a	17.5a	17.7a
16	27.3c	35.8a	8.8c	20.1a	4.4c	11.4b	7.9b	14.9b
				1979				
0	46.5a	40.5a	34.6a	33.0a	28.6a	32.4a	48.1a	35.9a
2	44.6a	38.7a	26.9b	35.0a	21.5b	29.1a	44.7a	36.1a
4	38.4b	35.3ab	19.6b	34.2a	11.9c	30.1a	37.3b	35.8a
16	32.4c	28.8b	6.3c	22.7b	1.7d	26.3a	11.3c	26.7b
				1980				
0	65.3a		67.1a	57.7a			53.2a	57.9a
2	64.2a		62.2a	54.0a			50.1b	
4	62.4ab		54.8b	55.4a			50.0b	56.9a
6	62.2ab		51.1bc	53.3a			44.0c	52.7a
8	59.0ab		47.1c	50.6a			39.0d	49.8a
10	55.0bc							
12	48.1c							

1. Adjusted gross seed weight = (gross seed weight/threshed panicle weight x (mean threshed panicle weight per test).
2. Means in the same column followed by the same letter are not significantly different (α=0.05), Duncan's New Multiple Range Test.

four species of panicle-feeding bugs. Subsequently, they used the determined relationship to establish dynamic economic threshold levels.

Adjusted gross seed weights of panicles infested with rice stink bug, southern green stink bug, conchuela stink bug, and leaf-footed bug generally decreased as the number of bugs increased (Table 1). All four species caused larger reductions in gross seed weight when infested from milk to maturity (28 days) than when panicles were infested from soft dough to maturity (20 days). No significant reductions occurred in adjusted gross seed weights when panicles were infested from hard dough to maturity (10 days) with up to 16 bugs of any of the four species. These data indicated that bugs caused more damage to sorghum when infestations began early during grain development.

Mean adjusted gross seed weights of panicles not infested with bugs tended to vary between years, due to differences in environments and/or hybrids (Table 1). Panicles tended to be larger in 1980. Field observations and percent yield losses at each infestation level indicated that bugs generally caused less damage to large sorghum panicles than to small ones.

Significant regressions using the linear model, E(Y) = a+bX, were fitted to data collected on percent yield reductions of panicles infested from milk to maturity and soft dough to maturity. However, plots of the residuals suggested a quadratic term

Table 2. Analyses of covariance for variation among years in percent yield reductions caused by rice stinkbug, southern green stinkbug, conchuela stinkbug and leaf-footed bug, using density^2 as a covariate.

Infestation period	Source	d.f.	Partial SS	F-Value (Pr > F)
	......Rice stinkbug......			
Milk to maturity	Density^2	1	17343.80	41.62 (.0001)
	Density^2* Year	2	1874.02	2.25 (.1082)
	Error	203	84585.64	
Soft dough to maturity	Density^2	1	9276.44	11.76 (.0008)
	Density^2 *Year	1	2674.55	3.39 (.07)
	Error	138	108886.86	
	......Southern green stinkbug......			
Milk to maturity	Density^2	1	20279.16	36.34 (.0001)
	Density^2*Year	2	551.78	0.49 (.6112)
	Error	121	67518.85	
Soft dough to maturity	Density^2	1	3321.57	5.55 (.0203)
	Density^2*Year	2	4.30	0.00 (.9964)
	Error	107	64004.68	
	......Conchuela stinkbug......			
Milk to maturity	Density^2	1	50987.39	74.73 (.0001)
	Density^2*Year	1	805.06	1.18 (.2813)
	Error	66	45033.42	
Soft dough to maturity	Density^2	1	7195.25	9.07 (.0039)
	Density^2 *Year	1	1082.75	1.36 (.2478)
	Error	55	43638.41	
	......Leaf-footed bug......			
Milk to maturity	Density^2	1	20383.57	42.97 (.0001)
	Density^2*Year	2	482.99	0.51 (.6021)
	Error	151	71635.30	
Soft dough to maturity	Density^2	1	3926.81	6.71 (.0107)
	Density^2*Year	2	389.52	0.34 (.7115)
	Error	127	72476.50	

was needed in the model, and r^2 -values were low. The second order model,

$$E(Y)=a + b_1 X + b_2 X$$

fitted to data on mean percent yield losses combined over years was significant for infestation periods milk to maturity and soft dough to maturity and had r^2 values greater than 0.90, but this model did not fit data on individual observations.

Regression analyses indicated that the yield loss-density relationship for each of the four species of panicle-feeding bugs was best described by one model:

$$E(Y) = bX^2$$

where E(Y) was expected percent yield reduction, b the regression coefficient, and X^2 the number (squared) of adult bugs per panicle. Regressions using this quadratic model were significant for infestations of each bug species from milk stage to maturity and from soft dough to maturity. Based on r values and plots of the residuals, the quadratic model $E(Y) = bX^2$ generally fitted yield reduction data for these infestation periods better than other models. Regressions were not significant using any of the models for a yield loss-density relationship for panicles infested from hard dough to maturity with any of the four panicle-feeding bug species. It may be that significant yield reductions by bugs during this infestation period occur at densities higher than 16 per panicle, but this aspect remains to be studied.

The coefficient estimates (b) from regressions of yield loss data for infestations from milk stage and soft dough stage to maturity varied from year to year. To investigate the possibility of determining an average yield loss-density relationship, data collected on percent yield losses were combined over years for each infestation period. An analysis of covariance of the combined data for each bug species was conducted using

$$E(Y) = bX^2 + ai\ X^2$$

where E(Y) was the expected percent yield reduction, b the regression coefficient associated with the covariate density^2 (X^2), and ai X the interaction between the effect due to the ith year (a) and the covariate. Partial sums of squares from these analyses indicated that percent yield reductions were significant with respect to the covariate density, but not with respect to density^{2*} year interactions (Table 2). Density^2 was needed in the regression model for the data combined over years, but a year variable was not. Thus, the relationship between number of adult bugs per panicle and percent yield loss did not change significantly over years. Ogunlana and Pedigo (1974) used similar analyses to justify combining data over years to establish an average damage-density relationship associated with infestations of potato leafhopper in soybean.

Regressions using the model $E(Y) = bX^2$ were

Table 3. Regression analyses of percent yield loss data, combined over 1978, 1979, and 1980, against infestation densities of rice stinkbug, southern green stinkbug, conchuela stinkbug, and leaf-footed bug.

Bug	Infestation period	Fitted Model' $E(Y) = bX^2$	Standard errror of b	r value	F value	Pr>F
Rice stinkbug	Milk-maturity	$E(Y) = 0.16X^2$	0.025	0.64	144.8	0.0001
	Soft dough-maturity	$E(Y) = 0.08X^2$	0.037	0.32	15.7	0.0001
Southern green stinkbug	Milk-maturity	$E(Y) = 0.32X^2$	0.041	0.78	193.7	0.0001
	Soft dough-maturity	$E(Y) = 0.13X^2$	0.043	0.53	41.8	0.0001
Conchuela stinkbug	Milk-maturity	$E(Y)=0.35X^2$	0.051	0.81	126.0	0.0001
	Soft dough-maturity	$E(Y) = 0.11X^2$	0.061	0.42	12.8	0.0007
Leaf-footed bug	Milk-maturity	$E(Y) = 0.30X^2$	0.034	0.81	285.5	0.0001
	Soft dough-maturity	$E(Y) = 0.11X^2$	0.035	0.48	39.6	0.0001

1. E(Y) is percent yield reduction, b is the regression parameter, and X is the number (squared) of adult bugs per panicle during the indicated infestation period.

significant for percent yield loss data (combined over years) for infestations from milk and soft dough to maturity of each of the four panicle-feeding bug species. Statistics from these regressions (Table 3) indicated a relatively strong positive relationship between the number of bugs per panicle and percent yield reduction. Based on r values, the percent yield loss model did not fit to data from panicles infested from soft dough to maturity as well as to data from panicles infested from milk to maturity. The fitted regression equations represent average percent yield loss-density relationships (Fig. 3). Actual yield losses may vary, depending on environment and hybrid. A more robust model relating density and yield loss would incorporate information on the biology of the bug x plant interactions.

Economic threshold levels for infestations of bugs from milk and soft dough to maturity may be estimated for rice stink bug, southern green stink bug, conchuela stink bug, and leaf-footed bug using the regression equations in Table 3. Estimates of the market price of the crop and cost of controlling panicle-feeding bugs are used to calculate minimum economic damage or the gain threshold (Stone and Pedigo 1972) as a percentage rather than a monetary amount: percent gain threshold = (control cost/market value) x 100. The economic injury level (EIL) for a given gain threshold may then be calculated for the appropriate infestation period, where

$$EIL = \sqrt{E(Y)/b}$$

the gain threshold is plugged into E(Y), and the b

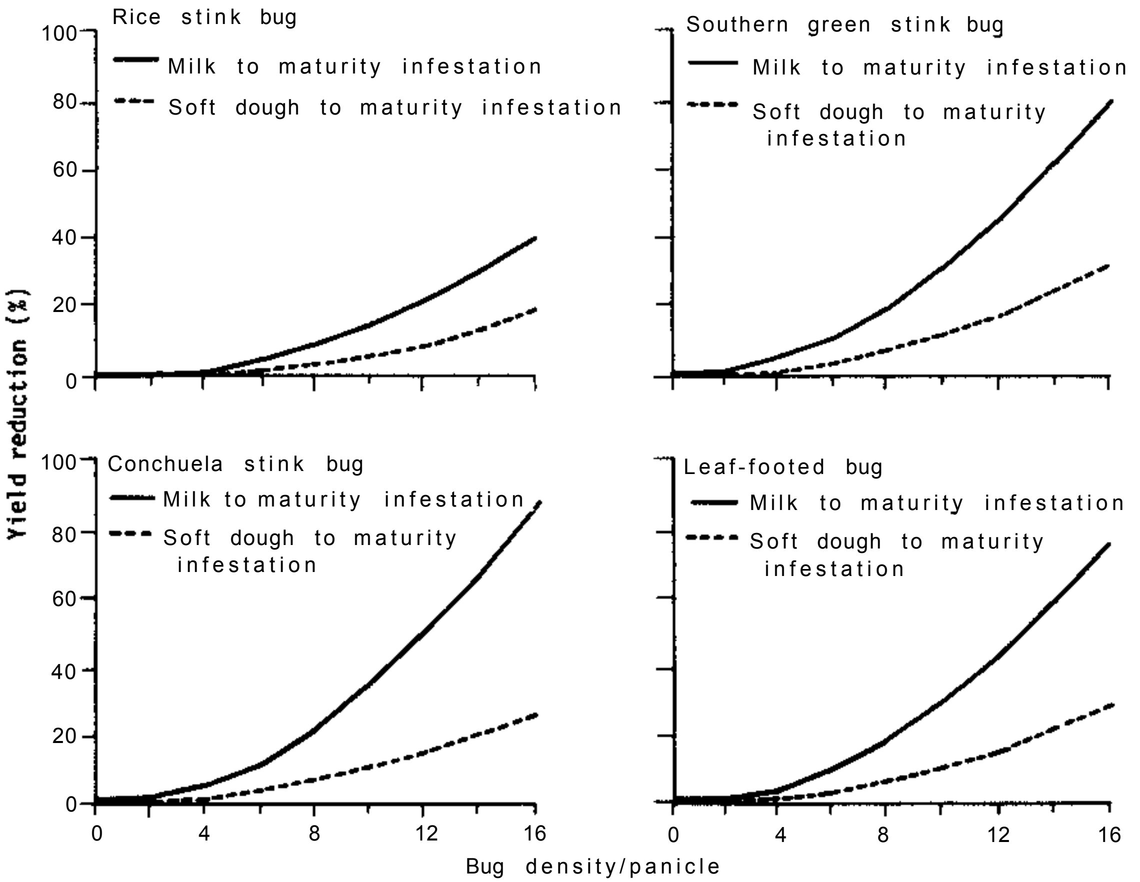

Figure 3. Regressions of percent yield data, combined over years, against infestation densities per panicle of rice stink bug, southern green stink bug, conchuela stink bug, and leaf-footed bug (see Table 3 for fitted regression equations).

value from the regression equation is used. For example, if the cost of controlling bugs is U.S.$5.00 per acre (0.4 ha) and the market value of grain is $115.00 *per* acre, the percentage gain threshold would be 5.00/115.00 x 100 = 4.35. The economic injury level for an infestation of rice stink bug beginning at the milk stage of grain development would be calculated using the regression coefficient determined for milk to maturity infestation period (b = 0.16):

$$\text{EIL} \ \sqrt{4.35/0.16} = 5.2 \text{ rice stink bugs/panicle.}$$

A yield loss-density relationship based on percentages allows producers faced with different gain thresholds to calculate EILs more easily. The infestation period must be estimated to calculate economic injury levels. Economic injury levels of rice stink bug, southern green stink bug, conchuela stink bug, and leaf-footed bug were higher than 16 adult bugs per panicle when infestations occurred during just the last 10 days of grain development, as regression analyses indicated yield was not significantly reduced by up to 16 bugs per panicle during this infestation period.

Regression analyses indicated that yield reductions increased quadratically as the number of

Table 4. Economic injury levels—calculated for a range of control costs and market values—for rice stinkbug infesting sorghum at anthesis, milk stage, and soft dough stage.

Control cost (U.S.$/acre)	Value (U.S.$/acre): 100	110	120	130	140	150	160	170	180	190	200	210	220
	Economic injury level (no. bugs/panicle)												
	Infested at anthesis												
2	3	3	3	3	3	3	3	2	2	2	2	2	2
3	4	4	4	4	3	3	3	3	3	3	3	3	3
4	5	4	4	4	4	4	4	3	3	3	3	3	3
5	5	5	5	4	4	4	4	4	4	4	4	4	3
6	6	5	5	5	5	5	4	4	4	4	4	4	4
7	6	6	5	5	5	5	5	5	4	4	4	4	5
8	6	6	6	6	5	5	5	5	5	5	5	4	4
9	7	6	6	6	6	6	5	5	5	5	5	5	5
10	7	7	7	6	6	6	6	5	5	5	5	5	5
	Infested at milk stage												
2	4	4	4	4	3	3	3	3	3	3	3	3	3
3	5	5	4	4	4	4	4	4	4	4	4	3	3
4	5	5	5	5	5	5	4	4	4	4	4	4	4
5	6	6	6	5	5	5	5	5	5	5	4	4	4
6	7	6	6	6	6	6	5	5	5	5	5	5	5
7	7	7	7	6	6	6	6	6	5	5	5	5	5
8	8	7	7	7	6	6	6	6	6	6	6	5	5
9	8	8	7	7	7	7	6	6	6	6	6	5	5
10	8	8	8	7	7	7	7	7	6	6	6	6	6
	Infested at soft dough stage												
2	5	5	5	5	5	5	4	4	4	4	4	4	4
3	7	6	6	6	6	5	5	5	5	5	5	5	5
4	8	7	7	7	6	6	6	6	6	6	6	5	5
5	8	8	8	7	7	7	7	7	6	6	6	6	6
6	9	9	8	8	8	8	7	7	7	7	7	6	6
7	10	9	9	9	8	8	8	8	7	7	7	7	7
8	10	10	9	9	9	9	8	8	8	8	8	7	7
9	11	11	10	9	9	9	9	9	8	8	8	8	8
10	12	11	10	10	10	10	9	9	9	9	8	8	8

1. Acre = 0.4 ha.

bugs per panicle increased, especially when grain was infested during anthesis and from milk to maturity. At the infestation densities studied, significant yield reductions occurred when panicles were infested during anthesis, from milk to maturity, and from soft dough to maturity, but not when infested from hard dough to maturity. Equations were determined which estimated yield losses at different infestation levels, and economic injury levels were calculated for different control costs and crop market values. Whether or not a producer should control an insect infestation depends on the stage of grain development at the time bugs move into sorghum, the number of bugs per panicle, the cost of controlling bugs, and the market value of the grain.

Using the Tables

To determine the profitability of controlling an infestation of rice, southern green, or conchuela stink bugs, or leaf-footed bugs, calculate the per acre control cost (insecticide and application) and the expected per acre market value of the grain (yield x price). Next, determine the approximate grain development stage when the infestation occurred. If the estimated stage of development is hard dough and the infestation level per panicle is 16 bugs or less, do not control bugs. For bug infestations beginning at the milk or soft-dough stages, consult the economic injury level tables. Economic injury levels for infestations of rice stink bugs per panicle at which control is justified is indicated for a given control cost and market value. The economic threshold level for an infestation of false chinch bug is 140 bugs per panicle when infestations begin at the milk stage of grain development. Economic thresholds for the rice stink bug are given in Table 4; for southern green stink bug, in Table 5; for conchuela stink bug, in Table 6; and for leaf-footed plant bug, in Table 7.

A method that can be used to establish the average number of bugs per head is the "beat-bucket"

Table 5. Economic injury levels—calculated for a range of market values and control costs—for adult southern green stinkbug infesting sorghum.

Control cost (U.S.$/acre)	Economic injury level (no. bugs/panicle) Value (U.S.$/acre): 100	110	120	130	140	150	160	170	180	190	200	210	220
	Infested at milk stage												
2	3	3	3	3	3	3	2	2	2	2	2	2	2
3	4	3	3	3	3	3	3	3	3	3	3	3	3
4	4	4	4	4	3	3	3	3	3	3	3	3	3
5	4	4	4	4	4	4	4	4	3	3	3	3	3
6	5	5	4	4	4	4	4	4	4	4	4	3	3
7	5	5	5	5	5	4	4	4	4	4	4	4	4
8	5	5	5	5	5	5	4	4	4	4	4	4	4
9	6	6	5	5	5	5	5	5	4	4	4	4	4
10	6	6	6	5	5	5	5	5	5	5	4	4	4
	Infested at soft dough stage												
2	4	4	4	4	4	4	4	4	3	3	3	3	3
3	5	5	5	5	5	4	4	4	4	4	4	4	4
4	6	6	6	5	5	5	5	5	5	5	4	4	4
5	7	6	6	6	6	6	5	5	5	5	5	5	5
6	7	7	7	6	6	6	6	6	6	5	5	5	5
7	8	7	7	7	7	6	6	6	6	6	6	6	5
8	8	8	8	7	7	7	7	7	6	6	6	6	6
9	9	8	8	8	8	7	7	7	7	7	6	6	6
10	9	9	8	8	8	8	7	7	7	7	7	7	6

1. Acre = 0.4 ha.

Table 6. Economic injury levels—calculated for a range of control costs and market values—for adult conchuela stinkbug infesting sorghum.

Control cost (U.S.$/acre)	Economic injury level (no. bugs/panicle) — Value (U.S.$/acre): 100	110	120	130	140	150	160	170	180	190	200	210	220
2	3	3	3	3	3	2	2	2	2	2	2	2	2
3	3	3	3	3	3	3	3	3	3	2	3	3	2
4	4	4	4	3	3	3	3	3	3	3	3	3	3
5	4	4	4	4	4	4	3	3	3	3	3	3	3
6	5	4	4	4	4	4	4	4	4	4	3	3	3
7	5	5	5	4	4	4	4	4	4	4	4	4	4
8	5	5	5	5	5	4	4	4	4	4	4	4	4
9	6	5	5	5	5	5	5	4	4	4	4	4	4
10	6	6	5	5	5	5	5	5	4	4	4	4	4
	Infested at soft dough stage												
2	5	5	4	4	4	4	4	4	4	4	4	3	3
3	6	5	5	5	5	5	5	5	4	4	4	4	4
4	7	6	6	6	6	5	5	5	5	5	5	5	5
5	7	7	7	6	6	6	6	6	6	5	5	5	S
6	8	8	7	7	7	7	6	6	6	6	6	6	5
7	8	8	8	7	7	7	7	7	6	6	6	6	6
8	9	9	8	8	8	7	7	7	7	7	7	6	6
9	10	9	9	8	8	8	8	7	7	7	7	7	7
10	10	10	9	9	9	8	8	8	8	7	7	7	7

1.1. Acre = 0.4 ha.

technique. Use the bottom 10 inches of a 5-gallon plastic bucket and shake the heads into the bucket with a sharp strike. The bugs from each head can then be counted.

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Table 7. Economic injury levels—calculated for a range of market values and control costs—for adult leaf-footed bug infesting sorghum.

Control cost (U.S.$/acre)	Value (U.S.$/acre): 100	110	120	130	140	150	160	170	180	190	200	210	220
	Economic injury level (no. bugs/panicle)												
	Infested at milk stage												
2	3	3	3	3	3	3	3	2	2	2	2	2	2
3	4	4	3	3	3	3	3	3	3	3	3	3	3
4	4	4	4	4	4	3	3	3	3	3	3	3	3
5	5	4	4	4	4	4	4	4	4	3	3	3	3
6	5	5	5	4	4	4	4	4	4	4	3	4	4
7	5	5	5	5	5	4	4	4	4	4	4	4	4
8	6	5	5	5	5	5	5	4	4	4	4	4	4
9	6	6	5	5	5	5	5	5	5	4	4	4	4
10	6	6	6	6	5	5	5	5	5	5	5	4	4
	Infested at soft dough stage												
2	5	5	4	4	4	4	4	4	4	4	4	3	3
3	6	5	5	5	5	5	5	5	4	4	4	4	4
4	7	6	6	6	6	5	5	5	5	5	5	5	5
5	7	7	7	6	6	6	6	6	6	5	5	5	5
6	8	8	7	7	7	7	6	6	6	6	6	6	5
7	8	8	8	7	7	7	7	7	6	6	6	6	6
8	9	9	8	8	8	7	7	7	7	7	7	6	6
9	10	9	9	8	8	8	8	7	7	7	7	7	7
10	10	10	9	9	9	8	8	8	8	7	7	7	7

1. Acre = 0.4 ha.

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Screening for Host-Plant Resistance to Mirid Head Bugs in Sorghum

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Abstract

Mirid head bugs (Calocoris angustatus *Leth.,* Campylomma *spp,* Creontiades pallidus *Ramb., Eurystylus* bellevoyei *Reut, and*Taylorilygus vosseieri *Popp.) have become important pests of grain sorghum in recent years. The developmental biology of* C. angustatus *and* C. pallidus *have been studied, but little is known about the biology and carryover of the other species. Use of infester rows, split planting at 15-day intervals, arranging the material according to maturity groups, and use of overhead sprinklers to maintain high humidity have been suggested to increase the efficiency of screening for resistance to* C. angustatus *under field conditions.*

A headcage technique to screen under no-choice conditions has been developed. Maximum damage occurs when the head bugs are released into the headcages at the pre-anthesis stage; 10 to 15 field-collected pairs per head completely damage the susceptible cultivar CSH 1. Maximum head bug population buildup in the headcage has been recorded 20 days after release. Nearly 10 000 germplasm lines have been screened for head bug resistance under field conditions. Less susceptible cultivars have been screened in headcages over several seasons. Ten cultivars supporting lower head bug populations, suffering less grain damage, or showing <30% reduction in grain germination have been identified. However, the levels of resistance observed are not adequate or repeatable under heavy field infestation. The degree of susceptibility is influenced by the growth stage of the panicle, and head bug population and grain damage are also influenced by the panicle size. Loose panicle types tend to support lower populations, though, quite often, even cultivars with loose panicles are completely damaged. None of the floral characters seem to be associated with head bug susceptibility. Some cultivars are nonpreferred under both field and laboratory conditions; they are also less suitable for the growth and development of nymphs.

Résumé

Criblage pour la résistance de la plante-hôte aux punaises des panicules Miridae chez le sorgho : *Les punaises des panicules Miridae (*Calocoris angustatus *Leth.,* Campylomma *spp.,* Creontiades pallidus *Ramb.,* Eurystylus bellevoyei *Reut., et* Taylorilygus vosseleri *Popp.) ont récemment pris de l'importance en tant qu'insectes nuisibles au sorgho grain. La biologie de* C. angustatus *et de* C. pallidus *en développement a été étudiée, mais on connaît peu la biologie et l'hivernage des autres espèces. La mise en place des rangs infestés, les semis échelonnés aux intervalles de 15 jours, la disposition du matériel selon la durée de la maturation, et l'aspersion des plantes d'en-haut afin de maintenir un niveau élevé d'humidité sont quelques-unes des méthodes recommandées pour un criblage au champ plus efficace pour la résistance à* C. angustatus.

On a mis au point une technique de criblage en cage avec choix unique d'un seul cultivar. Les plus graves dégâts se produisent lorsque les punaises sont libérées dans les cages avant l'anthèse. Une intensité de 10-15 paires par panicule a suffit à détruire le cultivar sensible CSH 1. La pullulation atteint le maximum dans la cage 20 jours après les punaises y sont libérées. Un essai de résistance a été réalisé, au champ, sur près de 10000 accessions. Les cultivars moins sensibles sont criblés en cages au cours de plusieurs campagnes culturales. On a repéré dix cultivars ayant de faibles

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populations d'insectes, une proportion inférieure de grains endommagés ou bien une réduction de 30% de la germination des semences. Cependant, ces niveaux de résistance ne sont pas suffisamment élevés ni stables en cas d'une forte infestation au champ. Le degré de sensibilité dépend du stade de croissance de la panicule. Le nombre de punaises sur la panicule ainsi que le nombre de grains endommagés sont liés à la taille de la panicule. Les panicules lâches normalement peu infestées, sont parfois complètement détruites par ces ravageurs. La sensibilité d'une plante ne semble être liée à aucun caractère floral. Certains cultivars ne sont pas préférés pour la ponte en conditions réelles et au laboratoire, ils sont aussi moins favorables à la croissance et au développement des nymphes.

Introduction

Mirid head bugs are important pests of sorghum in Asia and Africa. Species belonging to four genera *(Calocoris, Campylomma, Creontiades,* and *Eurystylus)* are known to attack sorghum. However, the authentic species identification and economic importance in different sorghum-growing areas are largely unknown. Head bugs have gained importance in recent years with the introduction of early-flowering cultivars with compact panicles.

Of the various mirid species damaging sorghum panicles, *Calocoris angustatus* Leth. is the most important in India. Various species of *Campylomma* are important in India and Africa (Sharma et al. 1983b; Anonymous 1983) *Campylomma nicolasi* Put. and Reut. and *Taylorilygus vosseleri* Popp. are known to feed on sorghum in Africa (Schmutterer, 1969). *Creontiades pallidas* Ramb. and *Eurystylus* sp (£. *bellevoyei* Reut.) occur both in India and Africa (Anonymous 1983; Sharma et al. 1983b).

At ICRISAT Center, C. *angustatus, Campylomma* sp, C. *pallidas,* and £ *bellevoyei* constituted 96.0, 3.9, 0.1, and 0.01 % of the total head bugs collected from 75 panicles of CSH 1 at milk stage during the 1981 rainy season. In the 1981 /82 postrainy season, *Campylomma* comprised 62.3% of the total population, followed by C. *angustatus* (29.3%), *E. bellevoyei* (6.5%), and C. *pallidus* (0.2%) in TAM 2566. The head bug population is generally higher in sorghum grown on Vertisols than that grown on Alfisols. C. *angustatus* and *C pallidus are* more active at half-anthesis to milk stage, while *Campylomma* sp and *E. bellevoyei are* more active on milk to mature grain stages (Table 1).

In Nigeria, nearly six species of mirid bugs attack sorghum, of which *Eurystylus* sp comprised about 80% of the total population during 1982 on cv S 18 (a medium-duration cultivar). Up to 880 head bugs/ head have been recorded. In another observation, *Calocoris* sp accounted for 71 % of the total head bugs observed. During 1983, *Eurystylus* sp and *Campylomma* spp accounted for 63 and 29% of the total head bug population at Samaru (Anonymous 1983).

The exact yield losses caused by head bugs

Table 1. Distribution of four head bug species in relation to head maturity and soil type at ICRISAT Centre, Patancheru, India, 1980.

	No. of bugs/10 earheads			
	Calocoris	*Creontiades*	*Campylomma*	*Eurystylus*
Soil type				
Alfisols	3	1	47	1
Vertisols	186	2	82	1
Panicle development stage				
Preanthesis	23	0	2	0
25% anthesis	55	0	1	0
50% anthesis	63	1	5	0
Full anthesis	45	1	4	0
Postanthesis	39	0	6	0
Milky grain	87	0	10	4
Hard dough	46	1	40	15
Mature grain	8	0	104	4

have not been quantified. From five insecticidal trials in India, the avoidable losses due to head bugs have been worked out to be 43.9% (Leuschner and Sharma 1983). These losses were probably caused by all panicle pests together, and were recorded on research stations which usually have higher pest populations than farmers' fields. However, the losses can vary from 5.8 to 84.3% (Rangarajan et al. 1973; AICSIP 1980,1982; Subba Rao et al. 1980). Avoidable losses due to panicle pests have been estimated to cost over Rs. 972 million in India (Leuschner and Sharma 1983).

Because of high head bug damage during the rainy season, farmers in the Deccan plateau in India have traditionally planted photoperiod-sensitive cultivars that flower in periods of low head bug activity during October-November. Traditionally, in many areas, the sorghum crop grown during the rainy season is used only for fodder, while grain sorghums are mainly grown in the postrainy season when the populations of panicle-feeding insect pests such as head bugs and midge are low.

Nature of Damage

The mirid bugs feed mainly on the developing grains and occasionally on other tender parts of the plant. The nymphs and adults suck sap from the developing grains, which remain unfilled, shrivel, and, in severe infestations, become completely chaffy. Damage during the early stages of grain development results in heavy yield loss; later infestation results largely in quality loss. The damaged grains show distinct red-brown feeding punctures, and in cases of severe feeding become completely tanned. In addition, such grains are more prone to disease attack and show poor germination. There is hardly any scope for the plant to compensate for the damage.

Biology

The biology and seasonal activity of head bugs attacking sorghum has not been adequately investigated. Ballard (1916) and Cherian and Kylasam (1941) published notes on the biology of C. *angustatus.* Studies carried out at ICRISAT Center have shown that the females, after a pre-oviposition period of 2 to 4 days, lay cigar-shaped eggs inside the glumes before anthesis.

Eggs hatch in 7 to 8 days, and the five nymphal instars complete development in 8 to 12 days. A female lays 182±21 eggs during the rainy, and 113± 12 eggs during the postrainy, seasons. Maximum head-bug activity has been recorded during August-September, and a smaller peak occurs during March-April (Fig.1). Thimmaiah et al. (1972) reported maximum bug activity (77-78 bugs/head) in sorghum planted on 12 and 19 August at Dharwad. Balasubramanian and Balasubramanian (1979) studied the effect of climatic factors on head bug populations during May-June at Bhavanisagar and Coimbatore in Tamil Nadu, India. The population buildup was negatively correlated with the number of rainy days (r = -0.51), and not influenced by the temperature, sunshine, relative humidity, or

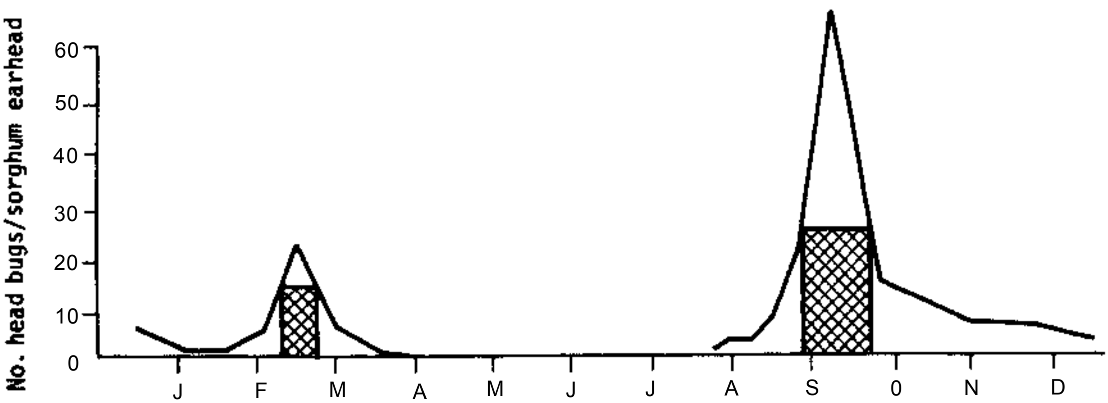

Figure 1. Population dynamics of sorghum earhead bug *(Calocoris angustatus)* at ICRISAT Center, 1981/82.

rainfall. However, maximum head bug incidence is normally observed during the second half of the rainy season. Crops planted during the late rainy season or postrainy season are comparatively less damaged. The off-season carryover of this bug is not known, except that the bugs are known to feed on fodder sorghum during the summer season.

Creontiades pallidus is an important pest of sorghum and cotton in Sudan (Schmutterer 1969). It lays cigar-shaped eggs in the milky grains after a pre-oviposition period of 2 to 5 days. Eggs hatch in 6 to 8 days, and the five nymphal instars complete development in 8 to 18 days. On cotton, the eggs are laid in the tender tips, and the development is completed in 17 to 20 days (Schmutterer 1969). Adults survive for 10 to 15 days. At ICRISAT Center, maximum population has been observed during October. In Sudan, the populations of this species are known to migrate from sorghum to cotton. During the off season, it is known to occur on *Cynodon* sp, in Congo. It also feeds on beans, cucurbits, eggplant, lucerne, etc. (Schmutterer 1969).

E. bellevoyei is a serious pest both in India and Africa. Eggs are laid in the grains and hatch in nearly 7 days. Nymphal development is completed in 7 to 8 days.

The biology of *Campylomma* spp has not been studied. C. *nicolasi* occurs in Sudan and feeds upon sorghum, cotton, tomato, cowpea, safflower, and *Hibiscus* spp.

Resistance Screening Techniques

Studies on resistance screening techniques, germplasm screening, and factors associated with resistance were confined to *Caiocoris angustatus.*

Field Screening

Screening for head bug resistance can be carried out under field conditions during periods of maximum bug activity. However, screening under field conditions is influenced by: (a) staggered flowering of sorghum cultivars; (b) bug population fluctuations, and (c) the effect of weather conditions on the head bug population buildup and damage. Early- and late-flowering cultivars normally escape head bug damage, while those flowering during midseason are exposed to very high populations. The following methods can be used to increase the screening efficiency for head bug resistance under field conditions.

Infester Rows

Infester rows of mixed maturity cultivars planted 20 days earlier than the test material help to build up the head bug population. Four rows of a susceptible cultivar can be planted after 16 test rows. Bugs collected from other fields can be spread among the infester rows at panicle emergence to build up the population.

Split Planting

The test material should be planted in two sets, with an interval of 10 to 15 days between plantings to reduce the chances of escape.

Maturity Groups

The material to be screened should be grouped and planted according to maturity and height. The sowing time of each group can be adjusted in such a way that flowering occurs during the peak activity period of the head bugs.

Sprinkler Irrigation

The use of sprinkler irrigation during the reproductive phase of the crop in the postrainy season helps to build up the head bug population.

Headcage Screening

To overcome the problem of staggered flowering and fluctuating insect populations, the headcage technique developed for midge resistance screening has been found to be useful for head bugs also. The headcage technique allows bug population buildup and grain damage to be studied under no-choice conditions in relation to different infestation levels and stages of panicle development.

Panicle Development Stage

Under headcage conditions, maximum head bug population buildup was recorded when the panicles were infested at pre-anthesis (Table 2). The population buildup and damage decreased significantly in panicles infested at postanthesis. Panicles

Table 2. Population buildup and damage with 10 and 15 pairs of *C. angustatus* under headcage on CSH 1 sorghum.

	No. of head bugs/head		Damage rating[2]	
Panicle development stage	10 pairs	15 pairs	10 pairs	15 pairs
Preanthesis	434(20.64)[1]	163(27.59)	4.90	5.00
Top-anthesis	213(14.48)	773(27.76)	3.50	5.00
Half-anthesis	61(7.46)	615(24.77)	3.40	5.00
Postanthesis	65(7.99)	40(6.16)	3.20	3.10
SE		SE		
No. of head bugs				
Panicle development stage		0.547		
No. of head bug pairs		0.291		
Visual score				
Panicle development stage		0.30		
No. of head bug pairs		0.30		

1. Figures in parentheses are square root transformations.
2. Damage rating:
   1 = grains fully developed. A few feeding punctures on the grains ;
   2 = grains showing slight shriveling and browning due to feeding punctures ;
   3 = grains half shriveled ;
   4 = Highly shriveled grains showing out of glumes;
   5 = Grains undeveloped; heads become chaffy.

infested with 10 pairs of bugs at pre-anthesis showed maximum grain damage while those infested with 15 pairs were completely damaged up to the half-anthesis stage. In another experiment, the head bug population buildup and grain damage were studied in five cultivars under a headcage (Fig. 2). Head bug population buildup decreased linearly with advance in panicle development at the time of infestation. Different levels of adult infestation did not show a linear response in population buildup recorded 20 days after infestation. Population buildup was significantly less on panicles infested with 5 pairs than those infested with 10 or 20 pairs. Minimum head bugs were observed in panicles infested with 20 pairs at milk stage, indicating possible food shortage resulting in death of the nymphs, or cannibalism among the head bugs. The extent of grain damage also decreased with progressive grain ripening; however, significant reduction in grain damage was only observed when adults were released at milk stage.

