Integrated Pest Management Research at ICRISAT

Present status and future priorities

International Crops Research Institute for the Semi-Arid Tropics

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Abstract

Crop productivity in the semi-arid tropics (SAT) has almost remained static over the past three decades. While potential yield of the ICRISAT mandate crops (sorghum pearl millet, pigeonpea, chickpea, and groundnut) is between 5 to 10 tons ha^{-1}, the actual yields only range between 0.5 to 1.5 tons ha^{-1}. The huge gap between the potential and actual yields can, for the most part, be attributed to the losses caused by insect pests and diseases (currently valued at over US$ 7.4 billion annually). Over 1,000 species of insect pests, fungal pathogens, viruses, and *Striga* cause damage to ICRISAT mandate crops. ICRISAT's research in this area is focused on pest problems that are globally important, such as pod borers (*Helicoverpa, Maruca*, and *Melanagromyza*), Fusarium wilt, and sterility mosaic in pigeonpea; *Helicoverpa*, Wilt, Ascochyta, and Botrytis gray mold in chickpea; Rosette virus, foliar diseases, Aflatoxins, and leaf miner in groundnut; *Striga*, grain molds, shoot fly, stem borers, midge, and head bugs in sorghum; and downy mildew, stem borer and head miner in pearl millet. The major components of integrated pest management (IPM) research are host-plant resistance, natural plant products, bio-pesticides, natural enemies, and agronomic practices. Modern biotechnological tools such as marker assisted selection, genetic engineering, and wide hybridization are also being used to develop crop cultivars with resistance to important insect pests and diseases. IPM promotion and capacity building are also of significant importance at ICRISAT.

Integrated Pest Management Research at ICRISAT: Present status and future priorities

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Introduction

In most developing countries, agriculture is the driving force for broad-based economic growth; and low agricultural productivity is a major cause of poverty, food insecurity, and malnutrition. Accelerated public investments are needed to facilitate agricultural growth through high-yielding varieties with resistance to biotic and abiotic stresses, environment-friendly production technologies, availability of reasonably priced inputs in time, dissemination of information, improved infrastructure and markets, and education in basic health care. The use of high-yielding varieties, irrigation, fertilizers, and pesticides has increased crop productivity five-fold in the past five decades. However, growth has been leveling off in the past two decades. Land and water resources are diminishing; there is no option but to increase crop productivity per unit area. There is a need to examine how science can be used to raise biological productivity without the associated ecological costs. Some productivity increase can be achieved through the application of modern biotechnology tools in integrated gene management, integrated pest management, and efficient post-harvest management. Biotechnology in agriculture and medicine can be a powerful tool to alleviate poverty and improve the livelihoods of the rural poor.

Insect pests, diseases, and *Striga* are serious constraints to production, productivity, and utilization of ICRISAT mandate crops (sorghum, pearl millet, chickpea, pigeonpea, groundnut) in the semi-arid tropics (SAT) (Table 1). Crop losses due to these pests have been estimated at over US$ 7.4 billion annually. While *Helicoverpa* control is heavily based on insecticides, chemical control of shoot and panicle feeding insects on cereals is beyond the reach of resource-poor farmers in the SAT regions in Asia, Africa, and Latin America. Current sensitivities about environmental pollution, human health, and pest resurgence are a consequence of improper use of synthetic pesticides. Host plant resistance, natural plant products, biopesticides, natural enemies, and agronomic practices are potentially viable options for integrated pest management (IPM). They are relatively safe for non-target organisms and human beings. Biotechnological tools such as marker-assisted selection, genetic engineering, and wide hybridization to develop crop cultivars with resistance to insect pests and diseases will play a key role in future pest management programs. Insect and disease modeling, decision support systems, and remote sensing could contribute to up-scaling and dissemination of IPM technologies.

ICRISAT's current research in biotechnology, crop improvement, and natural resource management focuses on the major pests:

- pod borers (*Helicoverpa*, *Maruca*, *Melanagromyza*), fusarium wilt and sterility mosaic in pigeonpea
- *Helicoverpa*, wilt, ascochyta and botrytis gray mold in chickpea
- rosette virus, foliar diseases, aflatoxins and leaf miner in groundnut
- *Striga*, grain molds, shoot fly, stem borers, midge and head bugs in sorghum
- downy mildew, stem borer and head miner in pearl millet.

IPM promotion and capacity building of partners are significant components of our work. Tables 2 and 3 list the important insect pest and disease problems affecting ICRISAT mandate crops in the SAT. Table 4 shows the key pest problems that need immediate attention, and the potential of different research interventions for managing these pests. The current and future areas of research on insect pests and diseases are outlined below.

IPM Research at ICRISAT: Progress

Considerable progress has been made in the past in developing resistance screening techniques, identifying sources of resistance and transferring resistance genes into high-yielding, improved and agronomically superior genetic backgrounds (Table 5).

Table 1. Losses due to major insect pests and diseases in ICRISAT mandate crops

			Potential yield gain ($ million)		
				Management	
Crop	Constraint	Yield loss ($ million)	Crop improvement	CI	RM
Sorghum	Stem borer	334	124	126	
	Midge	292		109	106
	Striga	153	83	56	
	Shoot fly	274	102	102	
	Head bug	198	38	38	
	Grain mold	129	121		
	Total biotic	**1714**	**795**	**428**	
Pearl millet	Downy mildew	134	118		181
	Head caterpillars	116	28	45	
	Stem borer	91	18	27	
	Striga	121		121	
	Total biotic	**462**	**164**	**193**	
Chickpea	Helicoverpa	328	164		
	Ascochyta blight	248	129		
	Wilt	218	109		
	Botrytis gray mold	33	13		
	Total biotic	**1137**	**540**		
Pigeonpea	Fusarium wilt	193	97		20
	Sterility mosaic	290	202		15
	Helicoverpa	317	137	137	34
	Maruca	30	16		
	Pod fly	256	60	85	
	Total biotic	**1324**	**573**	**253**	**167**
Groundnut	White grub	107		49	43
	Late leaf spot	599	300		255
	Rust	467	242		27
	Early leaf spot	326	82		140
	Leaf miner	164	82	66	
	Aflatoxins/termites	371	62	202	
	Spodoptera	97		32	
	Rosette/clump virus	194	143		
	Bud necrosis virus	89	45		
	Total biotic	**2754**	**1062**	**427**	**741**

