TAC Review on Plant Breeding Methods

Background Papers

ICRISAT
International Crops Research Institute for the Semi-Arid Tropics
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Introduction

Genetic Resources and Enhancement

Rodomiro Ortiz

Research and technology development, ensuing from genetic improvement, is organized at ICRISAT according to major topical thrusts, rather than crop mandates, to create more flexibility. In 1997 the Genetic Resources and Enhancement Program (GREP) was established at ICRISAT to help developing countries to:

I. Rescue and preserve endangered crop biodiversity;
II. Introduce and apply new biotechnological tools to the needs of the semi-arid tropics;
III. Identify valuable new traits for resistance to biological and environmental stresses; and
IV. Improve breeding populations as a vehicle for sharing new traits with national agricultural research systems (NARS).

The director of the program is based at ICRISAT's facilities in India, where the center's genebank and biotechnology labs are located. Particular problems will require special strategies involving partners throughout the semi-arid tropics (SAT), especially in Sub-Saharan Africa. The development of breeding populations will emphasize vigorous NARS partnerships with greater direct ICRISAT involvement in Africa. Genetic resources conservation and delivery of improved germplasm are the focus of GREP activities in Africa. Likewise, GREP scientists are conserving and enhancing crop genetic resources applying conventional and new tools at our headquarters in India. Other scientists are also identifying useful characteristics to improve crop adaptation in the SAT.

ICRISAT has decided to implement its medium term plan (MTP) 2000-2002 considering as a partnership-based plan for renewal. Accordingly, GREP has developed its research agenda with the aim of "building tomorrow" together with its partners worldwide. For 1999, research projects of GREP have been streamlined and consolidated by integrating activities in four research areas. This consolidation was a direct evolution from the nine GREP research areas originally included in the previous rolling MTP. Experience accumulated during 1998 showed that sets of independent projects within each of these research areas formed an operational continuum, thus a separate structure was not needed. One of the most important features of this consolidation is the focus in sub-Saharan Africa with the corresponding strengthening in both staff and resources.

GREP scientists are expected to continue building partnerships and submitting targeted proposals to apply molecular and bioinformatic tools for the genetic betterment of most important crops of the SAT, which have been included in our research agenda. Likewise, our scientists continue applying conventional and innovative cross breeding methods for the genetic enhancement of ICRISAT mandate crops. In this way, we are working along the lines suggested by the last CGIAR Systemwide Review and ICRISAT External Program and Management Review, which advocated an integrated gene management approach. Furthermore, the partnership-based refinement and exchange of useful breeding materials balances the GREP strategy.

The four research areas advocated in the new MTP by GREP are a logical progression from an appropriate conservation, management and utilization of plant genetic resources and the genes available in the different crop gene pools. GREP scientists expect that our work will culminate by sharing products with our local research and technology transfer partners and making impact together in the fields of our farmer clients.

The four research areas coordinated by GREP are:

- Rescue, analyze and conserve biodiversity to sustain crop productivity
- New tools: adapt and apply new science methods to SAT crop improvement
- New traits: the biology and improvement of disease and pest resistances, stress tolerance and quality
- Partnerships to share breeding materials in farmer-ready forms.

The conservation of genetic resources of important SAT food crops for the long-term benefit of humanity is the most important goal of our research in biodiversity. We expect that biotechnological outputs help to obtain a more effective and durable resistance to biotic and abiotic stresses, which may stabilize production of food crops of the poor in the SAT. Likewise, with an enhanced ability to manipulate genes, improved nutritional quality may be achieved that will benefit human health and household for food security The identification of new traits will allow ICRISAT and its partners in the national programs to develop a more stable, diversified germplasm with improved resistance to diseases and pests, stress tolerance, better quality, and higher productivity. The research in conventional breeding and seed delivery of improved genotypes integrates outputs from other research areas. Likewise, reduced crop cycle or modified plant structure will provide opportunities for new cropping systems Finally, with the utilization of new cultivars, we expect to enhance and stabilize agricultural production, farm income and farm-family welfare in the SAT.

There are in excess of 50 core, special project and affiliate scientists working at GREP, who are supported by technical and administrative staff in India, Kenya, Malawi, Mali, Niger, Nigeria, Senegal, and Zimbabwe. These scientists are applying their professional skills in agronomy, biometry, biotechnology, breeding, crop physiology, entomology, genetic conservation, genetics, information management, plant pathology, virology, technology transfer, research networking and project management to accomplish ICRISAT goals in the conservation and enhancement of crop genetic resources of the SAT.

GREP scientists are also supporting research of graduate students from both developing and developed countries, whose investigation focuses on crop improvement for the SAT.

Thematic Presentations and crop reviews

ICRISAT Genetic Resources

N Kameswara Rao

The Genetic resources unit was established in 1979 by incorporating various crop germplasm activities of the institute into one coordinated unit. The objectives of the unit were collection, evaluation, maintenance, conservation, documentation and distribution of the five mandate crops (sorghum, pearl millet, chickpea, pigeonpea and groundnut) and six small millets (finger millet, foxtail millet, barnyard millet, proso millet, kodo millet and little millet). The cereal germplasm initially acquired by ICRISAT comprised of 9000 sorghum and 2000 pearl millet accessions originally assembled by The Rockefeller Foundation from major sorghum and millet growing areas in 1960s. Other major donors of germplasm included Institut francais de recherche scientifique pour le development en cooperation (ORSTOM) and the United States Department of Agriculture (USDA), and national programs in Ethiopia and India. Chickpea and pigeonpea initially assembled by ICRISAT included material originally collected by the former Regional Pulse Improvement Project (RPIP), a joint project of Indian Agricultural Research Institute (IARI), USDA, Arid Lands Agricultural Development Program (ALAD) in Lebanon, and Karaj Agricultural University in Iran, while much of the groundnut germplasm was received from the Indian national programs, especially the National Research Center for Groundnuts (NRCG) and USDA's Southern Plant Introduction Station in North Carolina State University.

Collection

Collection of germplasm is of fundamental and strategic importance to all crop improvement activities. With over 113,500 germplasm accessions assembled from 130 countries, ICRISAT is serving as the world repository for germplasm of its five mandate crops and six small millets (Table 1). A large proportion of the germplasm was assembled through donations, but ICRISAT also collected several landraces from areas of diversity by conducting over 200 expeditions, jointly with scientists of national programs. Following an agreement between ICRISAT and the United Nations Food and Agricultural Organization (FAO) on 26 October 1994, ICRISAT germplasm collections were placed under the auspices of FAO as part of the international network of *ex situ* collections. The materials covered under the Agreement listed as "designated germplasm", consists of 97% of the assembled germplasm. In the interest of keeping this material available for future research and utilization, ICRISAT has undertaken not to claim legal ownership or seek any intellectual property rights over that germplasm or related information. To ensure continued free availability of this germplasm, ICRISAT has also agreed to pass on the same obligations to all future recipients of designated germplasm. Accordingly, no designated germplasm will be released unless the recipient signs the Standard Order Form.

Characterization and evaluation

Characterization and evaluation of the assembled germplasm are essential to facilitate its utilization. The germplasm is characterized using a set of descriptors for stable botanical characters and a few environmentally influenced agronomic and quality traits. The number of descriptors used for characterization varies with crop. Most of the germplasm assembled at ICRISAT, except the wild species, has been fully or partially characterized. The range of variation found in the collection is remarkable. For example, panicle length in pearl millet ranges from 5 to 120 cm, and the 100 seed mass in chickpea and groundnut ranges from 4 to 59 g, and from 14 to 140 g, respectively.

The germplasm accessions are evaluated against major biotic and abiotic constraints and several sources of resistance were identified (Table 1). For example, screening of sorghum germplasm resulted in identification 60 accessions resistance to shoot fly, and 70 accessions tolerant to stem borer and 35 accessions resistant to midge. Germplasm accessions that have resistant to more than one constraint were also identified; e.g. IS 3547 and IS 8283, resistant to grain mold, downy mildew and rust.

Efforts are also made to identify new and desirable traits in the germplasm and study their genetics. Thus several economically important traits like sweet stalk, scented (Basmati), high lysine sorghums, pearly white and yellow endosperm (high in β-carotene) pearl millet, twin poded chickpea, new cytoplasmic male sterility systems in pigeonpea and early maturity in groundnut were identified.

Multilocation evaluation of the germplasm was conducted in collaboration with National Agricultural Research and Extension Systems (NARES) at several locations in 20 countries. This has led to identification of locally adapted germplasm in all mandate crops.

Regeneration and maintenance

At ICRISAT, germplasm accessions are regenerated under irrigation during postrainy season. The lower temperature and humidity result in less pest and disease incidence and generally better seed quality. The breeding systems and multiplication rates differ for the mandate crops. These differences require the crops to be treated very differently for seed multiplication and regeneration. For example, sorghum is wind pollinated and pigeonpea is insect pollinated and both are partially out-crossing (0-30% and 0-40%, respectively). Pearl millet is wind pollinated and predominantly outcrossing, but chickpea, groundnut and small millets are self-pollinating. Groundnut has multiplication rate of about eight, whereas in pearl millet it is in excess of 200.

No pollination control is practiced for chickpea, groundnut and small millets, since they are self-pollinating. Sorghum is selfed by enclosing panicles in paper bags prior to anthesis. Special genetic stocks of pearl millet are maintained as inbred lines by selfing. However, landraces are being maintained by cluster bagging where, panicles from 3-4

adjacent plants are enclosed together in a single paper bag. However, studies have shown that sibbing is better for maintaining genetic integrity. The quality of seeds produced by cluster bagging was also found to be inferior. We therefore intend to maintain pearl millet landrace accessions by sibbing, in future. Pigeonpea plants are selfed by enclosing individual plants within muslin bags, but because of the reduced seed set with this method, we propose to use insect-proof cages.

To minimize genetic changes, adequate number of plants is grown and seed is sampled equally in constituting new seed stocks. The number of plants used varies according to crop - at least 50 in sorghum, 160 in pigeonpea, 120 in pearl millet and 80 in chickpea. The number of plants used in groundnut varies from 80-160 and is generally driven by the quantity of seed required.

Conservation

All mandate crops produce orthodox seeds, which can tolerate desiccation. The seeds are dried and stored at low temperature to prolong viability. However, a few wild species which do not produce adequate quantity of seeds (e.g. *Arachis* spp., Section: *Rhizomataceae*) are maintained vegetatively in screen-house. A few species of the *Sorghum*, *Pennisetum* and *Cajanus* species are perennials and maintained in filed genebank (botanical garden).

The germplasm is now conserved as active collections under medium-term storage. About 34% of the collection (39,025 accessions) are held as base collections under long-term conditions. Under the Agreement with FAO, the collection is required to be conserved as a base collection and ICRISAT is making efforts to meet this objective in the next three to five years. The available space is insufficient, but we have a strategy. Once the germplasm is transferred into long-term storage, only working collections will be kept under medium-term conditions and the space so relieved will be modified to hold the base collections.

Storage facilities: Facilities available for germplasm conservation at ICRISAT includes,

- six modules maintained at 4°C and 20-30% RH for medium-term conservation,
- three modules maintained at -20°C for long-term conservation,
- a glass house for the wild *Arachis* species, and
- a botanical garden for perennial wild species of sorghum, pearl millet and pigeonpea.

Ancillary facilities include,

- a short-term storage for temporary holding of harvested material,
- a seed drying room maintained at 15°C and 15% RH with a capacity to dry up to 10, 000 accessions at a time,
- a seed laboratory, and
- crop-work area for seed cleaning.

The genebank has a standby power generator to cope with longer periods of power failure and audible and visual electronic alarms to warn any rise in temperature and relative humidity. Each medium- and long-term storage room has independent standby refrigeration and dehumidification systems to help maintain the desired conditions.

Plant quarantine: For safe introduction of new samples and also safe exporting of the seeds, a Plant Quarantine Unit is located at ICRISAT, Patancheru. The work is done with the assistance of National Bureau of Plant Genetic Resources (NBPGR), the Plant Quarantine Authority of Government of India. The unit also takes care of the seed material imported by ICRISAT that is released by NBPGR to be grown out in the Post-entry Quarantine Isolation Area.

Sample size: For medium-term conservation, about 350 g of sorghum, pearl millet and chickpea, and about 450 g of pigeonpea and groundnut seeds are stored in screw capped aluminum cans or plastic bottles. For long-term conservation, about 75 g of sorghum and pearl millet, 350 g of chickpea and pigeonpea and 500 g of groundnut are stored in vacuum-sealed aluminum pouches.

Safety duplication: The Agreement with FAO requires off-site duplication of the designated germplasm accessions under long-term conditions. Memoranda of Agreement were signed for duplicate conservation of chickpea with International Center for Agricultural Research in Dry Areas (ICARDA), Syria and for pigeonpea with NBPGR, India. Efforts are being made for off-site duplication of other mandate crops.

On-farm conservation: ICRISAT conducted pioneering studies on farmer's management of pearl millet genetic resources in Rajasthan, India, where local landraces are still widely grown. Similar studies on management of sorghum genetic resources in Mali and pigeonpea in India are underway.

Distribution

ICRISAT has traditionally adhered to a policy of unrestricted availability of germplasm held in its genebank. Since 1973, some 623,700 seed samples were distributed to users in 141 countries. About 67% of the distribution were made within Asia, 22% in Africa and 7% in Americas. NARES received 46% of the germplasm, followed by universities (31%). Only 3% of the germplasm were distributed to commercial companies, but the demand from them is on the rise in recent years. Additionally, over 530,000 seed samples were distributed within ICRISAT for screening and crop improvement research (Table 1).

Documentation

Proper documentation and dissemination of information through user-friendly interfaces is essential to promote utilization of germplasm. Information on germplasm is mainly organized into Passport, Characterization, Evaluation, Inventory and Distribution

Databases using the Relational Database Management System (RDBMS) Microsoft SQL Server™. User friendly front-ends have been developed in Visual Basic™ for data entry and retrieval and an automated Genebank Management System for efficient management of the collections. Dissemination of information on the germplasm at global level is made thorough the System-wide Information Network on Genetic Resources (SINGER) and ICRISAT/GREP Web page.

Achievements

Identification of core collections: Core collections were developed for sorghum, pearl millet, chickpea and groundnut based on geographical origin and data on characterization and evaluation. These core collections are expected to improve management and use of the germplasm collections.

Germplasm utilization and impact: While thousands of samples supplied from ICRISAT genebank are used as raw material in breeding programs, occasionally, germplasm lines supplied to researchers were found to be superior and released for commercial cultivation. So far, 47 germplasm lines supplied from ICRISAT germplasm collection were released as varieties in several countries.

Restoration of germplasm: Collection and conservation of germplasm by ICRISAT ensured its continued availability when germplasm was lost in the countries of origin. Thus the sorghum germplasm lost during civil wars in Ethiopia (1991) and Rwanda (1993) has been replenished through the sorghum collections from those countries maintained in the ICRISAT genebank. The ICRISAT chickpea collections originating from Ethiopia, Iran and Nepal; pigeonpea originating from Kenya and Tanzania; and sorghum from Sudan and Botswana were restored to these countries for conservation and utilization. Currently ICRISAT is working for restoration of germplasm of Indian origin of the mandate crops to the Indian national genebank.

Publications: The progress made in various genetic resources activities was reported in more than 250 publications made between 1975 and 1999. They include 79 journal articles, 18 book chapters, 69 conference papers and 54 newsletter articles.

Training: Training courses on several aspects relating to genetic resources have been organized. From 1972 to date, over 355 participants from NARS have attended such courses and received training in genetic resources management.

Future outlook

We will emphasize on meeting international standards for germplasm conservation as required under the Agreement with FAO, especially on establishing long-term and safety duplicate storage of germplasm.

We shall establish regional working collections in West and Central Africa (WCA) and in Southern and Eastern Africa (SEA) to enhance use of germplasm in Africa. For WCA, we propose to have pearl millet and groundnut collections in Niamey and sorghum in Kao or Bamako. For SEA, we propose to have sorghum, pearl millet, chickpea, and groundnut in Bulawayo and pigeonpea in Nairobi.

Future emphasis will be on documentation, especially in improving data quality and availability.

We shall enhance our research on wild species, especially on their characterization and utilization, and also plan to study the diversity in assembled germplasm using molecular markers to better understand the collection.

Table 1. Progress in genetic resources (1975-1999)

	Sorghum	Pearl millet	Chickpea	Pigeonpea	Groundnut	Minor millets
Accessions assembled	36719	21392	17250	13544	15342	9255
Wild relatives[1]	33(417)	25(750)	18(135)	49(555)	42(452)	6(31)
Countries covered	90	50	44	73	92	43
Collection missions	43	42	41	50	31	7
Characterized						
At Patancheru	35473	20518	16992	12560	15342	7984
Multilocational	21534	17901	5000	6899	9700	1000
Distributed[2]						
Within ICRISAT	198446	39309	159399	66903	65965	2
In India	121111	57030	59387	40481	40497	25194
Abroad	118631	27788	51353	18562	45591	18097
Genetic stocks						
Disease resistant[3]	457	1066	1216	531	335	--
Insect resistant	150	--	22	37	31	--
Nematode resistant	-	--	--	3	2	--
Drought tolerant	246	7	10	10	46	--
Water-logging resistant	--	--	--	10	--	--
Salinity tolerant	--	--	--	4	--	--
Striga resistant	24	--	--	--	--	--
High protein	140	260	25	107	100	--
High oil	--	--	--	--	75	--
Glossy	512	8	--	--	--	--
Vegetable type	--	--	--	202	--	--
Agroforestry type	--	--	--	36	--	--
Popping	36	--	--	--	--	--
Sweet stalk	76	16	--	--	--	--
Male sterile	274	50	--	4	--	--
Dwarfs	37	13	3	8	2	--
Chlorophyll mutants	4	129	3	--	2	--
Twin seeded	163	--	--	--	--	--
Other traits	732	--	88	539	90	--

1. Number of species (number of accessions).
2. Number of samples
3. Includes multiple-disease resistant accessions.

Attachment

ICRISAT
Standard Order Form
Consecutive Number: SOF/Year/Number

I/we order the following material:

In so far as this material is "designated germplasm" under the Agreement between ICRISAT and the Food and Agriculture Organization of the United Nations (FAO) placing Collections of Plant Germplasm under the Auspices of FAO dated 26 October 1994.†

I/we agree:

a) not to claim ownership over the material received, nor to seek intellectual property rights over that germplasm or related information;
b) to ensure that any subsequent person or institution to whom I/we make samples of the germplasm available, is bound by the same provision.

Place/date

Name of person or institution requesting the germplasm

Address

Shipping address (if different from the above)

Authorized signature

† Whether or not the material is "designated germplasm" will be indicated on the seed list attached to the Shipment Notice and on the seed packets.

P6 SAT crop improvement through applied genomics

S Sivaramakrishnan

Background:

Biotechnology provides new and novel options for fulfilling ICRISAT's development objectives of alleviating poverty, assuring food security, fostering sustainable use of natural resources, and ensuring environmental protection. Rapid advances across the spectrum of plant biotechnology research can provide breakthroughs in crop improvement. Biotechnology provides techniques and tools to raise agricultural productivity in a more environmentally friendly manner. The technical potential for genetic improvement of crops, even for such complex traits as yield, nutritional quality, and durable resistance to diseases and pests, is rapidly increasing due to advances being made in a whole range of DNA technologies that complement the traditional methods of crop improvement. When integrated with traditional crop improvement programs, biotechnology enables a more efficient, environmentally compatible, and ultimately, cost-effective, utilization of resources for improving agricultural productivity. The technology is highly appropriate for developing countries, where current technical inadequacies are often compounded by increasing population pressure, intensive agricultural practices that in turn have contributed to the degradation of natural resources, and deterioration of soil quality.

The biotechnology research at ICRISAT has a history of about 10 years when the importance of this discipline was strongly recognized as an integral part of the crop improvement program and endorsed in two International meetings held at Patancheru in this area. Initially, biotechnology research was fragmented and several research disciplines including breeding, cytogenetics, molecular biology, pathology, virology, etc. worked independently but actively collaborated with ARIs in this area of research. As the separate cereals and legumes biotechnology programs could not meet the research demands in an effective manner the two groups were merged. The emphasis was then placed on research themes and on crops which led to an integrated approach in biotechnology for the mandate crops in ICRISAT. The increasing number of constraints that could be addressed by biotechnology-based approach put a strain on the requirement for funds. In the early years of biotechnology at ICRISAT the philosophy was to apply and transfer to NARS those developed by the ARIs than be partners in the development of the technologies. This philosophy resulted in considerable delay and even loss in transferring valuable technologies from the ARIs to ICRISAT. Two reasons could be attributed to this: (i.) Uncertainty due to the fast changing science with the rapid advances in the development of molecular tools, and (ii.) The resource-intensive nature of biotechnology research. In short, biotechnology research was an add-on to most of the other research carried out at ICRISAT than a prime research area with scientists from all disciplines who were directly involved. In this process ICRISAT could not adequately develop its capabilities to absorb some of the technologies offered by the mentor Institutes. This attitude changed in the last few years and ICRISAT took a concerted effort to solve the difficult problems of crop improvement through biotechnological approaches. This was in line with the changing needs in agricultural research in the global context.

At present, the main emphasis of biotechnology research at ICRISAT has been on two major areas: i. DNA marker technology and ii. Genetic transformation. Until recently the genetic transformation work was carried out under the same research project but it has been embedded in other projects (P9 and P10) this year. The applied genomics project mainly addresses the development and application of DNA marker technology for the improvement of the mandate crops.

Progress in biotechnology research:

Considerable progress has been achieved in the last few years in the application of DNA marker technology to our mandate crops although the effort varies with the different crops. In the case of cereals, the major achievement was made in pearl millet followed by sorghum and in the case of legumes it was chickpea. DNA marker research proceeded very slowly in both pigeonpea and groundnut though their potential was high. One of the reasons for the significant progress made in pearl millet was the availability of special project funding and the other was continuous interest shown by the ARIs.

The basic requirement for DNA marker research is the availability of a genetic linkage map. This requirement is met partially or completely only for sorghum and pearl millet. These maps are still far from saturated unlike in the case of rice or maize. In the case of legumes some progress has been made in chickpea but no progress has been made in the construction of a genetic linkage map for groundnut or pigeonpea. Despite the shortcomings we have made significant contributions to crop improvement research through biotechnological approaches. Some of the recent research highlights are listed below:

i. Construction of genetic linkage map

- A genetic linkage map for pearl millet constructed with JIC, UK.
- Genetic linkage maps of sorghum were constructed with University of Milan, Italy and with University of Hohenheim, Germany using RIP for *Striga* resistance and AFLP markers
- Development of genetic linkage map in chickpea (in progress)

ii. Evaluation of mapping populations and identification of QTLs

- Identification of several QTLs for downy mildew resistance in pearl millet
- Identification and evaluation of QTL for field tolerance of drought, and stover quality in pearl millet
- Identification of molecular markers for components of *Striga* resistance in sorghum
- Phenotyping of RILs for drought tolerant traits in chickpea for QTL identification
- Evaluation of mapping populations for P uptake efficiency for QTL identification

iii. Characterization of CMS lines using RFLP

- Pearl millet
- Sorghum
- Pigeonpea

iv. Characterization of genetic variability in pathogen populations using molecular markers

- Pearl millet downy mildew pathogen, *S. graminicola* using RAPDs, SSR, and ITS
- Sorghum anthracnose pathogen, *C. graminicola* using RAPDs
- Pigeonpea *Fusarium* wilt pathogen, *F.udum* using RAPDs, ITS, and AFLP
- Chickpea *Fusarium* wilt pathogen, *F. oxysporum* RAPDs, and ITS
- Mite vector for SMV using ITS

v. Identification and isolation of putative disease resistance genes

- 24 Resistance gene candidates (RGCs) isolated from mandate crops
- RGC sequences deposited in GenBank
- One of the RGCs from pearl millet was mapped onto LG1 that accounts for a major QTL for downy mildew

vi. Tissue culture and genetic transformation

- Development of genetic transformation Protocols for Sorghum, Pearl millet, Groundnut, and Pigeonpea
- Putative transgenics of groundnut with coat protein gene of Indian peanut clump virus generated
- Insect bioassays standardized to test insecticidal proteins
- Production of dihaploids in pearl millet
- Interspecific hybrids were produced

vii. Research in progress

- Development of mapping populations in sorghum, pearl millet, chickpea, groundnut and pigeonpea for other important agronomic traits
- Identification of parental lines for mapping fertility restoration genes in sorghum and pigeonpea

viii. Technology Exchange

- Training workshops on molecular methods conducted
- M.Sc., Ph.D. students and visiting scientists trained on DNA technologies
- Scientists served as resource persons

The status of progress made in different areas of biotechnology in the mandate crops is summarized in the following table:

Technology	Pearl millet	Sorghum	Chickpea	Groundnut	Pigeonpea
Genetic linkage map (Groups working)	Available 1	Available 4-5	In progress 2-3	NA 2	NA
Mapping populations (No. of mapping populations)	Available and more developed (>10)	Available and more developed (>15)	Available and more developed (>6)	Initiated (2-3)	NA
Availability of QTL for biotic stress	Downy mildew	Work in progress for *Striga*	NA	NA	NA
Availability of QTL for abiotic stress	Work in progress for drought tolerance and P uptake	Work in progress for Stay green trait	Work in progress for root trait	NA	NA
Marker-assisted backcross breeding	In progress	NA	NA	NA	NA
Molecular Characterization of CMS	completed	completed	Not applicable	Not applicable	completed
Gene isolation	Initiated	Initiated	Initiated	Initiated	initiated
Comparative Genome Mapping	In progress	In progress	NA	NA	NA
Molecular characterization of pathogen	Downy mildew	Anthracnose	Fusarium wilt	NA	Fusarium wilt and SMV
Genetic Transformation Protocols	NA	Developed	In progress	Developed	Developed
Interspecific hybrids	NA	In progress	Developed and more in progress	Developed and more in progress	Developed and more in progress

NA: Not available

Applied Genomics Laboratory: One of the long -standing needs for biotechnology research at ICRISAT has been the development of an Applied Genomics Laboratory (AGL) to carry out various DNA-related work that will support the research of all those scientists working in this area. Dr. S.