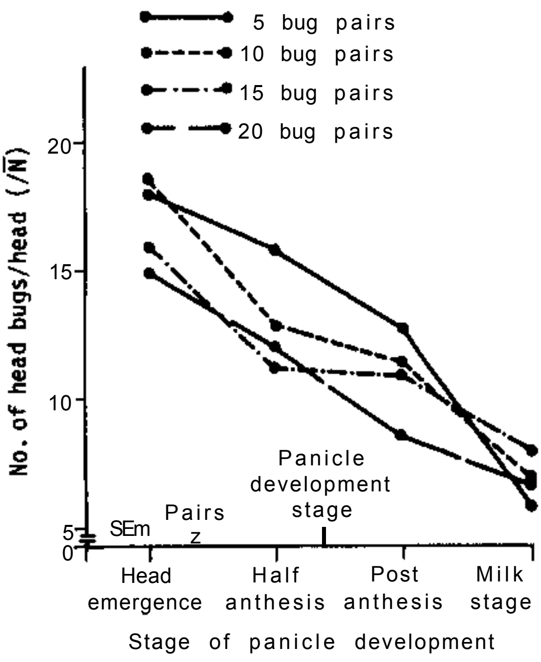

Figure 2. Susceptibility of different stages of earhead development to *Calocoris angustatus* at four levels of bug infestation (based upon five cultivars.)

Population Buildup and Infestation Levels

One of the problems observed under headcage testing was the variation in population buildup in different panicles Infested at the same time or at different times. This variation was studied at six infestation levels in SPV 351 (Fig. 3). The results showed that differences between 15, 20, and 25 pairs were nonsignificant. Significant differences were observed only between 15 and 30 pairs, and 30 and 50 pairs. The coefficient of variation (CV) was reduced to 11 % with 50 pairs; however, 50 pairs for resistance screening is too high; 10 to 15 pairs generally result in complete grain damage. The CV with 15 pairs is around 25%, which for insect numbers is not very high. Based on these observations, we decided to use 10 to 15 pairs for resistance screening in the headcage.

Laboratory-reared vs Field-collected Bugs

The population buildup was studied using 5, 10, 15, and 20 pairs of laboratory-reared and field-collected head bugs (Fig. 4). The population buildup was higher in panicles infested with field-collected bugs than in those infested with laboratory-reared ones at all levels of infestation. Panicles infested with 20 pairs recorded significantly higher head bug numbers than those infested with 5 pairs.

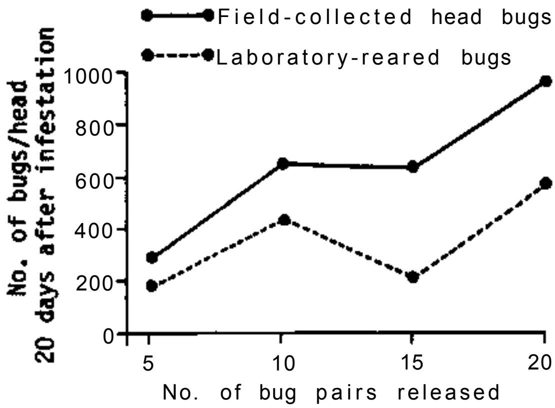

Figure 4. Population buildup of *Calocoris angustatus* on sorghum cv CSH 1 heads caged with 5, 10, 15, and 20 pairs of adults at head emergence (1982/83 postrainy season).

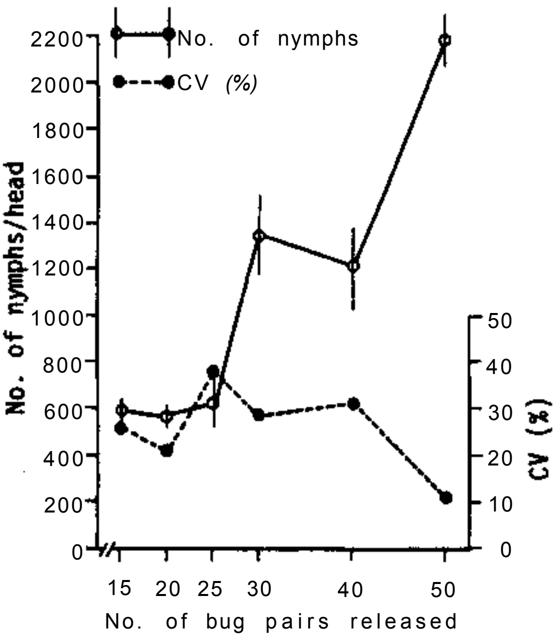

Figure 3. Number of nymphs emerged and the coefficient of variance (CV) at six levels of head-bug infestation under headcage on sorghum cv SPV 351.

Population Buildup and Grain Damage over Time

The population buildup and grain damage over time was studied in panicles infested at pre-anthesis with 10 and 25 pairs (Table 3). Maximum population buildup was observed 20 days after infestation. There was a slight reduction in head weight, I000-grain weight, and percent seed germination when the head bugs were confined up to 25 days; however, increasing confinement period to 30 days did not significantly increase grain damage.

Although the headcage technique allows for uniform infestation of the test cultivars, there is wide variation in population buildup among replications and experiments conducted at different times. This variation results from (a) the environmental conditions during the experimental period, (b) mortality due to a fungal disease, (c) cannibalism among the bugs, and (d) variation in earhead size, influencing availability of food. In spite of these differences, however, the headcage method has been found useful and a standard procedure has been developed for the number of head bugs to be released, stage of infestation, and time of recording observations under the headcage.

In addition, less susceptible genotypes can also

Table 3. Head bug, *C. angustatus* population in 10 cultivars under headcage (1981 rainy season)[1]

Cultivar	No. of bugs/5 heads			Damage rating[2]
	Adults	Nymphs	Total	
IS 8527	5	239	249	3
IS 2427	12	255	267	5
IS 4522	21	146	167	5
IS 3898	26	228	254	4
IS 61	27	65	92	3
IS 2359	482	25	507	5
IS 2327	247	25	272	5
IS 2328	239	38	277	5
CSH 5	236	118	354	5
Swarna	120	39	159	5

1. Ten pairs were released in the headcage at preanthesis. Population was recorded 20 days after infestation.
2. Damage rating - see Table 2.

be identified through studies on host-plant preference and consumption and utilization of food, as discussed in a later section.

Screening for Resistance

Field Screening

Over 10000 sorghum germplasm lines have been screened for resistance to C. *angustatus* at ICRISAT Center under field conditions. Selected lines have been tested for several seasons by using the headcage technique. Figure 5 shows a flowchart for the movement and selection of materials.

Headcage Screening

Ten field-selected cultivars were screened under headcages during the 1981 rainy season. Ten head bug pairs per head were introduced into the headcage at pre-anthesis stage. Only two cultivars (IS 8527 and IS 61) were moderately damaged, the rest showed a maximum damage rating of 5, with grains remaining undeveloped and heads becoming chaffy. The number of head bugs/panicle varied from 92 in IS 61 to 507 in IS 2359. The relative proportion of adults to nymphs was lower in IS 8527, IS 2427, IS 4522, IS 3898, and IS 61, but higher in IS 2359, IS 2327, IS 2328, CSH 5, and Swarna, probably because head bugs developed faster on the latter group of cultivars (Table 3).

During the 1982 rainy season and the 1982/83 postrainy season, a set of ten cultivars involving eight less susceptible and two susceptible cultivars was evaluated for head bug damage under natural and headcage conditions (Tables 4 and 5). Under natural conditions, fewer than 70 head bugs/5 heads were recorded at panicle emergence on Belkoiga, Myapaleg, and Noname 3 during the rainy season and fewer than 10 during the postrainy season. At milk stage, the head bug population was significantly lower in Noname 3, Belkoiga, Myapaleg, IS 2761, and IS 61 (<481 head bugs/5 heads) than in the susceptible checks CSH 1 and CSH 5. A maximum of 2090 head bugs was recorded in IS 1335 during the rainy season. Under headcage testing, cultivars Belkoiga, Myapaleg, and Noname 3 had lower head bug numbers, during the rainy and postrainy seasons. These cultivars also suffered moderate grain damage (damage rating < 3). Seed germination tests (another criterion for evaluating head bug damage) gave > 75% germination for IS 61, IS 2761, Belkoiga, Myapaleg, and Noname 3 compared with < 7% for CSH 1 and CSH 5 during the rainy season.

During the 1982 rainy season, 225 lines including cultivars less susceptible to grain mold and head bugs were tested under headcages, using 10 and 15 pairs of bugs/panicle. Seventeen lines were selected as less susceptible and tested again during the 1982/83 postrainy season using 5,10, and 15 pairs of head bugs/panicle in the head-cages. Cultivars IS nos.14476, 4544, 6383, 6984, 9692, 9639, 21217, and 2761 showed lower population buildup under headcage testing (< 112 head bugs) at all infestation levels (except IS 6984 at 15 pairs/ head). However, the grain damage was quite high and none of the cultivars could be grouped as less susceptible.

During the 1983 rainy season, the selected cultivars were again tested under headcages at two infestation levels (Table 6). Cultivars IS 2761, IS

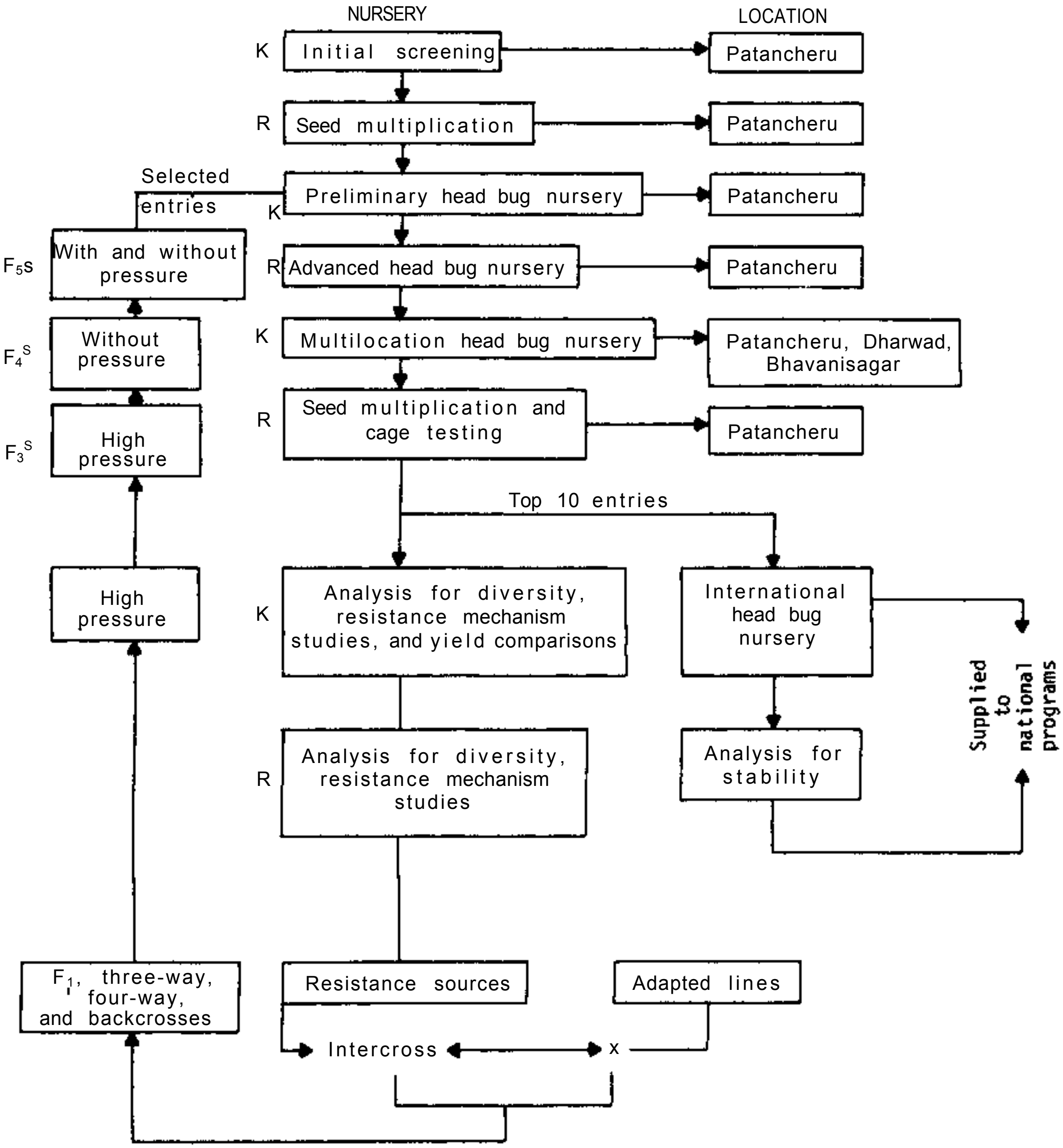

Figure 5. Screening sorghum for head-bug resistance (K = *kharif*—rainy season; R = *rabi*—postrainy season).

Table 4. Population buildup of head bugs and grain damage in 10 sorghum cultivars under natural and headcage conditions (1982 rainy season).

Cultivar	No. of head bugs/5 head, Natural conditions: Head emergence	Milky stage	No. of head bugs under headcage (10 pairs/head)	Grain germination (%)	Damage rating
IS 61	94(9.7)[1]	481(21.8)[1]	226(14.7)'	76	2.9[2]
IS 1335	34(5.8)	2090(45.4)	200(14.1)	4	3.8
IS 2761	113(10.6)	403(20.0)	247(12.0)	81	2.5
IS 4686	201(14.2)	1742(41.5)	163(12.1)	34	3.3
IS 7790	126(10.6)	1359(36.6)	169(12.9)	35	3.7
Belkoiga	69(8.3)	188(13.4)	85(9.2)	76	2.5
Myapaleg	33(5.6)	178(12.9)	111(10.5)	90	2.3
Noname 3	56(7.5)	129(11.4)	52(7.2)	95	2.4
CSH 1	102(9.6)	1021(31.9)	283(16.7)	7	4.2
CSH 5	149(11.9)	1085(32.8)	374(19.3)	7	4.0
Mean	(9.4)	(26.7)		51	3.2
SEm	(1.3)	(2.7)		10	0.2

1. Figures in parentheses are the square root transformations.
2. Damage rating - see Table 2.

6983, IS 6984, IS 9639, IS 9692, IS 14476, Myapaleg and Noname 3 had significantly fewer head bugs/panicle at both infestation levels, while IS 4544, IS 21217, and Belkoiga became susceptible at 15 pairs/panicle. Noname 3, Belkoiga, Myapaleg, and IS 4544 suffered moderate damage under both infestation levels. Grain germination was > 70% in IS 4544, IS 9639, Belkoiga, Myapaleg, and Noname 3 compared with < 11.5% in CSH 5 at 15 pairs/panicle.

Although ten cultivars have been identified as less susceptible under headcage testing or natural

Table 5. Population buildup of head bugs and grain damage in 10 sorghum cultivars under natural and headcage conditions (1982-83 postrainy season).

Cultivar	No of head bugs/5 heads under natural conditions: Head emergence	Milky stage	No. of headbugs under headcage (10 pairs/head)	Damage rating
IS 61	18(4.1)[2]	34(5.8)[2]	342(18.0)[2]	4.0'
IS 1335	37(6.1)	647(22.1)	143(11.8)	5.0
IS 2761	6(6.7)	30(8.5)	71(8.4)	4.8
IS 4686	44(6.4)	241(14.2)	455(21.3)	4.8
IS 7790	53(7.3)	212(141)	153(11.9)	4.2
Belkoiga	9(3.2)	6(2.6)	92(9.6)	3.5
Myapaleg	1(1.4)	3(1.9)	66(8.1)	3.3
Noname 3	3(1.9)	5(2.3)	22(4.7)	3.0
CSH 1	31(5.5)	42(6.5)	276(16.6)	4.2
CSH 5	30(5.4)	63(6.9)	316(17.7)	4.2
Mean	(4.40)	(8.20)	(12.82)	4.1
SE	±(0.77)	±(3.30)	±(1.41)	±0.19

1. Damage rating - see Table 2.
2. Figures in parentheses are square root transformations.

Table 6. Population buildup of head bugs and grain damage in 15 sorghum cultivars infested with 5 and 15 pairs of head bugs/earhead (1983 rainy season).

Sorghum cultivar	No. of headbugs/head		Damage rating[1]		Germination (%)	
	5 pairs	15 pairs	5 pairs	15 pairs	5 pairs	15 pairs
IS 2761	44(6.6)[2]	204(14.3)[2]	3.9	4.3	86	37
IS 4544	119(10.8)	374(19.3)	2.3	3.2	70	72
IS 6983	34(5.8)	57(7.1)	4.1	4.0	71	42
IS 6984	123(11.0)	50(7.0)	4.8	5.0	57	30
IS 9639	25(4.3)	204(14.2)	3.0	3.9	78	80
IS 9692	83(8.9)	232(15.2)	4.2	4.7	67	66
IS 14476	47(6.8)	63(7.9)	4.2	5.0	64	46
IS 21217	88(9.3)	297(17.1)	3.8	4.7	64	42
CSH 1	281(16.7)	625(25.0)	4.5	4.6	37	6
CSH 5	178(13.3)	394(19.8)	4.1	3.7	4	12
CSH 9	279(16.7)	495(22.2)	4.4	4.9	9	3
Swarna	226(15.0)	277(16.6)	5.0	5.0	7	1
Belkoiga	132(11.5)	312(17.7)	3.5	3.5	83	76
Myapaleg	104(10.1)	84(9.0)	3.3	3.0	72	85
Noname 3	83(8.9)	174(13.2)	3.0	3.2	74	84

SEm for comparison between:	SEm
No. of head bugs	
Cultivars	0.83
Head bug pairs	0.33
Damage rating	
Cultivars	0.06
Head bug pairs	0.12
Grain germination	
Cultivars	7.38
Head bug pairs	2.35

1. Damage rating - see Table 2.
2. Figures in parentheses are square root transformations

conditions, none showed adequate and repeatable levels of resistance under natural conditions or headcage testing. The extent of damage seemed to be influenced by a number of biotic and abiotic factors. Quite often, the lower head bug numbers and consequent grain damage are associated with the time of flowering and suitability of the prevailing environmental conditions for the buildup of head bug populations.

Head Bug Susceptibility in Relation to Panicle Development

Head bug feeding in the panicle is confined to certain growth stages of the earhead, though different species seem to be active at different stages (Table 1). The C. *angustatus* population and consequent grain damage were studied on three less susceptible and two susceptible cultivars at four growth stages (Tables 7 and 8). All cultivars showed very high susceptibility at head emergence. Head bug population buildup in the headcages decreased at the postanthesis and milk stages. This probably resulted from the difficulty in oviposition (generally the eggs are laid in florets before anthesis) and the inability of the nymphs to feed on hardened grains. Maximum head bugs were recorded in panicles infested with 10 bug pairs, indicating that higher infestation levels lead to intraspecies competition for food and oviposition, and possibly to increased cannibalism.

IS 2761 panicles supported the least number of head bugs at five pairs/head. The susceptible cul-

Table 7. Head bug, *C.angustatus* population buildup under headcage on five sorghum cultivars with four infestation levels and four stages of earhead development.

Cultivar	Head emergence	Half anthesis	Post anthesis	Milk stage	Mean
5 pairs/head					
IS 2761	52(72)[1]	89(4.3)	33(5.7)	17(4.1)	48(5.3)
IS 6984	138(11.6)	195(14.0)	114(10.4)	20(4.5)	117(10.1)
IS 9692	226(15.0)	143(12.0)	41(6.3)	46(6.7)	114(10.0)
Swarna	673(25.9)	223(11.9)	87(9.2)	72(8.5)	264(13.9)
CSH 5	240(15.5)	116(10.8)	121(11.0)	73(8.4)	138(11.4)
Mean	332(15.0)	192(12.2)	99(8.5)	57(6.4)	170(10.5)
10 pairs/head					
IS 2761	307(17.5)	138(11.7)	112(10.5)	24(3.8)	145(10.9)
IS 6984	307(17.5)	266(16.3)	247(15.7)	50(7.0)	218(14.1)
IS 9692	282(16.5)	115(10.6)	37(6.1)	36(6.0)	118(9.8)
Swarna	214(14.6)	85(8.9)	129(11.1)	101(10.0)	132(11.2)
CSH 5	703(25.4)	274(16.4)	211(14.4)	45(6.6)	308(15.7)
Mean	453(18.5)	220(12.8)	184(11.6)	64(6.7)	230(12.4)
15 pairs/head					
IS 2761	265(16.3)	8(2.7)	30(5.5)	9(2.9)	78(6.9)
IS 6984	42(6.4)	244(15.6)	59(7.4)	68(8.2)	103(9.4)
IS 9692	291(17.0)	163(12.5)	50(6.9)	85(9.2)	147(11.4)
Swarna	254(15.9)	55(7.2)	159(12.5)	87(9.3)	139(11.2)
CSH 5	528(22.9)	358(18.6)	466(21.6)	111(10.5)	366(18.4)
Mean	345(15.7)	207(11.3)	191(10.8)	90(8.0)	208(11.5)
20 pairs/head					
IS 2761	176(13.0)	10(3.1)	78(8.7)	6(2.3)	68(6.8)
IS 6984	306(17.3)	254(15.8)	106(10.3)	48(6.9)	179(12.6)
IS 9692	108(10.0)	31(5.5)	41(6.3)	42(6.4)	56(7.1)
Swarna	413(20.3)	414(20.3)	459(21.3)	14(3.2)	325(16.3)
CSH 5	928(30.4)	600(24.5)	293(17.1)	84(8.9)	476(20.2)
Mean	483(18.2)	327(15.8)	244(12.7)	49(5.6)	276(13.1)

SEm for comparison at two levels of :	SEm
Cultivars	0.22
Pairs released	0.21
Pairs released at same cultivar level	0.47
Cultivars at the same level of pairs	0.46
Earhead development stage	0.23
Earhead stage at same level of cultivars	0.52
Cultivars at the same level of earhead development stage	0.50
Earhead development at the same level of pairs released	0.47
Pairs released at the same level of earhead development	0.46

1. Figures in parentheses are square root transformations.

Table 8. Headbug, *C. angustatus*, damage at four infestation levels and four stages of earhead development in seven sorghum cultivars (1983 rainy season).

Sorghum cultivar	No. of pairs released/head															
	5				10				15				20			
	HE[1]	HA	PA	MS	HE	HA	PA	MS	HE	HA	PA	MS	HE	HA	PA	MS
IS 2761	3.5[2]	4.8	3.2	3.8	3.7	5.0	2.8	3.7	4.3	5.0	4.5	4.5	5.0	5.0	4.5	5.0
IS 6984	4.5	3.5	3.3	3.3	4.7	2.7	3.2	4.3	5.0	2.7	4.7	2.7	4.5	4.3	3.2	3.8
IS 9692	4.7	3.7	4.2	3.5	3.7	4.8	4.8	3.7	4.2	4.8	3.2	3.2	5.0	4.7	3.7	2.2
Swarna	4.7	4.8	5.0	2.3	5.0	3.8	5.0	4.8	4.5	4.3	4.0	3.2	5.0	5.0	5.0	3.8
CSH 5	4.2	3.7	5.0	3.3	5.0	5.0	4.7	3.0	3.7	4.3	5.0	3.5	5.0	3.5	4.8	3.2

SEm for comparison between	SEm
No. of pairs	0.07
Stage of head	0.07

1. HE = Head emergence, HA = Half-anthesis, PA = Postanthesis, MS = Milk stage.
2. = Damage rating (see Table 2).

tivars (CSH 5 and Swarna) had relatively higher head bug numbers than IS 2761, IS 6984, and IS 9692. In some cases, the head bug counts were also lower in Swama and CSH 5. These variations probably resulted from factors influencing the population buildup and damage in the headcage, as discussed earlier.

During the 1983/84 postrainy season, the susceptibility of IS 2761, was compared again with CSH 5 and Swarna at different stages of earhead development and infestation levels. IS 2761 had significantly fewer (Table 9) bugs/panicle in the headcage at all stages of development and four infestation levels. As seen in the previous experiment, the head bug numbers in IS 2761 and Swarna decreased at 20 pairs/head at head emergence. This possibly resulted from the early depletion of food supply.

The extent of grain damage, as worked out from grain weight/head showed that when panicles were infested with five pairs of head bugs, Swarna suffered maximum damage at the pre- and half-anthesis stages, while the differences between various head development stages were slight in IS 2761 and CSH 5 (Table 10). At 10 pairs/head, IS 2761 and CSH 5 also suffered severe damage when infested at pre-anthesis. The damage at the milk stage was significanty less than at pre-anthesis.

Factors Associated with Low Susceptibility

Panicle Type

Cherian and Kylasam (1941) and Balasubramanian et al. (1979) reported that cultivars with open panicles are less susceptible to head bugs. At ICRISAT Center, cultivars with compact, semicompact, and loose panicles had an average of 847, 205, and 252 head bugs/head respectively. However, there were wide differences in head bug numbers within each group, which could be due to factors other than panicle type (Table 11). Grain damage was moderate (damage rating <3.5) in IS 1025 (compact), and Myapaleg, Belkoiga, Noname 3, and IS 18408 (loose panicle types). There were substantial differences in head bug numbers between the compact and loose panicle types; however, all the loose panicle types are not neces-

Table 9. Head bug, C. *angustatus* population buildup under headcage at four levels of infestation and four stages of panicle development in three sorghum cultivars (1983/84 postrainy season).

Sorghum cultivar	No. of bug pairs released	Earhead development stage: Head emergence	Half anthesis	Post-anthesis	Milk stage
IS 2761	5	30(5.5)[1]	29(5.3)	33(5.7)	16(3.9)
	10	75(8.6)	37(6.0)	45(6.6)	32(5.6)
	15	72(8.3)	46(6.7)	59(7.6)	30(5.5)
	20	47(6.8)	88(9.3)	118(10.9)	50(7.0)
CSH 5	5	342(18.1)	35(5.8)	144(11.9)	141(11.6)
	10	325(17.7)	136(12.2)	275(16.0)	124(11.0)
	15	404(19.9)	224(14.4)	209(13.3)	179(12.9)
	20	582(23.9)	261(16.3)	260(15.5)	368(19.1)
Swarna	5	218(14.6)	162(12.7)	131(11.5)	45(6.9)
	10	229(14.9)	165(12.8)	246(15.9)	122(10.8)
	15	124(11.1)	181(13.4)	191(13.9)	91(8.9)
	20	66(7.8)	177(13.2)	250(16.0)	119(10.5)

SEm for comparison between:	SEm
Cultivars	0.83
Stage of head	0.41
Pairs of adults	0.38

1. Figures in parentheses are square root transformations.

sarily less prone to head bug attack. Over several seasons, we have observed thousands of loose panicle type cultivars being totally damaged by head bugs. In itself, the loose panicle may not be a strong and stable resistance character; however, cultivars with loose panicles are less hospitable to head bugs and generally do not allow rapid multiplication of the pests, probably because natural enemies have easier access to them and they are directly exposed to other environmental conditions and the nymphs tend to fall off the panicle. The role of loose panicles in reducing head bug densities needs to be studied further.

Head Size

During the experiments on screening for resistance at various developmental stages, we observed that lower head bug counts in less susceptible cultivars were quite often associated with smaller head size and fewer grains. To study this phenomenon, 10 head bug pairs/panicle were confined with CSH 1 heads having 5, 10, and 20 sprigs, and a normal head at pre-anthesis. All panicles across the different treatments were completely damaged. However, head bug numbers-/panicle increased with increasing head size There were 20±6, 63±17, 375±53, and 611±86 head bugs per panicle in earheads with 5,10, and 20 sprigs and a normal head, respectively. Therefore, population buildup is also influenced by the grain number available to support a certain number of head bugs. The lower head bug counts within or between cultivars may quite often be the result of variation in head size.

The effect of head size on population buildup was also studied at four infestation levels and at four stages of head development in CSH 1 (containing 20 sprigs) (Table 12). Maximum head bugs were observed with 10 pairs/head at all stages of head development. The population decreased significantly at 20 pairs/head, indicating inadequate food supply to sustain higher numbers of head bugs. The population decrease at postanthesis and milk stages can also be linked to decreased suitability of the grain for head bug development, apart from factors associated with oviposition. The grain damage was significantly less at milk stage.

Table 10. Grain weight per head (g) in three sorghum cultivars at four stages of development and four infestation levels.

Cultivar	No. of pairs released															
	5				10				15				20			
	HE	HA	PA	MS	HE	HA	PA	MS	HE	HA	PA	MS	HE	HA	PA	MS
IS 2761	7.6	8.9	8.3	8.0	6.7	8.4	7.1	8.8	2.6	7.7	6.1	9.3	9.7	4.0	6.7	7.9
CSH 5	18.6	18.3	20.0	19.1	9.1	18.7	19.0	18.1	10.3	18.7	15.9	18.1	5.8	18.2	17.3	17.8
Swarna	10.0	8.7	21.4	24.0	11.2	12.6	20.7	25.8	11.9	8.8	19.4	21.8	11.8	8.8	14.8	24.3
Mean	12.1	12.0	16.6	17.1	9.0	13.2	15.6	17.6	8.3	11.7	13.8	16.4	9.1	10.4	13.0	16.7

SEm for comparison between two levels of:	SEm	LSD at 5%		SEm	LSD at 5%
Cultivars	1.8	5.1	Earhead stage at the same level of head bug pairs	0.8	2.3
Earhead development stage	0.5	1.5	Earhead at the same cultivar level	0.9	2.7
No. of head bug pairs	0.3	0.9	Head bug pairs at the same cultivar level	0.6	1.6
Cultivars at same level of earhead development	1.9	5.6	Head bug pairs at the same earhead development stage	0.7	1.9
Cultivars at same level of head bug pairs	1.8	5.3			

HE = Head emergence ; HA = Half anthesis ; PA = Postanthesis ; MS = Milk stage.

Table 11. Head bug *C. augustatus* population on 15 cultivars with three head types (1981 rainy season)[1]

Cultivar	No. of bugs/head			Damage rating[2]
	Adults	Nymphs	Total	
Compact				
IS 1025	8	52	60	3
IS 1151	17	1110	1127	5
IS 7755	17	350	367	5
DJ 6514	12	88	100	5
IS 18482	3	456	459	5
Semicompact				
IS 1061	40	187	227	5
IS 8713	21	274	295	5
IS 1480	1	79	80	5
IS 12609	53	429	482	4
CSH 1	8	304	312	5
Loose				
Myapaleg	6	49	55	2
Belkoiga	6	66	*12*	3
Noname 3	4	5	9	3
IS 18408	25	64	89	3
IS 7032	28	643	671	5

1. Five heads were sampled in each cultivar at milk stage.
2. Damage rating - see Table 2.

Flower Morphology

Morphological flower characteristics were studied on five sorghum cultivars in relation to head bug population buildup and grain damage under head-cage conditions (20 pairs/head)(Table 13). Less susceptible cultivars tended to have hard and less hairy glumes and smaller pollen tubes. In IS 9692, the stigma did not emerge from the glumes. However, these observations need to be studied in greater detail since cultivars with long glumes and loose panicles (Belkoiga, Myapaleg, and Noname 3) are also known to suffer less damage. However, there is a need to study the rate of grain development (amount of food made available by the host plant) in relation to buildup of head bug populations.

Host-plant Preference

Host-plant preference/nonpreference is the result of chemical/morphological characteristics of the host plant that influence its selection by the insect

Table 12. Population buildup in headcages at four levels of head bug infestation and four stages of development of sorghum cv CSH 1 heads (20 sprigs/head).

No. of pairs released	Panicle development stage: Head emergence	Half-anthesis	Post-anthesis	Milk stage	Mean
5	200(13.9)	338(18.2)	285(16.8)	220(14.4)	261(15.8)
10	468(21.5)	503(22.4)	516(22.7)	157(12.0)	411(19.7)
15	328(18.1)	481(21.8)	456(21.2)	265(15.7)	383(19.2)
20	151(12.3)	412(20.1)	321(17.7)	170(12.8)	264(15.7)
Mean	287(16.5)	434(20.6)	395(19.6)	203(13.7)	
			SEm		
For comparison between pairs			(0.81)		
For comparison between stages of head development			(1.3)		

for food, oviposition, or shelter, or all three. Host-plant nonpreference (anti-xenosis) is an important mechanism of resistance in sorghum against the shoot fly *Atherigona soccata* Rond. (Jain and Bhatnagar 1962) and midge, *Contarinia sorghicola* Coq. (Harris 1961; Sharma et al. 1983a). Nonpreference by head bugs was studied under both field and laboratory conditions. Under field conditions, there were significant differences in the number of bugs attracted to the earheads of different cultivars at pre-anthesis. During the 1982 rainy season, 39 females were recorded per head in IS 2761 compared with 68 in CSH 5, while in the postrainy season there were 6 and 30 females/head respectively.

Cultivar nonpreference was also studied under laboratory conditions using an olfactometer with four arms (50 cm diameter, 50 cm high; each arm 11cm diameter, 20 cm long), and a glass bell jar (30 cm diameter, 40 cm high). Sorghum earheads at pre-anthesis or milk stage were kept in a vertical position along the sides or placed in the arms of the olfactometer. In the bell jar, all the panicles were put together in a flask vertically. Head bug adults reared on CSH 1 were released in the center. The number of head bugs attracted to different panicles were recorded after 24 h. Tests were repeated five to ten times. The positions of the cultivars were changed in each experiment to avoid position effects.

In the olfactometer tests, IS 6984 and IS 2761

Table 13. Morphological characteristics of five sorghum cultivars in relation to head bug susceptibility (infestation level: 20 pairs/head in headcages).

Sorghum cultivar	No. of bugs/ head	Damage rating	Glume length	Glume hardness	Glume hairiness	Pollen tube length	Stigma emergence
IS 2761	176	4.3[a]	1[b]	2[c]	1[d]	1[e]	C[f]
IS 6984	306	5.0	3	2	1	2	c
199692	108	4.2	3	2.5	2	2	I
Swarna	413	4.5	4	5	3	3	c
CSH 5	928	3.7	3	2.5	3	2	c

a. 1 < 10% damage; 5 = > 60% damage.
b. 1 < 1.5 mm ; 5 = > 3.5 mm.
c. 1 very hard on pressing; 5 = soft on pressing.
d. 1 very little hair; 5 = glume covered with hair.
e. 1 < 0.5 mm pollen tube; 5 = > 2 mm pollen tube.
f. C = complete; I = incomplete.

were less attractive to the head bugs than CSH 5 or Swarna, at both pre-anthesis and milk stages (Fig. 6). However, when panicles of all the cultivars were put togetner in the bell jar, fewer adults were recorded in the earheads of Swarna as well (Fig. 7). Covering the bell jar with green or red paper did not influence the behavior of head bugs.

Cultivar differences do exist in host-plant preference, and can be monitored under field and laboratory conditions. However, nonpreference is not strong enough to prevent grain damage to an appreciable extent. This mechanism of resistance can possibly be used in conjunction with other factors associated with resistance.