CI = Crop improvement, RM = Resource management
Source: ICRISAT medium term plan, 1992

Table 2. Important insect pests of ICRISAT mandate crops, and potential interventions

Insect species	Distribution	Agronomic practices	Biocontrol	HPR CPB	WH	MAS	GE	Chemical control
Sorghum								
Shoot fly	Asia, Africa	**	x	***	**	***	**	**
Stem borer	Asia, Africa	*	**	**	**	**	***	**
Midge	Asia, Africa	*	*	***	**	***	x	*
Head bug	Asia, Africa	x	x	**	x	*	x	**
Chickpea								
Helicoverpa	Asia, Africa	*	**	**	***	**	***	***
Pigeonpea								
Helicoverpa	Asia, Africa	*	**	**	***	*	***	**
Maruca	Asia, Africa	x	x	*	x	x	*	*
Pod fly	Asia, Africa	x	x	**	x	x	x	*
Groundnut								
White grubs	Asia, Africa	*	*	x	x	x	x	**
Defoliators	Asia	*	**	*	**	x	x	***
Thrips/vectors	Asia	x	x	**	**	x	x	***
Pearl millet								
Stem borer	Africa	*	*	*	x	x	**	*
Head miner	Africa	*	*	*	x	x	**	**

HPR = host plant resistance, CPB = conventional plant breeding, WH = wide hybridization, MAS = marker-assisted selection, GE = genetic engineering
x = No potential *, **, *** = Low, medium, and high potential respectively

Table 3. Important diseases of ICRISAT mandate crops, and potential interventions

Disease	Distribution	Agronomic practices	Biocontrol	HPR CPB	WH	MAS	GE	Chemical control
Sorghum								
Grain molds	Asia, Africa	*	x	*	x	*	*	*
Leaf diseases	Asia, Africa	*	x	**	x	**	x	*
Striga	Asia, Africa	***?	x	**	x	**	x	**
Pearl millet								
Downy mildew	Asia, Africa	*	x	***	x	***	*	**
Ergot	Asia, Africa	*	x	**	x	*	x	x
Smut	Asia, Africa	x	x	**	x	*	x	x
Striga	Asia, Africa	***	x	*	x	*	x	*
Chickpea								
Wilt	Asia	*	*	***	*	***	x	*
Ascochyta blight	Asia, Africa	*	*	**	**	**	*	**
Botrytis gray mold	Asia	*	*	**	**	**	*	**
Pigeonpea								
Wilt	Asia, Africa	*	*	***	x	**	x	*
Sterility mosaic	Asia	*	x	***	x	*	x	*
Groundnut								
Foliar diseases	Asia, Africa	x	x	***	***	**	x	***
Aflatoxin	Asia, Africa	**	**	*	*	*	*	*
Rosette	Africa	*	x	**	x	x	**	**
Stem necrosis	Asia	x	x	**	x	x	**	**

HPR = host plant resistance, CPB = conventional plant breeding, WH = wide hybridization, MAS = marker-assisted selection, GE = genetic engineering
x = No potential *, **, *** = Low, medium, and high potential respectively

Table 4. IPM research at ICRISAT: potential for future research

	Agronomic practices	Biocontrol	HPR	WH	MAS	GE	Chemical control	IPM module
Sorghum								
Shoot fly	*	*	***	**	***	*	*	*
Stem borer	*	**	**	**	**	***	*	**
Grain molds	x	x	**	x	x	x	x	*
Striga	**	x	**	x	**	x	*	***
Pearl millet								
Downy mildew	*	x	***	x	***	x	*	*
Striga	**	x	*	x	**	x	*	***
Chickpea								
Helicoverpa	**	**	**	***	**	***	**	***
Wilt	x	x	***	x	***	x	x	*
Ascochyta blight/Botrytis gray mold	**	*	**	*	**	*	*	**
Pigeonpea								
Helicoverpa	**	**	**	***	*	***	**	***
Wilt	x	x	***	x	*	x	x	*
Sterility mosaic	*	x	***	x	x	x	x	***
Groundnut								
White grubs	*	*	*	**	x	**	**	***
Leaf miner	x	**	*	*	x	x	*	**
Aflatoxin	**	*	*	*	x	*	x	***
Leaf diseases	x	x	***	***	**	x	**	***
Rosette, stem necrosis	*	x	**	x	x	**	**	**

HPR = host plant resistance, WH = wide hybridization, MAS = marker-assisted selection, GE = genetic engineering
x = No potential *, **, *** = Low, medium, and high potential respectively

Table 5. Screening techniques, genetic information and material generated at ICRISAT with a potential for IPM in the semi-arid tropics (one example from each crop for insect /pathogen)

	Screening techniques	Resistance source/ released cultivar	Mechanisms/ inheritance
Sorghum			
Shoot fly	Infester rows, cage technique	IS 18551 / ICSV 705	Leaf glossiness and trichomes. Additive gene action. QTLs linked to shoot fly resistance identified
Grain mold	Sprinkler irrigation	IS 14332 / SPV 801	Tannins, anthocyanins, grain hardness
Pearl millet			
Downy mildew	Infector rows, greenhouse inoculation	ICML 12 / WC-C 75	Oospore germination and penetration
Head miner	Field screening, artificial infestation	Ex-Bornu / IBMV 8001	Panicle compactness
Chickpea			
Wilt	Sick plot, indicator rows	WR 315 / ICCV 10	Major genes
Helicoverpa	Field screening, cage and detached leaf assay	ICC 506 / ICCV 10	Oxalic and malic acids. Additive gene action
Pigeonpea			
Wilt	Field screening	ICP 8663 / ICPL 8563	Major genes
Helicoverpa	Field screening	ICP 7203-1 / ICPL 332	Trichomes, flavonoids
Sterility mosaic	Infester rows	ICP 7870 / ICP 7035	-
Groundnut			
Late leaf spot	Infector rows	ICG II337 / ICGV 86590	Delayed incubation
Aflatoxins	Field screening, seed colonization	ICG 11682 / ICGV 91278	-
Spodoptera, leaf miner	Field screening, artificial infestation	NCAc 343 / ICGV 86031 ICGV 99016 / ICGV 86590	Antibiosis. trichomes, and leaf glossiness