Kresovich, Cornell University, USA who came as a consultant made a few specific recommendations for the operation of the AGL facility. A capital allocation of about US$600, 000 was made for developing the AGL by the ICRISAT with the consent of ICRISAT Governing Board. Dr. J.H. Crouch was appointed in the new position as Head, Applied Genomics laboratory. Appropriate space and equipments were identified for setting up the laboratory. The essential equipment in the AGL is the automated DNA sequencer which can be used for genotyping, fragment analysis, and sequencing.

Applied Genomics Project: The rapid advances taking place in the application of biotechnology to agricultural research provide many opportunities for making very significant advances in the improvement of the food crops of the SAT. This project will follow an integrated approach to the application of modern biotechnology, in close partnership with national agricultural research systems (NARS), advanced research institutes (ARIs), and other public and private sector organizations in developed and developing countries. ICRISAT has a unique comparative advantage as a bridge, broker, and catalyst between ARIs and the NARS of the SAT in helping our NARS partners to identify, adapt, and apply new biological tools to improve the largely neglected food crops of the poor living in this region. In concert with ARIs and NARS partners, this project leverages the continuing rapid advances in the field of molecular marker-based genome mapping, to more efficiently conserve and improve the basic germplasm of the food, fodder and market crops of people living in the SAT.

The overall objective of the project is to develop and apply the various DNA technologies for the improvement of ICRISAT mandate crops. This will eventually enhance the production and productivity of these crops grown in the SAT. The project will contribute to three major areas of research, which include genome mapping, marker-aided selection (MAS) and knowledge dissemination. Some of the tools developed in this project will be used for genotyping, DNA fingerprinting and other applications in germplasm. The database and computational tools developed in this project will find application in many other areas of research in the Institute and globally. The project has five specific outputs to meet the challenges outlined earlier.

1. Development of appropriate DNA marker technology, improved biometric and bioinformatics tools for crop improvement
2. Construction of genetic linkage maps and identification of DNA markers/QTLs for complex traits not easily manipulated by conventional breeding methods
3. Usefulness/stability of identified markers for MAS assessed across different genetic backgrounds and environments, and effectiveness of MAS demonstrated for specific target traits
4. Identification and characterization of useful genes, and comparative mapping of gene sequences/QTLs associated with biotic and abiotic stress-tolerance
5. Molecular characterization of genetic variability in important pathogens

Research on Biotic and Abiotic Constraints at ICRISAT

R P Thakur

Biotic and abiotic factors are major constraints to the realization of high yield genetic potential of crop cultivars. A large number of diseases and insects attack ICRISAT mandate crops (sorghum, pearl millet, groundnut, chickpea and pigeonpea) at various stages of crop growth. In addition, *Striga* (limited to sorghum and pearl millet) and several environmental factors, such as drought, temperature (heat and cold) influence the crop growth and productivity. Often times, these abiotic factors become more severe in the semi-arid tropical environments.

Research at ICRISAT has focused managing these biotic and abiotic stress factors by genetic manipulation wherever feasible. This has involved a continuum of research at basic-strategic-applied-adaptive levels through a multidisciplinary team of scientists from ICRISAT, advanced research institutes and NARS partners. This presentation highlights the achievements of research on biotic and abiotic stress factors, mostly through genetic manipulation using conventional breeding methods.

The number of biotic and abiotic constraints that have been addressed one time or the other at ICRISAT during the past 25 years. The number is large in any one crop and these have been prioritized time to time, at least, once in five years based on the recommendations of the External Review Panel and other considerations, including national and regional requirements, interest of collaborating partners and the available research funding.

Depending on the nature of the problems (prevalence, severity, biology and epidemiology) we have made more progress in identifying and utilizing resistance/tolerance to some stress factors than others. For example, downy mildew, rust, anthracnose and other foliar diseases (leaf blight, sooty stripe, gray leaf spot) of sorghum required less effort in identifying and utilizing resistance than those for grain mold, ergot and charcoal rot. Downy mildew of pearl millet has been widespread and severe, particularly on F_1 hybrids in India, and we have made impressive progress on understanding the biology, epidemiology, pathogen variability, resistance identification and utilization, and generating knowledge and impact. However, pearl millet downy mildew still remains the number one disease problem for wider adaptation of F_1 hybrid cultivars in Asia and Africa because of highly variable nature of the pathogen. Some advances have also been made in case of Fusarium wilts of chickpea and pigeonpea, Ascochyta blight and Botrytis gray mold of chickpea. Resistance to foliar diseases (leaf spots and rust) in groundnut has not been easy to obtain in cultivated types. Interspecific derivatives from crosses between cultivated and wild species have provided better sources of resistance than those from the cultivated types, but at the cost of agronomic desirability. Some impressive advances have also been made in characterizing viruses and identifying resistance, particularly to bud necrosis and rosette in groundnut and sterility mosaic in pigeonpea. *Striga*, however, still remains a major problem in Africa.

Insect-pests have posed problems similar to those of diseases. Panicle insects on cereals have been easier to deal with than those of pod borers in legumes. Shoot fly in sorghum, and stem borers of sorghum and pearl millet are still very important. Many foliar and soil pests, some of which are region-specific require enhanced research efforts to manage these economically, mainly through integrated pest management (IPM) approaches. For example, damage by pod borers in chickpea and pigeonpea, aflatoxin contamination in groundnut are difficult to manage by genetic resistance alone; integration of pesticide and cultural methods with host plant resistance provide a more feasible option.

Among the abiotic constraints, tolerance to drought continues to be the top priority research problem for all ICRISAT mandate crops. Some significant progress has been made in understanding, identifying, and utilizing genetic resistance for chilling tolerance in chickpea, response to daylength and tolerance to temperature sensitivity in pearl millet, groundnut and pigeonpea.

The current priority constraints of various crops are as follows:

Sorghum : grain mold, anthracnose, *Striga*, shoot fly, stem borer, head bug.

Pearl millet : downy mildew, *Striga*, stem borer, head miner, drought.

Groundnut : aflatoxin, early- and late leaf spots, rust, rosette, peanut clump, drought

Chickpea : Ascochyta blight, Botrytis gray mold, Fusarium wilt, Sclerotium root rot, pod borer, drought, chilling.

Pigeonpea : Fusarium wilt, sterility mosaic, pod borers, water logging, perenniality, daylength and temperature responses.

Because of time limitation, I will cite only three distinct examples (downy mildew resistance in pearl millet, pod borer tolerance in pigeonpea, and drought tolerance in groundnut) to illustrate the points of research continuum, knowledge generation, product development and technology exchange for likely research impact. However, advances similar or close to these are also available with other constraints (separate document).

Examples of Research Advances

Example 1. Pearl millet downy mildew (*Sclerospora graminicola*)

I. Methods used/developed to research the trait:

- To understand problem: several aspects of biology, epidemiology, pathogen variability

- To identify/select resistance: a) developed screening methods:
  Laboratory/greenhouse and field screening
  b) developed disease rating scales for incidence and severity

  c) Multilocation evaluation of lines through International Disease Nursery and repeated screening in greenhouse.

II. Current state of knowledge of the trait

- Numbers/effectiveness of original sources: many, and at least 7 lines with stable resistance (IPMDMN, 1976-88)
  Several lines with multiple resistances to all four diseases are also available.
- Mechanism(s) of resistance/tolerance: Seedling susceptibility and adult plant resistance; recovery resistance
- Genetic control of trait: major/minor genes; epistasis, DMR-QTL

III. Utilization of trait in breeding programs

- Breeding methods used to transfer the trait: Pedigree selection, backcross, pure-line selection, and recurrent selection
- Numbers/effectiveness of improved sources: Several lines have been used as resistance donors to develop composites and parental lines of commercial hybrids

IV. Successes achieved and impact generated

- Documentation of traits/methods sources (publications of all types): 20
- Technology exchange/use of results by others:
  -Several short-term training courses organized to demonstrate disease screening methods and these are being used at various locations by NARS in Asia and Africa
  -Large-scale use of downy mildew resistance sources and hybrid parental lines (resistant to one or more diseases) by NARS and private seed companies to produce commercial hybrids and open- pollinated varieties.

- Actual/Expected date of work completion: Downy mildew continues to be high priority research problem in Asia and Africa.

Example 2: Pod borers (*Helicoverpa armigera, Maruca vitrata*) of pigeonpea

I. Methods used/developed to research the trait

- To understand problem: Population dynamics, biology, pheromones, field surveys
- To identify/select resistance: split sowings, sowings under protected and unprotected conditions, pod damage, seed damage, yield loss, insect growth and development, and field screening

II. Current state of knowledge of the trait

- Numbers/effectiveness of original sources: PP = 30; CP = 15; *Maruca* (PP) = 5
- Mechanism(s) of resistance/tolerance: Indeterminate/semi-determinate growth habit, pods held separately, flowering pattern, presence of trichomes
- Genetic control of trait: not well known

III. Utilization of trait in breeding programs

- Breeding methods used to transfer the trait: germplasm selection, hybridization, pedigree selection
- Numbers/effectiveness of improved sources: PP = 5; CP = 5; *Maruca* (PP) = 5

IV. Successes achieved and impact generated

- Documentation of traits/methods sources (publications of all types): 10
- Technology exchange/use of results by others: Sources of resistance (ICPL 84060, ICPL 332) have been used by NARS, cv. ICPL 332 released in Andhra Pradesh
- Actual/expected date of completion of work: discontinued 3 yr ago, restarting now.

Example 3: Drought tolerance in Groundnut

I. Methods used/developed to research the trait:

- To understand problem: Drought tolerance described in terms of pod yield as a function of transpiration, water-use efficiency and harvest index

- To identify/select resistance/tolerance: Extensive use of an empirical, field approach, based on a subjecting materials to a gradient of moisture deficit and evaluating genotype ability to maintain both biomass production and partitioning to pods under increasing stress.

II. Current state of knowledge of the trait

- Numbers/effectiveness of original sources: Several sources of tolerance to mid-season and end-of-season drought identified in cultivated groundnut germplasm

- Mechanism(s) of resistance/tolerance: Drought tolerance described in terms of ability to maintain seed yield by maintaining high values of one or more of transpiration (drought avoidance), water use efficiency (drought tolerance) and partitioning to pods (harvest index)

- Genetic control of trait: both additive and dominant for specific leaf area and harvest index

III. Utilization of trait in breeding programs

- Breeding methods used to transfer the trait: Conventional breeding methods (pedigree and bulk pedigree) using empirical, field screening for maintenance of biomass and seed yield

- Numbers/effectiveness of improved sources: 35 new improved sources giving better yield performance under moisture deficit conditions identified

IV. Successes achieved and impact generated

- Documentation of traits/methods sources (publications): 5

- Technology exchange/use of results by others: Resistant sources (5-6) being used by NARS plant breeders in India and West Africa.

- Actual/expected date of completion of work: ACIAR-funded collaborative research on trait-based selection is underway in India, using conventional breeding methods, to evaluate its efficiency for future use.

Sorghum Breeding at ICRISAT during 1972-2000[1]

Belum V S Reddy

I. Introduction

Sorghum improvement at ICRISAT was initiated in 1972 with an objective to improve the genetic potential of sorghum grain and nutritional quality. The thrust on nutritional quality was changed to food quality in 1981. After 1998, management aspects have been envisaged along with genetic options to reduce yield losses due to pests and diseases. Stability of high grain yield with environmental sustainability was the main focus throughout the period.

II. Breeding Processes

Approach: The initial emphasis on wide adaptability was changed to regional adaptation, and to specific adaptation during 80s, and to thresh-hold traits breeding from late 80s onwards (Fig.1). This approach is expected to result in continuous improvement in grain yield, enhanced biodiversity and reduced yield losses due to pests and diseases.

Methods and regional centers: Population improvement methods (PIMs) involving *ms*$_3$ or *ms*$_7$ genes were extensively used along with the evaluation of introductions during wide-adaptability phase at Patancheru. During late 70s and 80s, "geographic functional" regions were identified, and four centers (Wad Medani in Sudan, Camboinse in Burkina Faso, Bulawayo in Zimbabwe, and Nairobi in Kenya) in Africa and two centers (Bhavanisagar and Dharwad) in India were established to provide enough opportunities for selection for specific adaptations and for resistance to specific yield constraints. Trait-based pedigree breeding method was used extensively in various projects aimed to address yield constraints prevalent in the regions (Appendix 1). PIMs were de-emphasized gradually deploying them to gene pools improvement with mass selection towards later part of 80s, as PIMs were resource consuming and the demand for specific adaptation was increasing.

Backcross breeding method was used to convert several tall photoperiod sensitive *caudatums*, a few *guinea* and *kaura* sorghums into short photoperiod insensitive sorghums (1978-85), and the maintainers into new male sterile lines (1977 onwards).

Although variability was significant for grain-food, -malt and -beer making quality traits, these traits were monitored in the advanced lines during early 80s at Patancheru (for grain-food quality traits), and subsequently at Bulawayo (for grain-malt and -beer making traits). Genetic variability was not significant for grain-nutritional qualities (e.g. amino acids balance) and the work was discontinued (Appendix 1).

1. Paper presented to the TAC Review Team on Plant Breeding Methods, 15-17 March 2000.

As the National Agricultural Research Systems (NARS) demands were increasing, and new information and knowledge on breeding materials and tools were available, gradual shift in resource deployment was effected over different methods over the years (Appendix 2).

Target materials: Varieties and hybrids (finished products) were the target materials up to 1990 at all centers. Centers in Africa continue to breed for finished varieties. Patancheru center targeted its research on parental lines after 1990, as the NARS in the region are capable of taking advantage of the parental lines.

III. Results and Discussion

Population improvement methods: Wide adaptability approach coupled with population breeding methods for grain yield initially followed at Patancheru facilitated extensive use of germplasm lines and helped to produce high yielding lines. In US/R and US/B populations, 7-19% gain cycle^{-1} was reported. However, this was accompanied by delayed maturity and increased plant height. Several lines derived from PIMs were released in different countries (e.g. Yuan 1-98, -1-28, -1-505, and Yuan 1-54 in China, Melkamash in Ethiopia).

Pedigree method: This method was followed at Patancheru in Asia, and Wad Medani , Bulawayo, Sotuba and Nairobi in Africa in different projects aimed at breeding for resistance to various pests and diseases.

Entries in the advanced trials represent the dynamics of a breeding program. Performance of a constant control over the years may provide allowance to variations due to years. Differences in the means of top five entries and the constant control are expected to be increased over the years if the breeding program is effective. These differences for grain yield were regressed over the years from 1982-87 for the advanced trials which were composed by including materials from different pedigree based projects. The results showed that grain yield levels observed initially were maintained across all the years later on (Fig. 2). This yield maintenance was accompanied by earliness and reduced plant height. Higher proportion of entries in the trials in 1982 and 83 belonged to the project aimed at high yield, while the projects on yield constraints contributed proportionately more in the later years. It is therefore significant that the yield advantage despite the enhanced emphasis on resistance was maintained. Many trait-based projects contributed to the high yielding varieties (Table 1).

Selection for tolerance to drought stress was compounded with maturity differences leading to negligible genetic gains from selection. This was therefore discontinued at Patancheru. Breeding for drought prone areas is being treated as a part of specific adaptation in other centers in SEA and WCA. Landrace hybrids approach was formulated for terminal drought areas such as postrainy season areas in India where photoperiod sensitivity is required.

The program on breeding varieties/restorers for resistance to *Striga asiatica* was discontinued at Patancheru in about 1980 as the emphasis was shifted to breed varieties resistant to *S. hermonthica* in WCA. The pedigree program for breeding for varieties resistant to insect pests was continued until 1998 at Patancheru. It contributed high yielding shoot fly resistant (Table 1) and midge resistant varieties (ICSV 745, ICSV 88032, etc.). Shoot fly resistance was shown to be season-dependant, which is due to differences in expression of trichomes in different seasons. This finding indicated that selection aimed at shoot fly resistance for rainy season adaptation should be carried out in rainy season, and for postrainy season in the postrainy season.

Initially, attempts were made to breed for grain mold resistance in white grain background capitalizing on the hardness of the grain in *caudatum* background. This program led to the high yielding varieties like ICSV 112, but these are susceptible to grain mold when it rains more. Later on emphasis was given to breeding red grain mold resistant varieties; but the project was discontinued later on. It was shown that mold resistant hybrids may be produced by crossing red (flavan-4-ols) grain females and white hard grain males, both of which are susceptible. Flavan-4-ols and grain hardness inherit as dominant traits, and they together contribute to resistance to molds.

In the regional programs, pedigree breeding method produced varieties which produce grain yield 29 to 43% higher and hybrids 64 to 91% higher than the local control in Western and Central Africa conditions. In Southern Africa, improved hybrids (SDSH 4, SDSH 48, etc.) yielded more than 4 t ha^{-1}, while the control, PNR 8544 produced 3.5 t ha^{-1} grain yield. In Central America, the improved varieties yielded more than 5 t ha^{-1} grain compared to 4.3 t ha^{-1} of the control, PP 290. On the other hand, the improved hybrids produced more than 6 t ha^{-1} while the local produced 5.1 t ha^{-1} (Tables 2 to 6). A separate note on sorghum breeding in Southern and Eastern Africa is filed elsewhere in this volume.

Gene pools: Diversification of breeding materials can be readily brought about by developing and improving populations. Several trait-based populations were developed over the years. There are 33 populations at Patancheru, five at Bulawayo, and three in Sotuba, Mali (Appendix 3). Only a few important trait-based gene pools are being improved through mass-selection.

Backcross method: Many of the partially converted *caudatum* sorghums were highly productive and were used in breeding programs not only at ICRISAT but also in other programs. The converted *guinea* and *kaura* sorghums were not productive and hence the program was discontinued. Backcrossing was also used to introduce rust resistance, tan plant pigment and stay-green traits in M 35-1, a rabi variety in India.

High yielding male-sterile lines were also developed through backcross breeding both at Patancheru in India and also at Bulawayo in Zimbabwe. Male-sterile lines resistant to various stresses (downy mildew, grain mold, leaf blight, anthracnose, rust, shoot fly, stem borer, midge, head bug and *Striga*) were developed (Table 7). These were mostly *Caudatum* based. High yielding *durra*-based male-sterile lines were also developed. Stay

green and sweet-stalk male-sterile lines were also identified. Minimum differential testers to differentiate A_1, A_2, A_3, A_4 systems were identified. Isonuclear lines with A_1, A_2, A_3 and A_4 were developed. A_2 cytoplasm system was found to be less stable for male-sterility than A_1 and A_3. Restorers for non-milo cytoplasm systems (A_2, A_3, and A_4), and dual restorers for A_1 and A_2 systems were also developed. Non-parental 296B single cross male-sterile lines were less sensitive to photoperiod and temperature than 296B *per se* which has seed setting problem in postrainy season. A_1 male-sterile cytoplasm was more susceptible to shoot fly while it was less susceptible to stem borer than its maintainer cytoplasm.

Participatory Varietal Selection and Breeding (PVS and PVB): Two varieties (ICSV 111 and ICSV 400) and two hybrids (ICSH 89002 NG, and ICSH 89009) were released in Nigeria in 1996. PVB is being used to develop high yielding lines and *Striga* resistant varieties in Nigeria. Efforts in participatory research in Mali are already bearing major results in identifying opportunities. Sorghum varieties, Macia and SDSL 89420 have been well received by farmers in Zimbabwe and Mozambique. The note on sorghum breeding in Southern and Eastern Africa provides further details on this subject.

Sources utilized: In various trait-based pedigree breeding programs, a large number of source lines were used in crossing to generate variability. The details are given in Appendix 4.

Spill-overs: Except in high altitude locations in Kenya, Ethiopia, and Zambia, ICRISAT center-bred varieties were significantly superior to the local control in all other regions in Africa, and in Central America. The superiority ranged from 2 to 75% for grain yield (Tables 8 to 13). Within India, the material bred at ICRISAT, Patancheru performed well in different domains (regression coefficient >1.0) (Table 14).

Inheritance studies: Genetics of grain yield, resistance to shoot fly, stem borer, midge, grain mold, downy mildew, leaf blight, anthracnose and *Striga* were studied. Polygenic inheritance with additive and/or additive x additive type of gene action was found in many resistance traits such as shoot fly, stem borer, midge, and grain mold apart from grain yield. For others such as leaf diseases, and grain characters both major and minor genes were involved. Some of the mechanisms contributing to resistance to insect pests (e.g. trichomes), and *Striga* (e.g. Strigol production) were controlled by major genes.

IV. Impacts

The annual rate of increase in sorghum productivity is about 1.1% globally from 1971 to 1999, while it is 0.9% for Africa, 3.9% for Asia and 5.3% for India. Research station trials data in All India Sorghum Program suggested a 2 to 3% annual rate of gain due to breeding. Therefore, 50% of the observed increase in productivity in different parts of the world may be attributed to the improvement in the genetic potential of sorghum. Details on various impacts are given in Appendix 5.

V. Limitations, and Future Plans

The limitations can be: technology transfer constraints, funding constraints, and research areas deficiencies. Lack of sufficient seed production and marketing mechanisms especially in Africa, lack of appreciation of resistance traits, insufficient involvement of farmers in NARS/ICRISAT products development, and lack of government support to coarse cereals *via a vis* fine cereals are some of the technology constraints. PVS, PVB, and project on seed production and distribution will address some of these issues. Deficiencies in research include inadequate exploitation of *guinea* grain and glume characters and antifungal proteins for grain mold resistance, lack of research strategy (such as landrace hybrids) and its implementation for drought prone areas (drought prone areas and "muskwari" areas in WCA and postrainy season areas in India), lack of consistent efforts in breeding photoperiod insensitive sorghums, lack of sufficient efforts to breed large grained parental lines to produce hybrids to meet farmers demands, inadequate use of other races in diversification of breeding materials, little emphasis on improving forage restorers, and large time-lag in applying the new tools such as marker technologies. Concerted efforts are being made to develop new project proposals for attracting special funds.

VI. Acknowledgements

The NARS including private and public sectors contributed to the research and impacts outlined here, and their contributions are very much appreciated. Also, advanced research institutions and funding agencies support is duly acknowledged.

Fig 1. Sorghum Breeding Approach at ICRISAT (1972-2000)

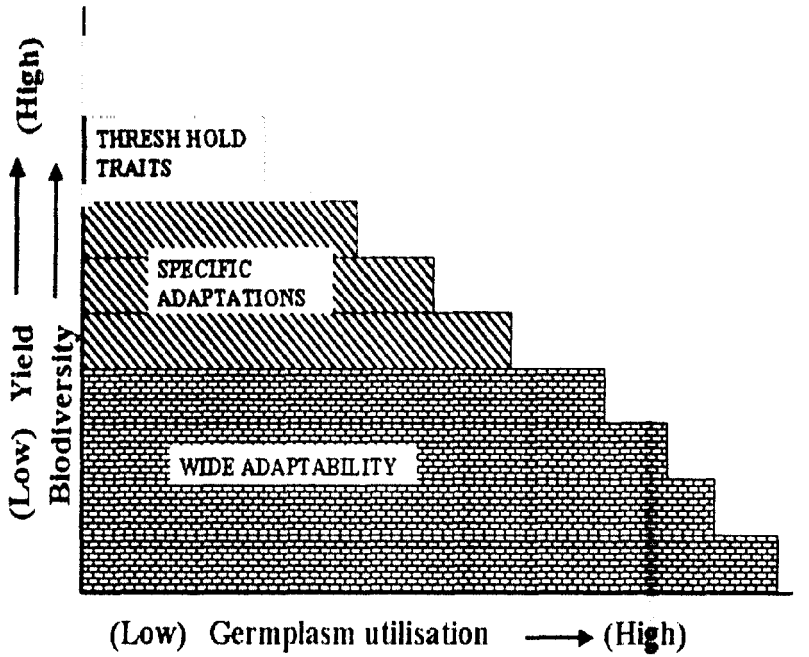

Fig 2. Changes in grain yield (mean of top 5 entries-mean of control) of Sorghum Varieties over years by pedigree breeding method [y= a+bx+cx2+dx3]

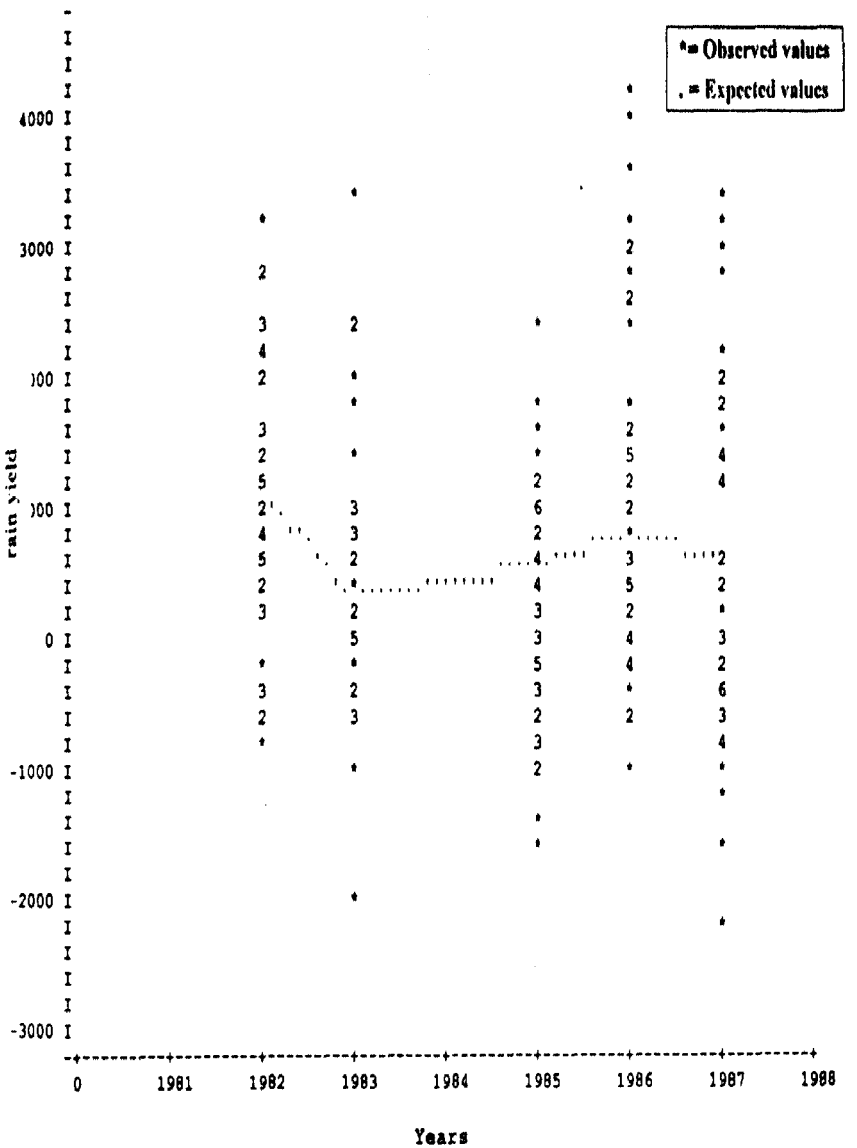

Table 1. Mean grain yield (t ha^{-1}) of selecte sorghum varieties evaluated[1] at India locations, rainy season 1986.