Consumption and Utilization of Food

A question of practical importance to host-plant resistance is how the plant selected for feeding will affect the growth and development of the insect. To examine this, we studied food consumption and

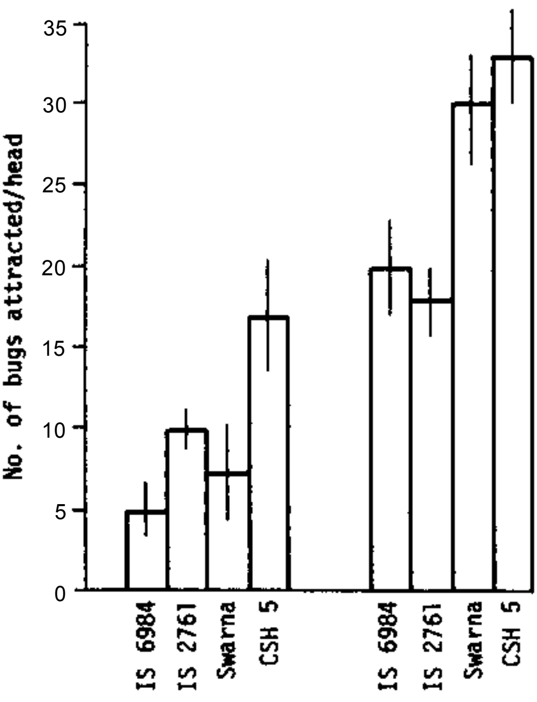

Figure 6. Attractiveness of four sorghum cultivars to adults of *Calocoris angustatus* in olfactometer tests under laboratory conditions.

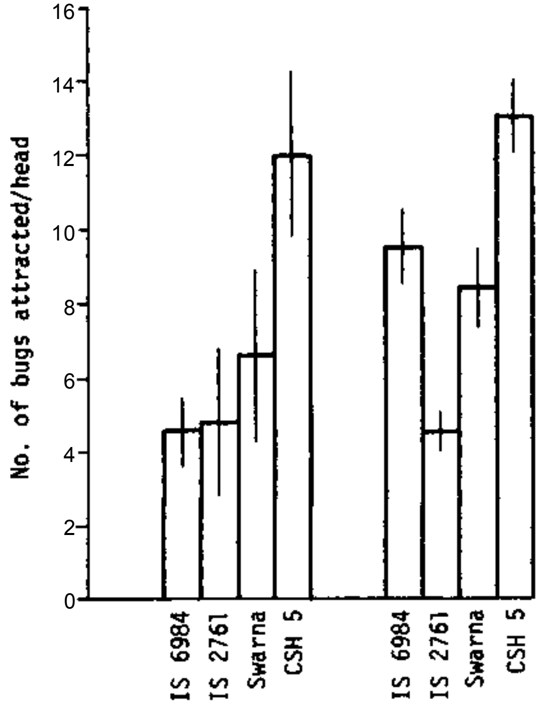

Figure 7. Attractiveness of four sorghum cultivars to adults of *Calocoris angustatus* in a bell jar under laboratory conditions.

utilization on some sorghum cultivars by nymphs of C. *angustatus.*

For proper understanding of the various parameters of food utilization, it is essential to compute the various indices on a dry-weight basis. However, because of the unique feeding behavior of this insect and lack of appropriate techniques to measure the food intake and excreta on a dry-weight basis, three indices (consumption index, CI; efficiency of conversion of the ingested food into body matter, ECI; and growth rate, GR) were studied on a fresh-weight basis as described by Waldbauer (1968).

Fresh 15-day-old grains were offered to fourth instar nymphs in plastic petri dishes (7.5 cm diameter) on a filter paper (soaked with 1 ml water) for 48 h. To standardize the technique, the role of moisture on the filter paper, the number of nymphs and grains required in each experiment, the growth stage of the insect, and the grains were studied.

Table 14. Effect of moistening filter paper in the petri dish on consumption and utilization of food by *C. angustatus*[1]

Water (ml)	Consumption index		Efficiency of conversion of ingested food		Growth rate	
	IS 6984	Swarna	IS 6984	Swarna	IS 6984	Swarna
Control (No water)	201.9	70.6	0.24	0.18	0.246	0.250
1 ml	17.3	11.6	0.18	1.71	0.031	0.188
2 ml	3.4	10.8	0.15	1.05	0.005	0.114

1. Ten fourth instar nymphs were released on 50 15 - day grains for 48 h. There were five replications.

On cv IS 6984, the consumption index decreased drastically from 201.9 on dry filter paper to 3.4 on filter paper soaked in 2 ml water (Table 14). The very high CI value in the former was the result of moisture loss from the grains, which was accounted towards insect feeding. There was no apparent effect of moisture on the efficiency of conversion of the ingested food (ECI) and growth rate (GR). The nymphs grew at a rate of 0.005 on the less susceptible cultivar, IS 6984, versus 0.114 on Swarna. The number of grains offered did not seem to influence CI or GR; however, ECI showed a decrease with increase in grain number. This may result from higher rates of food intake resulting in lower efficiency of utilization (Sharma and Agarwal 1981). The CI decreased as the number of nymphs increased from 5 to 10. The ECI and GR did not show any apparent trend. The CI and GR values did not differ much between the fourth and fifth instar nymphs (Table 15). The ECI values were slightly higher for the fifth instar nymphs. The ECI and GR were higher on 12-day and 20-day grains than on 16-day grains of all cultivars (Fig. 8). Among different cultivars, CI was higher on IS 6984 than on IS 2761 and CSH 5; but ECI and GR were lowest on IS 6984, followed by IS 2761 and CSH 5.

Thus ECI and GR (which measure the suitability of the host plant for insect growth and development) showed that IS 6984 and IS 2761 were relatively less suitable for C. *angustatus* than CSH 5, which may explain the lower population buildup on these cultivars under a headcage. Kogan (1972) found that adult preference closely follows host-plant suitability for growth and development of larvae. In sorghum, the cultivars that are less preferred by head bug adults also tend to be less suitable for the growth and development of the nymphs. Based on food utilization indices, the cultivars can be placed in different groups, and those showing antibiosis (as measured by food utilization) can be selected as less susceptible for detailed studies.

One of the major drawbacks in this approach is the variability or instability of the nutritional parameters. Sources of variability could be the differences in experiments conducted at the same time in iden-

Table 15. Consumption and utilization of food by fourth and fifth instar nymphs[1] of C. *angustatus* on sorghum cvs IS 2761 and CSH 5.

Sorghum cultivar	Consumption index		Efficiency of conversion of ingested food		Growth Rate	
	IV Instar	V Instar	IV Instar	V Instar	IV Instar	V Instar
IS 2761	13.2	13.8	0.31	0.5 0	0.040	0.070
CSH 5	16.0	14.1	0.42	0.47	0.065	0.065

1. Ten nymphs were released on hundred 15-day grains. One ml. water was used to soak the filter paper. There were five replications.

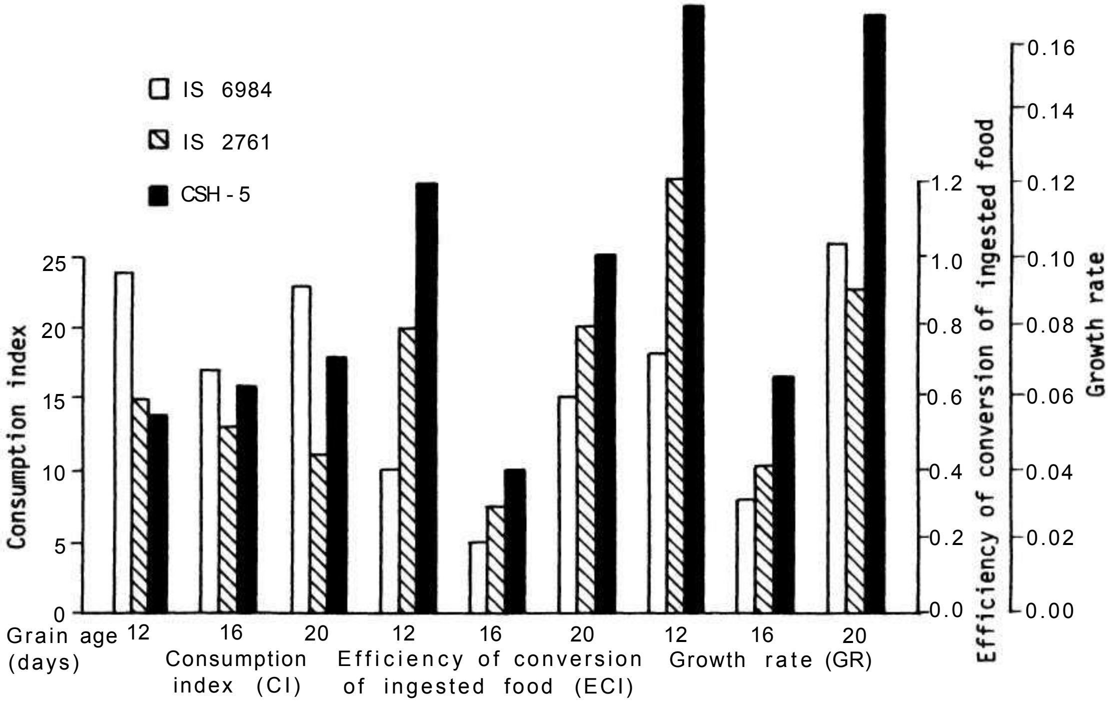

Figure 8. Consumption and utilization of grains of three sorghum cultivars by fourth instar nymphs of *Calocoris angustatus.*

tical conditions or due to "triggered discontinuties" (periodic feeding, molting, egg laying, circadian rhythm, maturation and aging, transition effects, and disequilibrium following a change in some environmental parameters). This variance could be of genetic, biological, or environmental origin. It is rather difficult to achieve near-ideal conditions for consistent results. However, this approach seems to be quite useful in situations where the differences between susceptible and less susceptible cultivars are sufficient to identify sources of resistance.

Looking Ahead

1. Head bug species should be precisely identified and economic importance studied carefully, particularly *in* the African continent.
2. The biology, particularly the population dynamics and off-season carryover studies should be undertaken at different places.
3. Resistance screening techniques have been developed. Attention needs to be focused on factors responsible for the variability in the headcage tests. Nonpreference and food utilization tests may be used to confirm the resistance observed under field conditions.
4. Germplasm screening should be intensified to locate cultivars with stable levels of resistance.
5. Factors associated with resistance should be studied to help in identifying and developing head bug resistant cultivars.

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Insect Pests of Stored Sorghum Grain

Robert B. Mills*

Abstract

Most stored-produce insects are cosmopolitan, having been distributed throughout the world in commerce. There are differences among the species in their ability to damage the various cereal grains, but in general most of them can develop in and damage all the cereal grains, including sorghum and millet.

Insect pests of sorghum and other cereal grains in developing countries include: Sitophilus *spp,* Rhyzopertha dominica *Fab.,* Trogoderma granarium *Evert,* Tribolium *spp,* Corcyra cephalonica *Staint.,* Oryzaephilus surinamensis *Linn.,* Cryptolestes *spp,* Plodia interpunctella *Hb., and* Cadra *spp. Biology and behavior of some of these are discussed.*

Storage losses are a complete loss, and there is no compensating for damage done by insect pests, as there may be in the growing plant. Loss estimates, generally, are poorly documented. Greater emphasis is now being placed on more objective and more accurate estimates.

In providing technical assistance on grain storage to developing countries, the existing situation should be carefully evaluated, and the extent of the problem should be accurately assessed. The present storage practices and reasons for them should be studied to determine if new or modified practices would be practical and effective. Use of chemical protectants and fumigants should not be recommended (particularly fumigants) unless there is assurance that it can be done safely and effectively.

Résumé

***Insectes nuisibles au sorgho emmagasiné :** La plupart des insectes des denrées sont cosmopolites, ayant été distribués partout dans le monde par le commerce. Les espèces varient selon leur capacité d'endommager les différentes céréales en grain, cependant la plupart peuvent se développer dans tous les grains des céréales, y compris le sorgho et le mil, et les endommager.*

Les insectes nuisibles aux grains de sorgho et d'autres céréales dans les pays en voie de développement sont : Sitophilus *spp.,* Rhyzopertha dominica *Fab.,* Trogoderma granarium *Evert,* Tribolium *spp.,* Corcyra cephalonica *Stainst,* Oryzaephilus surinamensis *Linn.,* Cryptolestes *spp.,* Plodia interpunctella *Hb., et* Cadra *spp. La biologie et le comportement de quelques-uns de ces insectes sont étudiés.*

Insects infesting stored grains and their stored products are cosmopolitan, having been transported throughout the world in commerce from wherever they originated. Distribution of individual species may vary due to their differences in adaptability to various environmental conditions, and to the distribution of their hosts. In a few cases, they simply have not been introduced and established as widely as other stored grain insects. Most species are thought to be tropical or subtropical in origin.

Several important storage insects that are pests of cereal grains and their products can infest a wide range of those products, e.g., whole grain, flour, meals, feeds, and a wide variety of processed foods, including the "convenience" foods. This paper will focus on the important pests of stored cereal grains, with particular attention to sorghum.

Stored-grain insect pests are often divided into groups according to their importance, such as the categories used by Cotton and Good (1937): major,

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minor, and incidental pests, and associated insects and other arthropods, such as, parasites and predators. The list of species in each group varies. The following lists of major and minor pests are modified from Wilbur and Mills (1978).

Major Pests of Stored Grain

Major insect pests are those few species that are particularly well adapted for living in stored grain. The species listed alphabetically by family in Table 1 are responsible for much of the insect damage all over the world.

Minor Pests of Stored Grain

Minor pests include a large number of insects and mites that may become abundant enough under particular conditions to cause considerable damage and contamination to stored grain. In these situations, those suffering the loss consider them "major" pests. Damaging infestations may be associated with high or low moisture or temperature, poor sanitation, out-of-condition grain, or they may be limited in geographic distribution. For example *Prostephanus truncatus* has long been a "major" pest in stored maize only in Mexico and Central America. It was recently discovered in Tanzania and Kenya, where it is a very serious pest in maize and cassava. *Lasioderma serricorne,* a serious pest of tobacco, may develop damaging populations in grain or grain products. *Tenebrio* spp, *Typhaea stercorea,* and *Ahasverus advena* may become numerous in moldy grain, feeding principally on the fungus, but contaminating the grain. Table 2 gives a selective list of minor pests.

Detailed descriptions, illustrations, and discussion of stored-grain insects in general may be found in USDA (1979), Wilbur and Mills (1978), and Cotton and Wilbur (1982). There are many papers widely scattered in the literature on groups of stored-grain insects or individual species, as well as on all aspects of stored-product entomology. Teetes et al. (1983) include illustrations and brief discussions of some important stored cereal grain pests in their handbook on sorghum insect *identification.*

Important Insect Pests of Stored Sorghum

Sitophilus oryzae (rice weevil) is a small snout beetle that infests cereal grains. The immature stages occur inside the kernel. The female, using mandibles at the end of her snout, chews a small hole in the kernel, turns around, and places an egg in the hole and then seals it with a gelatinous material. The egg hatches in a few days and the larva feeds and develops within the kernel up to the pupal

Table 1. Major insect pests of stored grain sorghum.

Common name	Scientific name	Family
Lesser grain borer	*Rhyzopertha dominica* (F.)	Bostrichidae
Saw-toothed grain beetle	*Oryzaephilus surinamensis* (L)	Cucujidae
Flat grain beetle	*Cryptolestes pusillus* (Schonherr)	Cucujidae
Rusty grain beetle	*Cryptolestes ferrugineus* (Stephens)	Cucujidae
Rice weevil	*Sitophilus oryzae* (L.)	Curculionidae
Maize weevil	*Sitophilus zeamais* (Motschulsky)	Curculionidae
Granary weevil	*Sitophilus granarius* (L)	Curculionidae
Trogoderma spp esp. Khapra beetle	*Trogoderma granarium* Everts	Dermestidae
Angoumois grain moth	*Sitotroga cerealella* (Olivier)	Gelechiidae
Indian meal moth	*Plodia interpunctella* (Hubner)	Pyralidae
Mediterranean flour moth	*Anagasta kuehniella* (Zeller)	Pyralidae
Confused flour beetle	*Tribolium confusum* (du Val)	Tenebrionidae
Red flour beetle	*Tribolium castaneum* (Herbst)	Tenebrionidae
Cadelle	*Tenebroides mauritanicus* (L.)	Trogositidae
Grain and flour mites	*Acarus* and *Tyrophagus* (spp.) *Glycyphagus* (spp.)	Acaridae

Table 2. Common minor pests of stored grain sorghum.

Ccmmon name	Scientific name	Family
Cigarette beetle	*Lasioderma serricorne* (F.)	Anobiidae
Drugstore beetle	*Stegobium paniceum* L.	Anobiidae
Larger grain borer	*Prostephanus truncatus* (Horn)	Bostrichidae
Squarenecked grain beetle	*Cathartus quadricollis* (Guerin-Meneville)	Cucujidae
Foreign grain beetle	*Ahasverus advena* (Waltl)	Cucujidae
Black carpet beetle	*Attagenus megatoma* (F.)	Dermestidae
Psocids	*Liposcelis* (spp)	Liposcelidae
Hairy fungus beetle	*Typhaea stercorea* (L.)	Mycetophagidae
Dried fruit beetle complex	*Carpophilus* spp	Ptinidae
Spider beetle complex	*Ptinus, Gibbium* and *Mezium* (spp)	Ptinidae
Rice moth	*Corcyra cephalonica* (Stainton)	Pyralidae
Meal moth	*Pyralis farinalis* L.	Pyralidae
Long-headed flour beetle	*Latheticus oryzae* (Waterhouse)	Tenebrionidae
Broad-horned flour beetle	*Gnatocerus cornutus* (F.)	Tenebrionidae
Slender-horned flour beetle	*Gnatocerus maxillosus* (F.)	Tenebrionidae
Small-eyed flour beetle	*Palorus ratzeburgi* (Wissmann)	Tenebrionidae
Depressed flour beetle	*Palorus subdepressus* (Wollaston)	Tenebrionidae
Larger black flour beetle	*Cynaeus angustus* Leconte	Tenebrionidae
Dark mealworm	*Tenebrio obscurus* F.	Tenebrionidae
Yellow mealworm	*Tenebrio molitor* L	Tenebrionidae

stage. The adult chews its way out of the kernel in about 35 days after oviposition. The adult is 3 to 4 mm long and has two light-colored areas on each elytron, and pits on the pronotum are nearly round and close together. S. *oryzae* is one of the most destructive grain insects. This species is particularly well adapted to sorghum and wheat. Each female can lay about 400 eggs; the adults live for 4 to 5 months.

Sitophilus zeamais (maize weevil) is closely related to S. *oryzae,* and in fact has been and still is confused with it. The color pattern of the two species is identical, except for subtle differences in pit pattern on the pronotum and genitalia. Habits and biology of the two species are similar, except that S. *zeamais* is more suited to maize and is a common pest of maize in many countries. It is well adapted to sorghum also. It is a stronger flyer than S. *oryzae* and commonly infests grain in the field before harvest, after which it is carried to the storage site, where infestation increases.

Rhyzopertha dominica (lesser grain borer) is also an internal-feeding beetle but it differs from the *Sitophilus* species. It lays eggs on the kernels and the newly emerged larva chews its way into the kernel or enters through a break in the pericarp. The adults are small, cylindrical, and about 3 mm long. The head projects downward from underneath the pronotum, and there are numerous tubercles located dorsally near the anterior of the pronotum. The females lay 300 to 400 eggs each. Minimum development time under optimum conditions is about 30 days from oviposition to adult. This insect requires a higher optimum temperature than most stored-grain insects (about 34°C) and can survive in grain of relatively low moisture content (< 9%). The larvae and adults produce considerable dust in the grain which has a characteristic, easily recognized odor. Both adults and larvae are very destructive to grain.

Prostephanus truncatus (larger grain borer) is not a sorghum or millet pest, but is included here to demonstrate the serious problem resulting from the introduction of a pest into a new geographic area. P. *truncatus* is similar to *R. dominica.* It is larger and the posterior end of the body is flattened, i.e., "truncated." The species has long been a pest in maize in parts of Mexico and Central America, and was not known to be established elsewhere until it was recently found in Tanzania and later in Kenya. Since the storage methods in Tanzania were developed in the absence of this pest, its introduction created a new set of circumstances. The ultimate solution may require a complete change in storage practices developed over generations, or change in crops grown. It prefers corn on the cob (as commonly stored in Tanzania) and is also a pest in cassava, which compounds the problem.

Sitotroga cerealella (Angoumois grain moth) larvae develop inside kernels. The moths are about 6.5 mm long. Hindwings have a fringe of long hairs, and the leading edge is extended into an "accusing" finger. Eggs (80 to 100/female) are laid among the kernels, and hatch in about 5 days. The larvae chew into the kernels or enter breaks in the pericarp and develop inside the grain. Prior to pupation, the larva tunnels out to the pericarp and prepares an exit hole for the adult. These emergence holes are the only damage visible in the infested grain. Moths live an average of 10 days and all eggs are laid within 3 days after adult emergence. The damage to bulk threshed grain is limited to the upper layers because the moths cannot penetrate or escape from greater depths. *Sitotroga cerealella* flies and infests grain in the field, particularly in warm climates.

Tribolium castaneum (red flour beetle) is a common pest in grain as well as in a wide variety of cereal products and other processed foods and feeds. Although considered a secondary pest that requires damaged kernels on which to develop, it can do this in whole grain if moisture content is >12.5%. Many kernels have enough damage for flour beetles to successfully attack them, even though that damage is not visible. Mechanical threshing and handling cause damage which makes the grain more susceptible to the secondary pests.

The adults are 3 to 4 mm long and uniformly brown or dark red-brown. Each female lays 300 to 500 eggs. Larvae are characterized by a conspicuous forked termination of the last body segment. This and related species feed on the germ of kernels first, and then feed on the endosperm, especially if moisture content is high. Development from oviposition to adult takes 30 to 35 days under optimum conditions. This species is easily confused with *T. confusum* (confused flour beetle) which is capable of infesting grain, but is more of a pest in flour, meals, and other processed cereals.

Cryptolestes spp (flat grain beetles) are small (2 to 3 mm long) flat beetles with long antennae. Males of some species have antennae nearly as long as the body. These are common pests in grain, and probably need damaged kernels to develop in whole-kernel grain. Damage done by the more destructive beetles renders the grain susceptible to *Cryptolestes* spp. Feeding is primarily on the germ of whole kernels, and the pests appear to be attracted to grain high in moisture. Each female can lay 300 to 400 eggs. Larvae are creamy white, flat, and the posterior half of the body is slightly wider than the anterior. There are two conspicuous, dark, slender horns on the posterior end of the body. Because of the similarity of the species, there have been frequent misidentifications; e.g., reports of flat grain beetles (C. *pusillus)* in the USA which may have been rusty grain beetles (C. *ferrugineus),* or flour mill beetles (C. *turcicus).* C. *pusillus* and C. *ferrugineus* were the most commonly found in a recent 2-year survey of farm-stored sorghum in Kansas, although not the most damaging.

Oryzaephilus surinamensis (sawtoothed grain beetle) is a common stored-grain pest. The adults are rather long, narrow beetles (2.5-3 mm long) with six "sawteeth" on each lateral margin of the prothorax. This species and a closely related species, O. *mercator* (merchant grain beetle) infest a wide range of cereal grains and their products, as well as oilseeds. O. *mercator* seems to be better adapted to the latter, while *O.surinamensis* is more suited to cereals. Both are common pantry and warehouse pests. The number of eggs per female averages 200 to 300. Damage is similar to that of *Cryptolestes* , and larvae require some minor damage to whole kernels to feed successfully; the germ is the common site of damage. These and *Cryptolestes* larvae often enter the germ area through cracks in the pericarp and develop as "internal feeders," thus contributing to the insect fragments in processed foods or feeds, just as do the internal-feeding weevils.

Trogoderma granarium (khapra beetle) is one of the most destructive storage pests in the warm, dry areas of Africa and Asia. It is not well established in a number of countries, including the USA. It was found in the southwestern parts of the USA and in northern Mexico, but was eradicated in the 1960s; this is one of the few examples of successful eradication of a well-established insect pest. It is frequently intercepted at ports of entry and occasionally is discovered after entry in a country where it is not established. Immediate monitoring of suspect areas and application of control measures usually eliminate the infestations.

Adults are oval and 1.5 to 3.0 mm long, and covered with fine hairs which are often rubbed off as the insects move about, leaving the surface of the elytra and prothorax rather shiny. Adults normally do not feed and are relatively short-lived; females lay 50 to 100 eggs. Larvae are characterized by numerous long hairs and tufts of setae on posterior segments. Development from oviposition to adult takes 30 to 35 days under optimum conditions. First evidence of *Trogoderma* infestation is usually the cast "skins" on the grain surface. According to Lindgren et al. (1955), the larvae can feed on grain having as little as 2% moisture content. They can infest a wide range of dried vegetable and animal materials. Larvae can live up to 3 years without food; this and their habit of hiding in cracks and crevices makes sanitation and other control measures difficult.

Corcyra cephalonica (rice moth) is a pest of stored rice, but also is a common pest of most other cereals, and occasionally attacks oilseeds and legume seeds. Sharma et al. (1978) reported that in a test including maize, groundnut, rice, wheat, and sorghum, this insect preferred sorghum grain. Adults are usually larger than other stored-product moths; males are smaller than females. They are gray-brown with thin lines along wing veins. A distinctive feature is the labial palps which point forward, in contrast to the curved ones of other common stored-product moths. Females lay about 150 eggs each and the larval period is 35.5 and 39 days, in pearl millet flour and broken wheat, respectively (Hodges 1979). Damaged cereal grains are more susceptible to infestation. In addition to larval feeding the grain is contaminated by fecal matter and webbing.

Plodia interpunctella (Indian meal moth) is cosmopolitan and a very successful insect on a wide variety of dried vegetable materials, including stored cereal grains. The adult is about 8 mm long and has a distinctive color pattern. The proximal half of the wings is light and the distal half reddish bronze, with irregular dark bands. This pattern gives a distinct light, transverse band across the body. Females lay an average of about 200 eggs. They do not feed and live for a few days only.

Larvae are typical caterpillars and feed only on the germs of the kernels. As the larvae move they leave strands of silk behind. They may web kernels together and feed within the clump. In bulk grain a heavy infestation can produce a sheet of silk over the grain surface and on walls. Mature larvae tend to leave the grain or other food medium and search for hiding places for pupation. The developmental period from oviposition to adult takes about 30 days under optimum conditions. This species is common in most cereal grains and in virtually all kinds of dry processed foods, feeds, as well as in nuts and dried fruits. Contamination of grain and processed cereals with silk, fecal pellets, and dead bodies is probably more important than loss by feeding.

There are other stored-product insect species that infest millet and sorghum, and other cereal grains, and may be "major" in certain situations. The fungus-feeding species can develop very high numbers where molding occurs and even though they may not directly damage the grain, they contaminate it. Two such species are *Ahasverus advena* (foreign grain beetle) and *Typhaea stercorea* (hairy fungus beetle). Psocids and mites may also be severe in high moisture situations. These types of organisms may be beneficial to the extent that they are recognized and warn the storekeeper of high moisture conditions within the grain. Important pests of stored sorghum and/or millet grain are listed in Table 3.

The similarity in the lists is evident, and the common species may be found in sorghum and millet in other countries also.

Table 3. Important pests of stored sorghum and/or millet grain.

Country	Pest genus
Benin	*Sitophilus. Sitotroga, Tribolium*
India	*Sitophilus, Rhyzopertha, Trogoderma, Sitotroga, Corcyra, Tribolium, Oryzaephilus. Plodia, Ephestia*
Mali	*Trogoderma, Rhyzopertha, Tribolium, Sitophilus, Sitotroga*
Northern Nigeria	*Sitotroga, Sitophilus, Rhyzopertha, Cryptolestes, Tribolium, Oryzaephilus*
Senegal	*Rhyzopertha, Sitotroga, Corcyra, Trogoderma, Oryzaephilus, Tribolium, Cryptolestes*
Sudan	*Trogoderma, Rhyzopertha, Tribolium, Corcyra, Oryzaephilus, Sitotroga*
USA	*Cryptolestes, Oryzaephilus, Sitophilus, Rhyzopertha, Tribolium, Plodia*

Losses

Storage losses from insect attack are often as great as or greater than those sustained by the growing crops. Losses to the growing crop are frequently obvious, but losses in stored grain may go unnoticed. A growing plant suffering damage from insects may recover and give a satisfactory yield, but storage losses are final. Losses caused by stored-grain insects may be direct, e.g., consumption of the grain; contamination by dead insects, cast skins, feces, odors, and webbing; and damage to containers and bags. Indirect damage results from heating, moisture, migration, and distribution of microbial spores. Where aesthetics are important, even light infestations result in loss of customers. Costs of labor and materials for control are also losses.

Estimation of losses is receiving considerable emphasis worldwide. Estimates of post-harvest losses to cereal grains have varied widely and often are not based on reliable data. This was substantiated by a survey of losses by Adams (1977b) involving wide distribution of questionnaires. He obtained information from 212 respondents in 30 countries. The survey pointed to the need for agreement on suitable methodology for measuring post-harvest losses, publication of the agreed methodology, and a glossary of terms commonly used in defining losses.

Adams (1976, 1977a) discussed the methodology for more objective and accurate loss estimates applicable to the developing countries. Subsequently, several other publications have shown interest in grain loss assessment and appropriate methodology for estimation, such as AAAS (1978), the U.S. National Academy of Sciences (1978a, 1978b), and the AACC (1979). Loss estimation is not as simple and straightforward as it might appear to the uninitiated. Some factors that must be dealt with are sampling technique, moisture content, kind of grain, type of damage, and pattern of grain use. Although we know that stored-grain insects are important as destroyers and contaminators of grain, the extent of the losses will not be known until we utilize objective and reasonably accurate methods of estimation.

Stored-grain Insect Control

All living organisms must have for survival: food, oxygen, water, suitable temperature, and protection from hazards in the environment; if the species is to survive, there must be reproduction. For any control measure to be effective, it should remove one or more of those life requirements. Sanitation removes food residues that might support an insidious infestation waiting to enter grain stores. Storing dry grain reduces its suitability for insects. Temperature, chemicals, and airtight storage may render the environment unsuitable. Other control measures affect the availability of life requirements.

In modem farm storage facilities, several options are available for insect control, such as forced aeration for cooling and/or equalizing temperatures, chemical protectants and fumigants, *grain* drying and cleaning, and modern sanitation procedures. The subsistence farmer, on the other hand, does not have all of these alternatives, and the practices he uses are generally those learned from experience over generations or centuries. Those providing technical assistance to developing countries have learned that those methods may be the best, given the resources of the farmers.

Some of the insect control practices that are available to the subsistence farmer include selection of varieties less susceptible to the insects (harder, smaller seeds, tight husks, etc.); mixing sand, ash, dust, or natural plant materials such as neem, with the grain; use of airtight or nearly airtight containers; and sanitation.

Recently, emphasis has been placed on the use of natural materials for insect control in grain, particularly for developing countries where other control measures may not be available. Grain stored in the head or husk is less susceptible to certain species than threshed grain. Some grain is stored over the cooking fire where it is heated, dried, and smoked. Spreading grain under a hot sun will kill insects or drive them out. In drier areas, pit storage is effective if it is tight enough, oxygen concentration is depleted, and the insects are denied entry. Mixing of a small-seeded grain with a larger-seeded (millet with beans) is believed to inhibit insect movement through the grain mass. Nongrain residues from threshing are sometimes used to make a layer under and over the grain that may be a barrier to insects. Upon first observation, some of the traditional insect control measures may appear to be unreasonable, but until they are adequately understood and tested, we should not discount them.

Chemical control of insects is controversial everywhere, but even more so in developing countries. Chemicals should not be used by anyone anywhere unless that person can and does read the label and understands what he is doing. Certain approved chemicals may be used around the storage structure and on the walls and floor inside, while some may be applied directly to the grain (malathion and pyrethrins in the USA, and these plus pirimiphos methyl, chlorpyriphos methyl, fenitrithion, resmethrin, and others can be used in various countries). While these are *relatively* safe chemicals and are considered harmless to humans if used on grain as directed, they should not be used by persons who do not understand pesticide use or are unaware of the potential dangers.

Use of fumigants by farmers and villagers in developing countries should be of even greater concern than chemical protectants. Even though fumigants can be used safely, they are deadly poisons. Liquid fumigants such as carbon tetrachloride, carbon disulfide, ethylene dichloride, and ethylene dibromide are commonly used. Some of these chemicals are banned or are under investigation in some countries. Another common fumigant is phosphine, which is released from aluminum phosphide. The fumigants act in the gaseous state and if the lethal concentration in the grain is retained long enough, all insects and rodents are killed. The gases eventually leave the grain. Only those trained in their use should use fumigants. An understanding of their limitations, dangers, and use is essential, both for safety and effectiveness. Building, bag, covered stack, or grain container, must all be tight enough to contain a lethal gas concentration.

In providing technical assistance in grain storage to developing countries, an important step is to study the extent of the problems in the area under consideration, rather than accepting poorly based high loss estimates made for developing countries in general. The present storage structures and practices should be studied to determine why they are used and how effective they are. Consideration should be given to modifying the traditional methods or to developing new practices feasible for the situation.

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Breeding for Insect Resistance in Sorghum and Other Control Approaches

Breeding for Shoot Fly and Stem Borer Resistance in Sorghum

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Abstract

The information on stable resistance sources, mechanisms, genetics, character associations, and breeding for resistance is reviewed, and progress made in breeding for multiple resistance to shoot fly and stem borer is documented. Resistance to these pests is found in some traditional Indian varieties which are agronomically inferior. Nonpreference for oviposition is a major mechanism of resistance to shoot fly, but antibiosis seems also to be present. For stem-borer resistance, antibiotic characters are more important than ovipositional nonpreference.

Heritability of shoot-fly resistance is fairly high, but that of stem-borer resistance is low. In the absence of sources of immunity, selection at one standard deviation (SD) below the population mean for pest damage can help to increase the resistance level gradually. A moderate level of multiple resistance (shoot fly and stem borer) has been built into a high-yielding background.

Résumé

Sélection pour la résistance à la mouche des pousses et au borer des tiges chez le sorgho : *Les informations présentées concernent la résistance stable, plus précisément, les sources, les mécanismes, la génétique, les caractères associés et la sélection. Le progrès dans le domaine de la sélection pour la résistance multiple à la mouche des pousses et au borer des tiges est documenté. La résistance à ces deux insectes se trouve chez certaines variétés traditionnelles indiennes qui sont autrement peu intéressantes du point de vue agronomique. La résistance à la mouche des pousses est fondée avant tout sur la non préférence pour la ponte et, peut-être, l'antibiose. En ce qui concerne la résistance au borer des tiges, les caractères antibiotiques sont plus importants que la non préférence.*

L'héritabilité de la résistance à la mouche des pousses est assez élevée mais celle du borer est inférieure. Dans l'absence des sources d'immunité, la sélection à un écart-type au-dessous de la moyenne de la population pour les dégâts permettra d'augmenter progressivement la résistance. Un niveau modéré de la résistance multiple (mouche des pousses et borer des tiges) est déjà incorporé dans un matériel à haut rendement.

Plant resistance should play a particularly important role in pest management programs in dryland crops. Landraces of cultivated sorghums from the plateaus of southern India survived under insect pressure and developed a high degree of resistance to shoot fly *(Atherigona soccata* Rond.) and stem borer *(Chilo partellus* Swin.). They are, however, low in productivity and are vulnerable to climatic fluctuations.

A systematic program of transforming these tropical sorghums into higher yielding genotypes in India commenced in the 1960s, utilizing early and dwarf temperate germplasm (Rao 1982; Rao and Rana 1982). The temperate x tropical crosses of sorghums provided the basis for combining resistance with more productive backgrounds. This paper analyzes the information on sources, mechanisms, and stability of resistance; genetics; selec-

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tion criteria; and advances from selection in breeding for shoot fly and stem borer resistance in sorghum.

Shoot Fly

Sources and Stability of Resistance

The genetic differences of resistance to shoot fly were first established by Ponnaiya (1951). Most of the resistant lines were from peninsular India. Subsequently, however, more than 10000 varieties from the world collection were systematically screened at different locations (Singh et al. 1968). Deadheart in the main shoot was taken as the parameter for evaluating resistance. A number of varieties showed consistently little damage, but none of them was found immune to shoot fly attack. Young (1972) has listed the following cultivars as promising sources: IS nos. 1034, 1054, 1061, 1082, 2122, 2123, 2146, 2265, 2269, 3969, 4507, 4522, 4545, 4553, 4567, 4646, 4664, 4776, 5251, 5285, 5383, 5469, 5470, 5480, 5483, 5490, 5566, 5604, 5613, 5615, 5622, 5633, 5636, 5658, and 5801.