Additional information may be found in annual reports and journal / conference papers

Development of screening techniques

- Infester row techniques to screen for resistance to sorghum shoot fly, sorghum midge and head bugs
- Artificial field infestation techniques to screen for resistance to stem borer in sorghum and *Helicoverpa* in chickpea
- No-choice cage, leaf disc and detached leaf assays to screen transgenic plants and map populations for resistance to stem borer, shoot fly and *Helicoverpa*
- Artificial diet impregnation assay to screen for resistance to stem borer, *Spodoptera* and *Helicoverpa*
- Controlled environment, greenhouse and field screening techniques refined for grain molds, downy mildew, foliar diseases and charcoal rot in sorghum
- Screening methodologies for resistance to *Striga* have been refined
- Screening method for *in vitro* seed colonization, field and screenhouse methods for seed infection and aflatoxin contamination by *Aspergillus flavus* in groundnut have been refined
- Growth room screening techniques and field screening at hot-spot locations for botrytis gray mold (BGM) and ascochyta blight (AB) in chickpea have been standardized
- Field screening in wilt sick plot to identify resistance to fusarium wilt in chickpea and pigeonpea, and sterility mosaic virus (SMV) in pigeonpea have been developed
- Greenhouse capabilities have been developed to screen for resistance to stem rot and crown rot diseases of groundnut.

Identification and utilization of resistance sources

- Pearl millet male-sterile lines, restorers and F_1 hybrids with resistance to downy mildew *(Sclerospora graminicola)* have been developed, and are widely cultivated in India
- High levels of resistance to insect pests and pathogens have been identified in the wild relatives of groundnut, pigeonpea and sorghum
- Several pigeonpea lines with resistance to wilt and SMV have been identified and are widely used in India
- Several pigeonpea and chickpea lines with reduced susceptibility to *Helicoverpa* have been identified, and are cultivated in India
- Sources of resistance to groundnut foliar diseases are widely available and several resistant varieties have been released for cultivation
- Resistance sources to chickpea wilt have been incorporated into high-yielding cultivars
- Resistance to shoot fly, stem borer, midge and head bugs has been transferred into improved cultivars and male-sterile lines of sorghum; some midge-resistant varieties have been released for cultivation by the national research programs in Asia and Africa, Australia, USA, and by private seed companies.

Mechanisms and inheritance of resistance

- Resistance to sorghum midge is governed by additive gene action with some interaction with factors in the cytoplasm
- Resistance to groundnut rust and leaf spots in interspecific derivatives is a complex trait, resulting in delayed incubation and latent periods, and low pustule/lesion frequency, leaf area damage and percent defoliation
- Oviposition non-preference, antibiosis and tolerance are the major components of resistance to stem borer *(Chilo partellus)* in sorghum
- Resistance to *Helicoverpa* in pigeonpea, chickpea and their wild relatives is a function of oviposition non-preference, antibiosis and tolerance
- Resistance to BGM and AB have been identified in wild *Cicer* spp and are being incorporated into high-yielding chickpea lines.

It is well recognized that host plant resistance (HPR) contributes significantly to sustainable crop production and environmental conservation and is easily adopted by farmers. ICRISAT also has considerable experience in the development of management practices to reduce pest pressure and minimize losses due to insect pests and diseases.

Strategies for Integrated Pest Management

Several management practices have been developed and tested in farmers' fields. Farmers both in Africa and Asia have adopted components of IPM packages. Major successes, for example, have been reported in management of groundnut and chickpea foliar diseases, pod borer in legumes, and groundnut pests. Many farmers have tested management options to control groundnut rosette in southern and eastern Africa and western and central Africa, and achieved significant increases in yield. These technologies are currently being scaled up in Malawi. In pearl millet, HPR and seed dressing with metalaxyl has significantly reduced the incidence of downy mildew. This simple technology has helped increase millet yield and farmers' incomes in Mali. In India, many private seed companies treat pearl millet hybrid seed with metalaxyl to protect the crop from downy mildew and prolong the commercial life of hybrids. A combination of HPR and weather-based minimal fungicidal protection has led to the rehabilitation of chickpea in BGM-prone areas in Nepal, Bangladesh and India. IPM of BGM, which also includes management strategies for wilt and pod borer control, has been adopted by several thousand farmers in Nepal and Bangladesh. Integrated management of groundnut foliar diseases – combining HPR in high-yielding varieties (both short- and medium-duration) and economical use of fungicides (based on critical growth stage of the host and weather conditions) – has been validated with over 800 farmers in the states of Andhra Pradesh, Karnataka and Tamil Nadu in India.

Host plant resistance

HPR research will focus on a few key insect pests and diseases of our mandate crops in the following areas:

- identification of stable sources, understanding components and inheritance of resistance
- utilization of wild relatives as gene sources to increase the levels and diversify the bases of resistance
- exploitation of novel genes and molecular marker approaches for pest resistance
- development of varieties with improved yields and better resistance to the target pests.

HPR is a highly effective management option, but cultivated germplasm has only low to moderate resistance levels to some key pests and diseases. Increased resistance levels are required to minimize pest losses. Further, some sources of resistance have poor agronomic characteristics. Development of cultivars with enhanced resistance will strengthen the control of pod borers in legumes, stem borers in cereals, and aflatoxins in groundnut. Resistant cultivars will provide an equitable, environmentally sound, and sustainable pest management tool. Therefore, we need to make a concerted effort to transfer pest and disease resistance into genotypes with desirable agronomic and grain characteristics. Knowledge of the mechanisms and inheritance of resistance is critical. Gaps in our knowledge of mechanisms of resistance, diversity of resistance sources, and inheritance of resistance have limited our success in developing cultivars with desired levels of resistance. There is a need to identify genotypes with different mechanisms for use in breeding programs to develop genotypes with stable and durable resistance.