Entry	Project source	Yield[2]
ICSV 295	Drought resistance	4.97
ICSV 298	Drought resistance	4.64
ICSV 272	Drought resistance	4.63
ICSV 273	Drought resistance	4.58
ICSV 233	High yielding	4.93
ICSV 234	High yielding	4.70
ICSV 361	Shoot fly resistance	4.73
ICSV 331	Shoot fly resistance	4.72
Controls		
ICSH 153	High yielding	5.90
ICSV 112	High yielding	4.13
CSH 9	AICSIP - high yielding	5.42
Trial mean		4.32
SE ±		±0.13

1. 6 x 6 triple lattice design.
2. Five locations in India.

Table 2. Mean grain yield (t ha^{-1}) of the highest-yielding early-duration varieties in the West African Sorghum Variety Adaptation Trial[1] (WASVAT) in West Africa, rain season 1988[2].

Entry	Yield[2]
ICSV 210 IN	3.41
ICSV 111 IN	3.27
S-35	3.23
ICSV 1087 BF	3.18
CE 180-33	3.17
ICSV 1078 BF	3.12
Control	
Local	2.37
Mean	2.77
SE ±	0.36

1. Randomized-block design with three replications
2. Ten locations

Table 3. Mean grain yield (t ha^{-1}) of selected hybrids in the West African Sorghum Hybrids Adaptation Trial (WASHAT)[1] in West Africa, rainy season 1988.

Entry	Yield[2]	Rank
ICSH 507	3.32	1
ICSH 330	3.09	2
ICSH 88042	3.03	3
ICSH 88040	2.92	4
ICSH 88038	2.92	5
Control		
Local	1.74	20
Mean	1.87	
SE ±	0.35	

1. Randomized-block design with three replications
2. Seven locations.

Table 4. Mean grain yield[1] (t ha^{-1}) of selecte sorghum hybrids from the SADCC Sorghum Advanced Hybrid Trial (SDAHT) at rain season 1988/89.

Entry	Yield[2]
SDSH 2	4.30(4)
SDSH 4	4.50(1)
SDSH 38	4.22(5)
SDSH 47	4.34(3)
SDSH 48	4.41(2)
Control	
PNR 8544	3.52(14)
Mean	3.8
SE ±	0.1%

1. Nine locations
2. Ranks are in parentheses.

Table 5. Mean grain yield (t ha^{-1}) of the highest-yielding varieties in the 1988 Mesoamerican Sorghum Variety Yield Trial[1] (MASVYT 88).

Entry	Yield[2]
ICSV 112	5.65
M-82080-5	5.48
M-81966-3	5.45
ICSV-LM 86523	5.37
ICSV-LM 86502	5.28
Control	
PP-290	4.26
Mean	4.86
SE±	0.175

1. Randomized complete block with four replications.
2. Seven locations

Table 6. Mean grain yield (t ha^{-1}) of highest-yielding hybrids in the 1988 Mesoamerican Sorghum Hybrid Yield Trial[1] (MASHYT-88) at in Latin America.

Entry	Yield[2]
ICSH-LM 88503	6.49
ICSH-LM 88506	6.25
ICSH-LM 88508	5.94
ICSH-LM 88510	5.84
ICSH-LM 88519	5.79
ICSH-LM 88501	5.79
Control	
Local control	5.14
Mean	5.39
SE ±	0.17

1. Randomized complete block with four replications.
2. Eleven locations

Table 7. Performance of resistant sorghum seed parents

Seed parent	Grain yield (t ha^{-1})	Days to 50% flower	Plant height (m)	Agro-nomic score	Disease(%)/ Pest[1] score
Downy mildew					
ICSB 205	6.3	74	1.4	2.3	0.0
ICSB 213	5.0	70	1.7	2.0	2.0
ICSB 243	4.7	81	1.3	1.7	2.0
ICSB 240	4.4	80	1.4	2.0	4.0
Controls					
296 B	3.3	89	1.1	3.0	100.0
QL3	-	-	-	-	4.5
Mean	3.4	80	1.3	2.4	9.7
SE±	0.30	0.95	0.03	0.13	15.33
Midge					
ICSB 516	4.2	72	1.3	1.7	2.2
ICSB 520	5.2	73	1.4	3.0	2.4
ICSB 493	2.9	72	1.1	3.0	2.7
ICSB 491	5.8	77	1.4	1.7	3.4
Controls					
296 B	3.3	83	1.1	3.0	5.8
ICSV 745	-	-	-	-	3.1
Mean	3.9	75	1.3	2.4	3.3
SE±	0.24	0.90	0.03	0.11	0.177

1= Percentage of plants for downy mildew, 1-9 scale for midge resistance where 1= completely free from midge damage, 9= >80% florets damaged.

Table 8. Grain yield (t ha^{-1}) of top five high-yielding sorghum cultivars along with standar control and local cultivar in Guatemala

Cultivar	Yield	% over local cultivar
ICSH 566	6.21	189
ICSV 725	5.47	167
ICSH 88074	5.36	163
CSH 9	5.14	157
M 82080-5	5.00	152
Controls		
ICSH 110	5.43	165
ICTA 1393 x 200 (LC)	3.28	100
Mean	3.97	
SE ±	0.45	

Table 9. Grain yield (t ha^{-1}) of top five high yielding sorghum cultivars along wit standard control and local cultivar in Egypt

Cultivar	Yield	% over local cultivar
ICSH 798	10.01	139
ICSH 566	9.56	133
STW 5503	8.94	125
ICSH 88056	8.52	119
ICSH 205	8.50	118
Controls		
ICSH 110	9.72	135
NES 1007 (LC)	7.18	100
Mean	7.08	
SE ±	0.51	

Table 10. Grain yield (t ha^{-1}) of top five high-yielding sorghum cultivars along with standard control and local cultivar in Nigeria.

Cultivar	Yield	% over local cultivar
ICSH 88058	6.67	335
ICSV 401	6.24	314
SPV 462	6.10	307
ICSH 807	6.00	302
ICSV 111	5.97	300
Controls		
ICSH 110	5.42	272
Framida (LC)	1.99	100
Mean	5.26	
SE ±	0.54	

Table 11. Grain yield (t ha^{-1}) of top five high-yielding sorghum cultivars along with standar control and local cultivar in Mali

Cultivar	Yield	% over local cultivar
ICSH 566	3.24	164
CSH 9	3.23	163
ICSH 205	3.21	162
85-F4-189	3.17	160
ICSV 725	3.12	158
Controls		
ICSH 110	3.33	168
CSM 417 (LC)	1.98	100
Mean	2.62	
SE ±	0.25	

Table 12. Grain yield (t ha^{-1}) of top five high yielding sorghum cultivars along wit standard control and local cultivar i Zimbabwe

Cultivar	Yield	% over local cultivar
ICSH 88071	5.60	167
ICSV 298	5.54	165
CSV 10	5.21	155
ICSH 401	5.18	154
SDSH 47	5.16	154
Controls		
ICSH 110	5.29	157
DC 75 (LC)	3.36	100
Mean	4.17	
SE ±	0.49	

Table 13. Grain yield (t ha^{-1}) of top five high-yielding sorghum cultivars along with standard control and local cultivar in Kenya

Cultivar	Grain Yield	% over local cultivar
ICSH 310	5.08	178
ICSH 566	4.15	146
ICSH 807	4.01	141
KAT 83369	3.92	138
SPV 462	3.69	129
Controls		
ICSH 110	3.41	120
Sererdo (LC)	2.85	100
Mean	3.10	
SE ±	0.56	

Table14. Estimated spill over matrix for sorghum improvement research at the sorghum domain level (from AICSIP trials data, 1975-1979).

Origin of cultivar	Sorghum Domain where cultivars were tested[1]			
	SD1	SD2	SD3	SD4
SD1	1.00	1.08	1.08	1.12
SD2	0.94	1.00	1.09	1.65
SD3	0.84	0.86	1.00	0.97
SD4	0.82	1.00	0.92	1.00
ICRISAT derived cultivar	1.08	1.11	1.23	1.12
1. SD1-Wide Adaptability; SD2-Dual Purpose, Specific Adaptability, SD3-Early Sowing Rabi, SD4-Late Sowing Rabi.				
Adopted from. Dr Uttam Kumar Dev				

Appendix 1. Major trait-based projects, target materials, duration and executing centers in sorghum.

Project	Target-materials	Approx. duration	Location/Center
Drought	Varieties/Restorers/Hybrids	1977-83	Patancheru
	Varieties/Restorers	1980-continue	WCA/Sudan
Striga	Varieties/Restorers	1975-80	Patancheru
	Varieties/Restorers	1980-continue	WCA (Sudan) and
	Seed parents	1989-96	SEA
			Patancheru
Grain mold	Varieties/Restorers/Hybrids	1975-98	Patancheru
	Seed parents	1989-continue	Patancheru
Charcoal rot/	Varieties/Restorers/Hybrids	1977-81	Patancheru
Stay-green	Varieties/Restorers	1980-continue	WCA and SEA
trait	Seed Parents	1989-96	Patancheru
Downy	Varieties/Restorers/Hybrids	1978-82	Patancheru
mildew	Varieties/Restorers	1986-92	SEA
	Seed parents	1989-96	Patancheru
Leaf blight	Varieties/Restorers/Hybrids	1986-continue	SEA
	Seed parents	1989-96	Patancheru
Anthracnose	Varieties/Restorers	1982-continue	WCA
	Seed parents	1989-96	Patancheru
Shoot fly	Varieties/Restorers/Hybrids	1979-98	Patancheru
	Seed parents	1989- continue	Patancheru
Stem borer	Varieties/Restorers/Hybrids	1979-98	Patancheru
	Varieties/Restorers/	1982-continue	WCA
	Seed parents	1989-continue	Patancheru
Midge	Varieties/Restorers/Hybrids	1979-98	Patancheru
	Varieties/Restorers/Hybrids	1986-92	SEA
	Seed parents	1989-96	Patancheru
Head bug	Varieties/Restorers	1982-continue	WCA
		1986-93	SEA
Grain yield	Varieties/Restorers/Hybrids	1972-90	Patancheru
	Seed Parents	1977-85	Patancheru
	Varieties/Restorers/Hybrids	1986-continue	SEA
	Varieties/Restorers	1980-continue	WCA
	Varieties/Restorers/Hybrids	1978-85	Sudan
High lysine	Varieties monitoring	1973-77	Patancheru
Grain grass	Varieties	1975-78	Patancheru
Early dual purpose	Varieties	1992-98	Patancheru
Conversion	Varieties – *caudatum*	1978-83	Patancheru
	– *guinea/kauras*	1984-88	Patancheru

Appendix 2. Breeding methods and Resources (%) invested over years in sorghum breeding at ICRISAT							
Process	1972-75	1976-79	1980-84	1985-89	1990-94	1995-99	2000-2004
Introduction	20	-	-	-	-	-	-
Population Imp. Methods	80	40	20	10	-	-	-
Pedigree	-	25	35	45	45	25	25
Screening techniques	-	25	-	-	-	-	-
Net working	-	-	35	25	25	15	10
Gene pools	-	-	-	-	10	10	10
Backcross method	-	10	10	20	20	15	10
Biotechnology	-	-	-	-	-	35	40
PVS/PVB							5
Total	100	100	100	100	100	100	100

Appendix 3. Sorghum populations being maintained at various ICRISAT centers.

Population name	Seed available (cycles)	Years of improvement	Seed multi-plied season	Maintained/ Developed at	Original source	Parents incorporated	ms gene	Target traits
US/B	C_0-C_6	1974-84	89R/90R	Patancheru	PP2, PP6, NP2, NP4	296B, 323B, 2219B, 2077B,	ms_3	High yield
US/R	C_0-C_8	1974-84	89R/90R	Patancheru	PP1, PP3, PP5, NP4, NP5, NP8	296B, 323B, 2219B, 2077B,	ms_3	High yield
RS/B	C_0-C_8	1973-84	89R/90R	Patancheru		296B, 323B, 2219B, 2077B, Sel. from US/R-C_t, RS/R, Ind. Syn., FLR_S 101, 274, RS1xVGC, IS_S 12645C, 9327	ms_3	High yield
RS/R	C_0-C_8	1974-83	89R/90R	Patancheru		GGs 370, 1483, Ind. Syn-250, Diallel 876, FLR 101, ISsS 1082, 9327,11758, SPVS 249, 393, 351,475 SARs 2, 4, PS 19230, SB 8104-1, PMs 7348,7349,7061, 7495	ms_3	High yield
FL/B	C_0-C_4	1981-84	89R/90R	Patancheru	NP2, NP6		ms_3	High yield
FL/R	C_0-C_4	1981-84	89R/90R	Patancheru	NP1, NP3, NP4, NP5, NP8		ms_3	High yield
WAE	C_0-C_4	1981-84	84R/90R	Patancheru	S1 Selections from Nigerian, WABC and Bulk Y populations	CS 3541, GG 370, SPVS 86, 422, 424, 393, Ind. Syn-323, ETS 1966, 4789, ISS 6373, 22233, 23555.	ms_7	High yield and photoperiod sensitivity

Tropical conversion	C_0-C_3	1974-76	89R/91R	Patancheru	Puerto rico population and Puertorico early lines	Heterozygous material from BC_1/BC_2s of Puertorrico conversion program crossed to Serere RS population	ms_3	High yield
Indian .Synthetic	C_0-C_1	1979-83	91R	Patancheru		GPRs 370, 148, CSV 4, IS 3691, CK 60B, 2219B, E 35-1, FLRS 101, 266, UChV2, SARs 2,4,6, PMs 7061, 7495, 7348, 7349, PB 8284, PS 19230	ms_3	High yield
Good grain	C_0-C_1	1974-82	91R	Patancheru	Serere	GPR 370 and 120 white corneous sorghums	ms_3	High yield and grain quality
Serere	C_0-C_1	1976	90R/91R	Patancheru	RS5DX, RS5DXCSF, RS1xVGC, Hyd RS	GPR 370 and 120 white corneous sorghums	ms_3	East Africa Adaptation
Serere Elite	C_0-C_1	1976	74R/87R	Patancheru			ms_3	East Africa Adaptation
ICSP1 B/R MFR	C_0-C_1	1984-89	89R/90R	Patancheru	US/R, RS/R, Indian Synthetic.	6 shoot fly, 9 stem borer, 7 midge, 6 downy mildew, 5 leaf diseses, 3 striga, 6 drought, 2 seedling vigor lines.	ms_3	Multifactor resistance
ICSP2 B/R MFR	C_0-C_1	1984-89	87R/89R	Patancheru	US/R, RS/R, Indian Synthetic.	39 temperature insensitivity, 22 photo period sensitivity, 9 shoot fly, 2 striga, 13 rabi breeding lines.	ms_3	Multifactor resistance
ICSP B/R MFR	C_0-C_1	1987-89		Patancheru	ICSP1 B/R-MFR and ICSP2 B/R- MFR	15 shoot fly, 5 stem borer, 7 midge, 6 non sene scence, 29 photo sensitive, and temperature insensitive, 30 bold grain, 17 terminal drought, 9 ms3 rabi adapted	ms_3	Multifactor resistance

						lines, 3 dwarf and early lines		
ICSP-LG	C_0-C_1	1988-	93R/97R	Patancheru	US/B C_6	ISs 80, 808, 2322, 2409, 9761, 9991, 10469, 10513, 14789, 15551, 15594, 16201, 18372, 18729, 18762, 22643, 23891, 23985, 23986, 24737, 33843, 33844, SS 25, 35, ICSV 735, E 36-1, M35-1	ms_3	Large grain
ICSP-HT	C_0-C_1	1994-	94R/97R	Patancheru		A 2267-2, B 24, SSG 59-3, SP 36257, IS 12611, 8 early lines and 3 high tillering lines, 7 sweet stalk lines, 3 sudan grass lines, 3 tall, late maturing tillering lines.	ms_3	High tillering
ICSP-B	C_0-C_7	1994-	94R/97R	Patancheru		10 Bold grain lines, 5 midge resistant lines, 8 dwarf stem borer resistant lines, PS 19349, 47 progenies of QL3 x 296 B	ms_3	Maintainer population, high yield, resistance
Early Dual-purpose		1976		Patancheru	ICSP US/R (DP)	ISs 869, 8101, 18758C-591-T, 18758C-618, 19159, 20545, 22500, 23897, 24335, 24436, HC 260	ms_3	Early maturity purpose
Medium/ Late			90R	Patancheru			ms_3	Mating mating
Early Dual-purpose		1991-97		Patancheru	US/R S_1	12 High biomass landraces - ISs 869, 3496, 8101, 19159, 20545, 22500, 23897, 24335, 24436, 18758C-591T, 18758C-618, HC 260	ms_3	Early maturity

Early Photo-period in-sensitive sorghum population		1996-97		Patancheru	MFR steriles, Russian x bold grain R-lines	CSV 15, SPV 881, AKR 150, ICSV 38, CSV 4, RS 29, CB 43, Seredo, Framida, Naga White, ISs 8744, 8785, 18520, 36571		Photoperiod insensitivity
Conspicum sorghum population		1995-97		Patancheru	Grain mold resistant guinea populations steriles	Conspicum landraces - ISs 7173, 23770, 23773, 23783, 24135, 24173, 24189, 24191, 24196, 24221, 24286, 24296		Yield, yield stability and photoperiod sensitivity
Sudan sorghum population		1995-97		Patancheru	[US/R(DP)C_1 x IS 22500]	ISs 366, 921, 3492, 9884, 13444, 18297, 22500, Ajab-Seido (drought tolerant, grain quality line)	ms_3	Yield and early maturity (<95d), regional adaptation
Indian Diallel		1974-78	90R	Patancheru	45 entries from world collection		ms_3	High yield and regional adaptation
Brown grain		1995-97	90R	Patancheru			ms_3	brown grain
WABC		1973-77	91R	Patancheru			ms_3	Regional adaptation
Bulk-Y		1973-77	91R	Patancheru			ms_3	Regional adaptation
NP10 BR Bulk		1976		Patancheru			ms_3	High yield
High Altitude		1973-76		Patancheru			ms_3	High altitude
Shoot pest	C_0-C_8	1978-	1978-96	Patancheru	Resistant lines from advanced populations - USB/R, RSB/R, FLB/R,	F_2s from crossing among 98 landraces, and 17 breeding lines representing diverse sources for shoot fly and/or stem borer resistance.	ms_3/ms_7	Shoot pest resistance

Serere Tropical					Serere, Tropical Conversion.			
Head pest	C_0-C_5	1985-	1985-96	Patancheru	Resistant lines from advanced populations - USB/R, RSB/R, FLB/R, Serere, Tropical Conversion.	F_2s from crossing among 27 landraces, and 6 breeding lines representing diverse sources for head bug and midge resistance.	ms_3/ms_7	Head pest resistance
Grain mold		1987-97	1984-97	Patancheru	US/R and US/B	58 Mold resistant and 4 susceptible lines, 27 high yielding, and 14 dwarf & early lines.	ms_3	Grain mold resistance
SDSP-Hot/Dry				SEA	TP24R04/TP15R05, TP21RB03, 84PP-19M, PP-19			Regional adaptaion
SDSP-Cool/Dry				SEA	TP24R04/TP15R05, TP8, WAE, KP8			Regional adaptaion
SDSP-Drought conditions				SEA	TP24R04/TP15R05, TP15, TP21RB03, KP9BSO			Drought resistance
SDSP-Broad Adaptation				SEA	TP24R04/TP15R05, TP21RB03			wide adaptability
East African Bulk			87R/90R	SEA				Regional adaptation

Guinea				WCA		13 Guinea lines from West Africa	ms_3	Race based
Caudatum				WCA		12 Caudatum lines with grain mold resistance, mostly colored, from Mali	ms_3	Race based
Guinea-Caudatum				WCA		Selected landraces, improved and adapted high yielding lines and a few resistant sources.	ms_3	Race based

Appendix 4: Resistant sources used in crossing and improved lines identified in sorghum improvement at ICRISAT.

Constraint	Resistance Sources used	Improved Lines	
		R-lines/varities	A/B lines
1. Drought Seedling emergence	IS 301, Naga white, D 71463, D 71464	IS 2877, IS 1045, D 38061, D 38093, D 38060, ICSVs 88050, 88065, SPV 354	VZM1-B, 2077B
Early	ISs 824, 1037, 3477, 8370, 10596, 10701, E 36-1	ICSVs 88056, 88057, 88059, 88063, IS 24025, SAR 35	ICSBs 3, 6, 11, 37, 54, 88001, 2219B
Midseason	ISs 1347, 13441	ICSVs 213, 221, 210, DS 71463, 71464	ICSB s 58, 296B, 2077B
Terminal	DJ 1195, M 35-1, IS 22314, IS 22380, IS 12611, E 185-2	D 38001, D 71283, D 71464, IS 13441	ICSB 17, 296B
2. Acid soils	Real-60, ICARAVAR, SBL 107 and other INTSORMIL Products	A 2267-2, ICSR 91020-1, ICSR 143, ICSV 93042, ICSR 93033, ICSR 102, ICSR 110	ICSB 89002, SPMD 94006, SPA 2-940021, SPA 2-940013, SPA 2-940039, SPAN 94046, ICSB 38
3. *Striga*	IS 18331 (N 13), IS 87441 (Framida), IS 2221, 555, 168	SARs 1, 29,36, ICSVs 697, 760, 761	SRN 4882B, SPSTs 94002, 94006, 94010, 94018, 94026, 94030, 94034
4. Charcoal rot	E 36-1, QL 101, QL 102, QL104	SPVs 504, 86, CS 3541, 20-67	296B, ICSB 17
5. Insects Shoot fly	PS 19349, IS 1082, IS 18551, IS 2146, IS 2205, IS 5604	ICSVs 702, 705, 708, PS 21318	ICSBs 37, 51, 101, 102, SPSFRs 94006, 94007, 94022, 94036, SPSFPRs 94002, 94007, 94012, 94025
Stem borer	ISs 2205, 5604, 1151, 1044, 5470, 2375, 18432	ICSVs 700, 702, 714, 112, ICSRs 7, 38, 63, 125, 89066, PB 14839-1-3	ICSBs 25, 37, 67, 70, 101, 102, SPSBRs 94005, 94011, 94013, 94017, SPSBPRs 94002, 94011, 94013
Midge	AF 28, DJ 6514, IS 12666c, TAM 2566, SGIRL-MR-1(IS 18699)	ICSVs 112, 197, 745, 743, 89057	ICSBs 3, 24, 25, 82, 102, SPMDs 94006, 94010, 94016, 94022, 94025, 94045, 94060

Head bug	Mali Sor 84-2, Mali Sor 84-7, IS 2573C	ICSV 92030, ISs 2761, 9692, 17610, 17645	ICSBs 13, 26, 37, 38, 42, SPHBs 94004, 94007, 94011, 94014
6. Diseases			
Grain mold	ISs 14332, 9225, 9470, 15119, E 35-1, CS 3541	ICSVs 96105, 96094, GM 950187, GM 950199	ICSBs 11, 17, 37, 42, 51, 70, SPGMs 94001, 94002, 94005, 94008, 94011, 94035, 94060, 94073
Anthracnose	ISs 2058, 7775, 3547, A 2267-2, IRAT 204, TRL 74C-57	ICSVs 173, 91020, 91021, 112, ICSRs 91001, 91006, ISs 8354, 6928	ICSBs 91001, 89004, 101, 55, PM 7061A, SPANs 94010, 94021, 94029, 94033, 94035
Leaf blight	A 2267-2, IS 18758, Iss 19667, 19669	ICSVs 1, 120, 138, ICSRs 91022, 91025	ICSBs 26, 53, 88004, 91002, BTX 2755, SPLBs 94004, 94007, 94010, 94023
Rust	A 2267-2, Iss 2816C, ISs 3574C, 13896	ICSVs 91022, 91023, and 197, ICRSs 91027, 91029	ICSBs 3, 11, 22, 70, 72, 101, SPRUs 94001, 94005, 94009, 94011
Downy mildew	QL 3 9IS 18757), Uchv2, SC 414-12, SP 36257, IS 20450	ICSRs 113, 89008, 90003, 90012, 90016, ICSV 91019	ICSBs 11, 37, 51, 88001, 9004, SPDMs 94002, 94006, 94022, 94035, 94060
Ergot	ETs 2454, 3135, 3147	ICSRs 64, 160, 89014, 89049, 89067	ICSBs 12, 15, 18, 70, 84, 101, 88001, 88009, 88015

Appendix 5. Impacts of ICRISAT/NARS's sorghum research - Abstract

Sorghum area in the world has increased from about 42 million ha in 1971-75 to 45 million ha in 1996-99, and grain production from about 50 million t to 66 million t during the same period. The annual rate of increase in the world acreage is 0.4% while production increased by 1.8%. The world annual rate of increase in productivity is 1.1%, while it is slightly less in Africa (0.9%), the target area of the research. The highest rate of increase in productivity is recorded in India (5.3%). Asia which includes India recorded 3.9% annual rate of increase in productivity. The rate of decrease in area in Asia is 0.7%, while it is 1.4% annum^{-1} in India. As a result, India is able to give up nearly 4.4 million ha and Asia 5 million ha areas of sorghum to other crops while maintaining sorghum production higher than that in 1971-75 when ICRISAT was established. The increased sorghum area in Africa (2.8% annually) coupled with increased productivity (0.9% annually) enhanced the total production by 3.8% annually in Africa signifying its contribution to African economy. About 50% of the increase in productivity in Africa and Asia, the target mandate areas of ICRISAT may be attributed to the improvement in the genetic potential of sorghum.