Subsequent screening in the All India Coordinated Sorghum Improvement Project (AICSIP) has identified the following resistant lines: IS nos. 2312, 5511, 5641, 8315, 15551, 18557, and 22133.

Identified resistant lines mostly come from the *maldandi* (semicompact head type) or *dagadi* (compact-head type) grown in the *rabi* (postrainy) season. Insect populations vary from location to location and season to season, causing varying degrees of damage. In the absence of high levels of resistance, persistence or stability of even a low level of resistance is of considerable value. Identification of varieties with such inherent genetic characteristics is useful for a resistance breeding program.

We modified the method of analysis for stability of performance developed by Eberhart and Russell (1966), and used a susceptibility index in place of their environmental index (Singh et al. 1978). The susceptibility index is defined as mean deviations from a known susceptible variety. A variety with low susceptibility and repeatable rate of change resistance performance over environments is considered to be stable. The absolutely stable variety is one with zero insect damage ($\bar{X}$ = 0), zero rate of change (b=0), and lowest deviations (σ_d^2), whereas a susceptible variety shows a higher degree of damage and high regression coefficient and deviations. Using this modified analysis, Singh et al. (1978) established genotypic differences for stability of resistance over different environments. Such changes in resistance over environments were additive in effect and could be predicted. Based on means and regression coefficients, the varieties were classified into homogeneous groups. The varieties IS 1054, IS 5469, and IS 5490, constituted a single group and provided the most stable sources of resistance.

Recently 23 germplasm and 13 breeders' lines were tested for stability of resistance (AICSIP 1983). Among them IS 1082, IS 2146, IS 4664, IS 5470, IS 5566, and IS 22121, and a breeders line, SPV 491, showed mean deadheart percentages slightly less, though not significantly so, than that for IS 1054 (Table 1). Their regression coefficients and deviations were lower than those for IS 1054, indicating better stability of resistance.

Mechanisms of Resistance

There is consistently less oviposition on resistant varieties than on susceptible ones. Jotwani et al. (1971), Sharma et al. (1977), and Singh and Jotwani (1980a) demonstrated ovipositional nonpreference to be the major mechanism of resistance. Screening of 20 resistant and 2 susceptible varieties over 3 years under late planting revealed 0.38 to 0.71 eggs per plant on resistant varieties versus 1.37 to 1.70 eggs per plant on susceptible controls (Sharma and Rana 1983). Nonpreference appears to be a relative term, as there is no resistant variety showing zero oviposition. Relative nonpreference operates at all levels of infestation, over different environments. However, when a preferred host is absent and the shoot fly does not have a choice, the nonpreference mechanism is suppressed under heavy infestations.

Low larval survival on resistant varieties, however, showed the presence of antibiosis (Soto 1974). Retardation of growth and development, prolonged larval and pupal periods, and poor emergence of adults on resistant varieties also provided direct evidence of antibiosis (Singh and Jotwani 1980b).

Ovipositional nonpreference and deadheart formation are related phenomena in the sense that less egg laying results in less deadhearts (Sharma et al. 1977). This relationship holds good in parental varieties as well as in their F_1 and F_2 generations. Deadheart formation as a consequence of the

Table 1. Stability parameters of some promising shoot fly resistant sorghum germplasm and breeding lines, rainy season 1983 (No. of locations = 9).

Entry	Shoot fly deadhearts (%)		
	$\bar{X}$	b	$\overline{\delta ij^2}$
Germplasm line			
IS 1054	24.5	0.68**	144.8
IS 1082	22.8	0.51**	357.2
IS 2146	19.0	0.51**	242.6
IS 4663	25.1	0.76**	151.4
IS 4664	23.5	0.41**	259.5
IS 5470	20.6	0.43**	160.4
IS 5566	21.4	0.51**	276.7
IS 5585	25.1	0.51**	385.9*
IS 22121	24.2	0.54**	431.5*
Breeding line			
SPV 491	20.7	0.53**	172.9
R 1207	24.9	0.70**	231.9
Local (control)	36.9	0.78*	499.6*
SE	±2.73	±0.11	

Source: AICSIP (1983).
* Significant at 5%; ** significant at 1%.
i = variety; j = environment.

death of the main shoot and main shoot survival depend on the level of primary resistance (Sharma et al. 1977). Recovery resistance does not operate under Indian conditions.

Some morphological factors, such as toughness of leaf sheath (Singh and Jotwani 1980d), presence of trichomes (Gibson and Maiti 1983), glossiness of leaves, presence of irregularly shaped silica bodies in the fourth to seventh leaves (Ponnaiya 1951), and lignification and thickness of cell walls enclosing *the* vascular bundles (Blum 1967) also contribute to resistance.

Information on the chemical basis of resistance is limited. Low nitrogen content, reducing sugars, total sugars, moisture, and chlorophyll content of leaf, and, especially, low lysine content of the leaf sheath are related to resistance (Singh and Jotwani 1980c).

Seedling height and plant recovery are characters negatively correlated with oviposition and percent deadhearts (Sharma et al. 1977). These relationships indicate that tall seedlings and high plant recovery are characteristics of resistant varieties. Tiller development consequent to deadhead formation in the main shoot and subsequent survival and recovery of the plant depend on the level of primary resistance. Varieties with better recovery resistance appear to yield more under moderate shoot fly infestation (Fig. 1).

Genetics of Resistance

The Ft hybrid shows an increase over the midparent value under low shoot fly infestation, but this relationship is reversed under high infestation. Resistance exhibits partial dominance under low infestation but appears to be partially recessive under high infestation (Rana et al. 1981; Borikar and Chopde 1980). Heterosis in S x S and R x R F_1 s for percent deadhearts was 1.9% and 3.9% respectively and therefore negligible. Heterosis in S x R F_1s however, was 17.2% (Sharma and Rana 1983). Inbreeding depression in the latter crosses was 6.7% and relatively higher than S x S and R x R groups. Parent versus F_1 and F_1 versus F_2 differences were nonsignificant for oviposition, indicating absence of heterosis as well as the presence of inbreeding depression for oviposition.

Parental performance is a good indicator of hybrid behavior (Sharma et al. 1977; Rao et al. 1978). Regression of F2 on F_1 was also significant for eggs per plant (b = 0.321**) and deadheart percent (b = 0.563**). Thus the resistant F_1 is expected to produce a resistant F2 (Fig. 2).

Shoot fly resistance in terms of deadheart percentage is a quantitative character, which is predominantly governed by additive genes in the F1 and F2 generations (Rao et al. 1974; Balakotaiah et al. 1975). Under heavy infestation, Sharma et al. (1977) reported 49.7% and 82.1% heritability for percent deadhearts in the F_1 and F_2 generations, respectively.

Borikar and Chopde (1980) evaluated a diallel under three different dates of planting to ensure various levels of infestation. In general, the proportion of additive:dominance variance increased with the increase in shoot fly infestation. Heritability in their studies was 48 to 86% for percent deadhearts and 77 to 93% for eggs per plant. Under selection, heritability of deadhearts in the F3 was about 25% (Rana et al. 1975).

Single plants of 16 F_2 progenies from crosses between susceptible x resistant parents were eval-

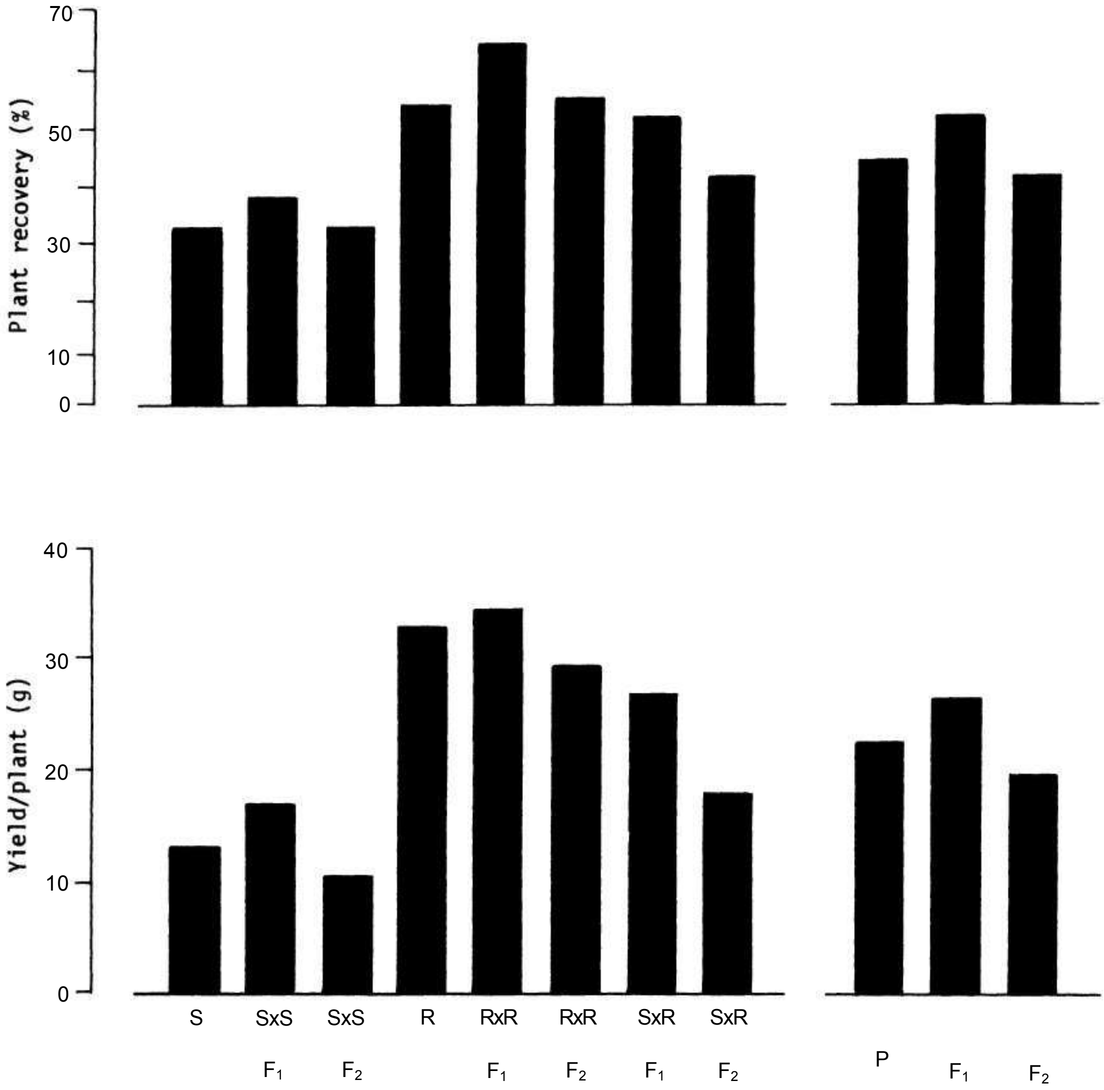
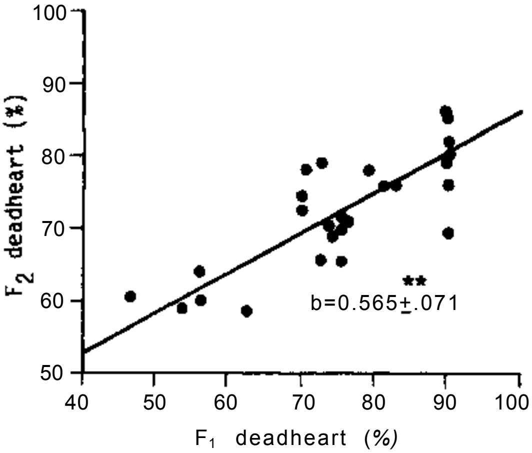


Figure 1. Recovery resistance to shoot fly and yield in different crosses between susceptible high-yielding (S) and resistant (R) sorghum varieties.



** Significant at 0.01% level of probability

Figure 2. Regression of F2 and F1 hybrids in sorghum for shoot fly deadhearts (%).

uated for oviposition and deadhead formation. F2 frequencies of resistant plants with and without eggs fit a 3:1, while deadhead resistant plants versus susceptibles fit a 15:1 Mendelian ratio (Table 2). These studies revealed that a single recessive gene governs nonpreference for oviposition and two duplicate recessive genes govern the resistance to deadhead formation (Rana and Sharma 1983). The double recessive genotype, npo npo is responsible for nonpreference for oviposition and the $dh_1 dh_1 dh_2 dh_2$ double recessive genotype governs the resistance to deadhead formation.

The presence of trichomes on the abaxial surface of the leaf is controlled by a single recessive gene (Gibson and Maiti 1983) and appears to be a highly heritable ($h^2 = 0.9$) trait (Omari, unpublished).

Glossy leaves, another character associated with resistance, are also governed by a single recessive gene (Tarumoto 1980).

Breeding for Resistance

Shoot fly resistance showed a systematic gradation in a series of crosses among susceptible (temperate), intermediate, and resistant varieties (Fig. 3). The F2 and F3 distributions conform to a normal distribution, immunity being absent (Balakotaiah et al. 1975). While F2 modalities enable identification of potential crosses, differences among resistant and susceptible progenies are established by the F3 generation. With such a situation, it is possible to select one standard deviation below the population mean in the F2 and F3 generations (Rana et al. 1975). The significant regression of the F1 on the parent (Rao et al. 1974) and the F3 on the F2 indicate that pedormance of selected progenies would be reflected in the next generation.

Although resistance in the F_1 and F_2 generations is highly additive, the heritability in F3 is reduced to 25%. Ten percent of the total F3 progenies tested for shoot fly resistance were selected under moderate fly pressure as less susceptible by considering only progenies with less than 20% deadhearts, which provides enough flexibility to operate selection within and between progenies. Selection in subsequent generations should be carried out under heavy shoot fly infestation. By adopting this selection procedure, it has been possible to develop agronomically desirable genotypes, such as CSV nos. 5,6, 7(R), and 8(R), and SPV nos. 102, 104, 107, 221, 292, 315, 491, 502, and 504, from temperate x tropical crosses with satisfactory levels of resistance.

Table 2. Genetics of shoot fly oviposition and deadheart formation in sorghum.

Class	F_2 frequency	Genetic ratio
(A) Oviposition		
No. of plants with egg laying	211	3
No. of plants without egg laying	87	1
X^2 =	2.79	(P 0.10-0.25)
(B) Deadheart formation		
Deadheart formation (Susceptible)	3076	15
No. deadheart formation (Resistant)	211	1
X^2 =	0.16	(P 0.50 -0.75)

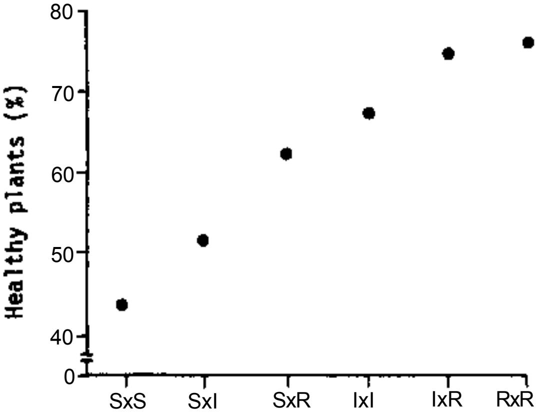


Figure 3. Shoot fly resistance (%) among resistant (R), intermediate (I), and susceptible (S) varietal crosses of sorghum.

Further selection in some high-yielding varieties was carried out under high infestation. Table 3 shows that the selected lines such as E 404, E 406, E 409, E 416, and E 426 possessed stable resistance to shoot fly (Prem Kishore and B.S. Rana 1984, Selection for shoot fly *[Atherigona soccata* Rond.] resistance in high-yielding varieties of sorghum, unpublished).

Selection for shoot fly resistance in segregating generations of temperate x tropical crosses has resulted in some highly resistant lines: E nos.103, 108, 109, 112, 115, 119, 124, 302, 303, and P 151. Some of the resistant breeding lines evolved at ICRISAT were also tested in AICSIP trials during the rainy season, 1982. Deadheads ranged from 23 to 39% against 58% in CSH 1. Five lines—PS nos. 14454, 18257, 18527-2, 18601-3, and 21113-showed less than 30% deadhearts. Agrawal and House (1982) reported 24 promising shoot fly resistant lines that showed only 27.7 to 60.0% deadheart formation at ICRISAT Center in Patancheru, against 100% deadheart formation in the susceptible control. The six most promising lines were: (IS 2816 C x 5D x Bulk)-2-2-1 - 1 , (UChV2 x IS 3962)-6-1-1-1, (ESGPC x IS 12573 Q-3-1-1-3, (ESGPC x IS 12573 C)-3-2-3-1, (IS 2816 C x 5D x Bulk)-2-1 - 1-1, and (SPV 29 x IS 3962)-1-2-1.

Stem Borer *(Chilo partellus* Swin.)

Sources and Stability of Resistance

The existence of resistance to stem borer in sorghum was reported by Trehan and Butani (1949) and Pant et al. (1961). Subsequently, Singh et al. (1968) screened 3953 germplasm lines from the world collection. Systematic screening was continued by Jotwani and his colleagues, who screened an additional 6243 germplasm lines. Twenty-four lines found consistently less damaged under repeated hatural and artificial infestation were: IS nos. 1044, 1056, 1155, 3096, 4424, 4552, 4651, 4689, 4707, 4764, 4776, 4782, 4827, 4841, 4875, 4934, 4994, 5030, 5031, 5470, 5837, 6041, 8314, and 9136. A further multilocation screening program enabled us to identify the following lines: IS nos. 2122, 2205, 4329, 4829, 4839, 4863, 4866, 5469, 5490, 6046, 6101, 6119, 10676, 10711, 10795, 12448, 17934, 18463, 18574, 18578, VZM 2B, BP 53, and DJ 6514.

Thirteen germplasm lines were tested over seven AICSIP locations during the rainy season, 1983; IS 5538, IS 18551, and IS 18584 were the most stable for resistance in terms of percent

Table 3. Shoot fly resistance in some sorghum selections over a 3-year period.

Selection No.	Origin	Deadheart (%) Year 1	Year 2	Year 3	Average
E 404	CSV 6	32.4	28.7	29.8	30.3
E 406	SPV 8	29.1	27.6	28.1	28.3
E 409	SPV 13	29.7	29.0	28.3	29.0
E416	SPV 29	31.1	28.5	29.4	29.7
E 426	SPV 70	32.5	32.8	30.7	32.0
Control	CSH 1	71.1	90.0	90.0	83.4
SE		±0.91	±0.89	±0.87	±2.97

Table 4. Stability parameters of some promising sorghum germplasm lines for stem borer resistance.

Entry	Deadheart (%)			Tunneling (%)		
	Mean	b	δij^2	Mean	b	δij^2
IS 5538	4.8	0.19**	6.44	6.4	-0.24*	0.68
IS 18551	4.1	0.17**	0.56	3.5	-0.11**	4.77
IS 18577	8.1	0.38**	18.90	4.0	-0.29*	6.78
IS 18578	5.9	0.26**	11.47	4.9	-0.50	4.65
IS 18584	3.7	0.13**	9.13	3.0	-0.07**	3.22
PB 8272	5.3	0.33**	1.01	2.7	0.37	2.81
PB 8313	4.3	0.15**	2.30	3.3	-0.01**	3.38
PS 21206	8.3	0.14**	11.48	2.3	-0.06**	3.62
Local	10.4	0.25**	36.75	4.0	0.17**	8.03
SE	±3.2	±0.12		±1.7	±0.33	

Source : AICSIP (1983), Unpublished data.
* Significant at 5%; ** significant at 1%.
i = variety ; j = environment.

deadhearts and percent stem tunneling (Table 4). IS 18577 and IS 18578 and some ICRISAT breeding lines, such as PB 8272, PB 8313, and PS 21206, were stable for resistance to stem tunneling (AICSIP 1983).

Resistance Parameters

Stem borer attacks both seedling and adult plants. Emerging larvae start feeding on leaf-whorls of seedlings and the leaf-feeding lesions appear after 20 days of crop growth. When stem borer infestation is heavy, feeding in the leaf-whorls results in deadheart formation. The second cycle of borers establishes on the adult plant by making holes in the stalk and peduncle. Thus, borer attack can be measured in terms of leaf-feeding injury; deadheart formation; and tunneling parameters such as number of holes, number of tunnels, and percent tunneling separately in stalk and peduncle.

Relationship among Resistance Parameters

Leaf-feeding injury rating, deadhearts, and tunneling percentages are not correlated and are inherited independently (Singh et al. 1983). However, tunneling parameters per plant are significantly correlated among themselves (Table 5). Number of

Table 5. Correlation between stalk and peduncle resistance parameters (DF= 151).

Parameter	Correlation coefficient					
	1	2	3	4	5	6
Stalk						
1. No. of holes	1.00	0.66**	0.64**	0.19	0.07	0.06
2. No. of tunnels		1.00	0.64**	-0.01	0.03	-0.13
3. Tunneling (%)			1.00	0.08	-0.05	-0.04
Peduncle						
4. No. of holes				1.00	0.29**	0.32**
5. No. of tunnels					1.00	0.55**
6. Tunneling (%)						1.00

** Significant at 1 %

holes, tunnels, and percent tunneling per plant, therefore, depend on one another. When these parameters were measured in stalk and peduncle separately, they were positively and significantly correlated. Stalk parameters were not significantly correlated with peduncle parameters, indicating possible independence of stem borer resistance in stalk and peduncle.

Correlation among Growth Parameters of Borer

Oviposition, larval duration, larval mortality, and pupal weights were studied separately on leaf-whorls and stalks of 70 sorghum varieties (Singh and Rana 1984). Number of eggs per plant was negatively correlated with larval duration and mortality and positively with pupal weights on leaf-whorl tissue. Thus, preference for oviposition is related to shorter larval duration, low larval mortality, and increase in pupal weights. In other words, these relationships indicate that nonpreference and antibiosis in the leaf are related characters. Longer larval duration associated with high larval mortality and low pupal weight was observed when the larvae fed on either the leaf-whorl or the stem tissue. The growth parameters of the borer on the leaf-whorl were not significantly related to corresponding or other parameters on the stem. Hence, the factors affecting borer biology in the leaf-whorl are different from those in the stalk.

Correlation between Oviposition, Larval Development, and Field Resistance Parameters

Oviposition and larval development in relation to field resistance under artificial infestation were simultaneously studied on released hybrids and varieties, experimental varieties, and two resistant controls (Singh and Rana 1984). The leaf-feeding injury rating was not related to oviposition or larval development parameters either in the leaf-whorl or on the stalk. The varieties preferred for oviposition showed higher deadheart and tunneling percentages. Low deadheart formation was significantly related to prolonged larval duration, higher larval mortality, and lower pupal weights on the leaf-whorl but not when larvae were raised on the stalk (Table 6). Tunneling percentage per plant showed a similar relationship to larval development parameters when larvae were fed only on stalk tissue. Antibiosis present in leaves thus hinders deadheart formation, while in the stalk it affects the larval growth and reduces tunneling percentage.

Mechanisms of Resistance

An experiment with one susceptible (Swarna) and one resistant (P 37) variety was laid out to study the mechanisms of resistance (Table 7). On both sides of these test varieties, three rows of another susceptible (CS 3541) variety were planted in a first,

Table 6. Correlation between stem borer biology and field resistance parameters of 70 sorghum varieties.

Parameter	Leaf-feeding injury	Deadheart (%)	No. of holes	Tunneling (%)	Grain yield
No. of eggs/plant	0.10	0.92**	0.32**	0.24*	-0.21
Leaf-whorl					
Larval duration	-0.01	-0.81**	-0.21	-0.27*	0.11
Larval mortality	-0.12	-0.06	0.40**	-0.81**	0.01
Pupal weight	-0.05	-0.69**	-0.20	0.18	-0.08
Stem					
Larval duration	0.09	0.21	0.50**	-0.83**	0.02
Larval mortality	0.02	0.64**	0.11	0.12	0.05
Pupal weight	0.01	0.17	0.06	0.50**	-0.07

* Significant at 5%; ** significant at 1 %.

Table 7. Relative stem borer resistance in resistant (R) vs. susceptible (S) sorghum varieties, under artificial infestation (1).

Experimental design				Tunneling (%)		
Border variety	Test variety	Border variety	Pupae/ plant	Stalk	Peduncle	Grain yield (g/plant)
S	S	S	2.4	16.2	13.9	35
S	S_1	R	3.1	13.5	11.8	39
R	s_1	R	3.3	13.8	12.6	31
S	R	S	0.1	7.9	7.0	33
S	R	R	0.1	7.4	6.7	31
R	R	R	0.0	6.9	6.9	31
SE			±0.16	±0.73	±0.75	±2.3

and three rows of a resistant (E 302) variety in a second, set of plots. In a third set, one side of the three test rows was planted with a resistant variety and the other side with a susceptible variety. The test varieties were infested with freshly emerged larvae at the leaf-whorl and boot-leaf stages of plant growth. The susceptible test variety when compared with the resistant one, showed a clear trend in having more pupae per plant and a higher percentage of tunneling.

Field-resistant sorghum varieties, when tested in the laboratory, were nonpreferred by the stem borer for oviposition and also slowed down larval development compared with the susceptible varieties (Singh and Rana 1984). Hence, both nonpreference and antibiosis mechanisms act together to determine the degree of resistance. The varieties that induced the most larval mortality on both the leaf-whorl and the stem were: CSV 8(R) and SPV 35; on the leaf-whorl alone: E 302, CSV 3, CSV 6, and SPV nos. 101, 292, 305, and 311; on the stem alone: SPV 103, SPV 104, P 37, P 151, R 133, IS 2312, and Aispuri. Thus genotypes exist with leaf-feeding and stem-feeding resistance expressed independently but the coexistence of both resistance characters in one genotype is also possible.

Deadhead formation was possibly reduced in those varieties where larval duration and mortality on the leaf-whorl was high (Fig. 4). The number of holes, number of tunnels, and tunneling percentages were negatively and significantly correlated with larval duration and mortality on the stem (Fig. 5). Thus, factors present in the stem that influence larval development also affect the tunneling parameters. The varieties relatively more resistant in the field were found to adversely influence larval development on both the leaf-whorl and stem. The magnitude of correlations of larval duration and mortality with tunneling parameters was higher than that of number of eggs per plant; i.e., oviposition (Table 6). Thus, the influence of antibiosis on field resistance is much greater than that of ovipositional nonpreference.

Earlier, Kalode and Pant (1967) and Jotwani et al. (1978) had provided evidence of antibiosis. Girdharilal and Pant (1980) also observed low larval survival on resistant sorghum varieties and expected it to be due to the presence of antibiosis factors.

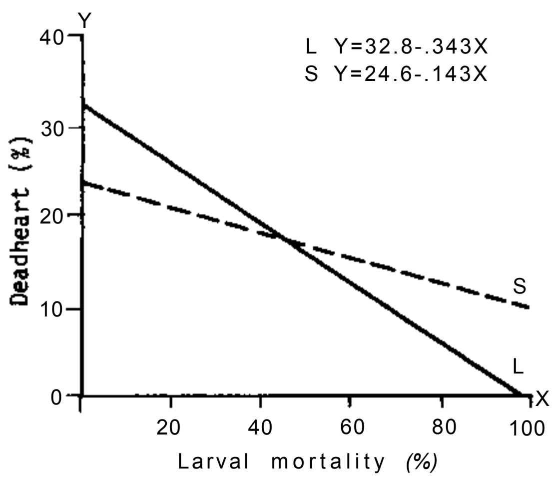


Figure 4. Relationship between deadhearts (%) and larval mortality of stem borer feeding in the leaf whorl (L) and on the stem (S) of sorghum.

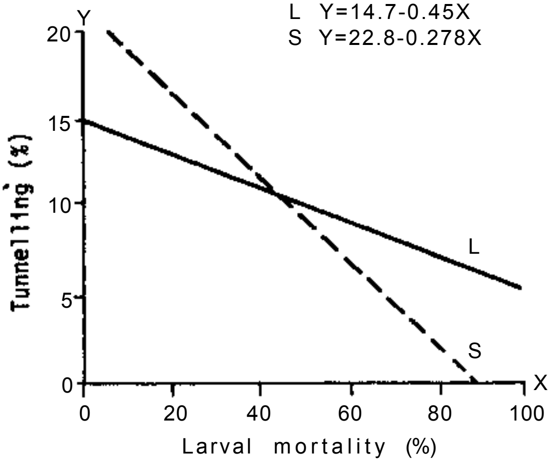


Figure 5. Relationship between stem tunneling (%) and larval mortality of stem borer feeding in the leaf whorl (L) and on the stem (S) of sorghum.

Genetics of Resistance

Rana and Murty (1971) had reported the quantitative nature of resistance. Male-sterile lines were not significantly different for secondary damage but male parents provided significant variability. These authors found that general combining ability was predominant for primary damage (leaf injury), while specific combining ability was 1.5 times more for secondary damage (percent tunneling).

Seventeen parental varieties and the 136 possible F_1 hybrids among them were evaluated under artificial infestation. Compared with midparental values, the F_1 hybrids were more susceptible for number of holes per stalk and tunneling percent per stalk and peduncle (Rana et al. 1984). Heterosis for these parameters was 94.5, 22.8, and 15.8%, respectively (Table 8). This reveals almost complete dominance of susceptibility for number of holes per stalk and partial dominance for the other characters.

Table 8. Heterosis for resistance parameters in 17 x 17 diallel crosses in sorghum

Parameter	Heterosis (%)
No. of holes/stalk	94.5
No. of holes/peduncle	6.3
No. of tunnels/stalk	16.4
Tunneling (%)/stalk	22.8
Tunneling (%)/peduncle	15.8

Combining ability analysis in a 17 x 17 diallel involving high yielding and resistant varieties was carried out by Rana et al. (1984). They reported σ^2 gca almost half σ^2 sca for number of holes per stalk and per peduncle and equal for number of tunnels per peduncle. Heritability was 44% for number of holes per peduncle and fairly low (10-15%) for tunneling parameters both in the stalk and peduncle.

Subsequent studies of a subset of this diallel (7 x 7) in the F_1, F_2, and F_3 generations indicated that heritability increased 14 to 34% for number of holes, and remained constant (20 to 21 %) for percent tunneling (Table 9). Heritability of resistance, especially in terms of percent tunneling per plant, was therefore fairly low.

Breeding for Resistance

Response to directional selection as well as correlated response in tolerant x resistant varietal crosses revealed that directional selection for

Table 9. Estimates of additive (σA^2) and nonadditive (σD^2) genetic variance for stem borer resistance in sorghum.

Estimate	No. of holes			Tunneling (%)		
	F_1	F_2	F_3	F_1	F_2	F_3
σA^2	0.38	1.3	5.2	5.3	0.32	9.9
σD^2	1.20	6.0	6.2	13.5	1.20	29.0
$\sqrt{\sigma A^2/\sigma D^2}$	1.78	2.2	1.1	1.6	1.94	1.7
Heritability (%)	14	17	34	21	21	20

number of holes was 0.369 and for percent tunneling in the stalk, 0.495 (Rana et al. 1984). Direct response for number of tunnels was very poor. Correlated response for percent tunneling due to number *oi* holes was very high. Thus, selection based on few holes would be helpful in selection for tunneling resistance in the stalk.

Selection based on low leaf-feeding injury rating and stem tunneling was practiced in the F_3 to F_6 generations of six crosses originally selected for agronomic traits and shoot fly resistance in the F2 generation (Kishore et al. 1984). A selected bulk of each cross was advanced. The progenies of CSV 5 x IS 4664, and R 147 x IS 4664 responded to selection (Fig. 6).

Singh et al. (1980) made selections in 17 advanced-generation derivatives of two temperate x tropical crosses, IS 2954 x BP 53 and IS 3922 x Aispuri. In spite of low heritability of resistance, it was possible to develop the resistant derivatives D 168, D 172, D 259, D 358, D 367, and D 369. By

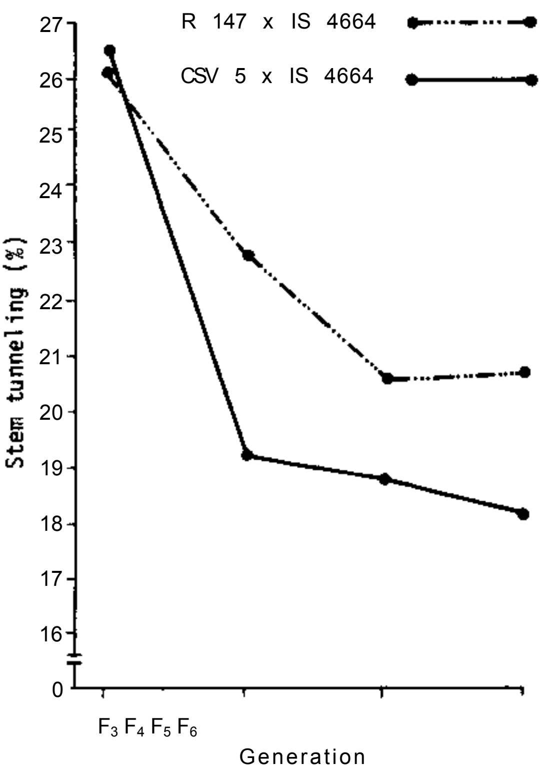


Figure 6. Effect of selection on stem tunneling (%) in two sorghum crosses.

continuous selection in segregating generations of other temperate x tropical crosses, 12 varieties—SPV nos. 35, 103, 107, 110, 135, 140, 192, and 229, and E 302, E 304, P 37, and R 133—were developed, which were at par with resistant varieties for percent tunneling per plant (Singh et al. 1983).

Breeding for Multiple Resistance to Shoot Fly and Stem Borer

Resistance to more than one pest can gradually be built up in the high-yielding background by using suitable parents, mating system, screening technique, and selection procedure. Tropical germplasm, particularly from India, furnishes the source of resistance to sorghum shoot pests. Generally, local cultivars resistant to shoot fly also show some degree of tolerance to stem borer. Some of these stocks, such as IS nos. 5538, 5566, 19551, 18577, 18578, and 18584, have been reported (AICSIP 1983). These sources are in no way immune to either pest. Ovipositional nonpreference and antibiosis are common resistance mechanisms but the factors controlling resistance are different for shoot fly and stem borer.

Derivatives of temperate x tropical crosses which combine a high degree of tolerance to both the pests in a desirable agronomic background furnish good parents for crossing (Rana et al. 1981). A selective mating system involving derivatives, resistant germplasm, and other varieties for diversity of alleles has been shown to be useful (Seshagiri Rao 1979). Testing the F3 segregating material in locations where the pests are endemic and rotating the selected progenies in those locations can enable selection for multiple resistance.

In the absence of absolute resistance, an approach outlined by Rana et al. (1975) for breeding shoot fly resistance can be adopted for other pests also. When selection for yield and resistance is simultaneously done, the genetic advance for resistance is fairly slow (Rana et al. 1981). A moderate degree of resistance could be combined in improved varieties with satisfactory yield levels (Table 10). Due to the high heritability of shoot fly resistance, it is possible to recover a high degree of resistance under high selection pressure, but this is not necessarily possible for stem borer resistance. Thus combining multiple insect resistance in a good agronomic background appears to be a slow process and requires several cycles of crossing.

Table 10. Shoot fly and stem borer resistance of some recently bred high-yielding varieties of sorghum. (No. of locations = 9).

Variety	Yield (kg/ha)	Av.% shoot fly deadhearts		Stem borer damage	
		Normal sowing[1]	Late sowing[1]	Leaf injury rating[2]	Stem tunnelina (%)
SPV 96	2530	8.6	45.9	1.8	10.4
SPV 97	2610	6.9	45.1	2.5	13.1
SPV 102	3020	10.2	40.9	1.7	11.3
SPV 104	3390	7.5	40.8	1.4	9.4
SPV 105	2730	8.2	55.7	1.3	10.7
SPV 106	2780	12.8	48.7	1.8	12.8
SPV 107	2470	4.9	42.3	1.7	11.5
SPV 108	2890	8.1	46.5	1.2	9.7
SPV 221	2900	5.5	40.0	2.0	12.9
SPV 225	2750	10.4	50.2	2.7	11.6
SPV 247	2470	6.3	42.0	1.8	9.2
Resistant control					
IS 5-90	1200	2.8	28.7	1.7	18.1
E 302	2000	7.2	41.3	1.6	15.9
Susceptible control					
CSH 1	2730	33.8	67.3	3.3	25.6
SE	±1.37	±1.98	±2.36	±0.05	±1.17

1. Normal sowing is done at onset of monsoon; late sowing, 15 days later.
2. Rating : 1 = resistant; 5 = susceptible.

Future Research Needs

Additional information on the biology, bionomics, economic injury levels, and reliable screening techniques, particularly for stem borer, is essential to effective work on host-plant resistance. Some of the stable sources of resistance to shoot fly and borer have been identified but these are in no way immune to the pests. A search for durable multiple resistance donors in better agronomic and disease resistance backgrounds should be continued.