Several *Striga*-resistant sorghum genotypes have been identified. Different mechanisms of resistance were identified – low stimulant production by host roots, mechanical barriers in the host root physiology, antibiosis, avoidance through root architecture, and post-infection resistance. Various varieties have been characterized for these traits. These studies indicate the need for more multilocational on-farm testing and demonstration/promotion of available resistant cultivars in *Striga*-endemic areas. The relationships

between *Striga* infestation, infection and yield loss and the effect of host genotype on *Striga* parasitism and reproduction were studied for 4 to 10 genotypes in agar-gel, pot and field tests. *Striga* parasitism and reproduction, and *Striga*-induced yield losses, can be significantly reduced through crop/genotype choice. Maximum aboveground *Striga* number is a reliable selection measure for resistance. *Striga* flower stalk dry weight can be used to identify genotypes that reduce *Striga* reproduction. The maximum relative yield loss is a suitable selection measure for tolerance in susceptible genotypes, while for genotypes that are more resistant the relative yield loss per *Striga* infection seems more appropriate. For these tolerance measures, yield assessment of nearby uninfected controls is indispensable at present. But chlorophyll fluorescence, precise photochemical quenching and electron transport rate, may enable screening for tolerance without this requirement.

Wide hybridization

Levels of resistance to shoot fly, stem borer, and *Striga* in sorghum, aflatoxins and early leaf spot (ELS) in groundnut, BGM, ascochyta blight and *Helicoverpa* in chickpea, and *Helicoverpa* and *Maruca* in pigeonpea are low to moderate in the cultivated germplasm. Wild relatives of all four crops have shown high levels of resistance. There is also some evidence that wild and cultivated types have different resistance mechanisms. Genes from the wild relatives can be tapped through wide hybridization for use in crop improvement. Where hybrids of cultivated and wild species cannot be produced easily, techniques such as embryo rescue and somatic hybridization will be used. High levels of resistance have been observed in wild relatives of pigeonpea to *H. armigera* in *Rhynchosia aurea*, *R. bracteata*, C. *scarabaeoides*, C. *sericeus*, C. *acutifolius*, C. *albicans* and *Flemingia bracteata*. Of these, C. *scarabaeoides*, C. *sericeus* and C. *albicans* cross readily with pigeonpea and transfer of genes can be achieved by conventional crossing techniques. Wild chickpea species, C*icer bijugum*, C. *judaicum*, C. *pinnatifidium* and C. *cuneatum* have shown low susceptibility to *H. armigera*. Accessions belonging to *Arachis cardenasii*, *A. duranensis*, *A. kempff-Mercadoi*, *A. monticola*, *A. stenosperma*, *A. paraguariensis*, *A. pusilla* and *A. triseminata* in groundnut have shown multiple resistance to leaf miner, *Aproaerema modicella*, *H. armigera* and *Empoasca kerri*. Accessions belonging to *Sorghum laxiflorum*, *S. australiense*, *S. brevocallosum*, *S. dimidiatum*, *S. matarkense*, *S. nitidum*, *S. purpureosericeum*, *S. timorense*, *S. versicolor*, *S. angustum*, *S. ecarinatum*, *S. extans*, *S. interjectum* and *S. intrans* are highly resistant to sorghum shoot fly, *Atherigona soccata;* while *S. laxiflorum*, *S. australiense*, *S. brevocallosum*, *S. dimidiatum*, *S. matarkense*, *S. nitidum*, *S. purpureosericeum*. *S. timorense*, *S. versicolor*, *S. angustum*, *S. ecarinatum*, *S. extans*, *S. interjectum*, *S. stipoideum* and *S. intrans* showed high levels of resistance to spotted stem borer, C*hilo partellus*.

Development of genetically modified plants for resistance to insect pests and diseases

Breeding for resistance to biotic constraints such as *Helicoverpa armigera* in pigeonpea and chickpea, stem borers (C*hilo partellus* and *Busseola fusca*) in sorghum, ascochyta blight and BGM in chickpea, and *Aspergillus flavus*, rossette and stem necrosis viruses in groundnut has not been very effective. Application of biotechnological tools shows promise in alleviating some of these constraints. Genetic engineering of plants makes it feasible to transfer genes from totally unrelated organisms, breaking species barriers not possible by conventional genetic enhancement. Integration of genetic transformation technology with conventional plant breeding would be most rewarding. At ICRISAT, efficient transformation and regeneration of transgenic plants of groundnut, pigeonpea, chickpea and sorghum has been accomplished. The next phase of research on transgenics will involve the integration of transgenics into IPM strategies. The status of development of genetically modified plants in different crops against key target pests at ICRISAT is summarized in Table 6.

Table 6. Development of genetically modified crops at ICRISAT for resistance to insect pests and diseases

Crop	Constraint	Genes	Status
Groundnut	IPCV virus	Coat protein / Replicase	T4-T7 events field tested in 2002, 03, 04 and 05; 5/50 events selected so far
	GRAV virus	Coat protein	61 T3 events ready for testing in Africa
	PBNV virus	N-gene	24/48 T2 events being evaluated in greenhouse and contained field tests (2005)
	TSV virus	Coat protein	12 T1 events available
	Aflatoxins	Rice chitinase	3/30 T4 events under greenhouse testing
Pigeonpea	Pod borer - *Helicoverpa*	*cry1Ab, cry1Ac*	T3-T4 plants under contained field testing in 2003-05
Chickpea	Pod borer - *Helicoverpa*	*cry1Ab, cry1Ac*	T2 plants under contained field testing in 2004-05
Sorghum	Stem borer - *Chilo partellus*	*cry1Ab, cry1Ac*	T2 plants tested in the greenhouse

Molecular marker-assisted selection

Molecular markers offer great promise for improving the efficiency of conventional plant breeding by carrying out selection, not directly on the trait of interest, but on molecular markers linked to that trait. Unlike the trait, the molecular markers are not environmentally regulated and are, therefore, unaffected by the conditions in which the plants are grown, and can be detected at all stages of plant growth. Several difficulties are associated with expression of resistance to insect pests and diseases across seasons and/or locations. In such situations, there is a need to identify molecular markers for use in transferring resistance into agronomically desirable and locally adapted cultivars. This approach is important to ensure transfer of materials across regions, and for pyramiding resistance genes. At ICRISAT, marker-assisted selection is a high priority for most constraints. But emphasis will be placed on the most important insect pests and diseases, and where conventional breeding has not been very successful due to low heritability of traits.