A total of 105 cultivars developed by ICRISAT and NARS were released all over the globe. The releases are: 55 in Africa, 29 in Asia (16 in India), 20 in Central America, and 1 in Europe. Most of the cultivars released were based on grain yield while one was for drought tolerance, one for midge resistance, two for head bug resistance, one for stay green, five for *Striga* resistance, and one for postrainy season adaptation.

Sorghum variety, S 35 which began diffusion in 1986 in Cameroon and in 1990 in Chad showed varying adoption ranging from 12 to 15% in Cameroon and 5 to 39% in Chad. It had a significant impact in terms of unit cost reduction at the farm level and adding value to food security during drought years. A yield differential as high as 600 kg ha^{-1} was noted in Cameroon. Its introduction into drought prone areas of Chad has been very successful with a net present value of research investments estimated at US $15 million representing an internal rate of returns of 95%. Although, the sorghum variety, SV2 released in Zimbabwe in 1987, it showed a rapid rise in adoption from 1991 onwards to reach 36% in 1994. The estimated internal rate of returns was 26% (with the use of fertilizer) and 22% (without the use of fertilizer).

The adoption of different varieties (Tiemarifing, CSM 63-E, CSM 388, CE 151, Siguetana, ICSV 1063 BF and ICSV 1079 BF) in West Africa ranged from 20 to 30% with an average yield advantage of 52%. The net present value as measured by the study was US$ 6.9 million. The dual purpose varieties (ICSV 112 and ICSV 745) introduced in Warangal district, A.P., India with yield advantages ranging from 29% in sole and 56% in intercropping produced income higher by 13% in ICSV 112 and 58% in ICSV 745.

Several ICRISAT-bred lines are contributing to the specific traits improvement in Queensland Department of Primary Industries research in Australia. These are: midge resistance, white grain color, tan plant color and stay-green trait. Two percent of F_2 populations and 14% of F_3 progenies contained ICRISAT-bred lines as parents. Four

lines in F_4 and one line in F_5 contained ICRISAT-bred lines as parents. Pioneer Seed company sorghum program also used several ICRISAT bred midge resistant lines. There are now 66 F_4 and F_5 progenies with an average infusion of 13% of ICSV 197. Further, the male-sterile breeding program for dual-purpose or forage sorghum contains about 10% ICRISAT infusion, and the restorer program about 13-15% infusion. Pioneer expects to release a commercial hybrid from ICRISAT materials in 2-4 years. Total expected value of ICRISAT contribution to the Australian economy is estimated to be 4.7 million Australian dollars.

Similarly, in India, various private sector seed companies have been using ICRISAT seed parents. For example, JKSH 22, the hybrid developed by J K Agri-Genetics, Secunderabad, India based on ICRISAT parental lines has been notified by Government of India for release to farmers in 1999. The company has been marketing it since 1997 and each year, more than 120,000 ha area is being cultivated in India..

Further 52 NARS scientists were trained in sorghum breeding from 1974-99. Of these 32 were visiting scientists, 4 research scholars - M.Sc, 3 research scholars - Ph.D., 7 in-service short-term trainees and 6 apprentices.

Pearl Millet Breeding Methods

K N Rai

Pearl millet is a highly cross-pollinated crop. It displays a high degree of heterosis for grain and fodder yield. Also, several economically viable CMS systems have been identified in this crop. These basic biological features put pearl millet in an extraordinarily interesting position for research and developmental activities related to various cultivar options, which include open-pollinated varieties (OPVs) and four different types of hybrids: single-cross (SCH), topcross (TCH), three-way (TWH) and inter-population hybrid (IPH). It is with these cultivar options in mind that we have conducted research and demonstrated applications of almost all the text book breeding approaches. The relative emphasis on various breeding approaches has greatly varied, however, depending upon the target end-products. For instance, where development of OPVs has been the main objective, the major emphasis has been on recurrent selection in constructed populations: backcross breeding, selection within landraces and participatory breeding approaches have also been followed. In contrast, where development of hybrid parents has been the major objective, it is the pedigree breeding which has been most used: substantial amount of backcross breeding has also been done. In fact, even mutation breeding, presenting a one-time event, has been successfully done to solve a specific disease problem.

Selection within landraces

is selection approach has been mostly used in our programs in Africa, the more so in the SADC region. Selection for grain yield within the landraces has not been successful, perhaps due to limited variability for yield components. Selection, done mostly for phenotypic uniformity, earliness, high downy mildew (DM) resistance and elimination of *shibras*, has been successful One of the most successful stories of an OPV developed from a landrace cultivar is that of ICTP 8203, selected from an *iniadi* landrace originating from northern Togo. It has not been verified whether ICTP 8203 had significantly higher grain yield over its parental landrace population (perhaps it did not), but it definitely had improved levels of DM resistance and morphological uniformity. This OPV, released in 1988, rapidly replaced the then leading commercial hybrid (MBH 110) in Maharashtra that had become highly DM susceptible in 1989-90. At the time of its peak adoption in 1992, ICTP 8203 was grown on more than 0.6 million ha (about 40% of the total pearl millet area) in Maharashtra alone, and it still continues to be cultivated on about 0.3 million ha. Inbreeding and selection within the same landrace population led to the development of maintainers of two male-sterile lines (863A and ICMA 88004), which are seed parents of some of the popular hybrids grown in India. The success of ICTP 8203 played a catalytic role in further development and release of *iniadi* germplasm-based OPVs, such as ICMV 221 in India and Eritrea, Okashana 1 in Namibia and GB 8735 in Chad, Mauritania, Benin, Niger and Mali.

Population improvement

ICRISAT has been a leading research center in population improvement. Since its inception, about 60 composites (including their upgraded versions) have been developed and improved for one or more selection cycles. Forty of these were developed at Patancheru and 10 each in the SADC and WCA regions. Almost all the OPVs (released or in pipeline) have been developed following this method. A detailed evaluation of four ICRISAT-Patancheru composites improved for more than three cycles showed 1 to 5% per cycle genetic gain for grain yield. This rate of genetic gain is similar to those reported for maize in the USA.

Various selection methods (and a combination of them) have been used in population improvement in all the three locations. A comparison of six cycles each of Gridded Mass Selection (GMS), Recurrent Restricted Phenotypic Selection (RRPS), and Full-sib Progeny selection (FS); and three cycles of S_2 Progeny selection in the World Composite at Patancheru showed that except for RRPS, which did not lead to any yield gains, the other three methods were equally effective. This confirmed an earlier conviction that RRPS is not an efficient method for grain yield improvement. It also showed that the choice amongst the other methods will depend on several other factors, which may be as important or even more important than the efficiency of a method. These include breeding objectives and time frame, material and manpower resources, field uniformity, maturity of the composite, genetic architecture of the composite, and last but not the least, breeder's skills and conviction. Thus, ICRISAT-Patancheru follows mostly FS selection, ICRISAT-Zimbabwe mostly a combination of FS and GMS, and ICRISAT-Niger, mostly Half-sib and S_1 (S_1 and GMS for cleaning some established farmers' varieties for *shibras* and contaminants to rebuild the original structure of these varieties).

A diverse range of high-yielding OPVs have been produced at all three ICRISAT locations. These include 16 OPVs in the SADC region and 12 each in the WCA and at Patancheru, most of which are released and some are in the pipeline. It has also been observed that introgression of improved breeding materials into composites is as effective for grain yield improvement as the cyclic gains from recurrent selection. Further, considering the grain yield advantage of hybrids over OPVs (see below), there has been an increasing emphasis in recent years on hybrid and hybrid parents research at all three locations. The thrust in the future, therefore, would be on evaluating and utilizing the existing OPVs for hybrid parents development, and building up resistance and adaptation traits in promising OPVs (e.g.,stalk strength in the OPVs in the SADC region; and Striga resistance and P-use efficiency in OPVs in WCA). New populations, however, will be developed for the western Rajasthan (where little impact has occurred) and these will be improved for grain yield, DM resistance and male fertility restoration by recurrent selection and introgression.

Pedigree/pedigree bulk breeding

It is the most common method of hybrid parents development in all the three locations, as is the case in other crops around the world. The basic philosophy behind this approach is "to build on lines of proven worth rather than explore something new of unknown merit". The complementarity between existing commercial A-lines and R-lines plays a decisive role in pursuing the above philosophy. Also important is the morphological diversity of acceptable plant architecture, which may not be directly available in composites that had been primarily constituted for breeding OPVs. New germplasm for this breeding method is sought with a view to trait upgradation and deficiency correction such that they are non-disruptive of co-adapted complexes.

Pedigree and pedigree bulk breeding has led to the development of more than 1400 diverse restorers and more than 60 male-sterile lines at Patancheru alone. Some of these lines are directly or indirectly involved in several commercial hybrids of NARS, which cover about 4.5 out of 5.5 million ha area under pearl millet hybrids in India. Promising male-sterile lines have now been developed by our two programs in Africa. In these two locations, there is much less emphasis on breeding R-lines as the initial thrust is on breeding topcross hybrids. A diverse range of promising OPVs are now being evaluated for heterotic patterns and hybrid potential, and some of these are being already

introgressed into dwarf background (e.g., ICMR 312 and MC 94 as sources of large grains and medium-long panicles, and SRC II and ICRISAT-Nigeria composite progenies as sources long-thin-compact panicles). Exploration of additional germplasm sources has also started (e.g., photoperiod-sensitive germplasm from Benin for very large grains, Zongo germplasm from Niger for very long panicles, and high-tillering genepool for high tillering combined with high biomass and greater stalk strength). These converted materials will eventually be channelized into pedigree breeding of hybrid parents, mostly by breeding program in NARS

Very little use of pedigree breeding has been made in developing OPVs. However, some very promising OPVs were developed using this method. The earliest example of this is a synthetic (ICMS 7703) developed at Patancheru in late 1970s. Two popular OPVs (GB 8735 and ICMV IS 89305) were developed by our program in Niger using this breeding approach. Pedigree/pedigree bulk breeding will continue to be the major breeding approach for hybrid parents development. Diverse potential B-lines developed will also be used to constitute trait-specific B-composites, which will serve as sources of variability to meet long-term hybrid parents breeding requirements of NARS.

Backcross breeding and biotechnology

Substantial application of this method has been made in pearl millet improvement at ICRISAT. Considering the nature of the material under backcross breeding and its objective, two broad categories of this breeding method can be recognized: (i) limited backcross breeding (ii) full backcross breeding.

In the limited backcross breeding program, generally BC_1 to BC_3, the objective is to recover a major proportion of the germplasm of the recurrent (recipient) parent along with the donor gene(s). The first major effort in limited backcross breeding was at ICRISAT-Patancheru during the late 1970s and early 1980s to mobilize seven tall composites into dwarf background. This approach is currently being used to mobilize two tall populations into dwarf background and *bmr* gene into adapted OPVs in Niger. It is also being used to mobilize four country-specific photosensitive gene pools into insensitive background, and to convert some promising OPVs into white grain and bristled versions at Patancheru. Considerable use of this breeding method has been made in our SADC breeding program as well.

In the full backcross breeding approach (BC_7 and beyond), the objective is to recover almost all the germplasm of the recurrent parent along with the donor gene(s). Its first successful demonstration was to develop early-maturing and photoperiod-insensitive (e_1e_1) version of a dwarf pollinator (ICMP 85410), which has good general combining ability for grain yield and also high DM resistance. More than 50 elite inbred lines (restorers of A_1 CMS system) from ICRISAT-Patancheru and collaborating institutes from India are currently at various backcross stages to develop their restorer versions for A_4 and A_5 CMS systems. This breeding method is likely to be increasingly used, first for molecular marker-assisted selection (MAS) of DM resistance QTL, and then later for other traits as QTL for these are identified. The MAS technique promises faster backcross breeding and more effective gene deployment.

In pearl millet, there is another class of backcross breeding that relates to conversion of maintainer lines (B-lines) into A-lines. This type of backcross breeding is rather simpler to do, provided the cytoplasm being incorporated into backcross progenies has stable male sterility. This approach appears to be more successful with the A_4 than with the A_1 CMS system because A_4 CMS system is more stable for its sterility and relatively higher frequency of inbred lines is its maintainers.

Mutation breeding

Following the DM epidemic in India, mutation breeding was used to fulfill a vital need of obtaining a DM resistant seed parent to ensure the continuity of hybrid development and their cultivation. Application of this method in 1975 led to the development of a highly DM resistant A-line (81A) from a gamma ray-irradiated highly susceptible dwarf stock (Tift $23D_2B$). The line 81A has been extensively used in India for hybrid development. An ICRISAT-bred hybrid (ICMH 451) on this line was grown on more than one million ha at the time of its peak adoption in 1989-90, and it is still widely grown. This breeding method was a one-time successful event. Mutation breeding is unlikely to be used at ICRISAT in the future because (i) it is difficult in a cross-pollinated crop to be sure about the origin of an induced mutant, and (ii) there is large natural variability in pearl millet for almost every trait, except for characters like resistance to *Striga* and some insect pests.

Participatory breeding

It is being increasingly realized that with the diverse and changing socio-economic conditions and food habits of the farmers and consumers, with changing and alternative grain uses, and with the on-station resource limitations in research programs, all players (scientists, extension workers, farmers, and processors) should work in a participatory mode of breeding, right from the goal and priority setting to the seed production stage, especially when a cultivar of a new characteristic is envisaged for a target environment. This requirement, however, has to be kept in balance with varied responsibilities of scientists and technicians, and a distinction between participatory breeding and participatory varietal selection needs to be clearly understood. It is nevertheless, clear that farmers' perceptions (with periodic updating) should be taken into account to ensure the likelihood of end-product acceptance.

Farmers participatory varietal selection, and to some extent participatory breeding, has been largely done in Rajasthan and in the SADC and WCA regions. Farmers participatory varietal selection led to quick acceptance of ICTP 8203 in Maharashtra, Okashana 1 in Namibia, and GB 8735 and SOSAT-C88 in several WCA countries. In Nigeria, farmers in several villages have been involved even in Gridded Mass Selection.

Seed parents research and development

All the three ICRISAT locations are lead centers in this research area in their respective regions, although in African locations, this is a relatively recent and exploratory activity of more applied nature. At Patancheru, the applied and strategic researches have received almost equal emphasis. Thus, about 60 A-lines and hundreds of seed parents progenies of diverse morphological characteristics have been developed and disseminated to NARS, mostly in India. As a result, more than 70% of the commercial hybrids in India use either ICRISAT-bred A-lines, or they use their own

A-lines that involve ICRISAT-bred seed parents progenies in the parentage. Development of A-lines for the SADC and WCA regions will be further strengthened. At Patancheru, there will be greater emphasis on technology demonstration (e. g., utility of A_4 cytoplasm in A-line breeding, utility of A_5 CMS system in hybrid breeding strategy, utility of trait-specific B-composites etc.) with applied aspects mostly devolved to NARS.

The strategic research has concentrated in searching and characterizing diverse and stable CMS sources, and evaluating the feasibility of F_1 seed parents (for three-way hybrids) and population seed parents (for inter-population hybrids). Three distinct and stable CMS sources have been identified/assembled. Their relative utility continues to be under evaluation for the stability of male sterility, (2) maintainer gene frequency in the germplasm, (3) genetic background effect , (4) fertility restoration behavior, and (5) character association. For this, we have already developed isonuclear A-lines in diverse genetic backgrounds. Double restorers have also been identified and triple restorers are being developed.

A-lines are generally used for producing single-cross hybrids. Topcross hybrids are considered to be of immediate utility, especially in drier parts of western Rajasthan and in the SADC and WCA regions. It has been observed both in India and in WCA that the use of high yielding composites and landraces as pollen parents on some of the existing A-lines can produce topcross hybrids with significantly higher grain yield than the populations themselves. A large data base of topcross hybrid ICMH 312 (not released, yet cultivated in parts of Maharashtra) and topcross hybrid GICH 501 (released, but yet to be commercialized) showed that these both hybrids yielded as much as (or slightly more than) the highest-yielding single-cross hybrid ICMH 451. These both topcross hybrids were similar to ICMH 451 for maturity and plant height. This is indicative of yield advantage of topcross hybrids. Moreover, once a high-yielding topcross hybrid combination is identified, there may be a good possibility of raising its yield level by doing recurrent selection in the OPV for specific combining ability.

The potential of F_1 seed parents (for producing three-way hybrids) has been evaluated. Results of a detailed study showed that F_1 seed parents had three potential advantages over inbred seed parents (A-lines). They gave 64 to 107% more grain yield than their higher-yielding inbred parental lines in those cases where inbred parental lines were unrelated. F_1 seed parents flowered generally as early as the early-flowering inbred parental lines and their height was in acceptable range (<1.5 m) in d_2 dwarf background. Also, the F_1s had DM resistance levels comparable to their most resistant inbred parental lines. As parents, therefore, F_1 seed parents have good potential of being used in three-way hybrids, provided the variability within three-way hybrids can be acceptable to farmers. Another aspect that needs to be evaluated is the cost of seed production of three-way hybrids as compared to topcross hybrids.

Looking a step further, we examined the possibility of inter-population hybrids. Research shows that inter-population hybrids can give up to 50% more grain yield than their higher-yielding OPV parents. This order of grain yield advantage in inter-population hybrids makes them an economically attractive proposition. Other advantages include higher seed yields of both parental lines (OPVs yield more than inbreds) and more stable DM resistance. The main issue then remained how feasible would it be to breed a male-sterile population. Using NCD_2 population and A_4 CMS system as a test case, we showed that two cycles of recurrent selection were effective in converting NCD_2

into a nearly complete maintainer version. While the NCD_2 was being improved for male sterility maintenance ability, we used a side car method for its conversion into a male sterile population. Results showed that even a third backcross population with the A_4 cytoplasm (NCD_2A_4-BC_3) had as high and stable male sterility as the two commercial A_1-system A-lines ($81A_1$ and $841A_1$). Thus, it is possible to breed stable population seed parents for use in breeding inter-population hybrids.

Restorer parents research and development

Restorer development is relatively easier business than seed parents development, with the extreme case being restorer parents of topcross and inter-population hybrids, which are simply OPVs with enhanced levels of male fertility restoration. Further, almost all the hybrid breeding programs in India have their own good restorer line collection. It is due to these factors that ICRISAT conducted much less research in this area: rather the thrust was on developing and disseminating a diverse range of DM resistant restorer lines. As a result, more than 1400 inbred lines were developed as restorers of the A_1 CMS system. There are indications that 10-20% of these lines will be restorers of the A_4 CMS system as well. The current emphasis at ICRISAT-Patancheru is to convert about 50 elite inbred lines into A_4 and A_5 restorer versions as technology demonstrations as well as to provide useful restorers to NARS for utilization in breeding A_4 andA_5-system hybrids. Another aspect of restorer development being emphasized is to determine heterotic patterns among high-yielding OPVs to identify complementary populations for hybrid parents development. In the meantime, inbreeding and selection in collaboration with NARS in some of these OPVs will be initiated for developing restorer lines from newer, diverse and more productive OPVs.

Chickpea breeding at ICRISAT

Jagdish Kumar

Introduction

Chickpea (*Cicer arietinum* L.) is the third most important food legume grown in 11 m ha with 9 m t production. It is grown in nearly 50 countries in all continents of the world. It provides a high quality protein to the people in developing countries. Two main types are recognized. Desi type with small and brown seed accounts for 90% of the cultivated and kabuli type with bold and cream-colored-seed, is grown in about 10% area. Nearly 90% of the crop is cultivated rain-fed, mostly on receding soil moisture and on marginal lands.

Potential seed yield in chickpea up to 6 t ha^{-1}. The realized seed yield of 850 kg ha^{-1} is a result of lack of widely adapted cultivars and susceptibility to several biotic and abiotic stresses. Generally the crop produces excessive vegetative growth under high input conditions and is unable to convert the bio-mass into high seed yields.

The crop is self-pollinated. Genetics of the crop is not well investigated. Efforts to investigate variability through molecular markers and to develop a genome map have recently been initiated.

ICRISAT has global mandate for chickpea improvement. In 1978 ICARDA was given a regional mandate to improve kabuli chickpea in the West Asia and North Africa (WANA) region. The two institutes collaborate on characterization of chickpea adaptation and molecular marker work.

The major abiotic constraints to production identified include drought, heat, cold and salinity and biotic constraints are fusarium wilt, ascochyta blight, rhizoctonia dry root rot, botrytis gray mold and chickpea stunt.

The objectives of chickpea improvement at ICRISAT are to assist NARS to widen the genetic base, enhance resistances to biotic and abiotic stresses, extend cultivation to newer areas and cropping systems, increase knowledge base and apply modern science to achieve all the above objectives.

Breeding methods

Pedigree, bulk, modified bulk-pedigree, back cross, single seed descent (SSD), selective random mating and mutation breeding methods have been used. We found pedigree, modified bulk and single seed descent methods more useful.

Accelerating plant breeding process through rapid generation turnover has been done. Off-season advancement was done at Lahaul valley in Himachal Pradesh, at Tapperwaripora in Jammu and Kashmir and at Patancheru (under rainout shelters). We can now grow upto four

generations a year with extended daylength at Patancheru. Chickpea growth room, growth chambers and glasshouses are used for specific screening and evaluation.

The breeding work was initiated at ICRISAT in 1974 and major emphasis was to attempt crosses among germplasm lines received from diverse regions. Constraints to productivity and sources of resistance were identified. Increased use of sources of resistance was made to generate segregating populations and advanced breeding lines. Early generation bulked populations and advanced breeding lines were distributed to NARS as part of the international nurseries and trials network. The feed back helped understand the constraints better, and hybridization was further refined. The progress made in the past 25 years, lessons learnt and recent changes in the research focus are described in the following sections.

Progress and achievement

A large number of germplasm accessions were collected from various parts of the world. Crosses were made to widen the genetic base, incorporate resistances to important biotic and abiotic stresses. Use of single- three-way- and multiple-crosses indicated that generally three-way crosses were more productive possibly because the third parent is usually an adapted variety.

To meet the requirements of diverse adaptation needs of NARS chickpea improvement programs, efforts were made to carry forward as much variation as possible through bulk advancement of individual crosses.

It was expected that desi-kabuli introgression will increase variability however, strict requirement for two types of the seeds reduces the size of segregating populations. Shuttle breeding program between short duration (Patancheru, 17^0 N) and long duration (Hisar, 29^0 N) environments was practiced during 1975 to 1990. A limited success was obtained, e.g., ICCV 10 which was released in India and Bangladesh. However, strong G x E interaction showed that we obtained a much larger progress with breeding for specific adaptation.

For fusarium wilt resistance a major break through was made when three complementary genes h_1, h_2, and H_3 were identified to confer complete resistance to race 1. (Table 1) Thus resistance to this disease is working well. However, there are races of this pathogen. Two genes were found to confer resistance to race 2. Using molecular markers it was found that genes for various races to Fusarium wilt are clustered on linkage group 6. Fusarium wilt resistant breeding material is routinely supplied to the NARS.

Limited resistance to dry root rot, stunt disease, and ascochyta blight has also been found. Much more needs to be done. There is negligible success with botrytis gray mold and helicoverpa pod borer and we look towards molecular tools to assist here.

Investigations on drought led to the identification of large root trait as a means of tolerance. Modification of crop ideotype (e g. small leaf size and a fewer number of pinnules) has been attempted through back crossing. Tolerance was identified to chilling temperatures. However, much variation could not be identified for resistance to heat and salinity.

Reduction of time to flowering and maturity has made a major contribution towards increasing and stabilizing chickpea productivity in the tropics. This was done through identifying a major gene *efl*-1 for earliness. So far more than 50 short-duration and fusarium wilt resistant cultivars have been released by national programs in several countries. Evolutionary history was made when kabuli adaptation was extended to the tropics with the release of ICCV 2 as Swetha in Andhra Pradesh.

It is obvious that chickpea-growing season is too long in the sub-tropics also. Our efforts to reduce maturity by the use of *efl*-1 gene were not successful. We have recently introduced tolerance to chilling to make this gene effective. Extra-short duration chickpea genotypes developed this way have reduced crop duration from 160 days to less than 130 days. These genotypes are under experimental observations.