Major genes governing resistance should be identified to enable easy transference and accumulation of resistance to more than one pest. With the biotechnological knowledge now available, the feasibility of transferring resistance to insect pests from wild genera to cultivated forms has also increased. A moderate level of multiple resistance to shoot pests in high-yielding backgrounds has been achieved. Efforts to transfer a high degree of resistance against both shoot and earhead pests in a suitable agronomic background will continue.

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Breeding Sorghum for Midge and Greenbug Resistance in the USA

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Abstract

Exotic sorghums have been identified with usable resistance to the key insect pests of sorghum in the USA. These resistance sources are from converted or partially converted lines in the sorghum conversion program. Elite adapted lines resistant to the greenbug (Schizaphis graminum *[Hondani]) and the sorghum midge {*Contarinia sorghicola *[Coquillett]) have been developed from these resistance sources and are now available. Screening techniques and breeding methods used for developing resistant lines and hybrids are described. Higher levels of resistance to both insects are possible, and areas of research needed to achieve these are outlined.*

Résumé

Sélection du sorgho pour la résistance à la cécidomyie et au puceron vert aux Etats-Unis : *Aux Etats-Unis, on a identifié des sorghos de type exotique à résistance utile aux principaux insectes nuisibles au sorgho. Ces sources de résistance sont obtenues à partir de lignées converties ou partiellement converties dans le cadre du programme de conversion des sorghos. On a créé des lignées élites adaptées et résistantes au puceron vert (*Schizaphis graminum *[Rondani]) et à la cécidomyie du sorgho (*Contarinia sorghicola *[Coquillett]) à partir de ces sources; ces lignées sont maintenant disponibles. Les techniques de criblage et les méthodes de sélection utilisées dans la création des lignées et des hybrides résistants sont décrites. Les domaines de recherches à approfondir pour obtenir des niveaux plus élevés de résistance sont proposés.*

Introduction

Plant breeders are concerned with insect problems in the planning of their breeding programs. Breeding nurseries where no insecticides are used, are established to provide early-generation evaluation of breeding lines for insect resistance. Breeding for host-plant resistance enables the development of improved lines or cultivars resistant to a particular insect pest while maintaining or improving other agronomic characteristics.

While host-plant resistance can be the chief means for controlling a pest, it is most likely to be used in conjunction with other control measures. Host-plant resistance is economical, specific for a particular insect, leaves no harmful residue in food or the environment, and is compatible with biological, chemical, and other control measures. This compatibility makes it valuable even when resistance is less than desired.

Breeding insect-resistant cultivars differs in no fundamental way from breeding for other characteristics. Any breeding method appropriate for sorghum may be used, once resistance has been identified and efficient evaluation techniques developed. It is important to: (1) develop agronomically suitable varieties resistant to insects of economic importance as rapidly as possible, (2) continue to find new sources of resistance, and (3) improve the level of resistance over that presently available.

Although sorghum is damaged by more than 50 insect pests (Teetes 1980) only the greenbug and

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the midge are consistently key pests of this crop in the USA and will be dealt with in this paper.

Germplasm

The development of sorghums resistant to insects, or other stress conditions, is contingent upon usable resistance sources in acceptable agronomic form. Because sorghum is an introduction to the temperate USA, many of the 25 000-plus accessions in the world sorghum collection from tropical, short-day regions of the world are too tall, too late, or otherwise unadapted to this climatic zone. U.S. sorghum workers dealt with a restricted germplasm base until a method was developed to make new germplasm available.

The sorghum conversion program, initiated in 1963, was established to enhance the available germplasm base (Stephens et al. 1967). The cooperative project is operated by the Texas Agricultural Experiment Station and the U.S. Department of Agriculture, Science and Education Administration, Agricultural Research Service.

The program involves changing a few major dominant height and maturity genes by a crossing and backcrossing program in Puerto Rico under short-day photoperiods during the winter, where the short days cause sorghums to mature early. Early, short genotypes are selected from F_2 populations grown under long-day conditions in Texas during the summer growing season. Maturity differences are expressed under long summer days, and individual plants with a suitable maturity for growth under long-day conditions can be identified.

Since the initial release of conversion material in 1969, the program has been a source of valuable new "tropically adapted" germplasm containing many desirable traits (resistance to insects, pathogens, and grain molds; drought tolerance; good grain quality; etc). All sources of midge resistance used in the USA have come from this program, except for AF 28.

Cooperative Research

Progress in the development of insect-resistant germplasm can be substantially enhanced with a cooperative effort between breeders and entomologists. While responsibilities may vary, it is important to have substantial interaction and dialogue between the two groups of scientists. With a team approach, the scientists view the nurseries together, the entomologists primarily for insect resistance, the breeders for agronomic traits. At the Texas Agricultural Experiment Station, the sorghum improvement program is a cooperative effort involving scientists from several disciplines; this has given substantially more and faster improvement in sorghum than if each group had worked in isolation.

Midge

The sorghum midge, *Contarinia sorghicola* (Coquillett), is probably the most cosmopolitan insect pest of sorghum. In the USA it was first reported as a pest in Texas in 1908 (Herrick 1909). Resistance sources have been reported from several countries (Johnson et al. 1973; Jotwani et al. 1971; Parodi et al. 1974; Santos and Carmo 1974; Wiseman et al. 1973, 1974).

Sources of Resistance

Lack of germplasm adapted to temperate regions hindered the identification of resistance sources and development of elite resistant germplasm until lines from the sorghum conversion program became available. Also, breeding nurseries were planted at a time designed to escape midge damage, or were sprayed with insecticides to control the midge if it became a problem. Independent observations in 1969 by Dr. D.T. Rosenow at Lubbock, Texas, and Dr. F.R. Miller at the Federal Experiment Station in Mayaguez, Puerto Rico, indicated a differential response by sorghum conversion lines to midge damage (F.R. Miller and D.T. Rosenow, personal communication). Prior to 1983, 211 lines had been screened for midge resistance (Wuensche et al. 1981). Of this group, 36 lines were identified as possessing useful resistance (Table 1). SC 175 was one of the first lines identified as possessing resistance and has been the most widely used. Hybrids with this resistance source at present have the highest levels of resistance available in agronomically acceptable form.

Two hundred and fourteen new converted lines are currently being screened for resistance. Results from 1983 indicate 10 lines have usable levels of resistance (Table 2). This group of lines is being screened again this year at several locations to further test for new resistance sources.

Table 1. Converted sorghum lines with high or moderate levels of resistance to the sorghum midge *(Contarinia sorghicola)* in the Texas conversion program.

IS no. of original line		SC no.	Working group	Midge damage rating[1]
2579C		423	Zerazera	3.09
7064C		420	Caudatum-Kafir	3.25
12666C		175	Zerazera	3.30
7142C		564	Caudatum	3.54
6392C		490	Nandyal	3.71
8337C		574	Caudatum-Nigricans	3.79
2816C		120	Zerazera	3.90
8231C		645	Caffrorum-Darso	3.91
3071C		237	Dobbs	3.95
8233C		643	Caffrorum-Darso	4.00
12593C		84	Durra-Nigricans	4.07
8263C		328	Dobbs	4.32
2862C		655	Caffrorum	4.34
2562C		734	Caudatum	4.34
2549C		228	Zerazera	4.41
12664C		173	Zerazera	4.65
2508C		414	Caudatum-Kafir	4.84
12609C		109	Zerazera	4.92
2403C		103	Caudatum	4.94
12683C		221	Durra	5.33
12589C		80	Durra-Nigricans	5.42
6446C		586	Nandyal	5.44
12676C		185	Caudatum-Nigricans	5.50
3574C		239	Zerazera	5.62
12610C		110	Zerazera	5.73
2757C		319	Dochna-Nigricans	5.76
8100C		424	Caudatum-Nigricans	5.85
12612C		112	Zerazera	5.86
12573C		63	Caudatum-Nigricans	5.88
8134CC		590	Durra-Nigricans	5.94
12608C		108	Zerazera	6.08
2662C		114	Caudatum	6.09
2573C		64	Nigricans-Feterita	6.11
12577C		68	Caudatum-Nigricans	6.28
6394C		491	Nandyal	6.28
2569C		60	Caudatum	6.33
TAM 2566[2]	(Resistant control)			5.58
Tx 2536				8.25
BTx 623	(Susceptible control)			8.67
BTx 3042				8.25

1. Rating scale : 0 = no damage, 1 = 10-20% blasted head, 2 = 21-30%, etc., 9 = 91 % or more blasted head.
2. Derived from SC 175.

Another resistance source currently utilized is AF 28, an introduction from Brazil, which contains the highest level of presently identified resistance. This excellent resistance is expressed in the derivative Tx 2782. Unfortunately, Tx 2782 has serious agronomic deficiencies (tight head, small seed size, tall height, etc.) that limit its usefulness as a parent in either breeding materials or hybrids.

Screening Techniques

Techniques to rear the midge artificially have not been developed, so it is not possible to use greenhouse screening. Naturally occurring infestations in field plantings must be relied upon. The unreliability and/or fluctuations of midge density levels and maturity variation of test plants are inherent problems associated with field screening.

Damaging midge infestations are best attained by delayed planting, multiple plantings of the same test materials, and/or earlier plantings of susceptible sorghums on which damaging levels of midge are obtained by the time test plants flower. As a variation of the latter technique, bulks (mixtures) of susceptible early, medium, and late hybrids, adapted to the areas where the tests are grown, are planted around the nursery and at regular intervals (every 25-30 rows) within the nursery. This increases midge density and allows for relative comparisons of maturity and damage ratings. For comparison, an adequate number of controls, both resistant and susceptible, should be planted at regular intervals throughout the nursery. These checks should represent a range of maturities and include the earliest and latest maturing lines adapted to the area in which the test is grown. This is especially important since the number of midge fluctuates on a daily and weekly basis.

Midge damage is usually rated as percent "blasted" seed. Plants can generally not be rated sooner than 20 days after anthesis. Individual heads in a row are rated and a mean damage rating calculated, or the entire row is rated by visual observation. A feasible rating scheme is a 0 to 9 scale where 0 = no damage, 1 = 1 to 20% blasted head, 2 = 21 to 30%, and so on to 9 = 91 % or more blasted head. A more objective evaluation can be obtained by "protecting" portions of the test plants with pollinating bags or insecticides. Seed yield comparisons of protected and unprotected heads are then made. Standard resistant and susceptible varieties should be included as controls. Susceptible checks that flower before, during, and after the test material flowers help give reliable screening data, especially if adult midge density is not determined.

Table 2. Preliminary listing of new converted sorghum lines with high or moderate levels of resistance to the sorghum midge *(Contarinia sorghicola).*

IS no. of original line	SC no.	Working group	Midge damage rating[1]
3390	572	Caudatum-Kafir	4.3
8232	642	Caffrorum-Darso	4.5
1340	432	Durra	5.0
7132	693	Dobbs	5.0
6911	715	Caudatum	5.0
2765	964	Dobbs	5.0
8237	644	Caffrorum-Darso	5.3
8112	725	Caudatum	5.3
12572	62	Conspicuum-Caudatum-Nigricans	5.7
2740	708	Caudatum	5.7
TAM 2566[2]			6.3
Tx 2282[3]			6.3
Tx 2767[4]			7.0

1. Rating scale: 0 = no damage, 1 = 10-20% blasted head, 2 = 21-30%, etc., to 9 = 91 % or more blasted head.
2. Derived from SC 175.
3. Derived from AF 28.
4. Derived from TAM 2566.

Breeding Methods

Any breeding method appropriate to developing new sorghum inbred lines may be utilized for developing midge-resistant sorghums. However, breeding for midge resistance is complicated by the nature of the resistance, with all known sources of midge resistance apparently being inherited as a quantitative recessive characteristic (horizontal resistance). It is difficult to maintain a high level of resistance in segregating breeding progeny, the progeny frequently exhibiting a lower resistance level than the resistant parent. To further complicate the problem, resistance has to be present in both parents of a potential hybrid.

Most of the research done by Texas Agricultural Experiment Station sorghum breeders to produce midge-resistant lines has been in pedigree or modified pedigree breeding systems. Utilizing this approach, a "high" level of resistance is transferred to agronomically acceptable types by hybridization and selection. Identified resistant lines are crossed with nonresistant agronomically acceptable lines with the least susceptibility to midge. Crosses of resistant and susceptible parents will produce susceptible F_1 plants. The F_1 s should be grown in an area without midge present, usually at an off-season nursery. Segregating generations beginning with large F2 populations are grown in areas of high midge density. Although selection in this generation may be done without midge present, the presence of midges will enable breeders to eliminate susceptible plants or populations. Selection for small-glumed types should increase the frequency of resistant plants. Concurrent selection is made for agronomic characteristics, although selection for midge resistance is of primary concern.

Evaluation of F3 progeny rows should be done under large midge populations. Material should be planted on several dates or at several locations to increase the probability of large midge populations being present during anthesis.

Beginning with the F_4 generation, selection should be done in replicated progeny rows. Undesirable agronomic characteristics may be eliminated by backcrossing superior plants to the elite parent, although this will probably reduce the resistance level. It may be difficult to maintain an adequate level of resistance while eliminating undesirable characteristics. Elite advanced generation material is evaluated in replicated trials at multiple locations to evaluate for resistance and adaptation. Elite lines are also tested in hybrid combinations in replicated trials at multiple locations.

Development of random-mating populations with adequate levels of midge resistance appears possible, since resistance is apparently controlled by recessive, quantitative genes. The use of random-mating populations to develop resistant germplasm has received attention and success mostly in the commercial sector (Pioneer Hi-Bred International). Resistant lines and elite germplasm are composited and random-mated, using a genetic male-sterile (usually ms3). Plants expressing genetic male-sterility are male-sterile but female-fertile, setting seed after pollination from neighboring plants. Following initial random-mating the population is selected for increased levels of midge resistance by selecting S_1 s (fertile heads) under midge pressure for resistance and agronomic traits, compositing equal amounts of seed from the selections, and growing the bulk in locations without midge pressure to obtain genetic recombination by selection of half-sibs (sterile heads). Equal amounts of seed from the male-sterile selections are bulked to constitute a new population. The cycle is repeated as many times as required to accomplish the program objectives. Material may be selected at any cycle to produce a homozygous line via the pedigree breeding method. To facilitate eventual progress, separate B-line (female) and R-line (male) populations should be utilized.

Selection of the proper genetic male-sterile can be crucial to the success of a population improvement program. Populations formed by scientists at the Texas Agricultural Experiment Station contain the ms_3 gene, which provides a reliable, usable male-sterile. Utilization of other forms of sterility, such as the antherless characteristic, have not always been successful.

Released Germplasm

A number of midge-resistant lines have been released, primarily by the Texas Agricultural Experiment Station (Table 3). The first-released midge-resistant line, TAM 2566, is a derivative of SC 175. In 1979, Tx 2754 through Tx 2781 were released, with the resistance primarily tracing back to SC 175. ISRI, released in 1979, and Tx 2782, released in 1981, contain the AF 28 type of resistance. The first group of released lines to utilize resistance other than SC 175 were Tx 2801 through Tx 2815, released in November 1983. Two random-mating

Table 3. Chronological listing of released midge-resistant sorghum germplasm.

Sorghum designation	State	Year released	Resistance source
SGIRL-MR 1	Georgia-USDA	1973	ODC-19
TAM 2566	Texas	1974	IS 12666
TP 8R	Texas	1975	42 Lines
Tx 2754-Tx 2781	Texas	1979	TAM 2566, TP 8, TP 6, SC 414
IS R1	Texas[1]	1979	AF 28
Tx 2782	Texas'	1981	AF 28, SC 175
SGIRL-MR 2	Georgia-USDA	1983	7 lines
Tx 2801-Tx 2815	Texas	1983	Varies with line

1. Joint Texas Agricultural Experimental Station and EMBRAPA (Brazil) release.

populations, TP 8R (R-line) and TP 23B (B-line), have been developed by the Texas Agricultural Experiment Station although only TP 8R has been released. Two germplasms, SGIRL-MR 1 and SGIRL-MR 2, have been developed and released by the USDA Agricultural Research Service and the Georgia Agricultural Experiment Station. The resistance of the germplasm is from several different sources. Several of the lines released will produce agronomically acceptable hybrids with suitable maturity and excellent levels of midge resistance. Some of these lines have been utilized by commercial companies to market and distribute midge-resistant hybrids. Commercial companies are also producing midge-resistant proprietary lines and hybrids with good levels of resistance and yield potential.

Future Research Needs

To increase the level of midge resistance over that currently available, different resistance sources need to be combined into the same genotype. Use of random-mating populations appears to be ideal for accomplishing this task. At the Texas station we have crossed other resistance sources into TP 8R and TP 23B and are currently random-mating the improved populations for genetic recombination. Selection for midge resistance in both populations will be initiated in summer 1985, using the method previously described.

Resistance sources are being crossed with elite adapted resistant lines that have been previously developed in the resistance breeding program. This should enable the selection of types with more than one resistance source in a good agronomic background. Additionally, resistant converted lines are being crossed to other resistant converted lines into which the ms_3 gene for genetic male-sterility has been incorporated. Progeny of these crosses will always segregate for sterility in the F_2 generation, and at that stage other resistance sources may be crossed into the material. While progeny may be lacking in certain agronomic traits, this allows for the rapid compounding of different resistant genes into the same genotype. Elite agronomic lines may be crossed onto the steriles to select for multiple resistance sources in an elite agronomic background.

Evaluation of material developed by these procedures will show whether there are different resistance genes in the various sources of resistance, and if mass selection for this trait is a viable process. If so, breeding procedures should ultimately intensify and stabilize resistance in new lines and hybrids. Assuming we are dealing with a multigenic or complementary type of host-plant resistance, these intensified resistance levels should make it more difficult for the midge to attack sorghum. While this should stabilize hybrid yields, it will not necessarily improve yield potential. Improved yield potential is vital, since midge resistant hybrids must be equal in yield to the best hybrids grown in areas where the midge is present.

Basic knowledge gained from research programs will have wide applicability, because of the cosmopolitan nature of the insect. There is a continual need to identify new sources of resistance, and to improve the level of resistance. Information is needed on the relationship between resistance sources and levels of resistance and corresponding morphological changes. We need to know the genetics of the resistant lines (number of genes, etc.) and the mechanisms and nature of resistance (how the plant is able to resist the insect). Information is also needed on the effectiveness of mass selection in random-mating populations, and on methods of identifying midge-resistant lines without using the midge.

Greenbug

The greenbug, *Schizaphis graminum* (Rondani) has been recognized as a major pest of sorghum in the USA since 1968, before which it was predominantly a pest of small grains. Due to its wide geographic distribution, the greenbug has received considerably more attention than the midge in both private and public host-plant resistance programs.

The original greenbug causing economic damage to sorghum was biotype C. Prior to 1968, the predominant biotype on small grains was biotype A. In the mid-1970s, biotype D appeared and was resistant to the organophosphate insecticides used at that time. It was never the predominant biotype and disappeared when the use of organophosphate insecticides was discontinued. Biotype E appeared at economically damaging levels in 1980 and has since become the most widespread and predominant biotype.

Sources of Resistance

Resistance to the greenbug has been reported in the seedling stage (Hackerott et al. 1969; Johnson 1971; Starks et al. 1971; Starks et al. 1972; Teetes and Johnson 1972; Weibel et al. 1972 Teetes et al. 1974a); and in the adult plant stage (Hackerott and Harvey 1971; Harvey and Hackerott 1971; Johnson 1971; Johnson and Teetes 1972; Teetes et al. 1974b). Resistant cultivars were not suitable for commercial use and much breeding effort has been expended to incorporate resistance into commercially acceptable types.

Sources of resistance to greenbug biotypes C and E are listed in Table 4. The inheritance of greenbug resistance in lines that have been studied is dominant or incompletely dominant for biotypes C and E. The resistance of lines derived from *Sorghum virgatum* was reported to be conferred by dominant genes at more than one locus (Hackerott et al. 1969). Several studies (Johnson 1971; Johnson and Teetes 1972) indicate that biotype C resistance derived from IS 809, SA 7536-1, PI 220248, and PI 302236 is incompletely dominant and simply inherited. Analysis of F_1 and F_2 populations from susceptible varieties and SA 7536-1, IS 809, and PI 264453 indicated the inheritance of the resistance to be incompletely dominant and simply inherited (Weibel et al. 1972). Resistance to biotype E derived from PI 220248, Capbam, and TAM Bk 42, a derivative of PI 264453, is not inherited as a recessive characteristic (Johnson et al. 1981). Lines resistant to biotype C are not necessarily resistant to biotype E. However, all known sources of resistance to biotype E are also resistant to biotype C.

Another source of resistance is the "bloomless" characteristic, where no wax is apparent on the

Table 4. Sources of resistance to the greenbug, *Schizaphis graminum,* in sorghum.

Sorghum designation	Type	Resistant to biotype C	Resistant to biotype E
IS 809	Grain	X	
PI 264453	Forage	X	X
KS 30	Grassy	X	
SA 7536-1	Grassy	X	
PI 302236	Grassy	X	
PI 220248	Grassy	X	X
PI 308976	Grassy	X	
PI 38108 (TS 1636)	Grassy	X	
Capbam	Grassy	X	X
PI 229828	Grassy	X	
PI 302178	Semigrassy	X	
PI 226096	Grassy	X	

plant surface. Bloomlessness is inherited independently of greenbug resistance and confers a high degree of nonpreference for oviposition by both greenbug biotypes C and E. However, "bloomless" plants are susceptible as seedlings and are not tolerant of either biotype C or E in the adult plant stage. At least two separate genes control inheritance of the characteristic, with both parents of a potential hybrid needing to possess the same gene to produce a bloomless hybrid.

Screening Techniques

Screening techniques for developing sorghum genotypes resistant to the greenbug have been developed for both seedlings and adult plants (Johnson et al. 1976; Starks and Burton 1977). For greenhouse screening, greenbugs are reared on caged culture plants, usually sorghum, grown in plastic pots or metal cans in a sterilized mixture of fertilized soil, sand, and peat. From 30 to 50 seeds per container are planted to a depth of 2.5 cm or covered with sand to that depth. Prior to plant emergence they are covered with a clear vinyl plastic cage to exclude extraneous insects, especially predators and parasites. When plants attain a height of 15 to 20 cm (ca. 2 weeks), they are infested with greenbugs. The culture should have a maximum number of greenbugs 2 weeks later.

Breeding lines to be evaluated for resistance are planted in galvanized metal flats filled with soil to about 2.5 cm from the top. Ten equally spaced rows about 2.5 cm deep are made in each flat by pressing a planting board on the top of the soil. Each flat will accommodate 10 entries if 1 entry is planted per row or 20 entries in rows 17.8 cm long.

Approximately 30 seeds per entry are planted and thinned to about 20 plants 1 week after plant emergence. Known resistant and susceptible lines should be planted in each flat as controls. If breeding selections from resistant crosses are to be evaluated, the resistant parent used in the cross should be included as the resistant control. After thinning, plants are infested by brushing or shaking greenbugs from culture plants fairly uniformly over flats, or by placing uprooted, infested, culture plants between rows and allowing the aphids to crawl to the test plants. Plants are examined about 2 days after infestation and additional greenbugs are applied as needed. Four to ten greenbugs per plant are considered adequate.

Generally, plants in each flat are rated for resistance when plants in the susceptible control row are near death, usually ca. 10 to 14 days after infestation. A visual rating of an entire row is possible for nonsegregating material; in segregating rows, individual plants can be rated. A 0 to 9 rating system for seedling evaluation, similar to that used for rating midge damage, is used.

Adult plant screening using leaf damage ratings offers a good measurement of resistance if an adequate natural greenbug infestation occurs. A rating scheme for assessing greenbug damage to adult sorghum is given in Table 5. Data may be collected at any plant growth stage when greenbugs are present. Aphid density and plant growth stage should be noted at the time of rating. If greenbug populations differ markedly among entries, an indication of the level of infestation on each entry can be made using the following code after the ratings: 1 = low incidence, 2 = average incidence, 3 = high incidence.

Table 5. Rating scheme for assessing greenbug damage on adult sorghum plants.

Score	Description of damage
1	No red spotting on leaves
2	Red spotting on leaves
3	Portion of a leaf killed by greenbugs
4	One entire leaf killed by greenbugs
5	Two entire leaves killed by greenbugs
6	Four entire leaves killed by greenbugs
7	Six entire leaves killed by greenbugs
8	Eight entire leaves killed by greenbugs
9	Plant killed by greenbugs

An alternative to natural infestations of aphids in the field is the use of cages. Cages can be relatively large to enclose groups of entire plants, or small plastic cages can be attached to a portion of a leaf. In large cages, aphid density increases rapidly, often to unnaturally high levels. Small plastic clip-on cages can be used in the field for evaluation of resistance. Small cages clipped to leaf blades need cloth-covered ventilation holes on at least one side. Five to ten aphids, usually adults, are put in each cage with a small artist's brush. The cages keep the aphids confined to a small area and exclude parasites and predators. Cages are inspected the day following attachment to the leaves to ensure that all aphids remain alive and feeding on the plant. Additional aphids are added where necessary to ensure equal numbers per cage. Ratings of the damaged leaf area covered by the cage begin about 1 week after infestation and continue at 2-day intervals until the caged areas of the susceptible plants are near death. A feasible rating scheme is as follows: 0 = no necrotic plant tissue in the caged area, 1 = 10-20% necrosis, 2=21-30%, and so on to 9 = 91 % or more necrosis.

Breeding Methods

Since greenbug resistance is simply inherited and can be retained through several backcrosses, it is relatively simple to produce elite resistant lines. The genetics of resistance has enabled breeders to develop elite resistant lines primarily using a pedigree or backcross breeding method. To develop resistant germplasm, the initial cross should be of lines with the highest level of resistance onto elite adapted lines. The F_1 plant of the cross between the resistant and susceptible lines is backcrossed to the elite parent. A large F_2 population of this backcross should be evaluated for resistance in the seedling stage or in the field. Resistant F2 plants can be backcrossed or selected for evaluation in F_3 rows, depending on the agronomic desirability of the plant. Selection for agronomic type may be done in any generation. Once an elite resistant line is developed, it may be used as the resistance source, thereby eliminating the need for extensive backcrossing to eliminate undesirable traits.

Utilization of random-mating populations to develop greenbug-resistant germplasm differs in no fundamental way from the procedure described for midge resistance. While the utilization of populations can result in genetic combinations that would normally not appear in a pedigree type breeding program, there are no data to indicate that resistance genes act in a complementary manner and intensify the resistance level. Combinations of resistance genes which occur in a random-mating population also occur with a pedigree breeding program, and with a higher probability of success. If resistance sources are discovered which utilize recessive *or* minor genes, then random-mating populations will be an excellent method to compound resistance sources and create broad-based (horizontal) resistant genotypes which are more difficult for the insect to overcome than the single-gene resistance presently used.

Released Germplasm

The greenbug has been the predominant insect pest of sorghum since 1968. The research time of many scientists, both public and private, is spent developing greenbug-resistant lines. Most commercial sorghum companies have developed, or are developing, hybrids resistant to biotype E in a range of agronomic types and maturities. Greenbug resistant germplasm developed with public support is available from the Agricultural Experiment Stations of Texas, Oklahoma, and Kansas.

Future Research Needs

Sorghum breeders need to expect continuing biotype changes and develop germplasm to meet these changes. Exotic lines and plant introductions need to be continually searched for additional sources of resistance, with as many resistance sources as possible utilized in a breeding program. Utilization of diverse resistance sources is particularly important since we are now dealing with single-gene (vertical) resistance.

Sorghum breeders have been particularly successful in producing resistant material. However, research effort has been for the most part confined to screening segregating material, with little emphasis on what is causing the resistance. Information on the plant chemical(s) causing resistance will enable us to become more specific in our breeding efforts in addition to determining biotype differences and elucidating the insect's ability to overcome resistance. Genetic information concerning the difference in resistance genes for a particular biotype or between biotypes is lacking.

Conclusions

Development of sorghums resistant to the midge or greenbug has accelerated with the availability of exotic sorghum genotypes in the USA. Sources of midge resistance from the sorghum conversion program are the basis of that breeding effort. The level of resistance available in elite lines has been increased, so that midge-resistant hybrids can be produced. To further increase the resistance level, resistance sources need to be combined in both male and female lines. With combined resistance sources sorghum will be less vulnerable to damage. Yield potential of resistant hybrids needs to be improved to enable resistant hybrids to be successful. Greenbug resistant lines and hybrids have received a great amount of research effort and are readily available. Development of resistant genotypes has been facilitated by the nature of the resistance and the availability of greenhouse-screening techniques. Sorghum is susceptible to continuing greenbug biotype changes and scientists need to be ready to meet those changes. Research progress can be accelerated by a cooperative effort between plant breeders and entomologists.

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Breeding Sorghum for Resistance to Shoot Fly and Midge

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Abstract

Genetic information available on different aspects of resistance to shoot fly and to midge is summarized. Trichomes and glossiness are associated with shoot-fly resistance. They are simply inherited, recessive, and highly heritable traits. A good level of diversity for resistance genes exists among the identified shoot fly and midge resistant sources. Shoot-fly resistance per se is a quantitatively inherited trait controlled by both additive and nonadditive genes. Midge resistance is also a quantitatively inherited trait governed by both additive and nonadditive, but predominantly nonadditive, genes. Midge resistant sources differ for resistance genes. Breeding methods being used for transferring resistance are briefly discussed.

The ICRISA T breeding program—which emphasizes an interdisciplinary approach—has made good progress in developing improved shoot-fly and midge-resistant breeding lines with reasonable yield and quality traits. Some of these resistant progenies have performed well outside India also and are already being used in various national programs. A few lines have been identified as nonrestorers with multiple resistance to different insect pests and diseases. Efforts are under way to develop resistant A and B parents for resistant hybrid production. Conversion of some of the agronomically unsuitable strong resistance sources into elite backgrounds is under way.

Résumé

Sélection des sorghos résistants à la mouche des pousses et à la cécidomyie : *La communication fait une synthèse des informations existantes sur les différents aspects génétiques de la résistance à la mouche des pousses et à la cécidomyie. Les trichomes et le caractère vernissé liés à la résistance à la mouche des pousses, sont d'hérédité simple, récessifs avec un taux élevé d'héritabilité. Il existe une diversité importante au niveau des gènes de résistance chez les sources identifiées pour la résistance à ces deux insectes. La résistance à la mouche des pousses est en soi un caractère à hérédité quantitative, contrôlée par les gènes additifs et non additifs. La résistance à la cécidomyie est aussi un caractère à hérédité quantitative, contrôlé par les gènes additifs et non additifs, avec dans ce cas, prédominance des gènes non additifs. Les sources de résistance à la cécidomyie varient selon les gènes. Les méthodes de sélection pour le transfert de la résistance sont décrites brièvement.*

Le programme sur la phytosélection de l'ICRISAT qui souligne l'approche pluridisciplinaire a fait des progrès dans la création des lignées de sélection ayant une résistance à ces ravageurs ainsi qu'un rendement et une qualité adéquats. Quelques-unes de ces descendances ont donné de bons résultats même en dehors de l'Inde, et sont utilisées dans le cadre des programmes nationaux de différents pays. Certaines lignées sont identifiées comme lignées non restauratrices avec résistance multiple à plusieurs ravageurs et aux maladies. Le travail est en cours pour la création de géniteurs résistants A et B pour la production d'hybrides résistants. La conversion en matériel élite, de certaines sources peu productives mais à forte résistance est en cours.

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Introduction

Shoot fly (*Atherigona soccata* Rondani) and midge (*Contarinia sorghicola* Coquillett) are the major pests that destabilize the performance of sorghum cultivars and ultimately reduce sorghum production in many parts of the world (Seshu Reddy and Davies 1978). Information on their distribution, life cycle, population dynamics, and type and stages of damage has been reported by Rao et al. (1978); Agrawal and House (1982); Sharma et al. (1983).

Several strategies for controlling these insects have been recommended and adopted in the past but have met with varying degrees of success. Host-plant resistance seems to be the most effective, economical, and practical way of controlling them. Sorghum shoot fly has been successfully controlled in many postrainy-season sorghum-growing areas in India through the use of resistant cultivars.

At ICRISAT, the major emphasis has been on developing cultivars resistant to these insect pests through an interdisciplinary approach in order to stabilize yields. This paper presents an overview of the host-plant resistance breeding work on shoot fly and midge at ICRISAT.

Breeding Objectives

Two decades ago, scientists around the world realized the importance of host-plant resistance (HPR) in controlling biotic and abiotic stress factors in crops. They organized cooperative teams, representing different disciplines, to incorporate genetic resistance(s) into the susceptible commercial cultivars of different crops. These teams started (1) developing effective screening techniques, (2) screening germplasm/breeding stocks to identify sources of resistance, and (3) transferring resistant genes into elite backgrounds. As a result of such team efforts, satisfactory screening techniques have been developed for large-scale testing of sorghum germplasm/breeding material for resistance against shoot fly and midge under both natural and artificial infestation. A sizable portion of the germplasm collections has been tested and a number of sources with confirmed resistance to each of these pests identified (Agrawal and House 1981; Sharma and Davies 1981; Agrawal et al. 1983; Taneja and Leuschner, these Proceedings; Sharma, these Proceedings).

Most sources have been found agronomically inferior and are of limited use to farmers and breeders. They can neither be adopted for direct commercial cultivation in the problem areas nor can they be used as convenient donors in resistance breeding programs. They are either photosensitive, very tall, poor yielders, or are susceptible to other pests and diseases. When such sources are used as donor parents, a small proportion of good segregants is recovered in their crossed segregating populations. However, the converted sources, particularly the midge-resistant sources converted by Texas A&M University, have been found very useful in transferring midge resistance into elite backgrounds. It may therefore be helpful to convert original sources into improved backgrounds and then use them as donor parents. It has also been observed that most of the identified sources do not possess absolute resistance or the same mechanism(s) of resistance.

In view of the above problems with the source material, we at ICRISAT felt that for rapid progress it was necessary to improve the source material simultaneously for agronomic features and resistance levels. Our resistance breeding program has the following objectives:

1. To transfer the resistance into agronomically good backgrounds.
2. To convert resistance sources into usable agronomic backgrounds.
3. To strengthen sources of resistance by accumulating diverse genes from various sources.
4. To generate basic genetic information for formulating an effective breeding program.

Breeding Procedures

To attain these objectives, both pedigree and population methods of breeding are being used, pedigree breeding as a short-term approach for the transfer of resistance particularly for a single pest; population breeding as a long-term approach particularly for strengthening the sources and simultaneously breeding for resistance to more than one pest. The conversion of source material is being done by the classical backcross method.

Two broad-based populations, one for shoot pests (shoot fly and stem borer) and the other for earhead pests (midge and earhead bugs), have been developed by using ms_3 and ms_7 male-sterility genes and are being improved by mass selection (shoot pests population) and a biparental sib-mating system (head pests population) using a low to moderate insect pressure for a few cycles. Once these populations are improved for such characters as height, maturity, grain quality, and resistance to downy mildew, rust, anthracnose, etc., the cyclic S2 recurrent selection will be used as outlined in Figure 1.

Figure 1 also outlines the procedures for handling donor parents, making the crosses, growing and screening for resistance, agronomic traits, and grain quality in pedigree breeding. There are three basic units in this approach: Unit 1 involves the identification, conversion, and strengthening of the source material; Unit 2, the development of agronomically elite cultivars and parents of hybrids; Unit 3, the transfer of resistance from Unit 1 material to the material in Unit 2.

Our position in Units 1 and 2, on screening techniques and source development as related to India and to ICRISAT's mandate, is defined in Table 1. Segregating material in Unit 3 is advanced as per the plans outlined in Figure 1. Promising entries with resistance are advanced to international testing to identify the lines that are well adapted and have stable resistance over locations and seasons and can be recommended for farmers' use.