Striga-resistant sorghums will be an important component of integrated *Striga* control if resistance is available in locally adapted farmer-participatory selected varieties. The application of marker-assisted selection in *Striga* resistance breeding would greatly accelerate progress since field screening is difficult, complex, and often unreliable; *Striga* seed is quarantined, thus confining tests to areas where *Striga* is endemic; and because some *Striga* resistance genes are recessive, increasing the time required for conventional backcrossing. QTL (quantitative trait loci) mapping for resistance of sorghum to *S. hermonthica* was performed using a population of F_3 to F_5 lines developed from the cross N13 × E36-1, where the resistant sorghum line N13 is characterized by 'mechanical' resistance. Composite interval mapping detected five QTLs common across five environments over two years of *Striga* resistance evaluation, with the resistance alleles deriving from N13. Since their effects were validated across environments, years and independent genotype samples, these robust QTLs are excellent candidates for marker-assisted selection. In a three-year

Table 7. Marker-assisted selection for resistance to insect pests and diseases in ICRISAT mandate crops

Trait	Mapping population	Genetic linkage map	Marker-assisted breeding
Downy mildew – pearl millet	√	√	√
Shoot fly – sorghum	√	√	√
Stem borer – sorghum	√	√	-
Striga – sorghum	√	√	√
Helicoverpa – chickpea	√	-	-
Fusarium wilt / BGM – chickpea	√	√	?
Fusarium wilt – pigeonpea	√	-	-
Leaf spots – groundnut	√	√	-
Bacterial wilt – groundnut	√	√	-

√ = Research in progress

project launched in April 2004, *Striga* resistance in farmer-preferred sorghum varieties in Eritrea, Kenya, Mali and Sudan will be enhanced through a combination of marker-assisted backcrossing and farmer-participatory selection. A complementary study will examine the impact of gene flow on the stability of the achieved *Striga* resistance. Simultaneously, a socio-economic study of the sorghum seed supply systems in these countries will be undertaken to guide the design of effective seed interventions by partner institutions so that improved materials efficiently reach farmers. Linkage with technology exchange will boost promotion of the improved varieties as a component of integrated *Striga* control.

Management Options

Natural enemies

Natural enemies are important in the control of major insect pests such as *Helicoverpa*. One of the factors limiting the exploitation of natural enemies for *Helicoverpa* control on pigeonpea and chickpea is the presence of glandular trichomes, and production of exudates that limit the activity and effectiveness of natural enemies. Scanning the germplasm for non-glandular genotypes that are compatible with the natural enemies can impart a new dimension in our efforts to control this notorious pest. Natural enemies are an important component for the management of stem borers and armyworm. Quantifying the effect of borer-resistant cultivars and transgenics on the activity and effectiveness of natural enemies will be a major concern in future pest management programs.

Biopesticides

Current sensitivities on environmental pollution, human health hazards and pest resurgence are a consequence of improper use of synthetic pesticides. Natural plant products and biopesticides offer a potentially viable alternative to synthetic insecticides since they are relatively safe to natural enemies, non-target organisms, and human health. There have recently been exciting developments in the field of natural products for pest management. Environment friendly products such as Spinosads and Avermectins produced by actinomycetes, nuclear polyhedrosis virus (NPV) and *Bt* toxins are now being widely tested. Several bacterial and fungal isolates have been identified as potential biocontrol agents. A few of them are compatible with fungicides and have the capacity to substantially reduce fungicide use; and resulted in up to 100% yield gains in groundnut foliar disease management trials. Effective integration of HPR, agronomic strategies and alternative natural pesticides requires an analysis of multi-trophic interactions in the context of benefits versus crop damage and yield loss. There has been tremendous interest from public and private institutions, both national and international, in natural plant products. New cultural practices that can reduce pest incidence and damage, need to be investigated. Several strains of *Trichoderma harzianum*, *T. viride* and *Pseudomonas fluorescense* have been shown to be effective against *A. flavus* in groundnut.

We are working on a range of botanicals and microorganisms (fungi and bacteria) pathogenic to insect pests. Neonates or 3rd-instar larvae of *Helicoverpa armigera* have been used to bioassay different biopesticides in laboratory and glasshouse conditions. Biopesticides (both botanicals and microorganisms) identified earlier as promising were used for crop protection under field conditions. This also involved reduced use of urea, and use of trap crops and intercrops. The expertise gained was shared with the biofertilizer/biopesticide industry in India, with a view to developing public-private partnerships for biopesticide research. This resulted in the formation of a Biopesticides Research Consortium in Jan 2005 with ten private companies as members.

Entomopathogenic microorganisms. The microbial collection at ICRISAT has a total of about 1500 microorganisms (fungi, bacteria and actinomycetes) for six traits; cellulose degradation, plant-growth promotion, P-solubilization, N_2 fixation, antagonists of disease-causing fungi, and pathogens of insect pests. About 200 of these are expected to have the ability to kill neonates of *Helicoverpa armigera.* Most of these were isolated from dead larvae. Nearly 100 isolates have been evaluated in laboratory/greenhouse

studies. Isolates with the ability to promote plant growth and kill neonates of *Helicoverpa* larvae were used for field studies. Published methods for rearing *Helicoverpa* involve the use of antibiotics. We developed feeds without antibiotics, an essential step to screen and identify promising microorganisms. A bacterial strain *Bacillus subtilis* (BCB19) and a fungal strain *Metarhizium anisopliae* (GVR) have shown promise. Another 15 strains have shown the ability to kill 70% of *Helicoverpa* larvae. *Metarhizium anisopliae* and/or a commercial strain of a *Bacillus thuringiensis* were used as a control. *Bacillus vallismortis* (HiB28), *Bacillus megaterium* (SB9) and *Bacillus megaterium* (SB21) appear promising in their ability to promote plant growth. Nomenclature at species level of the three strains is being re-examined due to differences in reports from two sources. During the 2002/03 cropping season, potential of *Bacillus subtilis* strain BCB19 was evaluated for protecting medium-duration pigeonpea and cotton, in two different field experiments. Pigeonpea plots sprayed with BCB19 (1.76 t ha^{-1}) were at par with those sprayed with synthetic pesticides (1.77 t ha^{-1}). In cotton, plots receiving BCB19 sprays yielded 10% less than those sprayed with chemical pesticides (1.47 t ha^{-1}).