Short-duration cultivars are making a large impact in extending chickpea cultivation to rice-fallows. Nearly 14 m ha rice fallows exist in South Asia. In collaboration with Bangladesh and IRRI, ICRISAT has been involved in chickpea expansion in Barind region of Bangladesh. Recently DFID, UK has approved funding for two chickpea projects for rice fallows in Bangladesh and in other countries of South Asia. DFID has also offered to fund a farmers participatory breeding program to incorporate earliness through ICCV 2 crosses for use in Gujarat, Rajasthan and eastern India.

Future

In recent times focus of research has changed to more basic and strategic aspects. Much effort is being made for developing genetic populations for studying inheritance, determine linkage groups and ultimately develop a genome map of chickpea. It is hoped that use of molecular tags to breeding difficult-to-evaluate traits, such as root volume will be more effective than conventional methods. This will also facilitate pyramiding of genes for single and multiple traits. Greater use of wild species genes is being emphasized. Increased collaboration in molecular technology with advanced research organizations is being sought. It is hoped that these developments will enhance the pace of progress for higher yields and stable performance of chickpea in the near future.

Table 1: The genetic constitution and wilt reactions of chickpea cultivars

Cultivar	Genetic constitution	Wilt reaction
JG 62	$H_1 H_1 H_2 H_2 h_3 h_3$	Early-wilting
K 850	$h_1 h_1 H_2 H_2 h_3 h_3$	Late-wilting
C 104	$H_1 H_1 h_2 h_2 h_3 h_3$	"
H 208	$H_1 H_1 H_2 H_2 H_3 H_3$	"
WR 315	$h_1 h_1 h_2 h_2 h_3 h_3$	Resistant
CPS 1	$h_1 h_1 h_2 h_2 h_3 h_3$	"
P 436-2	$h_1 h_1 h_2 h_2 h_3 h_3$	"
BG 212	$h_1 h_1 h_2 h_2 h_3 h_3$	"
JG 74	$h_1 h_1 h_2 h_2 h_3 h_3$	"

Groundnut Genetic Enhancement at ICRISAT: A Brief Review

S N Nigam

Groundnut (*Arachis hypogaea*), a native of South America, is an annual legume and is grown primarily for its high quality edible oil and protein in seed. Groundnut haulm is used as fodder in dry areas. Groundnut cake, obtained after extraction of oil, is used in animal feed industry. It's an income-generating crop and plays an important role in rural economy in the semi-arid tropics. Groundnut is grown on 24.8 million ha worldwide, with a total production of 32.8 million tons and average productivity of 1.32 t ha^{-1} More than 100 countries in the world grow groundnut crop. Since 1988, the groundnut area in the world has increased at an average annual growth rate of 1.8%, production at an annual growth rate of 3.3%, and productivity at an annual growth rate of 1.5%. Asia has contributed most to these growth rates. However, the crop is not comfortable at its home turf in South America, where both area and production have declined in spite of an increase in productivity.

Groundnut is grown in a range of farming situations varying from subsistence agriculture to high input management systems. However, under all the farming situations, the gap between potential yield and the realized yield remains large due to several biotic and abiotic constraints that affect groundnut productivity. Some of these constraints are wide spread and some others are region specific. Major constraints to groundnut production are foliar diseases (rust (*Puccinia* arachidis), late leaf spot (*Phaeoisariopsis personata*), early leaf spot (*Cercospora arachidicola*)), aflatoxin contamination of seed by *Aspergillus flavus,* virus diseases (peanut bud necrosis, peanut clump, peanut stripe, groundnut rosette), bacterial wilt (*Ralstonia solanecearum*), insect pests (tobacco caterpillar (*Spodoptera litura*), red hairy caterpillar (*Amsacta albistriga*), groundnut leaf miner (Aproaerema *modicella*), Aphids (*Aphis craccivora*), thrips, jassids (*Empoasca kerri*), white grubs, termites), drought, and low soil fertility.

Botany and genetic variation

Cultivated groundnut, an allotetraploid (with 2n=40), belongs to genus *Arachis* and species *hypogaea*. Species *hypogaea* has two subspecies, *hypogaea* and *fastigiata.* The former in turn has two varieties, *hypogaea* and *hirsuta* and the latter four varieties, *fastigiata, peruviana, aequatoriana,* and *vulgaris*. It's a highly self-pollinated crop due to cleistogamous nature of its flowers. Genetic variability in cultivated groundnut is difficult to detect by use of isozymes, RFLPs, and RAPDs. Because of the very limited DNA polymorphism observed among cultivated groundnut varieties, it is believed that the domesticated species originated from a single hybridization event, which was followed by polyploidy. Very little subsequent introgression from related diploid species has occurred. However, abundant morphological variation is present in the species. ICRISAT gene bank at Patancheru houses a collection of over 15000 *A. hypogaea* and 450 wild *Arachis* species accessions.

Breeding Methods

Like any other self-pollinated crop, the breeding methods in groundnut have not changed a great deal over time. These include direct introductions, mass or single plant selection in introduced materials, and hybridization followed by selection using mass or bulk, pedigree, single seed descent (SSD), and recurrent selection methods. In addition to germplasm, natural hybrids, mutations, and interspecific crosses have provided additional avenues of genetic variation for exploitation by the breeders. Tissue culture and embryo rescue techniques have been employed to access genes from incompatible wild *Arachis* species. Among the conventional methods of breeding, pedigree method is most frequently used in national programs, which have a well-defined geographical mandate. However, in international programs with mandate to provide improved breeding materials globally, bulk method of breeding is often resorted to ensure enough residual variability in breeding populations for exploitation by the scientists in national programs. In cases where national programs have strong breeding component, early generation segregating populations and SSD derived populations are also supplied. Lately, backcrossing method of breeding is increasingly used as simply inherited traits of economic are being discovered.

New tools in genetic enhancement include genetic transformation and molecular marker technology. Transgenic groundnut plants with virus coat protein genes have been produced and are currently under tests in containment facilities. In spite of large morphological variation for various traits, not much DNA polymorphism has been detected in cultivated groundnut. Newer tools are needed to develop and promote use of molecular marker technology in genetic enhancement of groundnut.

Genetic enhancement in groundnut at ICRISAT

Genetic enhancement in groundnut started in 1976 at ICRISAT. Two breeding approaches were adopted to address the issues of generally low realized yields and the large gap between the potential yield and the realized yield under all farming situations. For subsistence farming systems, where yields are low and unstable and the yield gap wide, the major emphasis was placed on resistance breeding. For high input farming systems, where yields are generally high and the yield gap narrow, increasing yield potential and seed quality received major attention. As in subsistence farming several constraints operate together; the aim was to combine moderate levels of multiple resistances into superior agronomic backgrounds in resistance breeding. In case of viruses, where plant death is involved, a higher degree of resistance was aimed at.

A massive exercise was mounted at the onset of the program to assemble available germplasm including wild *Arachis* species from various sources. Simultaneously, field and laboratory screening methods were developed and germplasm screened. Several sources with usable levels of resistance were identified for major biotic and abiotic constraints. A large-scale field hybridization program was established. Using appropriate

hybridization schemes and selection procedures breeding populations were developed to transfer resistance(s) into superior agronomic backgrounds. Depending up on their capacity, the NARS were provided with early-generation segregating populations, SSD derived plant progenies, and advanced breeding lines. Joint efforts of NARS and ICRISAT resulted in release of 37 cultivars in 9 countries in Asia, 25 cultivars in 11 countries in Africa, 1 cultivar in Jamaica, and 4 cultivars in Cyprus. Many more releases are in the pipeline.

In spite of significant achievements in genetic enhancement research in groundnut, several issues related to cultivar development still need resolution to make a large-scale impact at the farm level. Some of these include:

Foliar diseases: Foliar diseases resistant cultivars released till date have not found wide acceptability among farmers mainly because of their unattractive pod shape, low shelling %, and long duration. Unless these shortcomings in resistant cultivars are removed, their impact at the farm level would not be realized.

Aflatoxin contamination: In international trade of groundnut, complete freedom from aflatoxin contamination of produce is required. The level of resistance currently available in *Arachis* germplasm is not high enough to ensure complete freedom from toxin contamination. Alternate approaches using antifungal genes from other sources could provide long-term solution to this problem.

Virus diseases: Peanut bud necrosis in south Asia and peanut stripe in southeast Asia cause substantial loss in groundnut pod yield. Conventional breeding can provide only part solution to the problem. Genetic transformation can play a greater role in alleviation of virus stresses in groundnut.

Seed quality: With increasing use of groundnut in food and food industry, physical and nutritional seed quality aspects are assuming greater significance. Most of the national programs are not geared to address these issues.

The impact of genetic enhancement research in groundnut is not proportionate to cultivars and other technologies released to farmers in the semi arid tropics. The main limiting factor has been the non- availability of seed of improved cultivars. A concerted effort is required to overcome this problem. Further, farmers' participation is required in genetic enhancement research to increase their acceptance of newly released cultivars.

Overview of Pigeonpea Breeding Methods at ICRISAT

K B Saxena

The cultivation of pigeonpea benefits both, the grower -- by providing protein-rich food and the soil -- by improving its nutrition and structure. Therefore, it is an integral part of subsistence agriculture in the semi-arid tropical regions. The crop is popular because of its ability to tolerate drought and regenerate from losses caused by various biotic and abiotic stresses. Globally, pigeonpea is cultivated on 5.2 m ha in Asia, African, and the Caribbeans. Besides India, Myanmar and Nepal are other important pigeonpea growers in Asia. Kenya, Malawi, Uganda, and Tanzania are the major producers of pigeonpea in Africa while in the Caribbeans, pigeonpea is an important crop in a number of islands. Yields, often ranging between 2 - 3 t ha^{-1} at the experiment stations and 1 - 1.5 t ha^{-1} in on-farm trials were reported, but the average productivity in the farmers' field varies around 0.7 t ha^{-1}, indicating the presence of huge yield gaps. The prime factors responsible for these gaps are various biotic and abiotic factors and seed quality which play a major role in the expression of yield and its stability. Therefore, besides increasing yield potential of pigeonpea, the crop improvement research at ICRISAT has centered around understanding and alleviating important biotic and abiotic stresses.

Special Features of Pigeonpea

An important consideration in breeding pigeonpea at ICRISAT is the maintenance of genetic variability in advance generation materials to permit final selection for local adaptation by national program breeders. As a background information some special features of pigeonpea that influence decision in the breeding program need to be highlighted. These are natural out-crossing, specificity to adaptation, photoperiod reaction, and multiplicity of cropping system. Among these, natural out-crossing is considered most important because of its direct link with the methodologies chosen for breeding.

Breeding Methods

The flowers of pigeonpea are cleistogamous and generally favor self-pollination. However, unlike other legumes, a considerable degree (average 20%) of insect-aided natural out-crossing takes place, and it varies from place to place. Occurrence of natural out-crossing posses problem in developing pure lines. Due to variation in the pollination behavior of the crop, the breeding methods may be either the classic set-piece design of the self-pollinated crop or the population improvement designs that have been most effective in the improvement of cross-pollinated species. At present there are no clear guidelines regarding the optimum approach for pigeonpea breeding, but most contemporary programs are designed to exploit the tendency towards self-pollination. With the development of stable male-sterility even hybrid breeding, a standard out-cross breeding method, has been used effectively in pigeonpea.

Selection in germplasm: The natural out-crossing in pigeonpea has created and maintained a pool of recombinants in the farmers' fields and it is a continuous process. Breeders have exploited this genetic variation fruitfully and pure line selection from landraces has been a dominant breeding method in pigeonpea. In India, upto 1985, a total of 57 pigeonpea cultivars were released; of these, 43 (75.4%) were developed by selection from germplasm, 13 (22.8%) involved hybridization and selection, and only one (1.8%) cultivar was product of mutation breeding. At ICRISAT also, the genetic variability within and among landraces has played a major role in pigeonpea breeding program in identifying sources of resistance to diseases/insects and high yielding inbreds.

Twenty-one cultivars selected from ICRISAT–supplied materials have been released in 9 countries. Out of this, 6 were derived by direct selection from the germplasm. Also a number of collections and selections from these have performed well in both Asia and Africa which may be released soon. The resistant sources to diseases and insects identified from germplasm are the backbone of various resistance breeding programs at the national level.

Hybridization and selection: At ICRISAT considerable efforts were devoted to select the parental lines for hybridization. To develop breeding populations for selection we generally spend 2 – 3 years in purifying the promising lines before using them in the hybridization program. The main selection parameters are maturity, plant type, disease resistance, seed size, and the end-use. To develop breeding populations for pedigree selection, various mating schemes such as diallel cross, backcross, triple cross, double cross, and diallel selective mating have been used at ICRISAT. The selection in segregating populations was found effective for maturity, seed size, disease resistance, and plant type. Selection based on single-plant yield in early segregating generations, however, has been ineffective in pigeonpea due to high g x e interaction at individual plant level. Using hybridization and selection 15 cultivars were developed by 5 countries. All of them had one or more of special traits such as earliness, large seed or disease resistance which helped in their release.

Bulk hybrid advance: We used single-pod descent method of breeding which is a modified version of single seed descent method. In this method the segregating populations are grown late in the season to reduce plant size and thereby avoid competition. At maturity one pod from each plant is harvested randomly. This method has been found to be very economical and useful in handling a large number of populations which are supplied to NARS for selection under their local environment. Although a large number of populations have been supplied to NARS in the past years, the feed back on the utility of this material was invariably very poor. In India, two varieties 'Birsa Arhar' in Bihar and 'Vamban-1' in Tamil Nadu were released from such materials. As far as breeding efficiency is concerned, this method was found to be comparable to pedigree method in producing the number of elite inbred lines and it required relatively less resources.

Hybrid breeding: To address the issue of stagnant productivity levels of pigeonpea over decades, at ICRISAT we took a bold step of developing hybrid technology in the crop. In 1974, a deliberate search for male-sterility was launched to identify a stable male-sterility system which could complement with available limited extent of natural out-crossing in producing commercial hybrids. After 15 years of research a commercial hybrid pigeonpea technology, based of genetic male-sterility was perfected. In 1991, the world's first pigeonpea hybrid ICPH 8 was developed at ICRISAT. This hybrid demonstrated over 30% yield advantage in farmers' field. In comparison, to pure line varieties, the hybrids generally show high stability and better adaptation under adverse growing conditions. ICRISAT's hybrid pigeonpea technology had a significant impact on NARS. It attracted resources from public and private sectors and resulted in the release of three hybrids by NARS. At ICRISAT the male-sterility was transferred by back crossing to diverse genetic backgrounds including disease resistance to develop hybrids for different environments. This hybrid technology has further been advanced by replacing genetic male-sterility with a more efficient cytoplasmic male-sterility system, derived from a cross between a wild relative of pigeonpea and a cultivated type.

Population breeding: To take the benefit of natural out-crossing in pigeonpea, breeding schemes such as recurrent selection, population improvement, and dual-population improvement were used at ICRISAT. No encouraging results were obtained as far as yield is concerned, even after 5 cycles of inter-mating and selection.

Mutation breeding: In the Indian program two pigeonpea cultivars have been developed through mutagenesis. At ICRISAT relatively less importance was given to this approach. In a specific study, it was found successful in isolating wilt resistant plants from a wilt susceptible cultivar LRG 30.

Application of Biotechnology

(a) ***Transgenics*:** In pigeonpea, efforts to develop insect resistant cultivars have failed to make any significant impact. Genetic engineering of pigeonpea offers scope to control *Helicoverpa* in this crop. At present we are involved in research in inducing resistance in pigeonpea by incorporation of novel genes for resistance to insect pests and fungal pathogens in the cultivated varieties of this crop by genetic transformation. Some of the genes of immediate importance include those coding for insecticidal crystal protein from *Bacillus thuringiensis* (Bt-Cry genes) and inhibitors of insect metabolism such as trypsin inhibitor from soybeans (SBTI). Resistance to fungal pathogens is being attempted by using chitinases and gluconases. The work on the development of efficient protocols for genetic transformation of pigeonpea is being carried out by using marker genes such as neomycin phosphotransferase (NPT II), B-glucuronidase (GUS), and hygromycin phosphotransferase (HPT). We are exploring the possibility of identifying and cloning insecticidal genes for pigeonpea such as those for pigeonpea trypsin inhibitor and lectins

(b) ***Embryo rescue for wide hybridization***: *Cajanus platycarpus* (L.) Benth, a wild relative of pigeonpea, has resistance to phytophthora blight, cyst nematode, *Helicoverpa* pod borer, and podfly. Earlier attempts to cross *C. platycarpus* with *C. cajan* were unsuccessful. The barriers to hybridization were post-zygotic and we succeeded in developing hybrid plants by dissecting and culturing immature embryos. Among F_4 segregants, 14 plants were found to have high level of resistance to phytophthora blight.

(c) ***Somaclonal variation***: Somaclonal variation originating from *in vitro* plant regeneration is a potential source of genetic variability that can be used to widen the genetic base. The spontaneous mutations occurring in somaclonal population appear at higher frequencies than by conventional mutagenesis. In pigeonpea, somaclonal variation for various qualitative and quantitative traits has been generated and promising lines have been identified.

(d) ***Applied genomics***: Recently research activities on construction of genetic linkage maps and identification of DNA markers for disease resistance and fertility restoration of cytoplasmic male-sterility have started.

Introductions to Panel Discussions

Utilization of Wild Species at ICRISAT

L J Reddy, N Kameswara Rao, and Morag Ferguson

Introduction

In spite of the very good progress achieved through utilization of variability with in the crop gene pools, the ICRISAT mandate crops still suffer from several problems such as insects, diseases, and drought. The narrow genetic variability in the modern cultivars has increased their vulnerability to various pests. Hence, there is a continuing need to identify and incorporate the useful variability from alien sources to sustain crop productivity. Success in utilization of wild species in the past breeding programs was limited to unit transfers, such as disease resistance governed by major genes. Recent advances in molecular biology have provided us with new tools to identify and exploit the complex genes locked up in secondary and tertiary gene pools.

Currently, ICRISAT holds about 2300 wild and weedy relatives of its mandaate crops (Table 1). Over the past 15-20 years, a number of wild species have been evaluated for various biotic and abiotic stresses and several resistance sources and novel traits have been identified. However, very few attempts were made to utilize them for improving the mandate crops, except groundnut and pigeonpea. The extent of use of wild species in ICRISAT's breeding programs and potential for their exploitation to overcome constraints in crop productivity are given below:

Past Efforts

Sorghum

The genus *Sorghum* comprises 22 species placed under five sections. In the ICRISAT gene bank, 417 wild species accessions representing all the five sections and 18 species are available. The cultivated species, *S. bicolor* (2n= 20) comprises five races.

The results of screening of wild species for various constraints are given Table 2. Downy mildew, grain mold and anthracnose are important diseases of sorghum accounting for major yield losses. Only moderate levels of resistance to these stresses are available in cultivated germplasm. Among the wild species screened for resistance to downy mildew, two accessions of *S. sudanense* and almost all of the Chacto- *(S. macrospermum)* Hetero- (*S. laxiflorum*), Para- (*S. australians, S. brevicallosum, S. dimidiatum, S. matarankense, S. nitidum, S. purpureosericeum, S. timorense, S. versicolor*) and Stipo-sorghum (S. *angustum, S. ecarinatum, S. extans, S. interjectum, S. intrans, S. stipoideum*) were found to be immune. *S. sudanense* readily crosses with the cultivar, hence it can be utilized in traditional breeding programs. However, other species belong to tertiary genepool and attempts to introduce resistance through introgression have not been successful. Studies have shown pre-fertilization barriers, either due to failure of pollen germination or very slow and irregular pollen tube growth are responsible for the failure.

Among insect pests, stem borer and shoot fly together account for to over $300 million avoidable yield losses. At ICRISAT, high levels of resistance to these pests in terms of very low egg-laying and low percentage of deadhearts was found in five parasorghum accessions: three of *S. versicolor* (IS 14262, IS 14275, IS 18938) and one each of *S. dimidiatum* (IS 18945), and *S. australianse*.

Pearl millet

The genus *Pennisetum* comprises more than 140 species grouped under five sections. In the ICRISAT gene bank, we have 750 wild species accessions representing two sections and 24 species.

The screening results on wild species for various stresses are presented in Table 2. Downy mildew, smut, ergot and rust are the four major diseases of pearl millet. Although sources of resistance were identified, their resistance can be overcome when the inoculum levels are high or when there is very early inoculation.

P. glaucum subsp. *monodii* which belongs to primary genepool has dominant genes for resistance to rust (*Puccinia substriata* var *indica*) and *Pyricularia* leaf spot. Resistance to both the diseases has been transferred successfully to cultivated species and the disease resistant inbred line Tift 85 was developed in the USA. Use of *P. glaucum* subsp. *monodii* also led to identification of new source of cytoplasmic-nuclear male sterility.

P. purpureum (napier grass) is the only known species in the secondary genepool. It is a rhizomatous perennial, with desirable characters like, resistence to most pests, vigorous growth and outstanding forage yield potential. Napier grass readily crosses with pearl millet, but the hybrids produced were sterile. Nevertheless they produce high yields of good quality fodder.

The tertiary geenpool includes the remainder of the wild *Pennisetum* species. The group includes both sexual and apomictic species that are diploid and polyploid, annual and perennial rhizomatous and nonrhizomatous species. Some useful characteristics of the group include apomictic reproduction, perennial growth habit, drought tolerance, cold tolerance, pest resistance and cytoplasm diversity. Apomictic but highly sterile hybrids were produced between pearl millet and *P. setaceum* (triploid) and *P. orientale* (tetraploid). The hexaploid obligate apomictic species, *P. squamulatum* was crossed successfully to a tetraploid pearl millet and several partially male sterile, obligate apomictic interspecific derivative were produced in the USA. Interspecific hydrids were also obtained with *P. schweinfurthii*. Attempts to produce interspecific hybrids between pearl millet and *P. ramosum* and *P. mezianum* using conventional techniques were not successful. Pollen of *P. pedicellatum* and *P. polystachyon* though germinated on the stigmas of pearl millet, resulted in shriveled, immature seeds that did not germinate.

Chickpea

The genus *Cicer* comprises about 40 species grouped in four sections. In the ICRISAT gene bank, we have 135 accessions, representing all the four sections and 18 species.

The results on screening for various constraints are given in Table 3. *Cicer bijugum* (No. 201), *C. judaicum* (No. 185) and *C. pinnatifidum* (No. 188, No. 189) were found to be resistant to ascochyta blight. *C. bijugum* (No. 201) was also reported to be resistant to botrytis gray mold, wilt and root rots at ICRISAT.

At ICARDA, 228 wild species accessions were screened for six major stresses: ascochyta blight, fusarium wilt, leaf miner, bruchid, cyst nematode and cold. *C. bijugum* was highly resistant to all the six stresses, while *C. pinnatifidum* was resistant to five stresses, except cold.

Among the perennial species, *C. anatolicum* and *C. montbretii* have been reported to possess resistance to ascochyta blight at ICRISAT.

Among the eight annual species, *C. reticulatum* and *C. echinospermum* are cross compatible with chickpea. From chickpea X *C. reticulatum*, several high yielding lines were selected through introgression. Through embryo rescue and tissue culture techniques, hybrids have been obtained between cultivated chickpea and *C. pinnatifidum*, which has strong resistance to ascochyta blight. The remaining annual species and all the perennial species show no possibility of gene exchange with cultivated chickpea.

Pigeonpea

The revised genus *Cajanus* now comprises 32 species, with 18 species distributed in Asia, 15 in Australia, and one in Africa. The currently held accessions in the ICRISAT gene bank represent 20 species. The wild relatives of *C. cajan* possess many agronomically desirable traits (Table 4).

The major constraint in pigeonpea production is the pod borer (*Helicoverpa armigera*), which can devastate the crop with almost 100% yield loss. The other two insects that can cause considerable yield losses are Maruca and pod fly (*Melanagromyza obtusa*). For all the three pests good sources of resistance are not available within the crop gene pool.

It has been observed that wild relatives are rarely damaged, though the insects feed on the plants under no choice conditions. When 166 accessions of 16 species (six of *Cajanus* and 10 of *Rhynchosia*) were evaluated for resistance to pod borer, some of the wild species were markedly resistant to both pod borer and pod fly. For example, survival of the larva of *H. armigera* was lower on two wild species, *C. scarabaeoides* (21%) and *C. platycarpus* (56%) campared to *C. cajan* (78%). The dense covering of trichomes on pods of *C. scarabaeoides* was responsible for the low survival. It is suggested that resistance to *H. armigera* in cultivated pigeonpea could be improved by transferring genes regulating the production of dense covering nonglandular trichomes on pods from

C. scarabaeoides. Apart from physical resistance, *A. scarabaeodies* possesses antibiosis against *Helicoverpa.*

Wilt, sterility mosaic (SM), and Phytophthora are the major diseases of pigeonpea. Although resistance sources have been identified in the crop genepool, there are indications that these sources are not resistant to the new pathogen strains/ isolates. For instance, SM resistance sources identified earlier were found to be susceptible to Pudukotai strain and no resistance sources for P-3 3 isolate have been found in the crop gene pool; However, two accessions of *C. platycarpus* (ICPW61and 66) were found highly resistant to P-3 isolate.

C. platycarpus and *C. sericeus* were also reported to be immune to phytophthora blight. Most species of *Cajanus* and *Rhynchosia*, especially *C. scarabaeoides* and *C. albicans* have higher protein concentrations (28-30%) compared with 24% in cultivated pigeonpea. *Flemingia bracteata*, a closely related species showed high percentage of the essential aminoacids, methionine and cystine, which are limiting in pigeonpea. High protein content was successfully transferred to good agronomic backgrounds and high protein elite germpasm lines (e.g. ICPL 87162) were developed.

Accessions of *C. grandifolius* (ICPW 37), *A. scarabaeoides* (ICPW 94, ICPW 11), *Flemingia macrophylla* (ICPW 194) *F. stricta* (ICPW 202) and *F. strobilifera* (ICPW 203) *and Rhynchosia rothii* (ICPW 257) were found resistant to root-knot nematode (*H. cajani*).