Shoot Fly

The sorghum shoot fly is prevalent and severe on sorghums in south and southeast Asia, the Middle East, Mediterranean Europe, and Africa. It attacks the sorghum crop in the early seedling stage (up to 1 month after planting) and causes deadheart formation (death of central growing point). Subsequent tillers are also attacked and killed and ultimately the crop suffers total loss. Older seedlings become resistant to this pest.

As there exists good genetic resistance to shoot fly among different sorghum cultivars, there is good scope for incorporating host-plant resistance into commercially cultivated susceptible sorghum cultivars. Use of such resistant cultivars will help reduce the expense and save the time and labor involved in the use of other complicated protection measures.

Sources of Resistance

Screening for resistance. In 1979, a 10-year plan was developed to strengthen Unit 1 activities. We

Table 1. Current status of Unit 1 and Unit 2 activities, screening techniques, and source material development in the ICRISAT breeding program for pest resistance in sorghum.

		In India					As related to ICRISAT mandate		
		Unit 1 Source		Unit 2 Agron.					
Insect pest	Heritability[1]	Strength	Eliteness	Strength	Eliteness	Screening capability	Screening technique	Source development	Unit 3 Source utilized
Stem borer	Low	0.5	0.4	0.5	0.5	0.7	0.3	0.8	Yes
Midge	Low	0.7	0.5	0.7	0.7	0.5	0.5	0.8	Yes
Head bugs	Low	0.05	-	0.05	-	0.1	0.9	1.0	No
Shoot fly	Low	0.6	0.4	0.6	0.6	0.8	0.2	0.5	Yes

1. 0.1 = low; 1.0 = high.

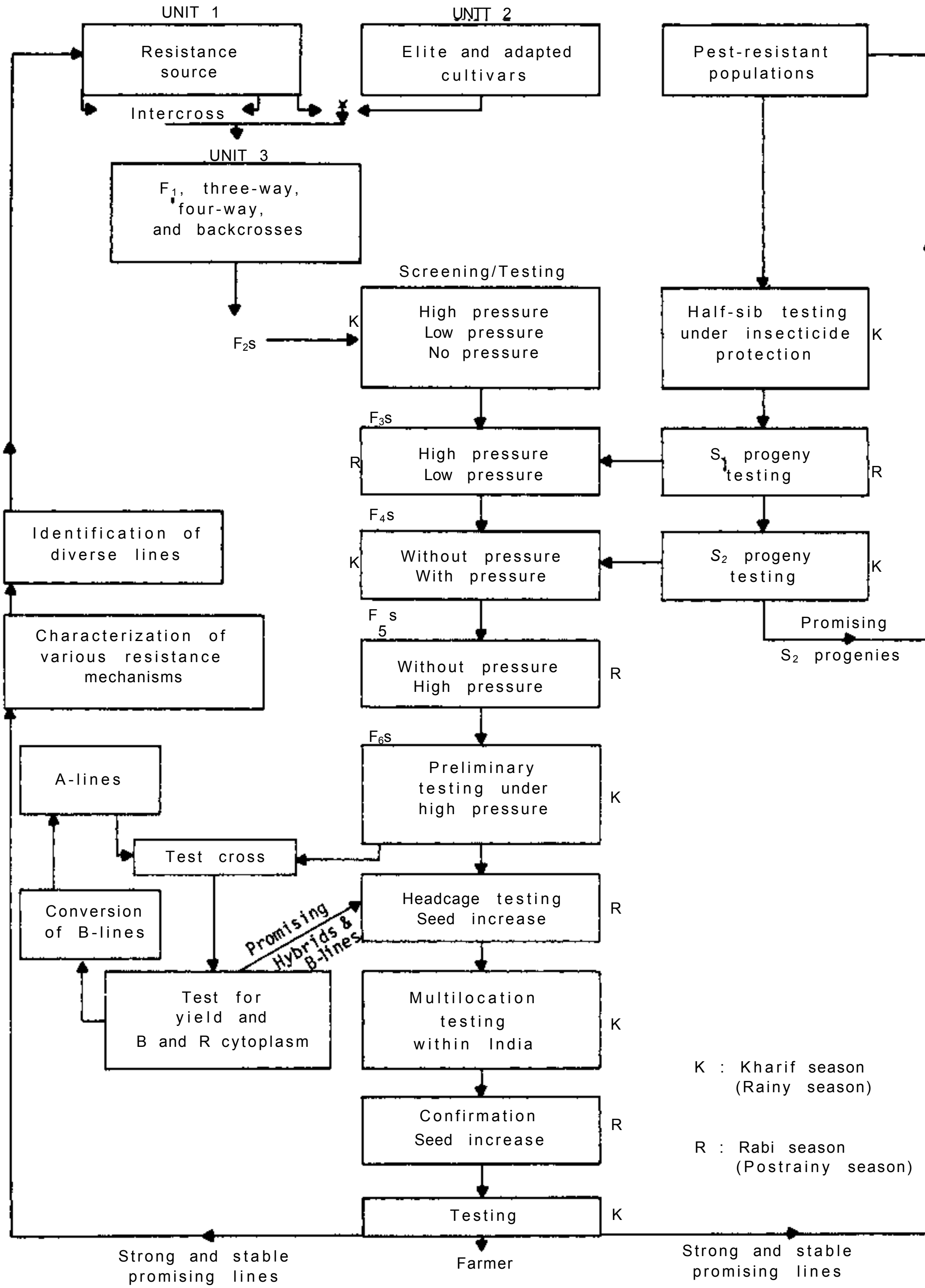

Figure 1. Scheme for pest resistance breeding in sorghum at ICRISAT Center, Patancheru, india. (*Kharif* = rainy season; *rabi* = Postrainy season).

considered the first 5 years of the 1980s as important to establish and stabilize screening procedures to deal with a large number of entries. Our entomologists have made good progress in this direction. Screening capacity has greatly improved for the evaluation of varietal material for resistance to shoot fly. Screening of large germplasm/breeding stocks has been made possible at ICRISAT by adopting the interlard/fishmeal technique of Starks (1970) under field/natural conditions, and the headcage technique of Soto (1972) for artificial testing. Both techniques are being used by ICRISAT entomologists for screening and confirmation of resistance of the identified sources.

Stability of resistance sources. The stable performance of the source material across environments and against different insect-pest species and their biotypes is equally important. This aspect is being studied through multilocation testing within and outside India.

Diversity among sources. With the development of effective screening techniques, a number of resistance sources, representing different taxonomic races and ecogeographical regions of the world, have been identified. Most of them appear to be morphologically distinct but may not necessarily be genetically distinct for resistance. Taxonomic or geographic diversity is not a true indicator of genetic diversity. Hence, it is important to know their genetic diversity and the sources listed in diverse groups. An attempt was made to study the genetic divergence in a set of 20 shoot fly resistant sources, using multivariate analysis. Genetic diversity was observed for shoot fly resistance in the sources. This was further confirmed by the good relationship observed between heterosis for shoot fly resistance per se and the genetic diversity. No such relationship was found with geographic or taxonomic classification.

Canonical variate and D-analyses gave consistently similar results over 3 years and appeared to be useful techniques for grouping the sources.

Mechanisms of Resistance and Plant Traits Associated with Resistance

The selection of shoot fly resistant sources/genotypes is primarily based on the deadheart symptoms. This is a tedious and time-consuming process, particularly when a large number of segregating populations are tested over generations. To simplify the selection process, ICRISAT scientists have tried to determine some easily identifiable plant characters that are closely linked with shoot fly resistance. The presence of trichomes (tiny microscopic hairs) on the leaves and seedling glossiness (pale green, smooth, shiny leaves) are two such traits, which we have found associated with resistance.

Trichomes. It has been noticed that genotypes that have trichomes on their abaxial leaf surfaces have fewer shoot fly eggs and suffer less damage (Table 2). The correlation coefficients given are the averages of four experiments. Trichomes have high correlation with ovipositional nonpreference (rg = -0.75, rp = -0.63) and shoot fly damage (rg = -0.78, rp = -0.72). Maiti (1980) made similar observations.

When these correlations were partitioned into direct and indirect effects through path coefficient analysis, it was noticed that, although trichomes were closely associated with shoot fly resistance,

Table 2. Phenotypic (p) and genotypic (g) correlation coefficients among factors contributing resistance to shoot fly in sorghum.

Resistance factor		Glossiness	Shoot fly egg laying	Shoot fly damage
Trichomes	P	0.79** - 0.84%	-0.51* - -0.77	-0.66** - -0.75
	g	0.81 - 0.85	-0.64 - -0.80	-0.73 - -0.82
Glossiness	P		-0.52* - -0.88	-0.73** - -0.89
	g		-0.78 - -0.92	-0.81 - -0.94
Shoot fly	P			0.74** - 0.92
egg laying	g			0.95 - 0.99

* Significant at *P* = 0.05; ** Significant at P = 0.01 ; % range figures of four experiments.

they did not contribute directly to it. Their direct effect was low (rg = -0.78/pg = 0.05, rp = -0.72/pp = -0.05) (Table 3). They contribute to shoot fly resistance through other traits such as ovipositional nonpreference and glossiness.

The presence of trichomes on both abaxial and adaxial leaf surfaces is simply inherited and highly heritable. Gibson and Maiti (1983) reported that the presence of trichomes on the abaxial surface was under the control of a single recessive gene.

Trichomes have been successfully used as a marker at ICRISAT to identify resistant genotypes at the seedling stage. They give good indication of the mechanisms of resistance (ovipositional nonpreference, antibiosis/mechanical resistance, and recovery). Ovipositional nonpreference could be identified by the absence of eggs on trichomed plants. Antibiosis is indicated when eggs are laid in the absence of trichomes but no deadhearts are formed. This system of identification of resistant plants at the seedling stage with selection for better agronomic types at maturity was first tried at ICRISAT in the postrainy season of 1977.

Glossiness. Expression of glossiness in seedlings is another important trait for identifying shoot fly resistance in sorghum. It is an easily identifiable and simply inherited character (Agrawal and House 1981). It plays a significant role in shoot fly resistance, and as Tables 2 and 3 show, glossiness is also highly correlated with shoot fly resistance. Path analysis indicates that it has linkages with some unknown inherent antibiotic factors. This needs to be investigated. The level of shoot fly resistance differs with intensity of glossiness and this may be used as a marker.

Tarumoto (1980) indicated that the presence of glossiness is controlled by a single recessive gene. However, its intensity is quantitatively governed and is controlled by both additive and nonadditive genes (Table 4).

More than 90% of ICRISAT's shoot fly resistant breeding and source materials have glossy seedlings, suggesting that this trait has some relevance to shoot fly resistance and could be exploited as a marker to identify resistant genotypes at the seedling stage. Efforts are already under way to explore the possibility of using this trait as a routine selection criterion in our shoot fly resistance breeding program. Initial results at ICRISAT are encouraging. If we have some easily identifiable highly associated traits, the transfer of resistances could be made easily and quickly. The identification of sources and the screening procedures alone are not sufficient.

Ovipositional nonpreference. Ovipositional nonpreference is an important mechanism of shoot fly resistance in sorghum (Sharma et al. 1977; Singh and Jotwani 1980). It is polygenically controlled and recessive in nature. Present studies confirm that it is predominantly controlled by additive genes (Table 4).

Shoot Fly Resistance

Shoot fly resistance per se is a polygenic recessive trait and is largely controlled by additive genes

Table 3. Phenotypic (p) and genotypic (g) direct and indirect effects of resistance factors on shoot fly resistance in sorghum.

Resistance factor		Correlation with shoot fly damage (r)	Direct effect on shoot fly damage (P)	Indirect effect on shoot fly damage via: Trichomes	Glossiness	Shoot fly egg laying
Trichomes	p	-0.66** - -0.75%	-0.11 - 0.06		-0.04 - 0.44*	-0.24 - -0.64**
	g	-0.73 - -0.82	-0.12 - 0.21		-0.02 - 0.43	-0.43 - -0.91
Glossiness	p	-0.73** - -0.89	-0.05 - -0.55**	-0.087 - -0.05		-0.25 - -0.73**
	g	-0.81 - -0.94	-0.03 - -0.53	-0.097 - -0.17		-0.53 - -0.95
Shoot fly Egg laying	p	0.74** - 0.92	-0.48* - 0.83**	-0.04 - 0.06	-0.05 - 0.37	
	g	0.95 - 0.99	-0.68 - 1.20	-0.16 - 0.08	-0.02 - 0.41	

Residual effect = 0.29 - 0.54
0.08 - 0.40

* Significant at P = 0.05; ** Significant *at P* = 0.01 ; % range figures of four experiments.

Table 4. Analysis of variance for combining ability for glossiness, shoot fly oviposition, and resistance in sorghum.

Source	df	Mean squares (F_1s)		
		Glossiness	Shoot fly oviposition	Shoot fly resistance
gca	19	6.956**	0.936**	911.08**
sca	190	0.296**	0.098**	77.65**
error	418	0.010	0.031	32.85
$\hat{\sigma}^2_g$	0.303	0.038	37.88	
$\hat{\sigma}^2_s$	0.286	0.066	44.80	
Predictability ratio $2\hat{\sigma}^2_g/(\hat{\sigma}^2_g+\hat{\sigma}^2_s)$		0.679	0.535	0.68

** Significant at 0.01 probability level.

(Rao et al. 1974; Balakotaiah et al. 1975; Rana et al. 1975; Sharma et al. 1977; Borikar and Chopde 1982). Predominance of different types of gene action and their heritability differ with the shoot fly population pressure (Rana et al. 1981; Borikar and Chopde 1982). Rana et al. (1981) observed ovipositional nonpreference mechanism under the influence of partially dominant genes under low to moderate shoot fly pressure and the reverse under heavy infestation. Borikar and Chopde (1982) observed both additive and nonadditive gene action to be important under low pressure and additive gene action under moderate to high shoot fly pressure. Studies conducted at ICRISAT revealed that both additive and nonadditive gene effects were equally important under high insect pressure (Table 4). Hence, it is suggested that breeding and selection for shoot fly resistance should preferably be done under moderate to high pressure.

Breeding for Resistance

Considering the genetic complexity of shoot fly resistance, both population and pedigree methods of breeding are being used at ICRISAT. A number of reasonably strong and stable sources of resistance, representing different geographic areas and taxonomic races, had been identified earlier, but none of them possessed absolute resistance. Efforts are under way to strengthen sources of resistance in usable *agronomic* backgrounds. Some sources with known mechanisms have already been intercrossed and incorporated into the shoot pest population. This population is being further improved by mass selection under moderate shoot fly and borer pressure and then advanced. Efforts are also under way to identify, among the wild relatives of sorghum,, genotypes with strong resistance, if not immunity, to shoot fly and to use them in the breeding program.

Several strong but agronomically unusable source materials are under conversion through the conventional backcrossing method.

Transfer of resistance. Many shoot fly resistant breeding lines with moderate levels of resistance and reasonable yield potential have been developed. Among advanced progenies, our best lines are: PS nos. 14093, 14103, 14413, 14454, 18601 -2, 18601 -3, 18817-2, 18822-4,18969,19230,19336-1-2, 19663, 19891-1, 21129-2, 21171, 21217, 21269-3, 21270, 21318, 21372-1, 19186, 19262, 19807, 19923, 20119, and 20267. Their levels of resistance are comparable with Maldandi (IS 1054), a local standard shoot fly resistant cultivar. Some of them-PS 21171, PS 21217, and PS 21318—have been found promising even under no-choice conditions. PS 14093, PS 14103, PS 14454, and PS 21318 have shown good promise against shoot fly both within and outside India. PS nos. 14093, 14454, 1801-3, 18817-2, 18822-4, 19230, 19663, 21217, and 21318 yield more than 60% of the yield of standard control (SPV 351) under good management, including insect control (Table 5).

Four lines have been found to possess multiple resistance to other insects and diseases: PS

Table 5. Performance of shoot fly resistant breeding lines during 1983 rainy season.

Origin	Pedigree	Plant height (cm)	Days to 50% flowering	Grain yield under good management (% of SPV 351 yield)	Resistance index[1]
PS 14093	(IS 5604 x 23/2 x CS 3541) CS 3541 x CS 3541-3-2-1-1-1	158	70	64.0	0.86
PS 14413	(IS 1082 x SC 108-3)-1-1-1-1-1	186	63	60.5	0.93
PS 14454	(IS 5622 x CS 3541)-6-1-1-1-1	196	78	66.1	0.60
PS 18601-3	(UChV$_2$ x IS 3962)-8-1-1-2-3	161	75	76.1	0.48
PS 18817-2	(UChV$_2$ x IS 3962)-3-1-1-1-2	211	68	90.1	0.94
PS 18822-4	UChV$_2$ x IS 3962)-8-1-1-2-4	183	75	68.2	0.38
PS 19230	(IS 1054 x Late Pop Bulk)-2-2-1-1-1	190	65	88.3	0.82
PS 19663	(IS 5622 x CS 3541)-6-1-1-1-6-1	186	77	60.2	0.61
PS 21217	(555 x IS 5604)-1-1-1-1-1	121	81	65.7	0.98
PS 21318	(IS 5622 x CS 3541)-6-1-1-1-1-1	195	77	67.2	0.44
SE		±6.1	±3.8	±402.6	
CV (%)		5.5	9.2	14.7	

1. Obtained by using IS 1054 (Maldandi) as standard shoot fly resistant check (1.0).

18601-3 has additional resistance to sorghum downy mildew, leaf rust, and shoot bugs; PS 18817-2 to rust, anthracnose, and shoot bugs; and PS 18822-4 to rust, anthracnose, downy mildew, and shoot bugs; and PS 19230 to anthracnose and downy mildew. PS 14413 has been identified as resistant to stem borer under both natural and artificial infestation. This line is now being extensively used as a new borer-resistant source for generating new segregating breeding stocks.

Shoot fly resistant lines PS nos. 20593B, 21131B, 21171B, 21443B, 21452B, and 21453B have been identified with nonrestoring cytoplasm and are in the advanced conversion stage (BC3 and BC4).

Utilization of improved resistant material. Lines PS nos. 18601-3, 18817-2, 18822-4, and 19230 have been found to have reasonably strong and stable resistance to shoot fly and are being used at ICRISAT and elsewhere to generate more useful breeding stocks. They appear to be better, and more easily usable, than the original resistance sources, as their progenies are agronomically superior to the first cycle material.

Resistant breeding lines such as PS nos. 14413, 14093, 14413, 18601 -3, 18817-2, 18822-4, 19230, 21313, and 21171 have been supplied to our various cooperators both within and outside India and some of them are already being used.

Midge

Sorghum midge is a cosmopolitan pest. It is a small, bright orange-red, rapidly multiplying fly that lays eggs inside the sorghum floret during flowering. The maggot feeds on the developing seed, prevents seedset, and quite often causes total grain loss.

Host-plant resistance to sorghum midge has been reported by several authors and may be used in controlling this pest.

Sources of Resistance

Nearly 100 midge-resistant sources have been identified at ICRISAT and elsewhere. Some of them, e.g., DJ 6514 and AF 28, show very strong and stable resistance. These identified sources represent different taxonomic races and ecogeographical regions of the world. They appear to be morphologically distinct but nothing is known about the genetic diversity of the resistance genes. This should be investigated and, if it exists, the sources need to be grouped according to their degree of diversity.

These sources are again agronomically inferior, like the shoot fly resistance sources. Most of them are difficult to utilize, except a few, e.g., DJ 6514. Some have been converted into usable backgrounds at Texas A&M University, Texas, USA, and are currently being used in several breeding programs throughout the world. At ICRISAT, a conversion program has recently been initiated for this purpose.

Screening for Resistance

During the last 5 years, efforts at ICRISAT have concentrated on establishing and refining screening procedures to deal with a large number of entries. Screening capabilities have been greatly improved for evaluating material under both natural conditions and artificial inoculation.

The selection of resistant genotypes is mainly based on seed setting after exposure to midge. No other criterion exists for detecting midge-resistant genotypes in the field. Efforts are being made to identify some floral characters closely linked with midge resistance.

Mechanisms of Resistance

As we learn more about methods of identifying resistant genotypes, we find ourselves more involved with mechanisms of resistance. Also, we recognize that the need for more detailed knowledge about a trait may result in improving the screening capabilities and our understanding of the complexity of midge resistance per se. In fact, we find ourselves gradually moving towards more basic studies.

It has been noticed that different resistance mechanisms seem to operate in different sources and hence it should be possible to club them in a common background and upgrade resistance levels.

Genetics of Midge Resistance

Very little genetic information is available on the inheritance of resistance against the sorghum midge. Widstrom et al. (1984) indicated that this resistance was a quantitative trait predominantly controlled by additive gene effects. They also noticed cytoplasmic effects. Patil and Thombre (1983) reported that both gca and sca effects were important for midge resistance. They found additive genetic variance greater than nonadditive genetic variance.

Table 6. Analysis of variance for combining ability for midge resistance in sorghum.

Source	df	Mean squares F_1	F_2
gca	6	341.88**	311.69**
sca	21	83.78**	40.02**
error	54	4.30	2.27
Components $\hat{\sigma}^2$g		28.67	30.18
$\hat{\sigma}^2$s	79.48	37.75	
Predictability ratio $2\hat{\sigma}^2 g/(\hat{\sigma}^2 g+\hat{\sigma}^2 s)$		0.419	0.615

** Significant at 0.01 level of probability.

Our studies also indicate that it is a quantitatively inherited trait, controlled by both additive and nonadditive, but predominantly by nonadditive, gene effects (Table 6). DJ 6514 and TAM 2566 are the best general combiners (Table 7). In general, parents having a high level of midge resistance show better combining ability. The DJ 6514 crosses exhibited high specific combining ability and hence DJ 6514 was found to be a useful parent in breeding (Table 8). Differences were also noticed for resistance genes in different source parents. AF 28 did not seem to be a very useful source as it did not show promise in any cross combination. In fact, this

Table 7. Mean performance and gca effects of the parents over F_1 and F_2 generations for midge resistance in sorghum.

Parent	Mean % seedset	gca effects F_1	F_2
SPV 422	25.8	-8.4**	-8.2**
TAM 2566	62.1	5.4**	4.r*
SGIRL-MR 1	50.3	2.1**	0.8
SPV 351	27.5	-5.3**	-3.7**
AF 28	61.9	0.7	2.7**
SC 108-3	38.6	-3.6**	-4.6**
DJ 6514	67.1	9.0**	9.0**
r		0.936*	0.942*
SE($\hat{g}$i)		±0.64	±0.46
SE ($\hat{g}$i-$\hat{g}$j)		±0.98	±0.71

* Significant at 0.05 probability level; ** Significant at 0.01 probability level.

Table 8. Mean performance and specific combining ability effects (sca) of the crosses over F_1 and F_2 generations for midge resistance in sorghum.

Cross	F_1 generation		F_2 generation	
	Mean	sca	Mean	sca
SPV 422 x TAM 2566	47.3	- 1.8	48.6	4.2**
SPV 422 x SGIRL-MR 1	51.3	5.5**	35.1	-6.0**
SPV 422 x SPV 351	41.4	3.0	41.3	4.6**
SPV 422 x AF 28	47.1	2.7	43.4	0.4
SPV 422 x SC 108-3	37.8	- 2.3	39.4	3.6**
SPV 422 x DJ 6514	64.6	11.9**	55.8	6.5**
TAM 2566 x SGIRL-MR 1	61.0	1.4	57.7	4.2**
TAM 2566 x SPV 351	57.7	5.5**	50.9	2.0
TAM 2566 x AF 28	53.3	- 4.9**	49.1	-6.2**
TAM 2566 x SC 108-3	60.4	6.5**	44.0	-4.1**
TAM 2566 x DJ 6514	61.4	- 5.1**	53.1	-8.5**
SGIRL-MR 1 x SPV 351	61.4	12.6**	55.3	9.7**
SGIRL-MR 1 x AF 28	39.8	-15.0**	48.1	-3.9**
SGIRL-MR 1 x SC 108-3	54.7	4.1*	47.9	3.1**
SGIRL-MR 1 X DJ 6514	66.5	3.3*	58.5	0.2
SPV 351 x AF 28	53.1	5.6**	47.3	-0.3
SPV 351 x SC 108-3	34.3	- 8.9*	47.3	7.0**
SPV 351 X DJ 6514	65.7	9.9**	58.9	5.0**
AF 28 x SC 108-3	59.9	10.7**	43.7	-3.0*
AF 28 x DJ 6514	45.8	-16.0**	57.5	-2.7*
SC 108-3 x DJ 6514	59.6	2.2	49.9	-3.1*
r	0.648**		0.255	

* Significant at 0.05 probability level; ** Significant at 0.01 probability level.

source has been extensively used at ICRISAT and has not given any promising resistant progenies so far. In another study, the dominance and additive x additive gene effects were found important in a majority of crosses; however, additive x dominance gene effects also showed good contribution in some crosses, alone as well as in combination. The dominant genes gave the maximum contribution; followed by additive x additive, additive x dominance, and additive gene effects.

In general, midge resistance per se seems to be genetically simpler than resistance to other insect pests of sorghum.

Breeding for Resistance

To accomplish all the outlined breeding objectives, both pedigree and population breeding approaches are being used at ICRISAT, following the procedures discussed under breeding methods.

The earhead pests resistant population is still being improved for height, photosensitivity, grain quality, leaf diseases, grain molds, etc.

Transfer of resistance. A number of promising midge-resistant breeding lines have been developed with reasonable agronomic superiority. The best advanced midge-resistant progenies are PM nos. 6751, 6932, 6981-2, 6981-3, 7022, 7032, 7064, 7068-1, 7068-2, 7092, 7172-1, 7327, 7400-1, 7400-2, 7400-3, 7400-4, 7494-1, 7499, 8686-1, 10825-1, 10825-2, and 11344.

PM nos. 6751B, 7060B, 7061B, 7318-2, 7322, 7390-1, 7397, 7495, 8787-2B, 7032, 7493, and 7526 yielded 300 to 800% more than the CSH 6 hybrid when evaluated under midge infestation at Dharwad during the 1983 rainy season (Table 9). Of these, PM 6751, PM 7061, PM 7318-2, PM 7322, PM 7390-1, and PM 7493 yielded more than 60% of the yield potential of CSH 6 hybrid when evaluated in the absence of the insect under good management.

Utilization of improved resistant material. PM nos. 7348, 7168, and 7357 also performed well against midge in El Salvador, Brazil, and Argentina, and are already being used in various national programs. PM 7348 and PM 11344 are now being extensively used as improved midge-resistant sources by the All India Coordinated Sorghum Improvement Project (AICSIP).

PM 11344, a crossed derivative of DJ 6514, has been found very promising and has better seed size, grain quality, and leaf disease reaction than DJ 6514, the source parent. It is hoped that PM 11344 may replace DJ 6514, a midge-resistant cultivar being commercially used in areas of Karnataka where the midge is endemic. The University of Agricultural Sciences (UAS), Dharwad, is going to test PM 11344 on farmers' fields in large-scale demonstrations in these areas of Karnataka during the 1985 rainy season. This derived line is also being tested by the All India Coordinated Sorghum Improvement Project of the Indian Council of Agricultural Research in preliminary yield trials all over India.

Midge-resistant breeding lines PM nos. 6751,

Table 9. Performance of midge-resistant sorghum breeding lines under good management at ICRISAT Center and midge infestation at Dharwad, rainy season 1983.

Origin	Pedigree	Days to 50% flowering	ICRISAT Center: Good mangnt[1]	ICRISAT Center: % yield of CSH 6	Dharwad: Midge infestn.[1]	Dharwad: % yield over CSH 6	Midge[2] damage
PM 6751B	(SC 108-3 x S GIRL-MR 1)-19-1-1	57	3430	81	1610	560	1.5
PM 7060B	(IS 152 x DJ 6514H-1-1	59	2340	55	1750	610	1.0
PM 7061B	(IS 152 x DJ 6514)-8-1-1	58	2720	64	2160	750	1.0
PM 7495	(PD 3-1-11 x DJ 6514)-14-3-1	57	2270	53	1770	620	1.0
CSH 6 (hybrid)		54	4250		290		4.5
SE			± 150		±189		
CV(%)			±10		±30		
PM 7318-2	(IS 12573C x SC 108)-7-3-5-1	56	4170	92	2120	370	1.5
PM 7322	(IS 12573C x SC 108-4-8)-7-4-3-1	56	3900	87	2170	390	1.5
PM 7390-1	(IS 12673C x PHYR)- 15-1-2-1	55	3430	76	2880	510	1.5
PM 7397	(FLR 119 x DJ 6514)-7-1-1-1	57	2460	55	1940	340	1.5
PM 8787-2B	[(FLR 119 x IS 2579C) x Ind-Syn 323-1-3]	58	2360	52	2640	470	1-3
CSH 6 (hybrid)		56	4500		560		4.5
SE			±216		±160		
CV(%)			12		17		
PM 7032	(EC 6434 x DJ 6514)-5-1-1-1	60	1820	38	3180	830	0.0
PM 7493	(PD 3-1-11 x DJ 6514)-14-3-1-1	62	2850	60	2290	600	0.5
PM 7526	(Diallel 1457 x DJ 6514)-12-1-1-2	63	2600	55	3220	840	0.0
CSH 6 (hybrid)		56	4740		380		4.5

1. Yield measured in kg/ha.
2. Damage rated on a 1 to 5 scale where 1 = low (< 20% damage), 5 = high (80-100% damage).

7060, 7061, and 8787-2 have been identified as nonrestorers and are being converted into male-sterile female stocks for the production of midge-resistant hybrids.

PM nos. 6751, 7060, 7061, 7348, 7495, and 11344 lines are being used as new resistant donor parents for generating breeding stocks. Their crossed derivatives appear agronomically better than the first cycle material generated by using the original sources.

Future Plans for Shoot fly and Midge Resistance Breeding

As we do not find high levels of stable resistance to shoot fly in cultivated sorghums, efforts will be made in collaboration with cytogeneticists at ICRISAT and other research organizations to transfer the resistance trait from wild sorghums into cultivated types.

No immunity exists to any insect in the sources and the resistances are polygenically controlled by genes with different gene actions; since pedigree breeding has not resulted in fast gains in the past, recurrent selection may be a useful approach to handle such complex traits more effectively. Hence, recurrent selection is planned as a main breeding approach in the future.

The identification of nonrestorer resistant lines and their conversion into female stocks is also going to be an important function of our objectives.

Emphasis will be placed on developing elite cultivars resistant to more than one insect pest.

More information on source diversification and genetics of major resistance traits needs to be generated.

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The cooperation extended by the ICRISAT entomologists is vital to the success of our insect pest resistance breeding program and their contribution is acknowledged. We also acknowledge the support of the ICRISAT Sorghum Improvement Program scientists in genetic resources, physiology, biochemistry, and cytogenetics.

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Grain Sorghum Yield Stability in Relation to Plant Resistance to Insects

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Abstract

Sorghum, Sorghum *bicolor (L.)Moench, has wide genetic diversity and has undergone selection by both nature and man, resulting in wild and grain types, respectively. Plant resistance to insects is found in both types; research teams are challenged to transfer such resistance while retaining desired traits. The ease with which this can be done depends upon the source of resistance and the gene action.*

Simply inherited resistance found in grain types can be transferred by backcrossing, but multiple genes require more laborious techniques. Nevertheless, the same breeding techniques used to transfer other characters can be used. Only the special procedures for uniformly infesting plants and accurately evaluating resistance need to differ. Genes conveying resistance may decrease, increase, or have no measurable effect on yield. Often the effect can be determined only after yield-testing under various environmental conditions.

Hybrid combinations should be yield-tested both in the presence and the absence of the targeted pest. Other major pests and prevailing cultural practices should also be considered. Little research has been done on the effect of insect resistance on grain quality, but direct effects are usually minimal. Pest resistance introduced into commercial sorghum adds variability that could reduce vulnerability.

Résumé

La stabilité des rendements de sorgho grain liée à la résistance des plantes aux insectes : *Le sorgho,* Sorghum bicolor *(L.) Moench, englobe une énorme diversité génétique. Il a subi la sélection aussi bien naturelle que par l'action de l'homme, aboutissant respectivement à l'élaboration de types sauvages et de types en grain. Tous les deux types manifestent une résistance aux insectes que les chercheurs tentent de transférer tout en retenant les caractères désirés. La facilité de cette opération dépend de la source de résistance ainsi que l'action des gènes.*

La résistance à hérédité simple présente chez les types en grain peut être transférée par le rétrocroisement; cependant les gènes multiples demandent des techniques plus laborieuses. On peut appliquer les mêmes techniques de sélection utilisées pour d'autres caractères. Seuls les processus d'infestation uniforme et d'évaluation précise de la résistance sont susceptibles de varier. Le rendement peut augmenter, diminuer ou même rester indifférent à l'influence des gènes de résistance. Souvent, leur effet ne peut être déterminé qu'après des essais de rendement sous différentes conditions de l'environnement.

Des essais de rendement devraient être réalisés sur les combinaisons hybrides à la fois en l'absence qu'en présence de l'insecte sous étude. Il faut également considérer d'autres ravageurs et les pratiques culturales existantes. Peu de recherches ont été consacrées sur l'effet de la résistance sur la qualité du grain, cependant les effets directs sont normalement négligeables. L'incorporation de la résistance chez les sorghos commerciaux augmente la variabilité tout en réduisant la vulnérabilité des plantes.

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Introduction

Worldwide, sorghum (*Sorghum bicolor* [L] Moench) ranks eighth from the standpoint of edible dry matter and protein production (Harlan and Starks 1980). About 45% of the total sorghum production is in developed countries, used mainly for domestic livestock feed or for export. The other 55% is produced in developing countries where sorghum is a staple in the diets of some 400 million people (Doggett 1976). Sorghum is used extensively as a forage, but its primary importance relates to the yield of grain in warm semi-arid regions unsuited for growing an equal yield of maize or small grains. Grain yield will be the primary focus of this article.

Wiseman and Morrison (1981) have estimated a 9% loss to field insect pests of grain sorghum in the USA. By contrast, the International Regional Organization of Plant Protection and Animal Health of Central America (1977) estimated a 20% field loss for sorghum in Central America and Mexico, and in certain locales of Africa and Asia losses have been estimated to be even higher (Jotwani et al. 1977). Such losses can be reduced by the use of plant resistance to insects.

General Considerations

Sorghum yields have increased only about 2% per year to a current average that is less than two-thirds the average yield of maize per unit area. Roughly half of the sorghum produced, but more than three-fourths of the area planted, is concentrated in the grain-deficit developing countries of Asia and Africa. Yields in these regions seem to have stagnated at about 0.76t/ha for the past decade. Sorghum plantings increase when drought cycles increase (ARPAC 1975), so overall production is a function of alternative crops as well as biotic and abiotic stresses. The desired strategy is to maintain consistent production and avoid extreme shortfalls.

The utilization of insecticides after World War II allowed crop specialists to observe significant yield increases when insect outbreaks were controlled. Subsequently, it became apparent that this change in crop production systems was not simple. We are just becoming aware of the complexity of agro-ecosystems and are developing adaptations of modeling and systems analysis to allow us to deal more effectively with the perturbations involved in crop production. As the title of this paper indicates, there are concerns about the maximizing of yield potential for sorghum and other crops as well as assuring stability of production.

The variability of the crop pest problem and environment are important considerations. The point at which differences between means will be considered as a result of this variability or as differences in populations needs further attention. Cramer (1976) has helped by pointing out that in present-day crop performance tests, differences may exist but cannot be demonstrated statistically. Crop yield always has an environmental as well as a genetic component, and with the frequent stresses encountered in sorghum-growing areas, skillful design and agronomic practices are necessary in order to discern the biotic and abiotic factors contributing to yield.

Teetes et al. (1979) pointed out that management of sorghum for food and feed varies considerably from small subsistence plots to immense monocultures, and many factors need to be considered within the context of each ecological region. While the paper by Bunting (1971) is becoming somewhat dated, his consideration of biological yield versus economic yield is important to understanding that in managing sorghum production there will be almost daily tradeoffs between optimum and economic maximum considerations in yield. We are not aware of any updates of economic analysis of alternative pest control strategies for grain sorghum since the one by Salkin et al. (1976), but such investigations should be conducted under varying environmental and cultural conditions. Economic thresholds as such must be considered on a field-by-field basis rather than the impact of insect control versus annual yield variances.

Variability in Crops and Insects

The genus *Sorghum* is highly diversified and mutates readily. Yet commercial production in most countries relies on a narrow germplasm base, frequently widely distributed and very vulnerable to potential hazards (U.S. National Academy of Sciences 1972). Sources of insect and disease resistance as well as male-sterility in sorghum cultivars are examples of vulnerability. The cooperative sorghum conversion program (Johnson et al. 1973) has contributed a large amount of germplasm usable in temperate climates. This approach is a positive factor contributing to greater production stability.