Of the 110 isolates of actinomycetes in the ICRISAT collection, 62 seem promising (for managing disease-causing fungi and/or insect pests) due to release of some compounds in the growth medium. Twenty-one of these were evaluated for bioefficacy against *Helicoverpa*. Commercially available Ivermectin (a product from actinomycetes) from Glaxo Smithkline Pharmaceutical Ltd was used as a control. Only one of the 21 isolates (BCA 70) showed some promise. Microorganisms can also be delivered on a strip (1 × 5 cm) of filter paper. Each strip had 1.88×10^9 *Bacillus subtilis* bacteria after 13 months storage at room temperature. Thirty such strips could be packed in a vial of about 30 ml capacity. A 4g tablet had 6.2×10^9 bacteria and 20g water dispersible powder contained 1.1×10^9 bacteria three months after storage at room temperature. Technology for making a small fermenter (developed at ICRISAT 20 years ago) was sold in 2005 to a private-sector entrepreneur, who then sold at least 13 units in one year. A small (30 liter) fermenter for mass-scale production of microbial biopesticides has been pilot tested using *Bacillus subtilis (*BCB19). Upscaling will be done in 2006. If successful, it will obviate the need for large fermenters (generally 300 L and above) currently used by the industry.

Botanicals. A novel method of extracting biologically active components from plant material using earthworms was evaluated. Water extract (wash) of compost prepared from foliage of eight plant species resulted in 48 to 70% mortality of *H. armigera* larvae compared to 42 to 78% mortality in neem-oil (used as a reference). Hot water extracts of most of the botanicals showed better activity than their respective compost washes. Wash of compost prepared from foliage of *Azadirachta indica*, *Datura metel* and *Parthenium hysterophorus* improved the growth of pearl millet (cultivar ICMV 155) by 19-22% over the un-inoculated control; and also caused 30-48% egg mortality compared to 75% mortality with acephate. *B. subtilis* strain BCB 19 survived for 8 days in extracts from *Nerium odorum*, *Pongamia pinnata* and *Dhatura fastuosa*; while *M. anisopliae* strain GVR survived for 8 days in the compost-wash of the three botanicals. This compatibility between microorganisms and botanicals may be useful for enhancing their efficacy.

Evaluation of different components for crop protection

A long-term experiment at ICRISAT Patancheru, initiated in 1999, compared four crop husbandry systems: two low-cost systems, traditional or mainstream agriculture, and mainstream agriculture + incorporation of biomass. The low-cost systems depended on biomass and microorganisms as sources of nutrients, and used a biopesticide-based protocol for crop protection. Use of *Bacillus subtilis*, *Metarhizium anisopliae* and botanicals (compost wash of *Azadirachta indica* and *Gliricidia sepium*) reduced the use of nitrogen fertilizer. Inclusion of trap crops reduced insect damage. In five out of six years, crop yields under the two low-cost systems were similar to yields under mainstream agriculture. This protocol was then evaluated on-farm in 2003, on large plots – approximately 4000 m^2, divided into two parts, chemical pesticides and biopesticides-based protocol. The trials were progressively extended to additional villages in Andhra

Pradesh and Gujarat states. The biopesticide plots gave similar or higher yields (1 to 30% advantage in cottonseed, 2 to 76% in tomato) compared to the plots where chemical pesticides were used. In a further development, ICRISAT provided training and support for a women's group in Andhra Pradesh that now produces and sells *Azadirachta* and *Gliricidia* wash to other farmers.

In future efforts will be made to screen microbial germplasm (bacteria, fungi, actinomycetes) against insect pests. Promising strains will be evaluated in glasshouse and field conditions. Biopesticides-based protocols will continue to be tested. Improved formulations and mass-scale production protocols will be developed for HaNPV, *Bacillus subtilis* strain BCB19 and *Metarrhizium anisopliae*, shared with industry, and also registered as biopesticides.

Surveys for natural enemies of *Striga* in Africa and India have revealed the presence of numerous insects and fungi that cause considerable damage to this parasitic weed. The genus *Smicronyx* was the most common insect natural enemy; *Fusarium* species were identified as potential pathogenic agents. Addition of *Fusarium* to the sorghum-*Striga* system led to significant decreases in germinated, attached and emerged *Striga* (80% killed in total). Additional field trials will test the efficacy and host specificity of local *Fusarium* isolates – keeping in view the health issues, since *Fusarium* spp. may produce mycotoxins hazardous to humans and animals. These concerns must be addressed before any large-scale use of *Fusarium* is tested or promoted. Practical, economic methods also need to be developed for mass production of inoculum.

Judicious use of pesticides

Pesticides are still the most reliable and economic way of protecting crops from pests. While accepting this, we need to find ways to maximize the efficacy of pesticide use, while minimizing harmful effects on the environment, and slowing down or reversing the rate of development of resistance in target pest species. Efforts have been made in the past to implement insecticide resistance management strategies in cotton in several parts of the world – but no attention has been paid to resistance management and efficacy of control operations in other crops that play an important role in pest population dynamics. Therefore, pest management efforts should focus on developing a comprehensive approach to the management of these pests in the SAT. Adequate knowledge of economic importance, farmer perceptions of pest losses, harmful effects of insecticides on the environment, and the potential benefits of IPM technologies for sustainable crop production is critical for setting priorities and making rational decisions on pest management.

Several chemical control methods for *Striga* were evaluated – fumigants, germination stimulants, antitranspirants, seed hardening, seed treatments and herbicides. We conclude that of these methods, the use of herbicides is best suited for *Striga* control. Evaluation of new herbicide formulations will remain an important activity. In addition, collaboration with farming-systems teams is important to develop control technologies that are adapted to local conditions, and economically feasible.

Cultural practices

When levels of resistance are low, it is still possible to reduce pest damage and achieve acceptable yield. Many of our past investigations showed clearly that the combination of management practices and genetic enhancement can significantly improve crop productivity. For example, shaking pigeonpea plants to dislodge *Helicoverpa*, planting a trap crop such as sunflower or castor to manage *Spodoptera* and *Helicoverpa* in groundnut, or application of overhead irrigation to manage sucking pests in groundnut. In Africa, groundnut rosette and foliar diseases have been managed using resistant cultivars and cultural practices, resulting in high yields.