Of the 13 wild species tested for salinity tolerance, *C. cajanifolius, C. platycarpus and D. ferrugenia* were more tolerant to salinity than the cultivated pigeonpea controls.

Novel traits such as cytoplasmic-genetic male sterility, partially cleistogamous flowers which ensure very low outcrossing (<1.0%), and dwarf plant types, amenable for mechanical operations have been recovered from interspecific crosses and have been transferred to agronomically superior backgrounds.

Six Indian wild species, *C. cajanifolius, C. scarabaeoides, C. trinervius, C. albicans, C. lineatus and C. sericeus* and five Australian species, *C. acutifolius, C. confertiflorus, C. lanceolatus, C. latisepalus and C. reticulatus* were successfully crossed with pigeonpea and possibility exists for incorporation of desirable traits from these species by conventional breeding.

C. platycarpus carries genes for photoperiod insensitivity, earliness and resistance to fusarium wilt, phytophtora blight and tolerance to salinity. Recently, this species was successfully crossed with pigeonpea and fertile hybrids were produced by performing large number of pollinations, embryo rescue, and chromosome doubling.

Groundnut

The genus *Arachis* possesses about 69 species placed in 9 sections. In the ICRISAT gene bank 452 accessions, representing eight sections and 42 wild species are available. Of the 27 known wild species under section *Arachis*, 20 are available at ICRISAT.

Several of the species were screened for resistance to major diseases and pests and resistance sources were identified (Table 5). *A. monticola*, the wild tetraploid species of section *Arachis* which crosses freely with *A. hypogaea* is grouped in the primary genepool. A variety ` Spancross' that was developed in the USA from this interspecific cross involving *A. monticola* was released in Tanzania. The diploid species of section *Arachis* are cross compatible with tetraploid *A. hypogaea*. But they required hormone treatment, embryo rescue, and chromosome doubling to restore fertility in the hybrids. Using backcross method via triploid, autotetraploid, and diploid routes several rust and late leafspot resistant and multiple disease and insect resistant elite germplasm lines (eg. ICGV 86699, ICGV 87165) were developed. These have been extensively used in the national breeding programs as donor parents. One of the interspecific derivatives, ICGV-SM 86715 was released as 'Veronica' in Mauritius. The members of section *Rhizomatosae* possess high levels of resistances to rosette, early leafspot, peanut stripe, and Spodoptera. However, they belong to tertiary genepool and cannot be utilized in conventional breeding programs.

Identification of critical gaps in wild species utilization

As evident from the above, during the past 20 years, we have identified several useful resistance sources in the wild species for the major stresses affecting our mandate crops and gained knowledge on various species with regard to their feasibility or otherwise for exploitation through conventional breeding methods. Now we have a fairly good idea about the genetic profiles of our mandate crops, based on which we can chalk out our future breeding strategies. Several gaps and problems in the use of wild species were also identified. They include: a) non-availabilty of some very useful species in our gene bank (e.g. Australian *Cajanus* species, which are extremely drought tolerant), b) *ex situ* conservation problems (e.g. non-seed producing *Arachis* species and perennial *Cicer* species), c) lack of information on useful traits especially at intraspecific level due to limited screening and non availability of information in a readily available form, d) barriers to crossability, fertilization, and sterility of hybrids, e). restricted recombination and/or linkage drag and other unknown reasons (e.g. non recovery of pod borer resistance in *Cajanus*, late leaf spot resistance in *Arachis* , and shootfly resistance in sorghum combined with other essential agronomic traits, and wild segregation in millet in the interspecific derivitives), and f) long gestation period due to pre breeding requirements before the derivatives are amenable for further exploitation in the traditional breeding programs.

Current efforts

Filling gaps in collections

Recently we have obtained 100 accessions of annual *Cicer* species from ICARDA. These are being characterized and evaluated for biotic stresses. Through correspondence, we are trying to obtain the Australian wild *Cajanus* species, with known drought tolerance that inhabit the rocky and sandy ecosystems (e.g. *C. aromaticus*, *C. crassicalus*, *C. pubescens*).

Conservation of problematic species

In vitro propagation procedures are being developed for perennial *Cicer* species and *Arachis* species. Also, the technique for encapsulation and synthetic seed production is being standardized in *Arachis*.

Screening

Targeted screening of wild species are in progress which include: screening sorghum wild species for shoot fly and spotted stem borer, new *Cicer* species accessions for botrytis grey mold and ascochyta blight, and new *Arachis* accessions for rosette, early and late leafspots, and leaf miner resistances, and *Cajanus* and *Rhynchosia* species for pod borer in pigeonpea..

Data base development

Attempts are underway to bring all the available information from past screenings against various stresses into to more readily comprehensible and accessible form by standardizing the raw data and developing easily retrievable computer-based databases.

Deployment of biotechnology tools

Molecular markers are currently being used at ICRISAT for assessing the diversity and gene discovery in the wild *Arachis* species (by using SSR and STMS markers) and diversity of cytoplasms in *Cajanus* species (by RFLP analysis of mtDNA).

With the objective to identify quantitative trait loci (QTL) attempts are being made to develop and saturate genetic linkage maps. This will ultimately facilitate marker assisted selection and genetic engineering in the ICRISAT mandate crops. In this direction mapping populations involving wild species are being produced in chickpea (drought resistance traits) and groundnut (disease resistance traits).

In sorghum, using *S. dimidiatum*, protocols have been established for using asymmetric protoplast fusion technique. This has been achieved by successful isolation and culture of mesophyll protoplasts and demonstration of direct regeneration of normal plants from plated cell cultures. This technique may pave the way for somatic hybridization and transfer of useful genes from the tertiary gene pool to the cultivated species.

Table.1. Availability of crop & wild species accessions at ICRISAT genebank

[redacted]	[redacted]	[redacted]
Sorghum	36302	417 (18)*
Pearl millet	20642	750 (24)
Chickpea	17115	135 (18)
Pigeonpea	12989	555 (6G, 20 sp.)**
Groundnut	14890	452 (42)
Total	101938	2309

* Figures in parentheses refer to no of species ; ** G= Genera, Sp= species

Table 2. Summary of screening against biotic stresses in wild species of sorghum and pearl millet

[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Sorghum	Grain mold	308	29	--
	Downy mildew	565	94	--
	Shootfly	268	13	Parasorghums immune
	Stem borer	50	15	Parasorghums Immune
Pearl millet	Downy mildew	534	220	*P. pedicellatum* and *P. polystachyon* immune

Table 3. Useful traits identified in wild species of chickpea

Species	Wilt	Soil borne rots	Grey Mold	Ascochyta Blight	Cyst Nematode	Leaf miner	Bruchids	High protein	Cold	Multi-Seeded	Twin pods
C. anatolicum (P)											+
C. bijugum	+	+	+	+	+	+	+	+	+		+
C. chorassanicum	+					+					
C. canariense (P)	+										
C. cuneatum	+	+				+				+	+
C. echinospermum	+					+			+		+
C. judaicum	+	+		+		+			+		
C. microphyllum (P)											+
C. montbretii (P)				+						+	
C. oxyden											+
C. pinnatifidum	+	+		+	+	+			+		+
C. reticulatum	+				+	+		+	+		
C. soongaricum (P)											+

P= Perennial species

Table 4. Useful traits in various wild species of pigeonpea.

Trait	C. albicans	C. [illegible]		C. platycarpa	C. scarabaeoides	C. sericea	C. [illegible]	[illegible]
Early Flowering				+				+
Photo-insensitive				+				+
Drought resistance	+		+		+	+		+
SMV resistance	+		+			+	+	
Phytophthora resistance				+		+		
High seed protein	+		+		+			
Pod borer resistance					+			
Salinity tolerance				+				

Table 5. Reaction of wild species of groundnut to diseases and insects

Section, Series, Species	Disease or insect											
	Rus	LLS	ELS	PSV	GRV	PMV	TSW	PCV	THR	APH	MIT	JAS
Arachis Annuae												
A. batizocoi	I											
A. duranensis	I			R					R			R
A. specazzinii	I											R
Arachis Perennes												
A. helds								T				
A. villosa	I								R	R		R
A. correntina	I					R	R		R	R	R	R
A.cardenasii	I	I				R	R		R			R
A. chacoensis	I	R	R/I		R	R	R		R	R		
A. stenosperma	R	R	R									
Arachis spp.						R						
Amblinervosae												
Arachis spp.				R								R
Caulorhizae												
A. repens		R	I	R	R				I			R
Extranervosae												
A. villosulicarpa	I	I	I									
Arachis spp												R
Triseminatae												
A. pusilla	I					R	R		R			R
Erectoides												
A. benthamii				R								
A. paraguariensis	I	R							I			
A. rigonii									R			R
A. appressipila	I	R			R							
Arachis spp.		R	R	R					I			R
Rhizomatosae												
A. glabrata	R	I	R	R	R	R			R	R		R
A. hagenbeckii	I	R	I									R
Arachis spp.		R	R				R/I					R

Rus = Rust, LLS = late leaf spot, ELS = Early leaf spot, PSV = Peanut Stunt Virus, GRV = Groundnut rosette virus, PMV = Peanut Mottle virus, TSW = Tomato spotted wilt Virus, PCV = Peanut Clump Virus, THR = Thrips, APH = Aphids, MIT = Mites, JAS = Jassids
I = Immune, R = Resistant, T = Tolerant

Potential of applied genomics at ICRISAT

N Seetharama

Genomics is the study of genes and genetic information organized in the genome, and how this organization determines their function. The famous Human Genome project gave the impetus to the development of Plant genomics, first using *Arabidopsis* as the model plant, and later with rice ("model crop"). The distinction between "applied" and "pure" genomics is not tenable, but the adjective "applied" is used to in crop improvement programs targeting selective deployment of genomic approach to enhance the effectiveness of the ongoing breeding efforts in an integrated fashion. ICRISAT, with multiple mandate crops, has only such an option of selective deployment of this new science. While we do not underestimate the needs for whole-hearted efforts on full-scale genomics of our mandate crops, practicality and cost-effectiveness demands such a strategy. Thus, the short term goals of our work on genomics is to develop and exploit the tools of genomics to increase the efficiency of breeding of our mandate crops and to enhance well-characterized germplasm.

In the light of above goals, our planned outputs remain almost same as before, i.e., enhanced and well-characterized germplasm for distribution to the NARS, and technology exchange. Increasingly, several intermediate products such as mapping populations, advanced backcross recombinant inbred lines (AB-RIL or contig lines), isolines, mutants, and other genetic stocks, and databases will also be developed and delivered. Gradually, we will be able to provide useful DNA probes and libraries, genes/gene constructs. Our noted advantages in phenotyping and data analysis skills are being enhanced with the fast developing skills in bioinformatics and advanced computational tools especially to handle the quantitative trait loci (QTL). These services will increase our ability for future technology exchange. They will increase our effectiveness to contribute to consortia and networks by supplementing our proven advantage such as access to germplasm and knowledge of biology of crops and their pests in the semi-arid tropics.

Status of research on genomics of ICRISAT crops compared

The genomic research on dryland crops (especially that on legume crops) is lagging behind most temperate crops (Table 1). For sorghum, and to a lesser extent for chickpea and groundnut, there are few interested groups in the USA, Europe, and Australia. For others, there are much less international efforts and the situation is unlikely to change. However, considering the global market for these crops, a pragmatic approach is needed while prioritizing research needs. This is especially so with respect to genomics research since it is resource and skill intensive. Efforts at ICRISAT are meant to maximize our comparative advantages, and to fully develop and utilize global consortia and networks. Fortunately, because of commonality in both technology and in genome structure and functions, significant advantages can be derived from research on other better-researched crops. Therefore, ICRISAT's efforts in basic investigations will be confined only to fill the critical gaps, and highlight special areas of significance such as prospects for isolating unique genes for specific adaptation (e.g., drought tolerance) or grain quality that will have impact on sustainable agriculture in the SAT.

Thrust areas for research

We will continue to put most of our resources in the area of development of genetic linkage maps, and identification of markers and QTL for complex and agronomically important traits. The demonstration of usefulness of MAS (marker-assisted selection) initiated in pearl millet at ICRISAT will also be other crops. Working with NARS and ARIs, we will try to develop consensus maps of ICRISAT mandate crops, saturate with different types of markers and annotate critical regions of these maps for important agronomic traits. Considering the generic nature of genomic research and the advances made in model plant species *Arabidopsis* and rice, we will place increasing emphasis on comparative mapping (see below).

The need to isolate unique 'genes' (coding structural or enzymatic polypeptides) and other useful sequences (such as promoters or others regulating gene expression) cannot be underestimated However, we would like to undertake such research on a selective basis, such as isolation, characterization and testing of candidate genes for disease or drought resistance. At a later stage we may develop specific expressed sequence tags (EST) both for mapping. EDNA libraries for identification of novel genes and identify map-based cloning can be best served through comparative mapping approach. We will emphasize significant efforts to further develop Plant Science Informatics with special reference to our crops. With our strong plant breeding teams, computational genomics, especially QTL analysis will be important areas for us to work. We will continue to contribute to the existing sorghum and millet genome databases, and develop new genomic databases for legume crops. No doubt, the knowledge and skills available at ICRISAT will eventually contribute to bioinformatics especially to the part related to genes or genomic regions contributing to agriculturally important traits for crop productivity, stress resistance and adaptation. Technology exchange continues to be an important and integral part of our program. Special efforts will be made to assist African programs through our locations as well as by cooperating with over CG centers..

Molecular marker technology - current & future

The use of DNA marker technology is the core of any applied genomics program. We are increasingly emphasizing development of PCR-based markers and will gradually shift towards high throughput (HTP) protocols. However, we realize that even a laborious technique like restriction fragment length polymorphism (RFLP) is needed for study of comparative genomics. Manual methods will be continued for some more time by our NARS collaborators, and ourselves especially for MAS. For some special applications, FISH (Fluorescent *in situ* hybridization) and even RLGS (Restriction Landmark Genome Scanning) may be appropriate. Most of our future emphasis will be on codominant sequence tagged micro-satellites (STMS) and ESTs. Dominant markers like amplification fragment length polymorphism (AFLP) and randomly amplified polymorphic DNA (RAPD) will be used for special applications like Bulked Segregant Analysis (BSA). We do not have any immediate plans to use chip technology, but will closely watch developments in ARIs.

Applications of Marker/QTL technology at ICRISAT

There are 3 major objectives for study of QTL:

1. Locating genes which account for genetic variation for agriculturally important traits
2. Cloning of genes underlying specific phenotypes after precisely locating individual QTL in mega base DNA contig
3. Ask and answer basic questions on evolutionary processes.

We will emphasise (1) above, but other applications will gradually find a place in our program.

Our current targets for search of QTL are for relatively less complex traits like disease resistance (only major races considered), but we will gradually move towards more complex and sensitive traits such as drought tolerance. The selection of traits will largely depend on target crop and region, and on opportunities for international collaboration. Pyramiding of resistances using DNA markers is an important area of research.

The DNA marker technology is already being used at ICRISAT to study germplasm variability, and to assemble core collections of sorghum. This type of research will be extended to more crops. Studies on pathogen variability, host x pathogen interactions and development of diagnostics (e.g., virus identification, seed health) will also be intensified.

Comparative genome mapping (CGM)

Comparative genome mapping (CGM) of major crops have shown extensive synteny (conservation of genetic linkages) and colinearity (conservation of gene order). This facilitates cross-referencing genetic information across groups of diverse species such as major cereals like rice, barley, wheat, maize, and sorghum, and related species like sugarcane. CGM holds great promise for the CGIAR system since we work on several important crops and traits, and has large well-characterized germplasm collections. In particular, the stress-resistant SAT crops on which ICRISAT works will prove to be a rich and diverse reservoir of novel and useful genes. Thus, the "neglected crops" of the poor will, in future, become rich sources of genetic diversity for all major crops.

CGM will also help to easily and quickly isolate genes based on map-positions by using another species with smaller genome. This will also provide alternate allelic forms for transgenic breeding. Such alleles could be substantially different in terms of their contribution to the adapted phenotype. Finally, an important application of CGM is the prospects for transferring and synthesizing information concerning syntenous genes and derivation of metabolic pathway across species. This will be of increasing importance, as we want to decipher the action of QTL and their interactions for practical crop improvement. CGM will be an important area for international collaboration in the future.

Gene isolation and characterization

Not withstanding its importance, efforts on gene isolation will be highly selective. We will continue to follow the candidate gene approach to isolate and characterize disease resistance genes. We will also isolate and clone differentially expressed sequences under defined stress patterns and try to map enquire sequences so as to find better markers for stress tolerance. Some cDNA libraries in relation to specific stresses may be developed and sequencing may be undertaken on a limited scale. Our preference for development of ESTs is logical. Under best funding scenario we may undertake the shotgun-sequencing approach for legumes. We will take advantage of CGM for map-based cloning in cereals. Obviously the targets for such cloning work will be the unique QTL identified in our mandate crops, and much of the work will be carried out in collaboration with ARIs.

Bioinformatics

Bioinformatics is an area where we may have comparative advantages, adequate resources and skills. We will develop both databases and software for specific data analysis and information retrieval. At this point, our priorities are on bibliographic data and database for germplasm, phenotypes, as these are expected to lead to development of a knowledgebase on ICRISAT crops. Since the genomic databases for sorghum and pearl millet are already available, we may concentrate on development similar genomic databases for the three legume crops. We will work very closely with others (particularly with USDA-NAL). With our collaborators we will organize training in database management and use, and may engage in the development of specific software to facilitate easy data access by non-specialists. We will deal with special molecular biological databases only at a later stage after sequencing facility is well-developed.

Computational Genomics

Our effort in this area is primarily driven by experimental genomics research at ICRISAT. This will provide unique opportunities for collaboration and technology exchange. In the near future, we will be mostly analyzing genomic data, which would mainly include phenotype and genotype data from mapping projects. Such data obtained from multiple environments, marker types, and genetic backgrounds in each mandate crop is a goldmine to apply existing, and develop new or improved computational genomic methods. Also, data on fingerprinting or diversity analyses of gene-bank accessions will have the opportunity to contribute in this area. These data will be used to work out optimal genomic research protocols with the aim of efficient and cost-effective use of available resources.

In the short term, we will concentrate on application and development of efficient biometric and computing tools for analysis of these data for:

- Single- and multiple-trait QTL mapping,
- QTL x QTL interactions
- QTL x Env Interactions
- Efficiency of Marker-Assisted Selection (MAS)
- Comparative mapping
- Assessment of molecular diversity for
    - Identifying unique germplasm (core collections)
    - Selection of desirable parental combinations
    - Studies on gene flow (population dynamics)

With the available genomic data on our germplasm, simulations using appropriate resampling techniques like bootstrap, jackknife, and Markov Chain Monte Carlo, will be used to assess and improve the *quality* (efficiency and accuracy) of genomic inferences.

Gradually we plan to work with DNA sequencing data when they are generated or freely accessed from other laboratories. The sequence data will offer challenge and opportunity to apply appropriate computational and biometric tools, including

- Probabilistic models of protein and nucleic acids for phylogeny reconstruction, and
- Identification of physical locations of genes (exons) using multivariate statistical pattern recognition techniques such as quadratic discriminent analysis.

Challenges, problems, and opportunities

We feel that there are excellent opportunities for us to engage ourselves in specific and applied research on genomics of mandate crops while learning from the experience with other better-researched crops (especially in cereals). However, to generate adequate impact we need to recognize several factors such as:

1. Periodic up-gradation of physical facilities including capital equipment
2. Adequate and regular supply of molecular biologicals at reasonable price
3. Trained skilled manpower, on-job training, constant communication with peers and experts
4. Protocols and linkages for sharing
    a. Germplasm (now a system is in place)
    b. Intellectual Property Rights (being addressed at CG level)
    c. Willingness to share results and credits (our operations under 'not-for-profit', and 'supplier of international public goods' status needs to be well-understood).
5. Ability to transfer technology to NARS (since most tools and techniques we deploy at ICRISAT may be the proprietary property of others, and we may not have the right to distribute freely)
6. Interactions with other players, especially with the private sector and international consortia
7. Ability to attract adequate funds for research

With the changing scenario of global plant breeding industry, our interactions with all other stakeholders keep evolving. With the increasing emphasis placed at ICRISAT to function as an "open center", we hope to be a major supplier of public goods in the semi-arid tropics. We hope to increase our effectiveness to serve the needy farmers of the tropics with the help of ARIs, development investors (like regional banks), seed and food industries, and the plant breeders of the tropics. With our skills and opportunities for networking and using IT, we will move towards the creation of a "virtual institute".

Table 1: Status of research on genomics of ICRISAT crops compared with model crop *Arabidopsis*, and rice.

Scores: 0 = work yet to start; 1= preliminary exploration; 2= initiated; 3=signs of progress evident; 4= significant advances; 5 = fast progressing.

	Technology or tool	Sorghum	Pearl millet	Chickpea	Pigeonpea	Groundnut	*Arabidopsis*	Rice
1	Linkage maps	2	2	2	1	1	5	5
2	Markers/QTLs identified	1	1	1	0	0	5	5
3	MAS	1	1	0	0	0	-	4
4	Fine map	1	0	0	0	0	4	4
5	Synteny & colinearity	2	2	1	0	0	4	4
6	Physical map, BACs	1	0	0	0	0	5	5
7	Genome sequencing, ESTs	1	0	0	0	0	5	5
8	Gene isolation	1	0	0	0	0	5	4
9	Routine genetic transformation	0	0	0	0	0	5	3
10	Functional genomics	0	0	0	0	0	4	3
11	Genomic database	3	2	0	0	0	5	5

Potential for impact through genetic diversification of ICRISAT mandate with resistance to biotic and abiotic stress factors

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Farming communities in the semi-arid tropics (SAT) are poor and cannot afford destabilizing crop losses due to biotic (drought, heat stress, low temperature, and flooding) and biotic (insects, diseases, viruses, and nematodes) stress factors. Crop losses due to biotic and abiotic stress factors in the ICRISAT mandate crops have been estimated to be over US$ 14.17 billion annually (ICRISAT 1992). Control of insect pests such as *Helicoverpa armigera* is heavily based on insecticides. In the SAT, management of some insects/diseases is either impractical or beyond the reach of resource poor farmers. Possibilities for minimizing losses due to abiotic stress factors such as drought through management, e.g., irrigation, are limited under rained agriculture, since farmers take up the cultivation of economically important crops as and when irrigation facilities are available. Current sensitivities about environmental pollution, human health, and pest resurgence are a consequence of improper use of fertilizers and pesticides. Therefore, host-plant resistance (HPR) offers a potentially viable option to reduce the extent of losses due to these stress factors. HPR is safer for the non-target organisms, human beings, and the environment. It does not involve any additional costs to the farmers, and is compatible with other crop management practices.

Improving plant resistance (adaptation) to biotic and abiotic stress factors through conventional breeding, marker aided selection, wide hybridization, and genetic transformation will significantly contribute to sustainable crop production and environmental conservation. Plant traits contributing for resistance to these stress factors can also be combined with novel genes such as Bt and protease inhibitors to reinforce host plant resistance to insects, and chitinase and antifungal proteins to increase the levels of resistance to plant pathogens. Crop cultivars with resistance to the target stress factor(s) will also increase the usefulness of fertilizer use, biocontrol agents, high yielding cultivars, improved agronomic practices, and synthetic pesticides for sustainable crop production, improve farm incomes, and alleviate poverty.

To reduce losses due biotic and abiotic stresses and explore the new market opportunities, there is a need to exploit host plant resistance to reduce the extent of losses due to these stress factors. ICRISAT is in a position to provide information on modern scientific techniques and improved germplasm with resistance to biotic and abiotic stress factors because of its strong research base and partnerships with NARS, NGOs, networks, and ARIs.

Importance of biotic and abiotic stress factors: The extent of losses

Losses due to biotic and abiotic stress factors in the ICRISAT mandate crops have been estimated to be over US$ 14.17 billion annually (ICRISAT 1992). In different crops, the losses due to biotic and abiotic stress factors are; US$ 2714 and 1714 in sorghum, 1372 and

462 in pearl millet, 1422 and 1137 in chickpea, 765 and 1324 in pigeonpea, and 1044 and 2754 in groundnut, respectively (Fig. 1).

Important stress factors in sorghum are sorghum midge, head bugs, shoot fly, head bugs, grain molds, foliar diseases, *Striga* and drought; downy mildew, stem borer, head miner, *Striga*, heat, and drought in pearl millet; drought, cold tolerance, biological nitrogen fixation, *Helicoverpa*, Ascochyta blight, *Botrytis* gray mold, wilt, and nematodes in chickpea; drought, water logging, wilt, sterility mosaic, *Helicoverpa*, *Maruca*, pod fly, and nematodes in pigeonpea; foliar diseases, leaf miner, white grubs, foliar pests, viruses, and nematodes in groundnut (Table 1).

ICRISAT core projects targeting research on biotic and abiotic stress factors

Five of the 12 ICRISATs' core projects have outputs targeted at developing technology/improved genotypes with resistance to the biotic and biotic stress factors.

P 5. Saving and utilizing biodiversity in the SAT.

- Access to desirable traits from wild and unadapted germplasm.

P 6. SAT crop improvement through applied genomics.

- Identification and characterization of useful genes, and comparative mapping of gene sequences/QTLs associated with biotic and abiotic stress-tolerance.
- Molecular characterization of genetic variability in important pathogens.

P 7. Genetic diversification and enhancement to increase crop productivity in SAT farming systems.

- Resistance sources, screening methodologies, and management options for diseases, pests and abiotic stresses.

P 9. Aflatoxins, drought, virus, and foliar diseases management to enhance groundnut production and quality.