Harlan's (1972) warning of the eroding of genetic resources in wild populations of crop plants such as sorghum is as true today as when the article was published. Germplasm collection expeditions seldom include an entomologist trained to identify diversity in insect responses. The frequency of such plants may be exceedingly low, but it would seem to be a desirable point to be investigated.

Denno and McClure (1983) observed that as our understanding of the molecular nature of plants and insects increases, we will come to recognize greater variability in all biological organisms—both plants and herbivores. The variability recognized in shoot fly species (Davies and Seshu Reddy 1981; Deming 1971) and the corn leaf aphid and greenbug biotypes (Cartier and Painter 1956; Pathak and Painter 1958; Starks and Burton 1977; Porter et al. 1982) is but a prologue to the actual variability within a pest complex.

Injury in Relation to Resistance and Yield

Yield might be expected to reflect the simple quantitative consumption of plant parts by insects, but the relationship is far more complex. The time, the nature, and the site of the injury interact with varying environmental factors to influence the plant growth processes that determine yield (Bardner and Fletcher 1974). Adding to this complexity are the genotypes that withstand infestations that severely damage others. A tolerant plant may compensate for injury by forming substitute root systems, by tillering, or by added development of grain, depending on whether insects damage the roots, shoots, or panicles. Tolerant plants may better withstand the injection of a feeding toxicant by sap-feeding pests or the abrasion and rupturing of tissue by chewing and boring insects. A subtle form of tolerance might involve the ability of an uninjured plant to efficiently occupy the niche vacated by an adjacent seedling killed by insects. Regardless of the form in which tolerance is expressed, it is a positive response of the plant, measurable in yield.

Antibiosis and nonpreference, the other mechanisms of resistance, can be just as important as tolerance in preserving plant health, but both are negative responses of insect pests to plant genotypes. There are fewer or less robust insects attacking plants, perhaps for a shorter length of time. Either antibiosis or nonpreference may give a carry-over effect that can suppress insect populations gradually but continuously if the resistance is widespread and sorghum is an essential host plant. Both are thought by some people to be less enduring than tolerance, but the literature does not fully support this belief. All three components of resistance are heritable, and all reflect injury and subsequent yield, whether the relation is indirect, as with antibiosis and nonpreference, or more direct as with tolerance.

Objective of Breeding for Resistance to Insects

The principal objective of breeding for insect resistance in grain sorghum and other field crops is to reduce yield losses from a targeted pest or complex of pests. As stated, the task seems simple. In the presence of a pest, acceptable resistant cultivars would need only to yield more than susceptible ones. However, most plant breeders, understandably, would not be satisfied with this narrow yield objective. They would want the resistant cultivar to yield more than the susceptible cultivar(s) in the *presence* of the pest, and to yield at least as much as the susceptible counterparts in the *absence* of the pest. There are a few exceptions. A lower-yielding variety may be accepted where pest problems are overwhelming. For example, Namatari, a tall, loose-headed, high-tannin variety grown in southern Uganda, can be exceeded in yield and quality by newer varieties, but it excels in multiple pest resistance (Doggett et al. 1970). Even so, many sorghum specialists would want insect-resistant releases to have the yield potential of replaced varieties, or else they would expect the pest to be controlled by methods other than plant resistance, even though alternative methods might not be available or might have adverse side effects.

Insect resistance in grain sorghum could perhaps be classified as "maintenance research" in contrast to "productivity-enhancing research" (Ruttan 1983), since the intent is to offset the yield loss that would otherwise result from a pest. Too many people take this to mean that plant resistance is of secondary importance and is in direct competition with other control strategies. In fact, plant resistance should be considered as a complementary method of pest control necessary for sorghum to reach its full yield potential. When the yield potential increases, the effort to reach this potential also needs to increase. Thus obtaining acceptable insect resistance becomes more difficult when the standards for comparison are elite sorghum hybrids.

The yield standards in many countries are thus high, and the task of equaling these standards with insect-resistant sorghum is challenging. The gene action of yield and yield components is complex and controlled by many linkages. This, along with our meager knowledge of the genetic control of most sources of insect resistance, makes the prediction of insect resistance x yield interactions very difficult. Frequently, when there is directional selection for a character such as resistance, other characters that influence yield will be altered. This is especially true of complex approaches such as breeding populations, where each component depends on other components in a cohesive system, and selection for a single character is difficult (Allard 1960).

Sources of Resistance

Centers of origin and centers of diversity of both plant and insect pests have been suggested as the best geographical areas to find sources of resistance. There is no assurance, however, that a search in one place will be more rewarding than a search in another. Resistance can even evolve in the absence of the pest, so one takes resistance wherever it can be found. Finding sources of insect resistance is still mainly a process of screening large germplasm collections without regard to the origin of the entries. If resistance is located in adapted grain types, the task of returning to yield standards may be relatively simple. If wild type species are the sources of resistance, the job is much more difficult. The latter is more probable.

When resistance is found, frequently more than one source is located in related entries. These sources usually carry genes in common for resistance, and no additive effect is gained by combining sources. In such cases, the breeder has an opportunity to use the source that is thought to offer the best yield potential. Large screening programs for insect resistance are notorious for giving false hope, as they are often nonreplicated, with numerous variables. Therefore, any source of resistance found in a screening program should be further evaluated before breeding efforts begin. On the other hand, undue evaluation before crossing begins can add credence to the belief that resistance as an insect control method takes too long to incorporate into cultivars. Certainly a breeding program can begin before the nature of resistance or the effects on the insect pest have been explored. A knowledge of heritability will be helpful to the breeder, but this is obtained only after the initial crossing is done and early generations have been evaluated.

Breeding Techniques

In grain sorghum with its wide genetic diversity, man has successfully selected characters such as large, nonshattering heads with large, good-quality seeds. On the other hand, natural selection has favored wild-type characters such as lateness and loose heads with fairly small, dark seeds. Cultivated grain sorghum crosses freely with wild types that also have 2n = 20 chromosomes. Such crosses can transfer valuable genetic characters such as resistance to insects. Yet the introduction of exotic germplasm into breeding material can disrupt established yield traits. The sorghum breeder is therefore challenged to transfer a character such as insect resistance, while retaining desired yield features.

Research on insect resistance in grain sorghum requires special procedures for uniformly infesting plants and accurately evaluating levels of resistance. Otherwise, the basic breeding techniques needed for an insect resistance breeding program are no different from those developed for the transfer of other characters in grain sorghum. The breeder strives to retain desired traits while incorporating insect resistance. The task may be easy and quick if the resistance is transferred from breeding lines, but arduous and drawn-out if the source is in exotic material such as alien species or genera. The source and complexity of the heritability of resistance determine the breeding method, and the breeding method will influence the genotype changes, including yield.

Simply inherited resistance, such as that to greenbug, *Schizaphis graminum* (Rondani), in an agronomically acceptable background, can be easily transferred by backcrossing to an elite genotype (Hackerott et al. 1969). Yield should be fairly predictable and close to the recurrent parent. Multiple additive genes for resistance, such as that to shoot fly (Harwood et al. 1972), stem borers (Rana and Murty 1971), and sorghum midge, require more complex breeding schemes such as population breeding (Starks et al. 1976). Yield will be influenced by the recombining of genes, and more time may be required to obtain the desired genotype.

Induced mutation breeding (Jotwani et al. 1977) is usually considered only if no other adequate resistance sources are available, since the process frequently introduces changes other than plant x insect interactions. At present, the production of genes for insect resistance in sorghum by recombinant DNA must be considered as an exciting academic venture, but not yet ready for the marketplace. Chemical assistance in making exotic crosses and tissue culturing of the progeny has increased over recent decades.

Evaluation of Characters

Since the main purpose of breeding for insect resistance is to reduce yield losses, the selection criteria should reflect the yield of infested plants in comparison with an infested standard. This may be done in a variety of ways involving natural or artificial infestations, insecticide-treated versus untreated plots, and caged insects or plants to enhance damage. These procedures, unfortunately, largely ignore the long-range reductions in pest populations and subsequent reductions in natural infestation levels that may be brought about by accumulative adverse effects on the pest's biological activities, but we have not yet designed satisfactory techniques for directly obtaining this information. Instead, we hope that long-term population suppression will be a fallout from the conventional plant resistance program measuring immediate yield effects.

The type of plant damage by the pest determines the complexity of the evaluation process reflecting yield. If the pest attacks germinating seed or small plants, often the evaluation criterion can be as simple as stand counts, percentage deadhearts, or a visual rating of plant recovery after attack from a uniform infestation. The success of a simple evaluation system is typified by the transfer of moderate levels of shoot fly resistance to high-yielding, agronomically acceptable varieties (Jotwani 1981).

Pests that tunnel in larger plants, especially at several stages of plant development, require more laborious evaluation techniques, frequently involving the sacrifice of infested plants in order to measure damage or obtain biological data (Jotwani et al. 1971). Often several types of measurements must be taken to find those with a high positive correlation with yield (Singh et al. 1983). The evaluation of leaf-feeding pests may appear simple at first, but there is frequently a poor positive correlation between the amount of leaf feeding and the grain yield (Wiseman and Morrison 1981). The complexity of the quantitatively inherited resistance to borers and leaf feeders such as *Spodoptera* spp may necessitate the rating of progeny rows or families, and the use of increasing levels of infestation as resistant genes are accumulated, in order to identify usable resistance.

Damage by panicle-feeding pests would seem to be a simple function of yield; however, the relationship may be influenced by factors such as the time of injury and the subsequent degree of compensation for damaged florets by an increase in the grain size of adjacent undamaged ones. Compensation may differ for a pest such as the corn earworm, *Heliothis zea* (Boddie), which mechanically destroys kernels, often late in grain development, and one such as the sorghum midge, which attacks earlier and has more complex feeding procedures (Hallman et al. 1984).

Ortega et al. (1980) gave an excellent discussion of evaluation procedures involving quantitative inheritance in maize, and their comments are equally applicable to insect resistance in grain sorghum. They also stated that "Breeding progress depends on the cooperation of scientists specializing in different disciplines. Isolated efforts by breeders, entomologists, and pathologists will produce varieties deficient in one or more aspects." The point is well made, but to avoid deficiencies in yield the breeder must assume the major responsibility for achieving yield objectives.

Even after selection and transfer of resistance has been completed, the evaluation for yield should continue, although the task may be somewhat anticlimactic. The resistant material needs to be tested as a variety or in hybrid combinations; under various growth conditions, which often involves multiple locations; and under varying levels of natural infestations of the target pest, with and without insecticidal protection. Also, the material needs to be evaluated against other major pests to ascertain that problems from these are not being enhanced. In fact, this should be done as early as possible, since the problem can often be corrected in early stages of breeding. For example, IS 809 had good resistance to the greenbug, but was highly susceptible to maize dwarf mosaic virus (MDMV). Knowing this, breeders introduced the insect resistance into lines with MDMV tolerance. Sometimes the unexpected interaction between insect-resistant material and management components will arise. One example is that at least some greenbug-resistant hybrids have been found susceptible to certain herbicides (Simkins and Moshier 1982). There is no logical end to yield-testing since possible environmental interactions are numerous, so the goal of getting insect resistance into commercial production should be realized if yields approach those of commonly proven susceptible standards under insecticide protection.

Effect of Insect Resistance on Yield

The incorporation of insect resistance into grain sorghum does not automatically result in either an enhancement or deterioration of yield. There are cases where genes conveying resistance, or more commonly genes linked with resistance, have improved or decreased yield components when measured in the absence of the specific insect pest. The transfer of greenbug resistance apparently originating in *Sorghum virgatum* (Hack.) Stapf to parents of grain sorghum hybrids added vigor that gave slight yield increases over near-isogenic lines (Dekalb Agresearch 1975). Conversely, there are several reported sources of insect resistance that have not been exploited because of the difficulty of maintaining present yield standards. To name a few, Nunaba was found to have sorghum midge resistance about 20 years ago (Bowden 1965), but the associated cleistogamous character makes hybrid production impractical. Rio has resistance to grass mite, *Oligonychus pratensis* (Banks) (Teetes 1980), and Piper Sudan grass has resistance to the corn leaf aphid, *Rhopalosiphum maidis* (Fitch) (Howitt and Painter 1956), but both of these varieties transfer undesirable dominant traits to grain sorghum.

Sometimes a trait that gives insect resistance is directly linked to yield. This is especially noticeable when the resistance character is morphological. For many years sorghum researchers have known that there is a correlation between the panicle type and damage by lepidopterous larvae, as well as certain head diseases. In general, the larval number increases with panicle compactness (Hobbs et al. 1979; McMillian and Wiseman 1972); therefore, breeders routinely select for panicle looseness sufficient to reduce infestations without unduly reducing yields. With other traits, a compromise between yield and insect damage is not as easy to reach. Sorghum with lower than normal amount of wax on the leaves and stems is nonpreferred by the greenbug (Starks and Weibel 1981), but plants homozygous for this character are susceptible to drought stress. So far, breeders have been unable to obtain nonpreference without subjecting the plant to the possibility of drought stress and consequent yield loss (Peiretti et al. 1980).

Effect of Insect Resistance on Grain Quality

Very little research has been done on the direct impact of insect resistance on grain quality. The results that are available usually have been obtained after the involved plant resistance was commercially available. Perhaps this delay in research on quality is conditioned by results that so far show no measurable deleterious effects of the pest protection, though many sources of resistance are thought to have a biochemical basis. For example, Pi and Hsieh (1982) were unable to correlate *Melanaphis sacchari* (Z.) resistance positively with HCN-p or phenolic acid content, but did suggest that resistant cultivars had higher epicuticular wax. The amount of wax was not shown to influence the quality of wine made from the grain.

The indirect effects of plant resistance on grain quality are thought to be similar to those related to other methods of insect control. Insect control can allow better photosynthesis and better transport of components that go into grain. Depending on the type of damage that would have been done by the controlled pest, kernels may be larger and more uniform, less subject to pathogens, and contain more total starch, oil, and protein, though shrunken kernels will usually contain a higher percentage of protein based on kernel weight. The milling quality of the grain should also be improved by controlling a damaging pest, regardless of whether the consumer is a person or a domesticated animal.

Conclusions

There is no unique incompatibility between insect resistance and sorghum yield. Therefore, insect resistance along with disease resistance should be an integral part of all comprehensive breeding programs where a pest limits sorghum production, even on an occasional basis. In regions where the shoot fly can cause 55% grain loss and the stem borer, *Chilo partellus* (Swinhoe), can cause 84% grain loss (Jotwani et al. 1971), plant resistance to insects should be a major part of the breeding program.

Even when damage from a pest is much lower and can presently be controlled by other means, plant resistance can be a vital part of pest management. For instance, Andrilenas (1975) reported that only 2% of the U.S. sorghum acreage grown in 1966 was treated with an insecticide, but 39% was treated in 1971 after the spread of biotype C greenbug. Plant resistance was able to reduce the insecticide usage by as much as 90% in some locations in Texas by 1976 (McWorther 1978). Insecticides, as in the above example, have a vital role in crop production as an emergency measure for insect control. However, the sole reliance on broad-spectrum insecticides can possibly lead to disaster, as evidenced by the devastation of cotton by pests in Peru (Haskell 1977). In such extreme cases of pest damage, genes for high yield are not given an opportunity to express themselves.

Even if plant resistance were not an important component of pest management, there might be some justification for its inclusion in breeding programs. The introduction of resistance into sorghum adds genetic variability, an essential ingredient for effective selection. The U.S. National Academy of Sciences (1972) stated, "present parents of grain sorghum hybrids have at most five or six varieties in their parentage; and most parents have only two or three. Thus, the genetic diversity in parents is not sufficient to give adequate protection against a catastrophic epidemic and a real threat exists. The use of insect resistance in commercial sorghums can broaden the germplasm base and could thus afford secondary benefits toward insuring continuing high production. Breeding techniques are available for the transfer of any source of interspecific insect resistance, and adaptability can be recovered, but some transfers of resistance, especially from exotic sources, will require specific breeding techniques to approach the ideal agroecotype.

Note: **Mention of a pesticide does not constitute a recommendation for use by the USDA, nor does it imply registration under FIFRA as amended. Article P-1661 of the Agricultural Experiment Station, Oklahoma State University, Stillwater, OK 74078, USA.**

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Effects of Different Sorghum-Based Cropping Systems on Insect Pests in Kenya

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Abstract

Intercropping experiments conducted at the International Centre of Insect Physiology and Ecology (ICIPE) Mbita Point Field Station (MPFS) on the shores of Lake Victoria, South Nyanza, Kenya, and on farmers' fields in South Nyanza district, and surveys conducted in other parts of Kenya between 1980 and 1982 indicated that there was a trend in pest population fluctuation. Early and late infestation, colonization, buildup, and establishment of pests were related to different maize-cowpea-sorghum combinations.

During 1983, data from MPFS and Ogongo indicated that stem borer infestation started later in the major season. The colonization and buildup of stem borers was also much faster in monocultures of sorghum or maize than a sorghum/maize intercrop. The fast buildup of the stem borer population at MPFS was due to high pest population at the station. At Rongo, however, population buildup was unexpectedly slow. This could have been due either to continuous rainfall which tended to wash off egg batches, or to the apparent inactivity of Busseola fusca, *which is the major stem borer in the area. Although* Marasmia testulalis *attack on intercropped cowpea at Rongo was low, probably due to similar reasons as given for* B. fusca, *higher damage was recorded in cowpea monoculture.*

Résumé

Les insectes nuisibles dans le cadre des systèmes de cultures du sorgho au Kenya : *Le Centre international de la physiologie et de la biologie des insectes (ICIPE) du Kenya a mené des essais sur les associations culturales à sa station expérimentale de Mbita Point sur la rive du lac Victoria et aux champs des paysans dans le district de Sud Nyanza, outre des enquêtes dans d'autres parties du Kenya entre 1980 et 1982. Les résultats montrent un rhythme dans les fluctuations des populations. Les infestations tardives et précoces, la colonisation, la pullulation et l'établissement des insectes sont liés aux différentes associations maïs-niébé-sorgho.*

D'après les données obtenues à la station de Mbita Point et d'Ogongo en 1983, l'infestation par le borer des tiges a débuté tard dans la saison principale. La colonisation et la pullulation des borers sont plus rapides chez les cultures pures de sorgho ou de maïs par rapport à une association des deux espèces. La pullulation rapide à Mbita Point est due à la population importante de cet insecte présente à la station. Par contre, la pullulation était anormalement lente à Rongo. Ceci est dû soit aux pluies continuelles qui ont emporté les oeufs pondus ou à cause de l'inactivité apparente de Busseola fusca, *borer prédominant de la région. De même, l'incidence de* Marasmia testulalis *chez le niébé en association à Rongo était inférieure par rapport à la culture pure de niébé; ceci serait pour la même raison évoquée plus haut à l'égard de* B. fusca.

Introduction

The use of intercropping systems as a cultural method of pest control is based on the principle of minimizing insect pest populations by increasing the diversity of an agroecosystem (Smith 1970; Solomon 1973). However, Smith (1970) cautioned that the same kind of diversity can be harmful in one instance and beneficial in another. In some cases, a particularly attractive host plant may concentrate

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insect pests by diverting them from the other crops and making them more vulnerable to predators and parasites. Also the feeding and searching behavior of insects which depend on olfactory stimuli can also be confounded by the presence of other plants giving off contradictory signals.

The intercropping research conducted at the International Centre of Insect Physiology and Ecology (ICIPE), Mbita Point Field Station (MPFS), on the shores of Lake Victoria, Kenya, on farmers' fields in South Nyanza district, and surveys conducted in other parts of Kenya, supported and confirmed most of these findings. The study had the following objectives (Amoako-Atta et al. 1983):

1 to standardize methodology and sampling of insect pests within intercropping systems, and

2. to assess pest complex and severity within sorghum, cowpea, and maize intercropping patterns.

Materials and Methods

Eight different treatments including the monocrops of sorghum, cowpea, maize, and their mixed and intercrop combinations were planted at MPFS and farmers' fields in a complete randomized block design. The varieties used were: (1) Serena, a sorghum cultivar suitable for lowland areas of East Africa below 1530 m, with a maturity period ranging between 110 and 120 days; (2) Katumani composite B, an early-maturing (90 days) maize that escapes drought; and (3) Ex-Luanda, a semi-erect local cowpea cultivar well established along the Lake Victoria region, with relatively short maturing period of about 70 days.

The eight treatments consisted of monocrops of sorghum, cowpea, and maize; two-crop intercrops of sorghum/maize, sorghum/cowpea, maize/cowpea; and three-crop mixed and intercrops of sorghum/cowpea/maize. The plant population was kept constant, using the substitutive model for intercropping (de Wit 1960). Plant equivalent ratios for this study were: one maize plant as crop unit, equal to two sorghum plants, or three cowpea plants. In intercrops, the spacing for maize was 100 cm x 30 cm, for sorghum 100 cm x 15 cm, and for cowpea 100 x 10 cm. In monocrops maize was planted 75 x 30 cm; sorghum 75 x 15 cm and cowpea 50 x 15 cm. The target pests were: sorghum shoot fly, *Atherigona soccata* (Rond.); stem borers *Chilopartellus* (Swin.), *Busseola fusca* (Fuller), *Sesamia calamistis* (Hmps.), and *Eldana saccharina* (Wlk.); and cowpea pod borer, *Maruca testulalis* (Geyer). The parameters assessed were insect-pest colonization, establishment, and the buildup process within different cropping patterns and their influence on crop yield and yield loss.

The experiment was planted in large plots measuring 24 x 21 m, subdivided into a number of 3 x 3 m subplots, four of which were sampled twice a week throughout the growing season, leaving the guard rows. At the end of the season, the subplots assigned were harvested for yield and yield loss assessment. The four randomly selected subplots satisfied the replication requirement, and the individual plants were considered as sample variable, within the subplot. The trial was repeated in both major (Mar-July) and minor (Sept-Dec) seasons for 3 years, 1980, 1981, and 1982.

The findings obtained during these 3 years were again tested for confirmation in two seasons; minor

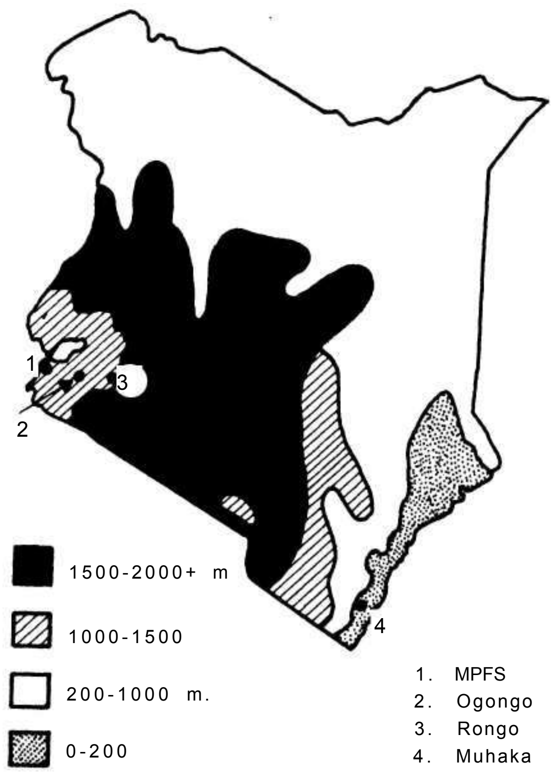

Figure 1. Assessing the pest complex in relation to intercropping systems: testing sites in Kenya.

season 1982/1983 and major season 1983 in three different ecological zones in Western Kenya (Fig. 1). The locations were: Mbita Point Field Station-erratic rainfall regime, both major and minor seasons unreliable, and high pest populations; Ogongo in the Lambwe Valley—only the minor season may be unreliable, with normal pest population in farmers' fields; and Rongo, high-rainfall regime, both seasons reliable, with low pest population. This was done to confirm whether or not these findings could have practical relevance for the benefit of the resource-poor farmers in the rural community.

Results and Discussion

Pest Status

Preliminary studies in screenhouses and small plots in the field indicated that a combination of maize and sorghum reduced *Atherigona soccata* damage in sorghum. However, in large plots, the differences were nonsignificant, although oviposition on maize was noted. Results from 3 years' study (Amoako-Atta et al. 1983) indicated that stem borer complex interactions on sorghum and maize were greatly influenced by both cropping system and season.

In the major season, stem borer colonization and establishment were delayed, unlike the early infestation observed during the minor season. The presence of cowpea (nonhost) in an intercropping combination consistently reduced stem borers on cereals. Stem borer activity on sorghum monocrop and sorghum maize combination was significantly higher throughout the study period. These findings concur with the work done by Singh and Singh (1974, 1977) who showed that the presence of mung bean *(Vigna radiata)* or urd bean *(Vigna mungo)* and pigeonpea reduced the succession and buildup of insect pests in sorghum and pearl millet. Cowpea monocrop suffered more attack by the pod borer and persistently realized heavy losses. When maize and sorghum (similar plant types and hosts for stem borers) were intercropped, the incidence of stem borers increased. On the other hand, intercropping with cowpea, a nonhost to stem borers, considerably reduced the incidence of stem borers on both maize and sorghum. The presence of these cereals also similarly reduced pod borer incidence on cowpeas.

Productivity

Using land equivalent ratio (LER) as an index for crop production, the sorghum/cowpea intercrop proved to be highly productive in farmers' fields and at the Station during both major and minor seasons, ending up with an overall LER of 1.3. The productivity of maize/cowpea in general was much better in the major season and poorer in the minor season, which is reflected in the low LER of 1.1. This combination is better for areas with assured rainfall. The productivity of the maize/sorghum intercrop was below that of either monocrop (LER = 0.89). This combination suffered heavy infestation of stem borers. The sorghum/cowpea/maize three-crop combination is only suitable for very high rainfall areas, because when water was not a limiting factor, it had an LER of 1.45 and above.

Growth Patterns

The dry matter (DM) accumulation of sorghum, cowpea, and maize within different cropping patterns was recorded after every 2 weeks (Amoako-Atta and Omolo 1983). It was interesting to note that different cropping systems did not interfere with the growth patterns of crops. Both maize and cowpea have similar growth patterns and therefore could not make a good combination. In both cases, the peak in DM was reached between 56 and 70 days after germination (DAG). For sorghum the pattern was entirely different. During the period of 56 and 70 DAG, growth rates slowed down, but thereafter picked up again. This may explain why sorghum and cowpea became the best combination, since there was no competition for natural resources for either during critical growth periods. Sorghum is also capable of slowing down its growth rate when conditions are unfavorable and picking up again when the situation improves; hence its ability to survive drought.

Significant Findings

Based on pest control, productivity, growth pattern, and yield loss assessed by Amoako-Atta and Omolo (1983), sorghum and cowpea was the best combination in both major and minor seasons. The maize and cowpea combination was only good during the major season, and the maize/cowpea/sorghum tri-crop performed well in high-rainfall areas. The worst combination was the maize/

sorghum intercrop, which showed a lower productivity than monocrops of either maize or sorghum.

Multilocation Testing, 1983

The objective of this test was to confirm the practical relevance of certain crop combinations for the benefit of the resource-poor farmers in the rural community. According to the results presented in Table 1, the percentage attack on sorghum by the stem borer complex at MPFS indicates that stem borer colonization, establishment, and buildup was much faster in the minor season (short rains) than in the major season (long rains). Therefore the pest complex interacted both with different cropping systems and with seasons. The pest-complex buildup was much faster in the sorghum monocrop and sorghum / maize intercrop than in any of the other cropping patterns tested, in both major and minor seasons.

Table 2 shows percentage attack on sorghum by the stem borer complex at Ogongo during the minor and major seasons. Although the pest population level was lower than that at MPFS, the pattern of buildup in both seasons was similar to that at MPFS; that is, pest population built up faster during the minor season than in the major one. The percentage attack on the sorghum monocrop and sorghum / maize intercrop was significantly higher than that on the sorghum / cowpea and the sorghum/ cowpea/maize intercrops. The mean percentage attack on cowpea by *M. iestulalis* and other pests at MPFS and Ogongo was much higher than expected in both places, with little difference between locations (Table 3). However, looking at the combined mean attack between the two sites, the cowpea monocrop was much more infested by *M. testulalis* (73.17%) than the cowpea / sorghum intercrop, in which only 53.8% of the cowpea plants were infested.

The pest population at Rongo was much lower than that at either MPFS or Ogongo. This could have been due to a number of reasons, such as continuous rainfall, which might have washed off the egg batches, and the apparent inactivity of *B. fusca,* the predominant stem borer species in the region. As Table 4 shows, there was no definite pattern in the pest population buildup in sorghum. It is important to note that despite the low overall pest population, the sorghum / cowpea still experienced the least attack.

The cowpea situation at Rongo was different, as shown in Table 5. The *M. testulalis* infestation was higher than that of stem borer on sorghum, indicating the abundance of *Maruca* in the region. The infestation on the cowpea monocrop was significantly higher than on the cowpea/maize or cow-

Table 1. Stem borer complex attack on sorghum at Mbita Point Field Station, Kenya, 1982-83.

Cropping pattern	Stem borer attack (%): Days after germination 14	28	42	56	70	84	98	Mean
	Minor season, 1982/83							
Sorghum monocrop	7.5	20.5	38.5	39.5	57.0	70.5	82.0	45.07[1]
Sorghum/maize intercrop	6.0	21.5	36.0	41.5	60.0	67.0	84.0	45.21
Sorghum/cowpea intercrop	6.0	13.0	26.5	37.0	45.5	48.0	68.0	34.86
Sorghum/cowpea/maize intercrop	3.0	13.5	25.0	32.0	39.0	49.0	59.0	31.5
Mean	5.62	17.12	31.5	37.5	50.37	58.62	73.37	39.16
	Major season, 1983							
Sorghum monocrop	3.75	14.25	19.25	26.28	42.0	62.25	75.5	35.75
Sorghum/maize intercrop	3.0	13.75	22.0	28.75	48.75	63.5	74.5	36.32
Sorghum/cowpea intercrop	3.0	8.5	13.25	18.5	31.0	31.0	49.5	26.07
Sorghum/cowpea/maize intercrop	1.5	6.75	14.0	18.5	25.0	40.25	56.5	23.18
Mean	2.81	10.81	17.12	23.0	36.68	53.87	66.3	30.08

1. Means followed by the same letter are not significantly different at $P = 0.05$.

Table 2. Stem borer attack on sorghum at Ogongo, Kenya, 1982-83.

	Stem borer attack (%)							
	Days after germination							
Cropping pattern	14	28	42	56	70	84	98	Mean
	Minor season, 1982/83							
Sorghum monocrop	0	8.0	0	13.0	27.0	54.0	69.0	24.43a'
Sorghum/maize intercrop	0	6.0	8.0	16.0	37.5	60.0	64.5	27.43a
Sorghum/cowpea intercrop	0	4.0	0.0	0	16.5	51.0	49.5	17.28b
Sorghum/cowpea/maize intercrop	0	0	3	5	12.0	31.5	54.0	15.1 b
Mean	0	4.5	2.75	8.5	23.25	49.12	59.25	21.05
	Major season, 1983							
Sorghum monocrop	0	4.0	4.0	8.0	21.0	36.0	57.0	18.57c
Sorghum/maize intercrop	0	0	7.0	4.0	26.0	26.0	60.0	17.57c
Sorghum/cowpea intercrop	0	3	4.0	6.0	11.0	17.0	27.0	9.71d
Sorghum/cowpea/maize intercrop	0	0	0	4.0	17.0	15.0	36.0	10.28d
Mean	0	1.75	3.75	5.5	18.75	23.5	45.0	14.03

1. Means followed by the same letter are not significantly different at $P = 0.05$.

pea/sorghum intercrops; however, the best combination with the least infestation was cowpea intercropped with sorghum.

In order to get an overall picture, data from the three different ecological zones were combined (Table 6). The mean percentage attack by crop borers showed no significant differences between monocrops of maize or sorghum and the maize/sorghum intercrop combination. This could be associated with the low rate of infestation at Rongo. However, it means that the maize/sorghum combination was infested as much as monocrops of either maize or sorghum. The data presented, particularly those from MPFS and Ogongo, strongly supported the previous findings (Amoako-Atta and Omolo 1983).

In general terms, there was a trend in pest population buildup and establishment that was related to different cropping patterns as well as seasons. In the case of *M. testulalis,* despite the fact that attack on cowpea at Rongo was extremely low, most of the damage was on the cowpea monoculture. The presence of maize or sorghum or both must have contributed to the reduction of the *M. testulalis* population in cowpea interplanted with maize or sorghum.

Table 3. Attack on cowpea by *Maruca testulalis* and other insect pests at Mbita Point Field Station and Ogongo, Kenya, minor season, 1982/83.

	Mean attack (%)'		Combined mean
Cropping pattern	Ogongo	MPFS	(%)
Cowpea monocrop	60.3	86.05	73 17c
Cowpea/maize intercrop	50.5	84.40	67.45b
Cowpea/sorghum intercrop	41.0	66.60	53.80a
Cowpea/sorghum/maize intercrop	48.4	78.28	63.34b
Mean	50.05	78.83	64.44

1. Means followed by the same letter are not significantly different at $P = 0.05$.

Table 4. Attack on sorghum by stem borer complex at Rongo, Kenya, major season 1983.

	Stem borer attack (%)							
	Days after germination							
Cropping pattern	14	28	42	56	70	84	98	Mean
Sorghum monocrop	0	0	6.0	0	1.0	1.0	7.0	2.14
Sorghum/maize intercrop	0	0	1.6	0	0	0	10.0	1.66
Sorghum/cowpea intercrop	0	0	0	0	1.3	1.1	0	0.34
Sorghum/cowpea/maize intercrop	0	0	4.15	19.0	0	0	1.0	3.44
Mean	0	0	2.94	4.75	0.57	0.52	4.5	1.81

Table 5. *Maruca testulalis* attack on cowpea and other crops at Rongo, Kenya, 1983.

	Stem borer attack (%)						
	Days after germination						
Cropping pattern	14	28	42	56	70	84	Mean
Cowpea monocrop	0	4.0	12.0	10.0	20.0	18.0	10.6 c[1]
Cowpea/sorghum intercrop	0	0	0	0.9	12.8	6.25	3.32b
Cowpea/maize intercrop	0	0	7.45	1.4	12.8	9.65	5.22a
Maize/cowpea/sorghum intercrop	0	0	12.5	0	20.0	2.6	5.85a
Mean	0	1.0	7.99	3.07	16.4	9.12	6.26

1. Means followed by the same letter are not significantly different at $P = 0.05$.

Table 6. Mean percent attack by crop borers' on sorghum, cowpea, and their combinations at Mbita Point Field Station (MPFS) Ogongo, and Rongo, Kenya, minor season 1982/83 and major season 1983.

	Sorghum				Cowpea			
Cropping pattern	MPFS	Ogongo	Rongo	Combined[2] mean	MPFS	Rongo	Combined[2] mean	Land equivalent ratio (LER)
Sorghum monocrop	35.7	18.6	2.1	18.8b				1.0a
Cowpea monocrop					60.3	10.6	35.4c	1.0a
Maize/sorghum intercrop	36.6	17.6	1.7	18.5b				0.9a
Sorghum/cowpea intercrop	26.1	9.7	0.3	10.0a	41.0	3.3	22.2a	1.1b
Maize/cowpea/sorghum intercrop	23.2	10.3	3.4	12.3a	48.4	5.8	27.1b	1.2c

1 At MPFS: *Chilo partellus. Eldana saccharine. Busseola fusca, Sesamia calamistis,* and *Maruca testulalis;* at Ogongo: *Chilo partellus. Busseola fusca, Sesamia calamistis.* and *Maruca testulalis;* at Rongo : *Busseola fusca. Chilo partellus. Sesamia calamistis.* and *Maruca testulalis.*

2. Means followed by the same letter in a column are not significantly different at $P = 0.05$.

The ICIPE's mandate covers only the three crops which have been used in this study. However, during the survey that was conducted in different parts of Kenya, a number of crops were grown in different combinations and the pest complex in these different cropping systems also needs to be studied.

Conclusions

Intercropping contributes to the diversity of the agroecosystem and changes in microclimate of the canopy, and has an influence on the population buildup of insect pests.