Studies on weed management have shown the economic advantages of managing long-term weed population dynamics while simultaneously implementing short-term weed control. An important component of

integrated weed management is monitoring and attempting to predict how cropping systems and control strategies affect the long-term population dynamics of weeds. The hemi-parasitic plant *Striga hermonthica* infests cereal-based cropping systems in many parts of sub-Saharan Africa. In order to be able to model long-term *Striga* seed bank dynamics, steps in the life cycle such as seed bank replenishment (seed production) and seed bank depletion (seed mortality in the soil) were quantified. In six field experiments, we tried to develop a reliable, standardized method for monitoring seed production and to determine the effect of rainy season length, seed density, host cycle length and several control strategies on aboveground demography leading to seed production. Seed bank germination and depletion was also measured in Mali and Niger during the rainy season under different cropping systems.

Seed production was affected by rainy season and host cycle length, and by different control strategies. A five-fold increase in initial seed density did not affect seed production; data indicated possible density dependence in underground stages, although with a very high variability. There were striking differences in aboveground *Striga* appearance between years and sites even with small differences in infestation or inoculation levels of (germinable) seeds. Finally, a relationship was found between allometric seed production estimates and soil seed content to a depth of 3 cm. Seed production and seed bank dynamics of *Striga* are affected by season length and host characteristics, and should therefore be incorporated into population modeling. Seed bank depletion was determined using two seed burial and retrieval methods: mesh seed bags filled with sand and *Striga* seeds; and soil inoculation and sampling, after which seeds were extracted by wet sieving and floatation. Exhumed seeds were assessed by a seed press test: empty seeds were considered to have germinated. Seed germination contributed most to seed bank depletion under a variety of vegetative cover types including host crops, non-host trap crops, intercrops of host and trap crops, and weedy fallow. The soil sampling method and the seed bag burial method yielded similar percentages of seed bank depletion, and treatment effects showed similar trends. Combining data from previous studies on seed production with these data on seed losses indicated that seed bank reduction by suicidal germination could be achieved only if seed production and seed bank replenishment are completely prevented. The results raise questions on the specificity of trap crops and whether previously reported differences in seed bank depletion between trap and host crops are simply caused by the prevention of seed production, rather than increased (suicidal) seed germination in the soil.

Several cultural control methods were evaluated for their ability to reduce *Striga* emergence in infested (sorghum and/or pearl millet) fields in collaboration with the International Development Research Centre in Burkina Faso and Institut de Economie Rurale in Mali, and at ICRISAT Niger. The methods evaluated were weeding and/or hand-pulling *Striga*, fertilizer application, herbicide application, reduced tillage, crop rotation, mixed cropping, and burning of *Striga*. Weeding and the combination of mixed cropping, with a groundnut rotation proved the most effective; but no single measure will completely eradicate the seed bank in the soil. Furthermore, reduced infestation (shoots as well as seeds in the soil) did not always lead to improved yields of the host (millet). Careful on-farm testing of control package components, followed by development of integrated control methods, will be the strategy to follow. Intercropping of pearl millet (a major staple in the West African Sahel) with sesame (an important oilseed crop well adapted to sandy soils) has been reported to reduce *Striga*, but research is lacking. Field trials were undertaken to evaluate this system; *Striga* emergence and fruiting were strongly reduced on pearl millet following sesame, compared to sole millet. This has important implications, particularly because sesame is being promoted to diversify agricultural production in the Sahel.

Promotion of IPM Technologies

Future management strategies will focus on combining different components that can significantly reduce pest and disease losses and improve crop yields. In chickpea, for example, a combination of available resistant

varieties (BGM, ascochyta blight and wilt), agronomic practices and judicious use of fungicides and insecticides need to be scaled up in disease and pest-prone areas. ICRISAT's recent experiences in evaluating these technologies in farmers' fields have shown that both diseases and pests can be managed to ensure profitable yields. Other IPM components will include biopesticides, biocontrol agents, and rational application of synthetic pesticides.

ICRISAT has developed several IPM packages. Most of them have been tested on farmers' fields, and proved to be efficient; but adoption levels are low, both in Asia and Africa. Large-scale testing of IPM technologies (eg, management of groundnut rosette) is ongoing in southern Africa, while IPM of chickpea and groundnut has been evaluated and scaled-up in Asia. But many other technologies need to be promoted and their impact assessed. Farmer-participatory studies in Asia have shown a 21 to 100% reduction in pesticide use due to adoption of IPM (Table 8).

In Mali and Niger, 6-year on-farm trials on integrated *Striga* management led to very large reductions in the number of emerged *Striga* plants as well as seed bank densities, compared to normal farmer practice. Although this was not quantified, farmers adopted parts of the package, if not the entire package, in other infected fields that were not part of the trials. To further increase impact, high priority will be given to testing and transfer of IPM technologies that are likely to be adopted. This will involve the following activities: policy and institutional options to stimulate adoption; on-farm testing and validation of IPM components; development of IPM packages for different crops and cropping systems; promotion of IPM technologies to national research and extension agencies, NGOs and farm communities.

IPM Research at ICRISAT: Future Research Thrusts

1. Biotechnological approaches for pest management

Marker-assisted selection

- Molecular breeding for downy mildew and Striga resistance in pearl millet
- Mapping stem borer *(Chilo partellus)*, shoot fly *(Atherigona soccata)* and *Striga* resistance in sorghum
- Mapping *Helicoverpa*, fusarium wilt, ascochyta and botrytis resistance in chickpea
- Mapping resistance to rust and early and late leaf spots in groundnut
- Mapping fusarium resistance in pigeonpea

Table 8. Cost of plant protection in IPM and non-IPM fields at different locations in India, 1997-2000

	Cost of plant protection (Rs ha^{-1})		
Location, State	IPM	Non-IPM	Cost reduction in IPM over control (%)
Hamsanpalli, Andhra Pradesh	898	1144	21.5
Bollibaithanda, Andhra Pradesh	1194	1870	36.1
Chincholi, Andhra Pradesh	859	1618	46.9
Kanjar, Andhra Pradesh	649	1467	55.8
Punukula, Andhra Pradesh	458	1017	55.0
Itagi, Karnataka	846	1448	41.6
Ashta, Maharastra*	800	-	-

* All farmers in the village implemented IPM

Rs 100 = US$ 2.25 approx

Source: IFAD-ICRISAT, IPM Project Technical Report 2000

Exploitation of wild relatives for resistance to insect pests and diseases

- Wide crosses for *Helicoverpa*, ascochyta and botrytis resistance in chickpea
- Wide crosses for *Helicoverpa* resistance in pigeonpea
- Wide crosses for resistance to early and late leaf spots in groundnut
- Wide crosses for shoot fly and stem borer resistance in sorghum