- Knowledge of inheritance of components of resistance to foliar diseases, groundnut rosette, and *A. flavus* infection and aflatoxin contamination in groundnut
- Efficient method of breeding for resistance to drought in groundnut
- Diversified agronomically superior groundnut genotypes with improved levels of resistance to aflatoxin contamination, drought, groundnut rosette, rust, leaf spots and adaptation to different eco-regions and uses

P 10. Host-plant resistance, genetic transformation, and integrated pest management (IPM) options for pod and stem borers for sustainable crop protection in the SAT.

- Screening and selection criteria for resistance to Helicoverpa/stem borers
- Genetic resistance, mechanisms, and inheritance of resistance to pod and stem borers, and information on influence of HPR/transgenics on ETLs and natural enemies.
- Interspecific derivatives with resistance to pod and stem borers.
- Transgenic pigeonpea/chickpea/sorghum/pearl millet with Bt and protease inhibitor genes developed, and cloning plant genes with insecticidal activity to pod and stem borers.

Current research activities addressing various stress factors in different crops are summarized in Table 2. Depending on the information generated in the past, the progress made, and the present need; the research on various stress factors is focused on resistance screening, genetic diversification, molecular markers, genetic transformation, and management.

Technology/material developed at ICRISAT in the past with a potential for impact in alleviating the losses due to biotic and abiotic stress factors

Considerable research effort has been made in the past at ICRISAT to develop the resistance screening techniques, identify the resistance sources, and transfer the resistance into high yielding varieties and hybrids (Table 3, Appendices I and II). As an example, Table 3 gives the continuum in progress made in developing the resistance screening techniques, identification of sources of resistance, released cultivars with resistance to the target stress factor(s), and the information generated on mechanisms and inheritance of resistance in different crops. A number of germplasm accessions, and the cultivars developed at ICRISAT, and those developed by the NARS by utilizing the material supplied by ICRISAT have been released for cultivation to the farmers (Fig. 2). Most of these cultivars have resistance/tolerance to different biotic and abiotic stress factors (Appendix I). Several sources of resistance identified in the germplasm collection, and the improved lines developed at ICRISAT have been supplied to the NARS. Release of these genotypes for cultivation *per se* or their use in crop improvement will lead to a considerable reduction in losses associated with biotic and abiotic stress factors, and thus lead to sustainable crop production.

Potential impact of research on biotic and abiotic stress factors in future

There is a tremendous potential for impact on agriculture production through research on biotic and abiotic stress factors. Several studies are in progress to assess the impact of technology/materials developed at ICRISAT in several countries. While the impact on production and productivity through the adoption of improved high yielding cultivars is easy to quantify, the degree of impact from information on the biotic and abiotic stress factors, resistance screening techniques, utilization of resistance sources, and the information on mechanisms and inheritance of resistance is difficult to quantify. The adoption of wilt resistant pigeonpea variety ICP 8863 in India, and the cold tolerant varieties of chickpea (Heera and Sona) in Australia gives an indication of the impact of research on biotic and abiotic stress factors in the developed and developing countries, respectively. Research effort in wilt resistance in pigeonpea has lead to rapid adoption of

wilt-resistant cultivars in central India with annual benefits of over 61.7 million (with a 65% net rate of return on research investment) (Table 4). The utilization of midge-resistant varieties of sorghum and cold tolerant varieties of chickpea (developed by ICRISAT) in the Australia has resulted in annual benefit of A$$ 1.14 million and 1.36 million, respectively (Table 5). Over a period of 20 years, these materials will benefit the Australian agriculture by 27.3 and 36.4 million dollars, respectively. There are several such examples of adoption/utilization of technology/materials developed at ICRISAT in the SAT.

The potential for impact through research on biotic and abiotic stress factors can be assessed from the yield gap that exists between the average yield of these crops in different continents, and the potential yield under optimum conditions (Fig. 3). While the average yields on the farmers' fields in Asia and Africa range from 0.5 to 1.0 tone ha^{-1}, their potential yield under optimum conditions ranges from 4.5 to 17.0 tones ha^{-1}. Thus, there is a huge gap between the potential yield and the actual harvest by the farmers (Table 1). Biotic and abiotic stress factors are a major constraint in increasing the production and productivity of these crops in the SAT. HPR to biotic and abiotic factors can be used as one of the approaches to minimize the extent of losses due to these factors under subsistence farming conditions. Hence, there is a great opportunity for impact on agriculture production through research on biotic and abiotic stress factors in the SAT.

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Table 1. Extent of yield losses due to biotic and abiotic stress factors in ICRISAT mandate crops

Crop	Constraint	Yield loss ($ million)	Potential yield gain ($ million)		
				Management	
			CIP	CIP	RMP
Sorghum	Drought/water deficit	1744	143		503
	Low temperature	28	3		
	Total abiotic	**2714**	**146**		**1415**
	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		
	Anthracnose	102	67		
	Leaf blight	77	43		
	Smut	21	15		
	Sooty stripe	6	4		
	Foliar diseases	128	89		
	Total biotic	**1714**	**795**	**428**	
	Total others	**427**	**295**		**132**
Pearl millet	Drought/water deficit	630	142		356
	Heat	214	44		
	Total abiotic	**1372**	**186**		**884**
	Downy mildew	134	118		181
	Head caterpillars	116	28	45	
	Stem borer	91	18	27	
	Striga	121		121	
	Total biotic	**462**	**164**	**193**	
	Total others	**43**	**19**	**24**	
Chickpea	Drought/water deficit	1058	525		66
	Cold	42	20		
	Biological N fixation	253	100	74	
	Total abiotic	**1422**	**645**	**74**	**135**
	Helicoverpa	328	164		
	Stunt virus	42	24		
	Ascochyta blight	248	129		
	Wilt	218	109		
	Root rot	98	44		
	Botrytis gray mold	33	13		
	Nematodes	170	57		
	Total biotic	**1137**	**540**		
	Total others	**12**		**12**	

Pigeonpea	**Drought/water deficit**	**570**	**92**		
	Water logging	**110**	**85**		
	Total abiotic	**765**	**177**		
	Phytophthora **blight**	92		31	1
	Fusarium **wilt**	193	97		20
	Sterility mosaic	290	202		1
	Helicoverpa	317	137	137	3
	Maruca	30	16		167
	Pod fly	256	60	85	
	Nematodes	146	61		
	Total biotic	**1324**	**573**	**253**	
	Total others	**207**	**207**		
Groundnut	Drought/water deficit	520	208		
	Total abiotic	**1044**	**208**		
	White grubs	107		49	4
	Late leaf spot	599	300		255
	Rust	467	242		27
	Early leaf spot	326	82		14
	Leaf miner	164	82	66	741
	Aphids	93	38		
	Aflatoxins	264	62	126	
	Termites	107		76	
	Spodoptera	97		32	
	Nematodes	45	15		
	Peanut stripe virus	36	18		
	Rosette virus	156	121		
	Peanut mottle virus	59	35		
	Bud necrosis virus	89	45		
	Clump virus	38	22		
	Millipedes	107		78	
	Total biotic	**2754**	**1062**	**427**	
	Total others	**452**	**452**		

ICRISAT (1992). CIP = gain in production through research in crop improvement. RMP = gain in production through research in resource management.

Table 2. Research focus on biotic and abiotic stress factors in different crops at ICRISAT

Crop	Trait	Resistance screening	Genetic diversification	Molecular markers	Transformation/wide hybridization	Management
Sorghum	Shoot fly		*	*		
	Stem borer		*	*	*	
	Head bugs/Midge		*HB	*SM		*HB
	Grain molds	*	*	*		
	Anthracnose	*	*			*
	Striga	*	*	*		*
	Drought			*		
Pearl millet	Stem borer	*	*			*
	Head miner	*	*			*
	Downy mildew		*	*		*
	Drought		*	*		
Pigeonpea/	*Helicoverpa*-PP/CP	*	*		*	*
Chickpea	*Fusarium* wilt-PP/CP		*	*		
	Sterility mosaic-PP		*			
	Botrytis/Ascochyta CP	*	*	*	*	*
	Drought PP/CP		*	*		
	Low temperature-CP		*CP	*CP		
Groundnut	Rossette	*	*		*	*
	Early leaf spot	*	*	*	*	*
	Late leaf spot		*	*	*	*
	Rust	*	*	*	*	*
	Aflatoxins/drought	*AF	*AF/DT			*

HB = Head bugs, SM = Sorghum midge, CP = Chickpea, AF = Aflatoxins, and DT = Drought tolerance.

Table 3. Techniques, genetic information, and material generated at ICRISAT with a potential for crop improvement in ICRISAT mandate crops[1]

Crop	Trait	Screening techniques	Resistance source/ Released cultivar	Mechanisms/ Inheritance
Sorghum	Midge	Infester rows, Cage technique	DJ 6514 ICSV 745	Short glumes, grain growth rate, high tannins, Additive, dominant/recessive
Pearl millet	Downy mildew	Infector rows, Greenhouse inoculation	ICML 12 WC-C 75	Oospore germination and penetration Major genes
Chickpea	Wilt	Sick-plot, Indicator rows	ICC 2682 ICCV 2	? Susceptibility dominant, 2-3 genes
Pearl millet	*Helicoverpa*	Field screening	ICP 7203-1 ICPL 332*	? ?
Groundnut	Late leaf spot	Inoculant spray	ICGV 86699 FDRS 10**	Delayed incubation Major genes, dominant

1 = One example cited from each crop. * = Low levels of resistance. ** = Also less susceptible to *Helicoverpa/Spodoptera*, and leaf miner.

Table 4. Impact of wilt resistance in pigeonpea: Adoption of ICP 8863

Year	Karnataka	Andhra Pradesh	Maharashtra
1991	55.1	34.3	4 0
1992	59.9	48.9	13.2
1993	58.9	51.8	17 2

Bantilan and Joshi (1996) Net value of benefits from Research on Fusarium wilt = US$ 61 7 million; internal rate of return = 65%

Table 5. Benefits to Australian agriculture from ICRISAT research

Crop	Germplasm	Trait	Total annual benefit	Aggregate benefit* (1999-2022)
Sorghum	ICSV 197	Midge resistance	1.14	27 3
	DJ 6514	Midge resistance		
Chickpea	Heera	Cold tolerance	1 52	36 4
	Sona	Cold tolerance		

Brennan and Bantilan (1999)
* = Million dollars

Fig. 1. Extent of losses due to biotic and abiotic stress factors in ICRISAT mandate crops

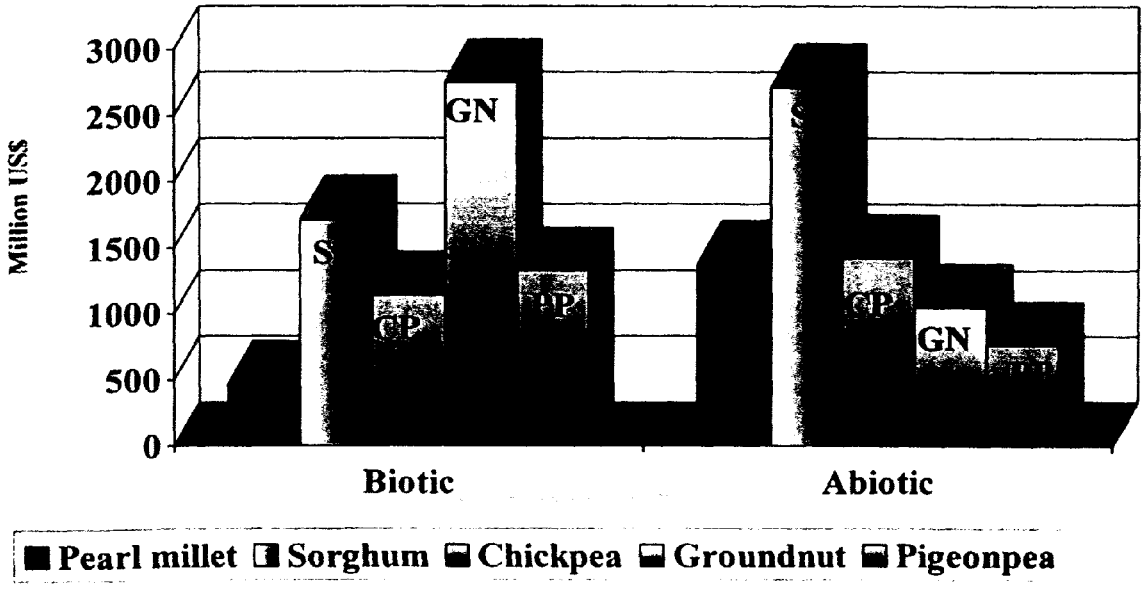


Fig. 2. Number of cultivars developed by ICRISAT and/or NARS released for cultivation

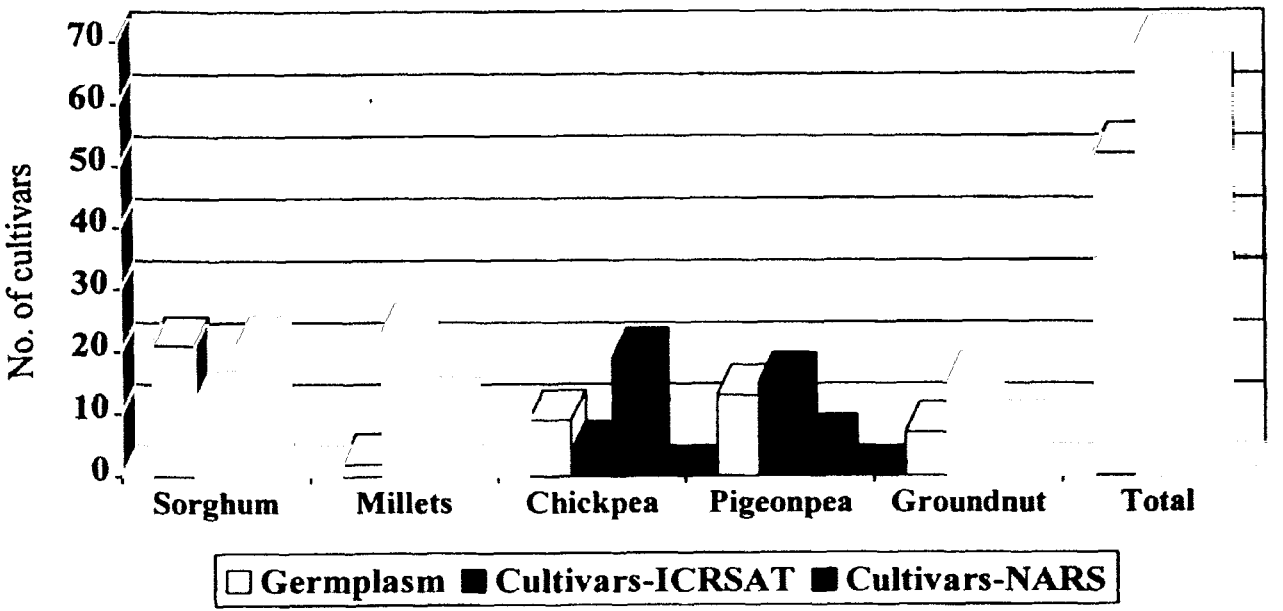
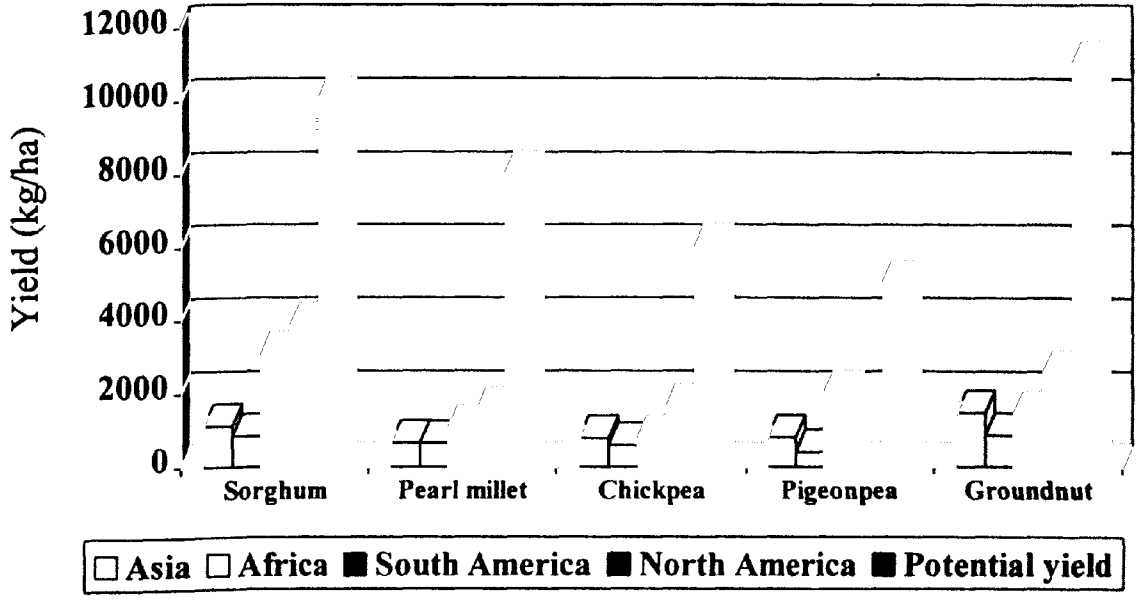


Fig. 3. Yield gap in different crops: The need to address the constraints and potential for impact



Appendix 1.

Appendix 1a. Sorghum cultivars with resistance to biotic and abiotic stress factors released for cultivation

Cultivar	Country/ State	Trait	Remarks
ICSV 197	Karnataka	Sorghum midge	Tested on farmers' fields. Also used in breeding programs.
ICSV 745	Karnataka	Sorghum midge	Also used on breeding programs.
ICSV 735	Myanmar	Sorghum midge	Also distributed for farmers in A.P., India.
ICSV 758	Myanmar	Sorghum midge	Released as dual purpose cultivar.
ICSV 804	Myanmar	Sorghum midge	
ICSV 145	India	*Striga*	
CSM 388	Mali	Head bug	Also less susceptible to *Striga*.
Malisor 84-7	Mali	Head bug	
CSM 63-E	West Africa	*Striga*	
C 151	West Africa	*Striga*	
ICSV 1063BF	West Africa	*Striga*	
ICSV 1079BF	West Africa	*Striga*	
SRN 39	Sudan Niger		

Appendix 1b. Pearl millet cultivars with resistance to biotic and abiotic stress factors released for cultivation

Cultivar	Country	Pedigree	Remarks
WC C75	India	7 full sib progenies of WC	Variety
ICMV 2	Senegal	IBV 8001	Variety
ICMV 3	Senegal	IBV 8004	Variety
ICMV 7703	India	7 inbred lines	Variety
ICMV 5	Niger	ITMV 8001	Variety
ICMV 6	Niger	ITMV 8002	Variety
ICMH 451	India	81A x ICMP 451	F_1 hybrid
ICMH 501	India	83A x ICMP 501	F_1 hybrid
ICMH 423	India	841A x ICMP 423	F_1 hybrid
Pusa 23	India	841A x D 23	F_1 hybrid
ICMA 81	India	23D2A	Male sterile
ICMB 81	India	23D2A	Maintainer
ICMA 4	India	834A	Male sterile
ICMB 4	India	834B	Maintainer
ICMA 841	India	5141A	Male sterile
ICMB 841	India	5141B	Maintainer
ICTP 8203	India	$5S_2$ progenies of selected from a landrace from Togo	Variety
Okashana 1	Namibia	ICMV 88908	Variety
PCB 138	India	ICTP 8203 selection	Variety
Kaufela	Zambia	ICMV 82132	Variety
IKMV 8261	Burkina Faso	ICMV 84400	Variety
ICMV 155	India		Variety
Pusa 322	India	841A x PPM 1301	F_1 hybrid
ICMH 356	India	88004A x ICMR 356	F_1 hybrid

Singh and Hariprasad (1998)

Appendix 1c. Chickpea cultivars with resistance to biotic and abiotic stress factors released for cultivation

Cultivar	Country	Trait	Remarks
PDG 84-10	India	Wilt resistant	ICCC 28 x WR 315
ICCV 10	India	Wilt and *root rot*	
GNG 146	*India*	Ascochyta	Selection from IARS material
ICCV 1	India	*Helicoverpa*	Less susceptible.
ICCV 2	India	Wilt	Also less susceptible to *Helicoverpa*
ICCV 37	India	Dry root rot	

Sethi and van Rheenan (1994).

Appendix 1d. Pigeonpea cultivars with resistance to biotic and abiotic stress factors released for cultivation.

Cultivar	Release name	Country	Trait	Remarks
ICP 8863	Maruti	India	Wilt	1985
ICPL 332	Prabhat	India	*Helicoverpa*	1991
ICPX 78120-WB-WB-WB	Birsa Arhar-1	India	Wilt	1993
ICPL 87119	Asha	India	Wilt and sterility mosaic	1993
ICPL 87051	-	India	-do-	-
ICP 7035	Kanica	Fiji	-do-	
ICP 9145	Nandola Wanswara	Malawi	Wilt	1985
ICP 11384	Bageshwari	Nepal	Sterility mosaic	1992
ICP 6957	Rampur Rhar 1	Nepal	Sterility mosaic	1992
ICPL 295	-	Philippines	Wilt	-

Ariyanayagam and Jain (1994)

Appendix 1e. Insect pest and disease resistant pigeonpea lines recommended for use in breeding program by the All India Coordinated Pigeonpea Improvement Project.

Insect/disease	Location	Genotype(s)
Helicoverpa	Lam, AP	ICPL 332
Wilt	Lam, AP	ICP 8859
Wilt/sterility mosaic	Lam, AP	ICPL 87119, ICP 8868
Sterility mosaic	Dholi, Bihar	ICP 7035, ICP 8862, ICP 10976
Wilt	Rahuri, Maharashtra	ICPL 89044, ICP 8094, ICPL 86005, ICPL 88023, ICPL 88025
Wilt/SM	Rahuri, Maharashtra	ICPL 88046, ICPL 88047, ICPL 87119, ICPL 87104.

Ariyanayagam and Jain (1994).

Appendix 1f. Groundnut crop cultivars with resistance to biotic and abiotic stress factors released for cultivation

Cultivar	Country	Trait	Remarks
ICG (FDRS) 4	Guinea/Conakry	Foliar diseases	Pre-release trials 99
ICG (FDRS) 10	Lesotho, Niger		On-farm trials 1999
ICG 7886 (Cardi-Payne)	Jamaica	Foliar diseases	On-station trials 1997
ICG 7878 (Waliyar tige)	Lesotho	Foliar diseases	On-farm trials 1999
ICGV SM-86715 (Veronica)	Mauritius	Foliar diseases	1992
ICGV-SM 85048 (Stella)	Mauritius	Web blotch	1992
ICGV 83207 (Syria)	Mauritius	Foliar diseases	1997
ICGV 87853 (Venus)	Mauritius	Foliar diseases	1999
ICGV 87160 (Sinpadetha)	Myanmar	Foliar diseases	1993
ICGV 87157 (ICG (FDRS-4)	Sierra Leone	Foliar diseases	On-farm trials
ICGS 11	India	Field tolerant to BND	1986
ICGS 44	India	Field tolerant to BND	1988
ICGS 37	India	Field tolerant to BND	1990
ICG (FDRS)10	India	Foliar diseases	1990
ICGV 86325	India	Foliar diseases	1991
ICGV 86011	India	Moderate resistance to foliar diseases, jassids, and root rot.	1994

Nigam, S.N. (personal communication).

Appendix 1g. Groundnut germplasm with resistance/tolerance to biotic and abiotic stress factors.

	Resistance/tolerance to	
Genotype	Insects	Diseases
ICGV 87157	-	Rust, late leaf spot, and bud necrosis
ICGV 86031	*Spodoptera*, leaf miner, jassids, and thrips	Bud necrosis
ICGV 86699	*Spodoptera* and jassids	Rust, late leaf spot, bud necrosis, and stem and pod rots.
ICGV 88145	-	Aflatoxins
ICGV 89104		Aflatoxins
ICGV 86388	Thrips and jassids	Bud necrosis
ICGV 87165	*Spodoptera* and leaf miner	Rust, late leaf spot, and bacterial wilt
ICGV 86252	Jassids and thrips	-
ICGV 86393	Jassids and thrips	-
ICGV 86455	Jassids and thrips	-
ICGV 86462	Jassids and thrips	-

Nigam, S.N. (personal communication)

Appendix II

Information bulletins published by ICRISAT describing resistance screening techniques/sources of resistance to biotic and abiotic stress factors

Mehan, V.K., and **McDonald, D.** 1995. Techniques for diagnosis of *Pseudomonas solanacearum*, and for resistance screening against groundnut bacterial wilt: a manual. Technical manual no. 1. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 68 pp.

Nene, Y.L., Haware, M.P., and **Reddy, M.V.** 1981. Chickpea diseases: resistance screening techniques. Information bulletin no. 10. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 12 pp.

Nene, Y.L., Kannaiyan, J., and **Reddy, M.V.** 1981. Pigeonpea diseases: resistance screening techniques. Information bulletin no. 9. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 16 pp.

Pande, S., Bock, C.H., Bandyopadhyay, R., Narayana, Y.D., Reddy, B.V.S., Lenne, J.M., and **Jeger, M.J.** 1997. Downy mildew of Sorghum. Information bulletin no. 51. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 32 pp.

Sharma, H.C., Faujdar Singh and **Nwanze, K.F.** (eds.). 1997. Plant resistance to insects in sorghum. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 216 pp.

Sharma, H.C., and **Nwanze, K.F.** 1997. Mechanisms of resistance to insects in sorghum and their usefulness in crop improvement. Information bulletin no. 45. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 56 pp.

Sharma, H.C., Saxena, K.B., and **Bhagwat, V.R.** 1999. The legume pod borer, Maruca vitrata: bionomics and management. Information bulletin no. 55. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 42 pp.