When two crops of similar plant type and host range for a particular insect pest are intercropped, the colonization, establishment, and population buildup increases. On the other hand, intercropping of nonhost plants brings about a considerable reduction in the incidence of most insect pests on the host species.

It is therefore fair to conclude that intercropping, which is one of the traditional cultural practices in Africa and Asia, has a great potential in reducing insect pest incidence.

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Concepts for Biological Control of Arthropods Attacking Sorghum

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Abstract

Biological control by importing, conserving, or augmenting efficacious natural enemies is described as ideally suited for controlling selected pests of sorghum, especially in developing countries. Requisites are discussed for evaluating and implementing a program of biological control, and these requisites are illustrated by research conducted on controlling spider mites (Acari.Tetranychidae) on Texas sorghum. Major sorghum arthropod pests which should be objects of biological control effort are characterized according to their current status regarding biological control understanding, the probable role for biological control, and the most likely of the three biological control tactics to be useful.

Résumé

Notions pour la lutte biologique des arthropodes s'attaquant au sorgho : La lutte biologique comprenant l'importation, la conservation et la prolifération des ennemis naturels efficaces est considéré comme un moyen idéal pour lutter contre certains insectes nuisibles au sorgho, surtout dans les pays en voie de développement. L'es éléments nécessaires à l'évaluation et à l'exécution d'un programme de lutte biologique sont cités en présentant un exemple de la recherche sur la lutte contre les acariens (Tetranychidae) chez le sorgho au Texas. Les principaux arthropodes ravageurs du sorgho qui seront susceptibles d'être l'objet de ce type de lutte sont caractérisés selon l'état actuel des connaissances sur la lutte biologique de l'insecte en question, le rôle de la lutte biologique et lequel des trois stratégies de lutte biologique sera à adopter dans le cas particulier.

Sorghum *(Sorghum bicolor* [L]) is a common grain crop within a region of about 40 on either side of the equator. This range includes both advanced and subsistence agriculture, with about 75% of the world's total sorghum acreage serving as a primary crop in subsistence agriculture (FAO 1979). Sorghum grain is consumed by humans and their livestock, the foliage is often fed to livestock after harvest, and post-harvest plant stalks may be used as construction materials. Though the type and extent of sorghum utilization vary depending on the area of production, sorghum in all parts of the world suffers losses to arthropods. Areas having high technology and considerable ecological understanding attempt to minimize such losses with multitactic insect pest management (IPM).

Theoretically, IPM optimizes low-cost tactics and utilizes insecticides only when these tactics fail or need additional support. Insecticides are generally not economical in subsistence agriculture, making it particularly important for subsistence farmers to take advantage of all low-input tactics for preharvest crop protection. Thus, biological control is often described as holding special promise for subsistence agriculture.

But, despite its potential, *documented* examples of biological control of sorghum pests are rare, even where extensive sorghum monocultures and high technology agriculture are commonplace, primarily because very few sorghum entomologists are trained to conduct biological control studies. Thus, training of entomologists in biological control will be essential to increasing the use of this pest control method for sorghum production.

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The objectives of this paper are to (1) examine biological control concepts for sorghum production and (2) explore the potential of biological control for major sorghum pests in developed and subsistence agriculture.

Biological control manipulates natural enemies of a pest, which in turn reduce the numbers of pests to nondamaging levels. The manipulated natural enemies include arthropod parasites and predators, and disease-producing microbes. Biological control does not occur in the absence of man's active and purposeful role and is not fortuitous or accidental. An action program of biological control requires an active role for man using one of three tactics: (1) conservation, (2) augmentation, or (3) importation.

Extant natural enemies that are efficacious can be conserved and promoted in annual crops by providing habitat continuity, minimizing the use of insecticides, using only insecticides least likely to kill natural enemies, providing or maintaining alternate host plants or host insects for natural enemy survival, providing essential foods for adult parasites or predators, or by providing shelters or nesting sites for natural enemies.

Augmentation consists of releasing cultured natural enemies for temporary control of an arthropod pest by artificially increasing natural enemy numbers when naturally occurring enemy populations are not great enough for control, or when the enemy occasionally becomes extinct.

Importation consists of importing new species of natural enemies for permanent establishment in the pest's environment. A completely successful importation program significantly and permanently reduces a pest's numbers. Biological control by importation has a long history of successes, dating from 1890 when cottony-cushion scale was controlled on citrus. Since 1890, more than 602 importation programs have been attempted; 349 of these have resulted in at least partial success and 96 have resulted in complete success (Hall et al. 1980). In totally successful programs, the pest is so completely suppressed that additional controls are never again needed to prevent pest damage. This record is particularly impressive considering that historically very few entomologists have been engaged in such programs.

Generally, only one or two pest species cause significant damage in a single sorghum production area. Using the terminology described by Young and Teetes (1977), these pests are characterized as key, secondary, or occasional. The key pests are perennially serious and persistent species which usually require deliberate human intervention to prevent significant yield losses; secondary pests are usually nondamaging unless a disruptive agronomic tactic is used; and occasional pests cause damage only in localized areas in some years.

Biological control should be considered as at least part of the regional solution for most key pests of sorghum. However, it is also true that biological control generally solves only one or several pest problems of a given crop within a given area. Thus, it is not a panacea for controlling all pests of sorghum in all sorghum-producing areas. The possible role(s) for biological control in a particular area can usually be evaluated in a relatively short period of time. The length of the evaluation period depends in part on how much is known regarding the pest, the cropping system ecology, and the natural enemies for utilization. However, because few entomologists are trained for biological control and these are even more scarce in sorghum research, most biological control programs in sorghum will usually start from very little or no previous knowledge.

Certain considerations are requisites for evaluating the role and for implementing a program of biological control, and these are particularly appropriate for programs on sorghum (Table 1). Requisite 1 deals with obtaining knowledge of the natural enemy diversity attacking the object pest and is a common ingredient to all three types of biological control. Samples of all predators and pests, including immature stages of pests, are regularly collected from study plots to survey the diversity of enemy species and their temporal phenologies. It is particularly important that these study plots be continued without interruption for several cropping seasons, that crop residues be left intact for at least part of the studies, and that these studies include "weedy" plants hosting the pest.

This study continuity is needed because destruction of sorghum residues often also destroys natural enemies with the residues. Pests of sorghum actually function in a permanent ecosystem, and the sorghum crop is only part of this ecosystem. The biological control specialist focuses on the sorghum pest and its natural enemies in the context of the *whole* ecosystem. The study area should be comprised of plots which can be sampled well after the normal time for harvest; ideally, until after the cropping cycle is reinitiated the following season.

Requisite 2 is a review of agronomic or other crop

Table 1. Requisites for proper conduct of biological control.

Biological control requisite	Biological control tactic[1]		
	Importation	Conservation	Augmentation
Ecosystem description			
1. Identify extant enemy species attacking object pest	+	+	+
2. Review production practices that may limit enemy efficiency	+	+	+
Biological control tactic application			
3. Identify enemies of same/related pest occurring elsewhere	+ -		-
4. Modify agroecosystem for effect on enemies	-	+	-
5. Determine if excess enemies can control pest	-	-	+
6. Calculate if enemy production is cost effective	-	-	+

1. + = studies for this requisite are complete and results were positive; - = studies complete and results were negative.

production practices which may be adversely affecting natural enemy efficacy. These studies examine possibilities for manipulating the sorghum crop to avoid the adverse effects and enhance the impact of the natural enemies.

Having established the species diversity of natural enemies and estimated their potential efficacy when operating in a permanent ecosystem, the next step is to establish which of the biological control action tactics the project should pursue.

Requisites 3-6 (Table 1) consider which of the three types of biological control is likely to be most efficacious. Where new natural enemies are imported, the identification of pest and natural enemies (Requisite 1) provides access to the taxonomic and biological literature on the pest and its natural enemies, or the near relatives of each. These identifications also permit access to literature regarding pest and natural enemy geographic distribution. If the pest (or a near relative) occurs in other parts of the world, additional natural enemies are probably available for importation from these areas (Requisite 3).

Where biological control by conservation is to be used, the primary concern should be to establish that the enemy can be efficacious when man does not interfere (Requisite 4). This step is essential for conservation, for what is the value of conserving enemies that cannot contribute significantly to control of the pest? Requisite 4 studies should also suggest adjustments in the timing or extent of sorghum crop residue destruction which can significantly conserve important extant natural enemies. The studies should suggest whether alternate host plants, especially wild plants, contribute significantly to the ecological continuity needed for survival of natural enemies. If insecticides are commonly applied to sorghum during production, studies for Requisite 4 should establish the effects of these on potentially important natural enemies. Simple screening studies can identify insecticides and application rates that are least toxic to key natural enemies operating in the agroecosystem.

For biological control by augmentation, the options are generally more expensive and labor-intensive. Additional natural enemies may be produced in laboratory facilities or in outdoor nurseries. However, it would do little good to release an enemy that is nonefficacious even when it is present in astronomical numbers. Thus if augmentation is anticipated, studies for Requisite 5 should establish for certain that a numerically augmented enemy can be effective when not limited by reproductive capacity. Furthermore, Requisite 5 studies must establish the numbers of enemies needed per unit area and the most effective method of distributing the enemies. Clearly, effective biological control by augmentation requires more study than either importation or conservation.

A last point is that the costs of conserving or augmenting natural enemies should be more than offset by the improved production (Requisite 6). Generally, the greater the monetary value or input to a crop, the more likely that such biological control can be cost-effective; otherwise, importation is the proper tactic for incorporating biological control.

According to Hagen et al. (1976), biological control of arthropods attacking grain, forage, and range crops has been seldom attempted; they explain this as a function of the ephemerality of the agroecosystem. Actually, this is not the total explanation. Most biological control effort and attention has historically been devoted to perennial crops, usually tree ecosystems where established natural enemies are constantly in association with their host (pest) all year round. Such ecosystems are fairly permanent, in contrast to grain, forage, or range crops. Hagen et al. (1976) characterized these ephemeral crops as "not the ideal ecosystem in which to attempt...biological control." I disagree categorically.

In fact, these *crops* are not the ideal ecosystem for biological control, but then these crops are not the total ecosystem in which the pest and natural enemies survive. Both the pest and its enemies typically maintain themselves from year to year because they typically occupy plants *outside* the cropping system during the period when the crop is unavailable. Thus, it is absolutely imperative to realize and study the real ecosystem for the pest and its enemies before attempting to optimize the interaction between them. Too many researchers in biological control have been philosophically constrained by the relative simplicity of the perennial ecosystems where most biological control successes have been recorded. Researchers have been discouraged because they expect to see a perennial ecosystem and fail to see that the real ecosystem of the ephemeral crop pest includes a population outside the crop. The result has been that very little energy has been devoted to biological control of grain, forage, or range crop pests, particularly in sorghum. Once the true perenniality of the annual crop agroecosystem is addressed, the considerable prospects for biological control in these crops become obvious and exciting.

We have worked for about 3 years on biological control of the Banks grass mite (BGM), *Oligonychus pratensis* (Banks) (Acarina:Tetranychidae), on Texas sorghum. A brief description of this work illustrates the progression of events for Requisites 1 -6, and describes how biological control should be conceptualized in dealing with pests of annual crops. Figure 1 illustrates what we know about the *real* ecosystem for BGM. The plants commonly occupied by BGM include sorghum, wheat, corn, and Johnson grass (*Sorghum halepense* L). The crop hosts in all cases are completely destroyed after harvest, thus disrupting the interaction between BGM and its natural enemies. Johnson grass, however, is a weedy host providing a habitat

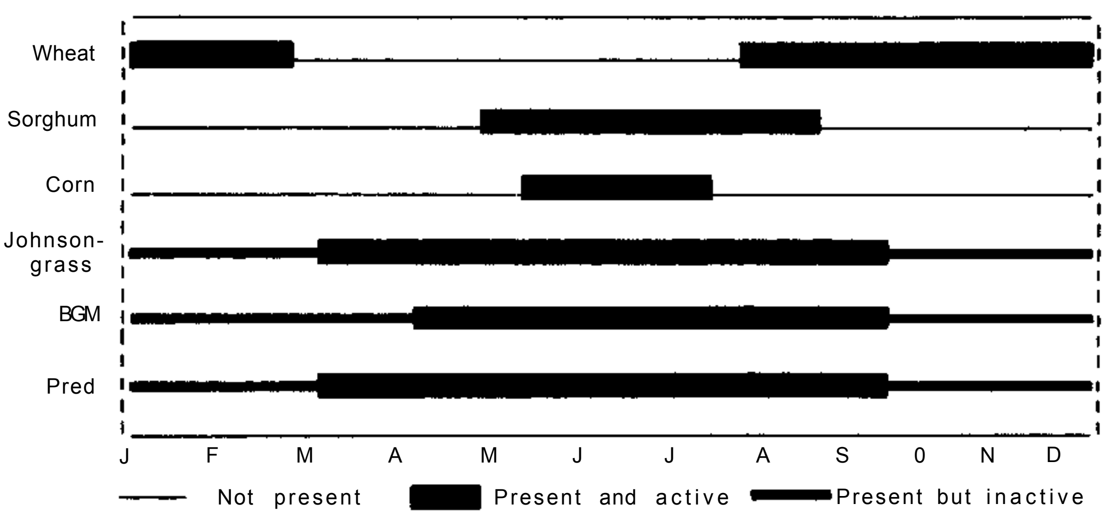

Figure 1. The ecosystem and phenology of the Banks grass mite (BGM) *Oligonychus pratensis,* its host plants, and a phytoseiid predator (PRED), *Amblyseius scyphus,* in West Texas.

with temporal continuity and arthropods occupying this habitat are not unnaturally disrupted (Fig. 2). The BGM and its predators occupy undisturbed stands of Johnson grass year after year without man's influence.

Our first task was to discover the phenology of BGM and its enemies on Johnson grass and on sorghum. We learned in our initial studies that BGM is attacked by a phytoseiid predator, *Amblyseius scyphus* Schuster and Pritchard, and that this predator is present in most stands of Johnson grass. Johnson grass is a year-round host providing undisturbed overwintering habitat for BGM and its predators.

Each year BGM and its natural enemies opportunistically leave this host to occupy sorghum (Fig. 3). BGM invaded sorghum very early in the season and occupied 100% of the plants before day 75, whereas it was not until about day 90 that the predator occupied even 50% of the available sorghum plants. Successful invasion of sorghum is ecologically simplified for BGM, as its food (e.g. sorghum) is regularly spaced, planted in relatively large fields, and is generally well cared for. However, the phytoseiid predator dispersing into sorghum does not possess such advantages. The predator's food source (BGM) in the spring is generally widely scattered through the sorghum. BGM begins feeding and reproducing nearly anywhere it lands in the field, whereas the predators must first find the BGM to sustain themselves before they begin reproduction. As the season progresses, more and more predators invade the field and those that succeed in finding BGM also survive to feed and reproduce. A relatively uniform distribution of predators eventually occurs in part because a few predators successfully establish in the field early in the season and in part because they move to new food sources (BGM) as prey become more uniformly distributed with the passage of time. These two processes act together, improving the odds of an encounter between predator and BGM.

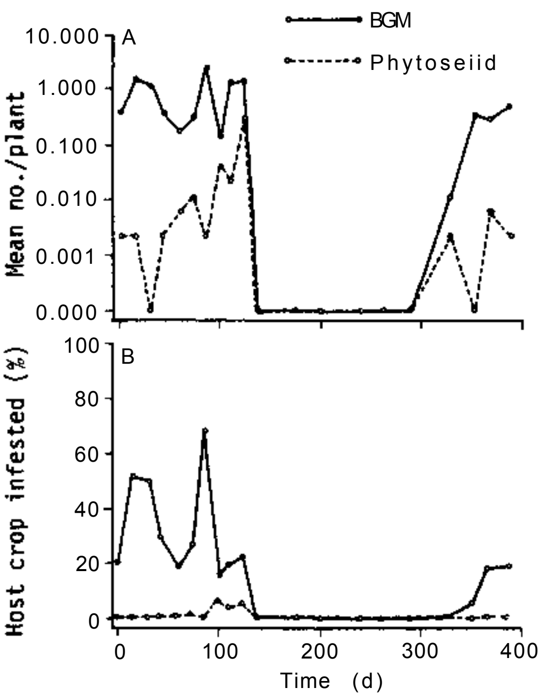

Figure 2. The population dynamics of the Banks grass mite (BGM), *Oligonychus pratensis,* and its phytoseiid predator, *Amblyseius scyphus,* on Johnson grass in West Texas.

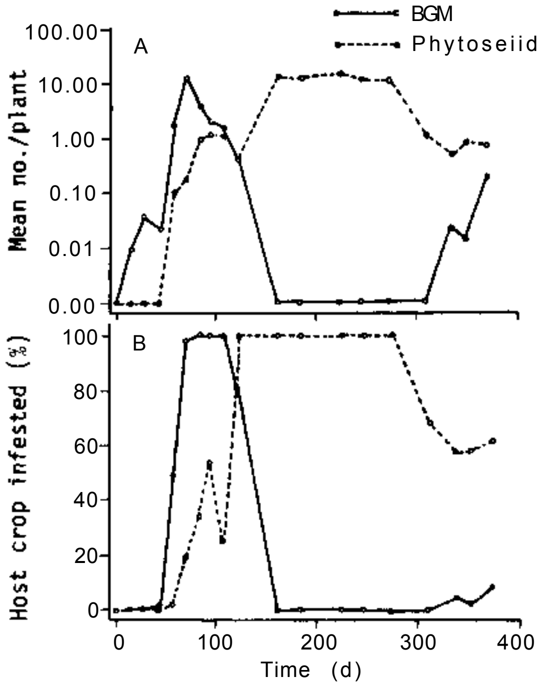

Figure 3. The population dynamics of the Banks grass mite (BGM), *Olygonychus pratensis,* and its phytoseiid predator, *Amblyseius scyphus,* in West Texas in plots where sorghum stalks were left standing after harvest. Samples consisted of sorghum leaf blades only prior to 1, of area beneath sorghum leaf sheaths after 1, and of wheat and Johnson-grass whorls after 2.

Sorghum in West Texas is typically harvested in the late summer or early fall (at about 120 days post-planting), the residues are destroyed, and BGM and its predators are eliminated from the field. The scenario must then repeat itself next year, hopefully, with the predators moving into the field early enough to prevent an outbreak of BGM. We harvested our plots on day 110, and then left the postharvest sorghum plants in the field for overwintering habitat. Because we could find no predators on the leaves, we began tearing apart the plants. We discovered that nearly 20 predators per plant were overwintering in the dead stalks (Gilstrap et al. 1979). The phytoseiids overwintered on the dead sorghum stalks and then moved naturally to the volunteer wheat and Johnson grass of the following season. If a sorghum crop had been available the following spring, it is almost certain that the predators would have transferred just as easily to the new sorghum. Assuming that the phytoseiid can be an efficacious control for the BGM, it would already be well distributed in the field very early in the season and thus able to exert a control capability before the BGM increases substantially.

By providing an overwintering habitat, we duplicated the essence of the interaction between BGM and *A. scyphus* on Johnson grass. Habitat continuity in the sorghum field conserved the predator's numbers and maintained their distribution across the field for the next year's BGM population. Several cultural modifications could accomplish this effect in commercial sorghum, including leaving sorghum stalks at periodic intervals across a field, leaving outside rows of sorghum stalks standing through the winter, collecting sorghum stalks in the fall, and redistributing them across the next season's sorghum seedlings, providing a noncrop overwintering host plant, etc. The objective would be to take advantage of a useful predator's prior season numbers and distribution, thus promoting control of BGM by the predators.

Our next step was to study exotic predators which had potential for controlling BGM: *Phytoseiulus persimilis* Athias-Henriot and *Amblysieus califomicus* (McGregor). We decided initially to evaluate augmentative releases of these predators as we did not know if they could overwinter on the Texas High Plains, and even if they overwintered, we did not expect they could invade the sorghum crop early enough to be efficacious (i.e, because of our previous studies with *A. scyphus).* The predator releases were made at the rate of about five predators per plant when spider mites were present at a density of about one per plant.

Results of the studies showed that either *Amblyseius californicus* or *Phytoseiulus persimilis* can be efficacious in controlling BGM (Pickett and Gilstrap, unpublished data). At present we are preparing to test several methods of making releases of these exotic predators on a commercial scale. When all of our BGM biological control studies are complete, we will have evaluated the dominant indigenous predators and ways to conserve them, and have evaluated and developed methodology for augmentative releases of exotic predators. All of these studies are needed to establish a scientific basis for an IPM specialist to incorporate biological control tactics into a crop protection strategy, whether the tactic is importation, conservation, or augmentation. These same types of studies are needed for numerous pests of sorghum, both in developed and subsistence agriculture.

The major arthropod pests of sorghum were described by Young and Teetes (1977) (see Table 2) and their major pest status was reaffirmed by Gahukar (1981), Davies (1982), and Seshu Reddy (1982). In my view, each listed pest should be the object of a major biological control effort. Each pest is also characterized in Table 2 by my evaluation of the current status of biological control understanding, the probable role for biological control, and the biological control tactic most likely to be useful.

Control of aphids by natural enemies has had an excellent record of success. *Schizaphis graminum* (Rondani) in the USA has been the focus of an enemy importation program since 1969, but has yet to be controlled via exotic parasites (Gilstrap et al. 1984). Conservation of extant natural enemies is often sufficient for control (Kring 1984), especially when the sorghum crop consists of a variety resistant to S. *graminum* damage (Teetes 1982). Numerous additional enemies of S. *graminum are* known (Gilstrap 1980) and should be transported to and established in all areas where S. *graminum* is a pest.

Sipha flava (Forbes) is occasionally a serious pest and is also something of a biological control curiosity because apparently few parasites attack it. Most reported enemies of S. *flava are* members of the Coccinellidae (Gilstrap 1980) which are general aphid feeders. Thus the probability of biological control for this pest seem low because of the apparent paucity of enemies attacking it. *Aphis sacchari* (Zehntner) is also an occasional pest with few reported natural enemies (Gilstrap 1980) and it also has received little concerted attention for bio-

Table 2. Selected insect pests of sorghum and the prospects for their biological control.

Pest type/scientific name	Geographical distribution[7]	Pest status	Biological control: Status/Requisite[2] 1 2 3 4 5 6	Prospects[5]	Type[4]
Aphid					
Schizaphis graminum	COS	Key	+ + + + - -	E	I,C
Sipha flava	NW	Occasional	? ? ? ? ? ?	?	I,C
Aphis sacchari	AF,AS	Occasional	? ? ? ? ? ?	E	I,C
Shoot fly					
Atherigona spp	AF,AS	Key	+ ? + ? ? ?	?	?
Stem borer					
Chilo partellus	AF,AS	Key	+ ? + ? ? ?	E	I,C
Diatraea grandiose/la	NW	Occasional	+ ? + ? ? ?	E	I,C
Diatraea saccharalis	NW	Occasional	+ ? + ? ? ?	E	I,C
Eldana saccharina	AF	Occasional	? ? + ? ? ?	E	I,C
Busseola fusca	AF	Occasional	? ? + ? ? ?	E	I,C
	EE	Occasional	? ? + ? ? ?	E	I,C
Sorghum midge					
Contarinia sorghicola	COS	Key	+ ? + ? ? ?	P	I,C
Head bug					
Calocoris angustatus	AS	Key	? ? ? ? ? ?	?	?
Nysius raphanus	NW	Occasional	? ? ? ? ? ?	?	?
Dysdercus susperstitiosus	AF	Occasional		?	?
Leptoglossus phyllopus	NW	Occasional		?	?
Pentatomidae	COS	Occasional	? ? ? ? ? ?	P	I
Spider mite					
Oligonychus spp.	NW,AS	Secondary	+ + + + + +	E	I,A
Armyworm	AF, NW, AS,0	Occasional	+ ? + ? ? ?	P	C,I

Source : Young and Teetes (1977).
1. COS = Cosmopolitan, AF = Africa, EE = Eastern Europe, NW = New World, AS = Asia, 0 = Oceania.
2. Requisites described in Table 1 ; + = studies for this requisite started, results positive; - = studies at least started, results negative; ? = studies not yet done.
3. E = Excellent, P = Possible.
4. I = importation, C = conservation, A = augmentation, and ? = unknown.

logical control.

Because these three aphid species function in similar agroecosystems, the conceptual approaches for their biological control should be similar. Though historically the ideal parasites have often been host-specific, parasites collected for control of any one of these aphids should also be tested for their capability to attack the other two species.

Sorghum shoot flies, *Atherigona* spp, are key pests of sorghum in Asia and Africa. Very few references are available on natural enemies for *Atherigona spp,* though several parasites are known (Seshu Reddy 1982), Though shoot flies have been studied on alternate host plants (Granados-R 1971), intensive studies are lacking, especially on shoot fly parasites on wild host plants. Thus, parasite diversity has not been sufficiently examined and parasitism may be far more common than currently thought.

A survey of natural enemies attacking shoot fly on sorghum and its other host plants is essential to accurate assessment of biological control potential. Because several species of *Atherigona* occur in different parts of the world, importation is a possibility. It may also be possible to gain significant benefit from conservation of natural enemies by managing these enemies in wild hosts. Ignoring economics for a moment, augmentation of enemies by laboratory production may also offer some benefit. First, however, intensive efforts are required on Requisites 1 and 2; until these are met, biological control oi*Atherigona* is unlikely and prospects cannot be accurately assessed.

Stem borers are widely distributed and well known for biological control success. Though the greatest success has been on *Diatraea sacchara-//s*, the general level of understanding for stem-borer ecology and parasite activity is quite good. Regardless, none of the listed stem borer species has been studied sufficiently to evaluate biological control by conservation or by augmentation. Except for *D. grandiosella* (Dyar) and *Eldana saccharina* Walker, each of the listed species is reportedly attacked by numerous species of parasites (Gilstrap 1980). Biological control by importation of exotic parasites is an ideal prospect for controlling at least some of these stem borers. A major effort should be undertaken to exchange parasites of these pests on a global basis.

The sorghum midge, *Contarinia sorghicola* (Coquillett), is a sorghum pest with a cosmopolitan distribution, and very little is known regarding natural enemies. Studies of enemies attacking this pest on wild host plants are rare and of particular importance to biological control. Also, the reported diversity of enemy species is quite limited (Gilstrap 1980). It is almost certain that additional parasite species exist, but only an intensive taxonomic effort on these parasites can resolve this issue. An accurate assessment of biological control potential must await further work on Requisites 1 and 2.

Natural enemies of the hemipteran head bugs as a group have also been insufficiently studied (Seshu Reddy 1982). An encouraging note is that ait least one prior example of successful biological control is reported for a pentatomid pest of numerous annual crops in Hawaii (Davis 1967). Similar success may be possible on sorghum for other species of Hemiptera. However, an accurate assessment of biological control potential must await further work on Requisites 1 and 2.

Spider mites are excellent candidates for biological control. They support a diverse group of natural enemies and these enemies tend to be nonspecific for prey species. The most studied and effective natural enemies are often phytoseiid mites, and these are easily transported to areas where mite problems are serious. Preliminary results indicate that these predators can be used effectively via augmentation, though the circumstances for cost-effectiveness are not yet established.

Armyworms are widely distributed and typically support a diverse fauna of parasites (Gilstrap 1980). Because armyworms are polyphagous, the entomologists interested in their biological control must look at hosts in the *whole* ecosystem of these pests. As with stem borers, armyworms should be the focus of a major program of global parasite exchange among all parts of the world where armyworms occur. The value of conservation or augmentation has not yet been thoroughly examined.

Summarizing prospects for biological control in sorghum, very few sorghum pests have been the objects of biological control study. Greenbug is certainly the most completely studied key pest in terms of utilizing natural enemies by conservation. We know that augmentation of greenbug enemies is not economically feasible at present and that conservation of extant enemies is an important aspect of greenbug control. We may be close to complete control of greenbug in the USA by imported parasites, and intensive efforts on this aspect are in progress. Spider mites are well studied for all types of biological control, and are also an excellent example of what is possible for other sorghum pests when properly studied. Sorghum midge parasites have been well studied in several parts of the world. The limitations for biological control of the sorghum midge are primarily the insufficiency of taxonomic understanding of midge parasites. The most promising early avenues for biological control of sorghum midge are by importation. However, better ecological understanding of these parasites will almost certainly be required for developed agriculture to obtain significant benefits by conserving midge parasites on alternate host plants. The stem borer parasites are relatively well known and importation of parasites should be pursued. However, stem borer parasites will also almost certainly require conservation efforts in order to obtain optimal benefit from them. Biological control of shoot fly is possible, but very little study is currently available. Essentially nothing is known of parasites attacking head bugs, and any assessment of biological control prospects on these pests must await parasite diversity studies.

Conclusions

As evidenced by discussions during this workshop, breeding sorghum resistant to various preharvest losses continues to receive tremendous emphasis. However, it is clear that breeding sorghum resistant to insects has distinct limitations, both in terms of species of insects for which resistance is a satisfactory unilateral solution and in terms of the numbers of identified sorghum lines in which arthropod resistance is available. Protection from sorghum losses in developing countries will continue to be incomplete without knowledgeable use of natural enemies of crop pests, i.e., biological control. To date, significant research efforts are essentially nonexistent in developing countries for controlling sorghum pests by importing, conserving, or augmenting efficacious natural enemies.

Biological control, placed in proper perspective, *is not* a panacea for controlling all pests of sorghum; however, it has a long history of successes and is ideally suited for selected pests of sorghum for the same reasons as is host-plant resistance. Biological control by importation in particular can be accomplished in the context of other important agronomic needs, is generally stable and dependable once developed, requires no specialized equipment or sophisticated understanding to use at the farm level, and is relatively inexpensive to use. Furthermore, successful biological control of arthropod pests is totally compatible with host-plant resistance and, in fact, can create an environment permitting effective use of lower levels of resistance.

The most significant obstacle to increased biological control of sorghum pests is the fact that very few educators and scientists are specifically trained to research and implement principles and action. Some of the greatest needs and most exciting opportunities for completely successful biological control exist in subsistence sorghum production. In my view, it is absolutely essential to emphasize in-depth biological control training for students from developing countries. These students' contributions to problem solving can be immediate if the degree research is conducted in the student's home country. Biological control in sorghum has real and important potential for significantly reducing preharvest losses in sorghum. We are verifying this in Texas, though slowly because of the paucity of researchers trained for such studies even in the USA.

The greatest promise for biological control in subsistence agriculture is from importing new species of natural enemies to control a particular pest. This method can be effective with little technology, and with limited or no understanding from producers. Even in high-technology agriculture, sorghum production can undoubtedly benefit from biological control by conservation and/or importation, and possibly from augmentation. In developing countries, where resources are particularly limited and the need for dependable food production is so great, biological control is essential.

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Recommendations

Recommendations

The following recommendations were derived from participants' discussions following each major paper presentation session. The recommendations are presented in a chronological sequence, starting with basic sorghum insect pest surveys, yield loss assessment, various possibilities for insect control tactics and integrated pest management systems for sorghum production areas worldwide.

Sorghum Insect Pest Surveys

Country surveys are necessary to assess the sorghum insect pest situation based on local agricultural production systems. Papers presented during the Regional/Country Reports (Session 2) gave a fairly comprehensive review of the major insect pests of sorghum in various regions of the world. From these, it is evident that the insect pest situation is certainly not a static one. Changing ecological conditions and the introduction of short-duration, high-yielding sorghum varieties susceptible to insect pests have increased the severity and spectrum of sorghum insect pests. For example, there has been a sharp increase in occurrence and severity *of* the sorghum midge and several species of panicle-feeding true bugs following the introduction of new sorghum varieties and hybrids.

It is therefore recommended that:

1. Surveys be conducted at regular intervals in all major sorghum-producing areas in order to assess likely changes in the sorghum insect spectrum.
2. The possibilities of the development of insect biotypes be monitored following the large-scale use of insect-resistant sorghum cultivars.

Assessment of Yield Loss due to Sorghum Insect Attack

A large proportion of the discussion focused on yield loss assessment and economic injury levels for the various sorghum insect pest species. The amount of crop yield loss caused by an individual insect is an indicator of its economic importance. It was apparent that quantitative yield loss data for many insect pests of sorghum do not exist. The lack of such data makes it difficult for administrators and researchers to decide objectively which insect pest species should receive research priority.

A second point of discussion related to the determination of economic injury levels. The importance of research to determine such levels was considered to be very important in terms of crop-loss assessment and as bases for the need for control. However, little research was being conducted in this vital area.

It is therefore recommended that:

1. Methodology for yield loss assessment should be improved so that such estimations could be made during insect pest surveys;
2. Trials on yield loss from insect pests be conducted in the various sorghum growing areas to obtain more quantitative data;
3. High priority be given to developing the methodologies necessary to quantify economic injury levels for each of the important sorghum insect pests in different ecological regions, wih entomologists, agronomists, and economists working closely together to design, conduct, and describe appropriate research.

Strategies for Sorghum Insect Control

The development of appropriate sorghum insect pest control strategies for the different sorghum-growing areas of the world should have a priority equal to breeding for higher yield. As mentioned by G.L. Teetes during Session 1, control strategies and methodologies used in developed countries are not necessarily directly applicable in developing countries. Depending on the insect pest, the agroecosystem, and the education and research standards of the country, methodologies for sorghum insect control must either be evolved within the country or be transferred from an appropriate source. In any case, as K. Leuschner said, control strategies and methods should be based as much as possible on traditional control practices.

Breeding Sorghum Resistant to Insects

Breeding for resistance to insects was considered to be a safe and inexpensive insect control method, highly applicable to small-farm conditions in the developing world. Research should be intensified to produce insect-resistant sorghum cultivars.

It is recommended that:

1. The collection and exchange of insect-resistant sorghum germplasm be intensified and liberalized;
2. Screening programs for identifying insect-resistant sorghums be developed in those countries which presently have none;
3. Insect-host relationships and behavior of the major sorghum insects be studied in greater detail to identify weak links that could be exploited to develop control strategies and resistance screening methodologies;
4. Resistance mechanisms be identified and detailed chemical analysis be carried out by, or contracted to, specialists in the area;
5. The inheritance of resistance be studied;
6. Plant breeders intensify their efforts to breed for insect-resistant and stable-yielding varieties and hybrids as these are likely to be more important than high, but undependable, yields.

Cultural Control

Cultural control methods were considered to have great potential, either alone or as one component in an integrated management system. A number of cultural control methods are currently used by farmers, such as early planting to avoid shoot fly in India and sorghum midge in the USA.

It is recommended that:

1. Traditional control practices be studied in more detail to enhance their direct use, or their use in a modified form;
2. Special emphasis be placed on crop maturity duration, time of planting, crop hygiene, and improved agronomic practices as factors that reduce insect density.

Biological Control

Natural enemies of sorghum insect pests are considered to contribute significantly to overall insect pest mortality. To what extent biological control can be used in sorghum is yet to be fully determined, but the paper on biological control presented an optimistic outlook. There was general agreement that everything possible should be done to keep natural enemy density as high as possible.

It is recommended that:

1. The natural enemy complex of sorghum insect pests be identified and their efficacy determined;
2. Factors influencing the biology, ecology, and behavior of key natural enemies be researched in relation to cropping systems;
3. Simple strategies such as suitable cropping systems and beneficial wild hosts be developed to increase natural enemy density;
4. The effectiveness of exotic natural enemies be determined especially for such pests as sorghum stem borers.

Chemical Control

It was realized that chemical control of sorghum insect pests is, in 'some areas, the backbone of insect control. However, the need is for insecticide use to be kept at an absolute minimum for economic and safety reasons.

It is recommended that:

1. Research be intensified to develop strategies which allow for judicious insecticide use and discourage prophylactic spraying;
2. Recommendations for when and how to spray be developed.

Development of Integrated Sorghum Insect Pest Management Systems

The group realized that integrated pest management systems must be developed for sorghum, as for other crops. Notable progress has already been made in the USA, but less in developing countries. The greenbug and sorghum midge programs in the USA could be used as models on which to base management systems for other insect pests in other countries. It should be realized that experience and technology can only be transferred to a certain extent.

It was therefore recommended that sorghum entomologists stay in close contact with each other in order to exchange ideas and research results. Integrated pest management strategies should then be based on the technical standards and capabilities of each country.

The International Sorghum Entomology Workshop was a significant and successful activity that surely promoted a spirit of collaboration among sorghum entomologists and other disciplines (such as breeders) concerned with sorghum improvement throughout the sorghum-growing world.

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