Genetic engineering of crop plants for resistance

- Transgenic *Helicoverpa* resistance in pigeonpea and chickpea
- Transgenic resistance to stem borer *(Chilo partellus)* in sorghum
- Transgenic resistance to Indian peanut clump, rosette and stem necrosis viruses
- Transgenic resistance to fungal diseases of groundnut, chickpea and pigeonpea

2. Characterization and diagnosis of plant pathogens and insect pests, and environmental biosafety of transgenic crops

- Assessing biosafety of transgenic crops to non-target organisms in the environment
- Characterization and diagnosis of groundnut viruses and sterility mosaic disease in pigeonpea
- Characterization of downy mildew, fusarium, ascochyta, botrytis, stem borer, sorghum midge and *Helicoverpa*

3. Host plant resistance and integrated pest management

Introgression of resistance genes into high yielding varieties and hybrid parents

- Evaluate germplasm for resistance to insect pests and diseases, and introgress the identified sources into improved high-yielding cultivars
- Develop diverse populations and breeding lines with improved yield potential and resistance
- Develop parental lines of potential hybrids in sorghum, pearl millet and pigeonpea with resistance to insect pests and diseases

Strategic research to improve the efficiency of genetic enhancement

- Refine *Helicoverpa*, grain mold and BGM resistance screening techniques
- Identify physiological/chemical traits associated with resistance
- Study inheritance of resistance to insect pests and diseases

Integrate IPM components and validate their effectiveness for insect pest and disease management

- Evaluate beneficial microorganisms such as *Bacillus thuringiensis*, HaNPV, *Metarhizium anisopliae*, *Beauveria bassiana*, and natural plant products
- Evaluate IPM modules for management of aflatoxin in groundnut and *Helicoverpa* in grain legumes
- Develop technologies for mass production, storage and utilization of microorganisms pathogenic to insect pests and plant pathogens
- Study low-cost agronomic practices for integrated pest/*Striga* management, and develop strategies to manage pest or disease epidemics
- Work with national research and extension agencies and NGOs to learn how farmers view pest problems, what control options they prefer, and how these can be applied on-farm. This will accelerate technology adoption and adaptation
- Develop integrated pest/*Striga* modules that serve multiple goals: for example, crop diversification, introduction of potential cash crops, control methods that also increase soil fertility (eg, organic amendments, legume intercrops or rotations).

Scientists involved in different components of IPM research across ICRISAT

Crop	Target pest	Component/scientists involved			
		Bio-ecology and HPR	Breeding for resistance	GT, MAS and WH	IPM
Sorghum	Shoot fly	HC Sharma	BVS Reddy	CT Hash (MAS) KK Sharma (GT) S deVilliers (GT)	HC Sharma
	Stem borer	HC Sharma	BVS Reddy	CT Hash (MAS) KK Sharma (GT) S deVilliers (GT)	HC Sharma
	Grain molds	RP Thakur	BVS Reddy EW Rattunde	CT Hash (MAS)	RP Thakur
	Striga		FW Rattunde B Haussmann Mary Mgonja	D Kiambi (MAS) D Hoisington (MAS) CT Hash (MAS)	Mary Mgonja B Haussmann FW Rattunde
Pearl millet	Downy mildew	RP Thakur	KN Rai Mary Mgonja B Haussmann	CT Hash (MAS)	RP Thakur
Chickpea	*Helicoverpa*	HC Sharma GV Ranga Rao	CLL Gowda PM Gaur	KK Sharma (GT) S deVilliers (GT) N Mallikarjuna (WH) RK Varshney (MAS) D Hoisington (MAS)	GV Ranga Rao OP Rupela HC Sharma
	Wilt	S Pande	PM Gaur	R Varshney (MAS) D Hoisington (MAS)	S Pande
	AB/BGM	S Pande	PM Gaur	RK Varshney (MAS) D Hoisington (MAS)	S Pande
Pigeonpea	*Helicoverpa*	HC Sharma GV Ranga Rao	KB Saxena SN Silim E Gwata	KK Sharma (GT) S deVilliers (GT) N Mallikarjuna (WH) HD Upadhyaya (WH) RK Varshney (MAS) D Hoisington (MAS)	GV Ranga Rao OP Rupela HC Sharma Mohan Rao
	Wilt	S Pande	KB Saxena SN Silim E Gwata	RK Varshney (MAS) D Hoisington (MAS)	S Pande
	SM	S Pande Lava Kumar	KB Saxena	RK Varshney (MAS) D Hoisington (MAS)	Lava Kumar S Pande
Groundnut	Whitegrubs Termites	GV Ranga Rao	-	-	GV Ranga Rao R. Padmaja
	Leaf miner/ *Spodoptera*	GV Ranga Rao HC Sharma	SN Nigam/R Aruna	-	GV Ranga Rao
	Aflatoxin	F Waliyar Lava Kumar	SN Nigam/R Aruna BR Ntare	KK Sharma (GT) N Mallikarjuna (WH) RK Varshney (MAS)	F Waliyar Lava Kumar M Siambi RB Jones
	Leaf diseases	F Waliyar	SN Nigam/R Aruna BR Ntare ES Monyo	N Mallikarjuna (WH) RK Varshney (MAS)	F Waliyar Lava Kumar
	Viruses (Rosette, stem necrosis, IPCV)	Lava Kumar F Waliyar	SN Nigam/R Aruna ES Monyo	KK Sharma (GT) N Mallikarjuna (WH) S deVilliers (GT)	Lava Kumar F Waliyar

WH = Wide hybridization, MAS = Marker assisted selection, GT = Genetic transformation
AB= Ascochyta blight, BGM=Botrytis grey mold, SM=Sterility Mosaic, HPR=Host plant resistance

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About ICRISAT®

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a nonprofit, non-political organization that does innovative agricultural research and capacity building for sustainable development with a wide array of partners across the globe. ICRISAT's mission is to help empower 600 million poor people to overcome hunger, poverty and a degraded environment in the dry tropics through better agriculture. ICRISAT belongs to the Alliance of Centers of the Consultative Group on International Agricultural Research (CGIAR).

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