Sharma, H.C., Taneja, S.L., Leuschner, K., and **Nwanze, K.F.**. 1992. Techniques to screen sorghums for resistance to insect pests. Information bulletin no. 32. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 53 pp.

Singh, A.K., Mehan, V.K., and **Nigam, S.N.** 1997. Sources of resistance to groundnut fungal and bacterial diseases: an update and apprisal. Information bulletin no. 50. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 48 pp.

Singh, S.D., Wilson, J.P., Navi, S.S., Talukdar, B.S., Hess, D.E., and **Reddy, K.N.** 1997. Screening techniques and sources of resistance tao downy mildew and rust in pearl millet. Information bulletin no. 48. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 104 pp.

Subrahmanyam, P., McDonald, D., Waliyar, F., Reddy, L.J., Nigam, S.N., Gibbons, R.W., Ramanatha Rao, V., Singh, A.K., Pande, S., Reddy, P.M., and **Subba Rao, P.V.**. 1995. Screening methods and sources of resistance to rust and late leaf spot of groundnut. Information bulletin no. 47. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 24 pp.

Thakur, R.P., King, S.B., Rai, K.N. and **Rao, V.P.** 1992. Identification and utilization of smut resistance in pearl millet. Research bulletin no. 16. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 36 pp.

Thakur, R.P., Rai, K.N., King, S.B., and **Rao, V.P.**. 1993. Identification and utilization of ergot resistance in pearl millet. Research bulletin no. 17. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 40 pp.

Vasudeva Rao, M.J. 1985. Techniques for screening sorghums for resistance to Striga. Information bulletin no. 20. Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). 20 pp.

Breeding methodologies – Cereals

F R Bidinger

Current Research Themes in Cereal Improvement

- Development of molecular maps, and identification of QTL
- Evaluation and use of QTL in breeding
- Targeted diversification of gene pools and breeding populations
- Diversification and improvement of hybrid parental lines
- Research on new breeding opportunities
- Support of regional/national breeding programs

GREP Global Cereals Research Program Staff I

- **Southern/Eastern Africa**

  Genetic Resources, Breeding, Entomology, Network Coordination, Technology Exchange, Seed Systems plus 2 research sites

- **West/Central Africa**

  Genetic Resources, Breeding (2), Pathology, Entomology, Technology Exchange, Network Coordination (2) plus 2 research sites

GREP Global Cereals Research Program Staff II

- **Asia**

  Genetic Resources, Breeding (2), Genomics (3), Statistics, Physiology, Pathology, Entomology, Bioinformatics,

  plus major research site, genebank, and applied genomics lab

Development of molecular maps, identification of QTL I

Traits for which we have made limited progress by conventional means

- **SG: shoot and panicle pests, grain mold, *striga,* drought tolerance**

  RIL breeding, genotyping and phenotyping

- **PM: downy mildew pathotype resistance, stover quality, drought tolerance**

➢ **9 mapped F2 pop, active phenotyping**

Development of molecular maps, and identification of QTL II

Exploration of other opportunities to use molecular genetic maps

- **SG/PM : consensus and comparative maps**
  - **existing maps, collaboration**
  - **opportunities to exploit synteny**
- **PM : contiguous segment substitution lines**
  - **response/adaptation traits**
  - **systematic diversification**

Evaluation and use of QTL I

Quantification of effects/mechanisms of identified QTL

- **SG: stay green and *striga* resistance**
  - **near-isogenic lines**

- **PM: downy mildew resistance and drought tolerance**
  - **near- isogenic hybrids**

Evaluation and use of QTL II

Evaluation of QTL as selection criteria

- **marker assisted backcrossing**
- **pedigree selection**
- **marker assisted introgression**

QTL deployment strategies - PM downy mildew and drought QTL

- **pyramiding/rotation strategies**
- **QTL + phenotypic selection**

Targeted diversification of breeding gene pools I

Problem oriented diversification

- Trait based populations:
  - SG: large seed, high tillering, maintainer
  - PM: panicle size, seed size, dual purpose, brown midrib, white grain,

- Resistance populations:
  - SG: midge, *striga,* grain mold, leaf disease
  - PM: downy mildew

- ➢ Population methods, recurrent progeny and mass selection

Targeted diversification of breeding gene pools II

Regionally oriented diversification

SG: improved *guinea* populations
- brown seeded populations
- acid soil tolerant populations
- feed/milling quality populations

PM: higher yielding populations
- purified landrace populations
- diversified landrace-based populations
- farmer participatory populations

➢introgression, pedigree and population breeding, mass and progeny selection

Diversification/improvement of hybrid parental lines I

New cytoplasmic male-sterility systems

- PM: A4 and A5 cytoplasms
  - iso-nuclear maintainer comparisons
  - improvement in A4 restoration
  - F1 CMS seed parents
  - CMS populations
- SG : A2 cytoplasm
  - A1 vs A2 comparisons
  - diversification of A2 maintainers

Diversification/improvement of hybrid parental lines II

Broadening the adaptation/ resistance base of hybrid parents

SG: shoot pest, grain mold resistance and large grain size for Asia

guinea, *durra* and late *caudatum* backgrounds for west Africa

Striga and insect resistance for eastern/southern Africa

- Mainly pedigree breeding, plus multiple crosses to combine traits

Diversification/improvement of hybrid parental lines III

Broadening the adaptation/ resistance of hybrid parents

PM: general adaptation (West and southern Africa)
downy mildew resistance/ combining ability (West Africa)
trait diversification and A4/A5 restoration (Asia)

- population improvement with inbreeding of progenies

Research on new plant breeding opportunities

- participatory breeding opportunities
- improved straw feeding quality
- selection strategies for important traits for West African SG varieties
- exploitation of heterosis in PM landrace-based topcross hybrids
- heterotic patterns in PM varieties
- seed production/supply systems

Support of regional and national breeding programs

- Support to regional networks in Africa
  - planning, coordination, reporting, etc
  - supply of trials, breeding materials
  - technical backup
  - seed production
- Collaborative ICRISAT-ICAR projects
  - shared research projects
- Bilateral special projects
  - technical assistance in plant breeding
- Breeder seed supply

Breeding methodologies – Legumes

C L L Gowda

Breeding legume crops at ICRISAT

- Involvement of international research groups in legumes is low to medium
- International investment to legume breeding is meagre
- International knowledge base for legumes is small
- Legumes are essentially self-pollinated (except PP)
  - Hybridization is tedious and expensive
  - Lack of male-sterility system (except PP)
- Limited opportunities for rapid generation turnover
  - Possible in GN, and limited extent in CP and PP
  - Progress in breeding is slowed down

GREP Global Legumes Research Program staffing

- **Southern and Eastern Africa**
  Genetic resources (1*), Breeding (2), Entomology (1*), Seed systems (1) + 2 research sites
- **West and Central Africa**
  Genetic resources (1*), Breeding (1*), Pathology (1), Entomology (1*) + 2 research sites
- **Asia**
  Genetic resources (3*), Breeding (5*), Genomics (3) Transformation (2), Wide-Hybridization (1), Physiology (2), Pathology (3*), Entomology (1*), Bioinformatics (1*) + major research site, genebank, and genomics lab, field and glasshouse screening

Breeding emphasis : Past – (1)

	Chickpea	Groundnut	Pigeonpea
Creating variability	xxx	xxx	xx
High yield potential	xxx	xxx	xxx
Stability/Adaptation	xxx	xxx	xxx
Maturity duration	xx	xxx	xxx
Cropping system adaptation	x	-	xx
Ideotype	xx	-	xx
BNF	xxx	xx	x
Hybrids – GMS, CMS	-	-	xx
Grain quality	xx	xxx	xx

Breeding emphasis : Past – (2)

	Chickpea	Groundnut	Pigeonpea
Stress resistance/tolerance			
- Foliar diseases	xx	xxx	x
- Soil-borne diseases	xxx	x	xxx
- Foliar pests	xx	xxx	x
- Pod borers	xxx	x	xxx
- Drought tolerance	xxx	xxx	xx
- Cold/heat tolerance	xx	x	-
Water logging	-	-	x

Current research themes: Legumes

- Diversification of genetic material
- Incorporation of resistance to pests and diseases, and drought tolerance
- Combining multiple resistances (to biotic/abiotic stresses)
- Developing molecular maps and identification of QTL
- Inter-specific crosses to transfer traits (including CMS)
- New opportunities and methods for efficiency/efficacy
- Supporting networks and national programs

Breeding legumes: Issues for future

- Use of genetic resources for variability
  - New sources of genes for yield & adaptation
  - Wild relatives and secondary gene pool

Partnerships
  - Private sector companies – breeding, markers
  - AROs – markers, transformation
- Increased use of marker-assisted selection
- New methods/strategies to incorporate genes from wild relatives
- Targeting local v/s regional adaptation
- Search for CMS and hybrids

West and Central Africa

Pearl Millet breeding in West Africa[1]

Introduction

The area planted to pearl millet in West Africa is estimated at 12 million ha with an annual production of 9.6 million tons. Major pearl millet producing countries are Nigeria, Niger, Mali, Burkina Faso and Senegal and between them account for 84% of the production. Average grain yields range from 0.5 t to 1.0 t ha^{-1}. Nearly 80% of the pearl millet is grown in the Sahelian Zone (300-600 mm annual rainfall and a growing season length of 60-100 days), and the rest in the Sudanian Zone (600-900 mm and 100-150 days). The reasons attributed to low productivity include constraints of: stand establishment, moisture and nutrient stress, insect pests, *Striga*, diseases (downy mildew), low yield potential of local cultivars, and traditional management practices. Millet grain has little commercial status and is mainly used in the preparation of traditional foods. Millet stover has an important role in feeding livestock during the dry season. Because the crop has originated and was domesticated here, a diverse range of landraces occurs in the region often with very specific adaptation. In West Africa severity of diseases, such as downy mildew is very high, and the crop suffers infestations by insect pests and *Striga*, a unique situation that occurs only here.

Procedures and methodologies

Goal. The principal goal is to contribute to stable and improved production and productivity of pearl millet. This is accomplished through (i) contribution to the development, evaluation and release of Open-pollinated Varieties (OPVs) by the National Agricultural Research Systems (NARS), either directly or with the support of the West and Central African Millet Research Network (WCAMRN); with well-endowed millet breeding programs (for example Niger, Nigeria) we are involved in collaborative breeding, (ii) active participation in the research projects of the WCAMRN that emphasizes farmer participatory technology evaluation, and (iii) responding to emergency seed production projects that contribute to building seed stocks and have a significant multiplier effect on variety adoption. In West and Central Africa (WCA) the informal seed system that involves retention of seed from own crop and farmer-to-farmer exchange is highly predominant. This has implications in impact surveys, as taking into account only quantities multiplied by formal seed systems tends to under-estimate total coverage by improved varieties.

Early history. Evaluation of elite genetic material and OPVs bred at ICRISAT in India for direct use in WCA indicated that they were not adapted to the harsh conditions prevailing here. Progressively, the breeding program concentrated in introgressing local germplasm into the breeding material and populations. This approach of introgressing local germplasm and its extensive use in variety development has resulted in some very successful varieties and more recently hybrid parents for the region. Gradually, the use of genetic material developed in India has been significantly reduced, except for new sources of cytoplasmic genetic male sterility.

[1] Background notes prepared by K Anand Kumar for TAC Review on 'Plant breeding methodology' March 2000.

Breeding priorities. Breeding priorities have been established through several regional workshops conducted in mid-eighties, through active participation in the WCAMRN's priority setting process, and more recently with involvement in farmer participatory technology transfer activities.

Selection criteria. As drought is a recurring problem, earliness (55-75 days to flower) is an important selection criterion. As earliness is positively related to insect pest infestations, selection is for genotypes with a cycle length of 90-105 days. Because stability of production is important sufficient levels of host plant resistance are needed to the major pests and diseases. Selection criteria for plant traits include: a medium stature (2.0 – 2.5 m), 3-4 effective tillers, 40-65 cm head length and a large grain size (>10g 1000 grains^{-1}). In addition, consumer quality of the grain and stover yield is assessed with landrace varieties providing the yardstick.

Selection for stress factors

For drought tolerance research by physiologists suggests that breeding for higher-yielding, shorter-cycled genotypes as a productive strategy. Varieties need to flower earlier to escape drought, and have high grain growth rates for a short grain filling period. To achieve success we ensure that the maturity duration of the genotypes approximately fits the growing season length with no large deviations. Selection for earliness is relatively easy as the heritability of time to flowering is high, and the trait is easily assessed.

Downy mildew (DM) is the most important disease on pearl millet. Variability in the pathogen exists in WCA and is assessed through a multilocational West African Downy Mildew and Smut Observation Nursery (WADMSON). Though DM occurs in sever proportions in most locations in WCA (except Senegal) the pathogen present in Nigeria appears to be most virulent. Thus it is a better location to screen for resistance because of high disease pressure and lines resistant in Nigeria are resistant in most other countries, including India. Resistance screening is carried out with the field screening technique developed in India. A glass house screen is used for specific studies. In general, as most of the breeding material is derived from West African sources it carries desirable levels of resistance. Particular attention is given to the male sterile development material as the sources of cytoplasmic sterility from both USA and India are highly susceptible.

The millet head miner has become a major pest following droughts of the early seventies. Our data clearly show that under natural pest infestation levels, both very early flowering genotypes (45-50 d) and late flowering genotypes (75-80 d) escape damage. We have begun using a screening technique developed recently that uses a fixed number of eggs earhead^{-1}.

The millet stem borer larvae feed within leaf sheath and tunnel through the stems that results in early 'dead hearts'. We monitor reaction of advanced varieties using population argumentation, achieved through the use of shade-stored infested stalks of the previous season. Varieties that record higher levels of infestation than the controls are discarded.

Striga hermonthica parasitizes pearl millet and causes widespread damage. Early varieties (<80-85d maturity) escape infestation. Our preliminary screening of a range of genotypes in pots and sick plot identified four improved varieties with a lower level of infestation. A practical system of control would include a *Striga* resistant cultivar, application of fertilizer and FYM, manual weeding of the parasite to prevent seeding, and non-cereal crops (such as cowpea) in rotation.

Breeding products: OPVs or hybrids?

We concentrate on the development of OPVs through recurrent selection. This is because all the area planted to pearl millet in WCA is grown to open-pollinated varieties, pearl millet breeding activities in NARS have limited human and physical resources, and the functioning seed multiplication projects are only familiar with the multiplication of OPVs. A review of breeding efforts in the region shows that they concentrated on selecting for earliness to avoid effects of drought but the *improved varieties* do not show significant yield advantages over farmer's varieties. Breeding hybrids provides an opportunity to increase grain yield potential. Prospects for hybrid use appears to be high in Nigeria where seed companies are getting established, and are capable to produce and market hybrid seeds. They are already marketing maize hybrids. Nigerian NARS is keenly interested in collaborating with ICRISAT on hybrid development.

The balance of breeding effort between varieties and hybrids will depend on whether it will be possible to produce and distribute hybrid seed. Currently there is no significant private hybrid seed industry (including for maize and sorghum) in the region and all seed production and distribution activities are undertaken by public sector NARS and to a limited extent by NGOs. The development of pearl millet hybrids is at an early stage and in the next 5 years there are prospects for the development of a hybrid seed industry, in time for multiplication and commercialization of superior hybrid combinations. Hence under the prevailing situation the development of hybrids has to remain complementary to the breeding of OPVs.

Breeding methods

Composites are largely based on maturity (early, mid-late and photoperiod sensitive), and morphological characters (long head, large seed, dwarf) and are formed through intervarietal and interpopulation crosses. Our choice of the recurrent selection procedure depends not so much on the relative efficiency, but more on the breeding objective, and physical and human resource capability. Thus we have used mass selection, S_1/S_2 progeny selection, in combination with screening for DM reaction of the selected progenies. Selection in population progenies has been used essentially in inter-varietal populations for breeding OPVs and or eliminating intermediate forms (shibras) from landraces. Provided the base population has sufficient variability and includes locally adapted material, there is more assurance of producing improved varieties with the expected rate of grain of 1 to 2% per year, since selection for multiple traits is involved. Worthwhile gains in terms of reducing DM susceptibility and contamination by shibras have been obtained by using one or two cycles S_1 selection. Varieties are formed from progenies selected using a higher selection intensity. The number of progenies selected to recombine into a variety varies from 8

to 25. Gridded Mass Selection has been used in the improvement of varieties that have severely deteriorated. Pedigree breeding is used for introgressing specific traits.

For hybrid breeding the emphasis is on topcross hybrids (TCHs, cytoplasmic genetic male-sterile x OPV / landraces) as they tend to avoid epidemics of downy mildew and ergot. Use of landraces assures local adaptation, and our experience shows that TCHs elicit responsiveness to improved environmental conditions. Seed parents have to exhibit stable sterility and DM resistant and pollinator parents should be prolific pollen shedders and restore fertility of the hybrid.

Farmer-preferred traits

It is becoming increasingly clear that for acceptance of an improved variety, farmer participation in varietal evaluation should be integrated into the on-going breeding programs. Farmer participation in the evaluation of varietal trials is beneficial in identifying varieties with traits of importance. Such evaluations have shown that farmers prefer a maturity duration of 90-100 days, high number of productive tillers, long earheads, large grain size, and a plant stature of around 2.5 m. Extensive data generated by individual countries through participatory evaluation of such farmer-preferred traits through the WCAMRN seed project is used in our selection.

Genetic diversification

To ensure that our populations and parental material is broad-based, after every 3-5 years variability in populations is enlarged through merging or introducing new germplasm accessions. Recent introduction of new variability includes large earhead circumference (15+ cm), vitreous grain, and large grain size (> 16 g 1000 grains) combined with earliness. New seed parents developed at ICRISAT, India are assessed for DM reaction and resistant entries are used in male-sterile development. Elite lines from NARS have also been used in variety crosses to develop inbred lines as parents for top cross hybrids. Specific traits such as **bmr**, *tr*, and bold seed have been derived from sources ex USA and West Africa. Whenever sources from USA and India are used, a rigorous selection for DM resistance becomes necessary.

Partnerships

There is a close involvement of ICRISAT breeders in Project P1/7 (development and diffusion of improved varieties to farmers) of the WCAMRN. Collaboratively bred ICRISAT-NARS varieties are contributed to and tested in the network-coordinated trials. Seed of varieties that perform well is increased and provided to requesting NARS for their on-station and on-farm trials. Descriptions of released varieties are putout as 'fiche-techniques' jointly by the national program, WCAMRN and ICRISAT. Collaboration is also being developed with NGOs and private industry.

NARS scientists are involved in joint publication of results. ICRISAT breeders both in Nigeria and Niger supervise student thesis. In addition, ICRISAT collaborates with INTSORMIL (Tifton, GA.) in the development of CMS lines.

The range of partnerships involved is illustrated by ICRISAT's partnership with two Nigerian research institutes [Lake Chad Research Institute (LCRI), Maiduguri, and

Institute for Agricultural Research (IAR), Samaru] for improving pearl millet, sorghum and associated systems. ICRISAT works closely with extension programs such as Kano Agricultural and Rural Development Authority and Agricultural Development Programs, and Sasakawa Global 2000 and Sokoto Agricultural and Community Development Project for evaluating research products on-farm. ICRISAT has established linkages with seed companies such as Premier Seeds, and Nagoma Seeds and National Seed Service for the production and seed certification.

Spillovers

There have been spillovers of plant breeding research from ICRISAT breeding research into several countries within West Africa (9 countries), and to Zambia. OPVs and breeding populations serve as source material in our Southern and Eastern African program based in Zimbabwe. In addition, elite genetic material, including sources of specific traits, and advance varieties have been provided to our program in Patancheru for introgression into new populations /composites.

Achievements

To ensure optimal utilization of outputs and efficiently serve NARS our programs located in Niger and Nigeria exchange seed material and are involved in collaborative seed parent and hybrid development. In the last few years, there is an incremental adoption of OPVs. Among the principal constraints that are resulting in low levels of diffusion of improved varieties is the absence of effective seed multiplication and distribution services in many countries. However, the situation is slowly changing with increasing emphasis on farmer participatory seed production (see section below). Development and testing of hybrids is now accepted as a complementary approach towards development of improved varieties. Because of the activities of the network, there is increased production of good quality seed and most of it is participatory on-farm seed production. Some of the recent achievements are highlighted under four heads: (i) new populations, (ii) Open-pollinated varieties, (iii) seed production and supply, and (iv) seed parents and hybrids.

New Populations

New populations. We developed four populations for recurrent selection that combine new trait combinations such as large grain and earliness, large earhead circumference, and vitreous grain. These populations offer, for the first time novel trait combinations to millet breeders worldwide.

Selection in composites by farmers. ICRISAT- Lake Chad Research Institute (LCRI) developed Early maturing composite (< 55 days to flower), Medium maturing composite (55 to 70 days), Late maturing composite (70 to 90 days) and a Dwarf composite (1.7 to 2.0 m plant height)] were selected using gridded mass selection by farmers in two villages. They selected about 10% plants of their choice. Farmers preferred early maturing and dwarf composites. The selection criteria varied slightly in each village. Farmers preferred long panicles of medium maturing composite. Late maturing composite was rejected by farmers in one village due to poor seed set. This farmer participatory gridded mass selection will be continued.

Elimination of shibras. At ICRISAT-Niger, shibras (weedy species *Pennisetum glaucum* subsp. *stenostachyum*). were eliminated from Ankoutess [a Nigerién landrace characterized by a distinct short and stubby ear heads] containing 30% shibras following S_1 selection. In collaboration with INRAN seed of the improved version is being multiplied for on-station and on-farm tests.

Stover quality. In collaboration with ILRI and INRAN the value of the single recessive gene, brown-midrib (**bmr**) in stover quality is being investigated. This gene obtained from Purdue University has been incorporated into adapted backgrounds. It appears to have several negative pleiotropic effects that could offset advantages gained in forage digestibility. These include reduction in grain yield, and stover yield. However, there is significant reduction in lignin content and increased digestibility. In collaboration with ILRI, We have initiated studies on variation for digestibility of stover of Niger landraces.

Open-pollinated Varieties

Of 14 ICRISAT-NARS co-developed OPVs over the last ten years, eight have performed extremely well in several countries and are becoming highly popular (details of six are given here). Farmers and NGOs in several countries are giving appropriate names in local languages that denote their primary contribution. For example, in Mauritania GB8735 is called *Rijal-el-ghaiss* (harbinger of good fortune) as its early harvest allows men to stay back in the village instead of finding work in the capital city during the hungry period and in northern Nigeria, it is called *Kora yunula* (drives away hunger).

Variety SOSAT-C88 was co-developed by ICRISAT-Niger and Institut d'Economie Rurale of Mali. from a population derived from two Malian landraces, Souna and Sanio. SOSAT-C88 has been released Chad, Mali, Mauritania, Nigeria, Cameroon, in advanced test in Burkina Faso, being distributed by CARE in Niger. Following excellent performance in on-farm trials this variety was released in Nigeria in January 2000 as LCIC-MV1 (Lake Chad research Institute/ICRISAT-Millet Variety 1). In several hundred on-farm trials conducted in Nigeria in the last two years, this variety was selected by majority of the farmers as their first choice. As there is a large demand for the Commissioner of Agriculture of Kano State is making arrangements for seed multiplication. This variety is rapidly gaining popularity in several countries in WCA and is estimated to be grown on about 30 000 to 50 000 ha. An adoption study is planned during year 2000 in both Chad and Nigeria that should give us a better picture. This variety is preferred for its food quality in Chad, Niger, and Burkina Faso. From Nigerian women's point of view, SOSAT-C 88 is easy to thresh, taking only ½ the time than local varieties. In Nigeria this variety is expected to b grown by 10 000 farmers in 2000.

Variety GB 8735 is one of the most successful varieties that has been developed using pedigree selection. It is derived from a cross involving Iniari [Togo]x Souna [Mali]. This variety is early, and recovers and produces near-average grain yields when normal conditions follow a severe drought spell. GB 8735 has been released and grown by farmers in Chad, Mauritania, Benin, Niger (Keita valley, with two crops in the same season), and Mali. It is a component of variety LCIC –9702 developed by ICRISAT-Nigeria and possibly be released in 2001. In Benin and

Mauritania it is reputed to be the best variety that provides grain during the hungry period. Incremental adoption is occurring in Chad through use of mini-doses (small packets containing 500 g seed; an estimated 12 000 farmers have bought the mini-doses) and is estimated to cover around 30 000 ha. In other countries the estimate is around 3000-4000 ha. An adoption study is planned during year 2000 in both Chad should give better picture

Varieties CIVT and HKP are two very popular pearl millet varieties in Niger. As seed multiplication was undertaken under unsatisfactory conditions for several years, these two varieties have severely deteriorated. In collaboration with INRAN, these two varieties were improved through gridded mass selection for uniformity in time to bloom, head type, seed set, seed color, and absence of shibras. Through INRAN, NGOs, and private seed producers, good quality seed is being supplied to farmers to replace the degenerated versions. We expect a very rapid dissemination of these two varieties. We are producing 1.2 tons of seed of HKP-GMS for the next rainy season. If properly multiplied and distributed this should serve to cover an area of over 120 000 ha. by early 2002.

Variety ICMV IS 89305 derived through pedigree breeding is unique in the sense that it performs as well as the local under farmers traditional management *(unlike most improved varieties whose performance is inferior to the local under low fertility situations)* and responds extremely well to fertilizers. This variety released for general cultivation in Burkina Faso and Niger and is popular as reflected in the increasing seed demand. This variety has all the characters preferred by farmers from Western Niger including good stover yield.

Variety LCIC 9702 is early and involves Togolese backgrounds such as GB 8735, and Okashana. It is preferred by farmers because of its extra earliness. This variety is adapted to drier parts of Kano, Jigawa, Sokoto, Kebbi and Katsina states in Nigeria. Based on performance it has been included in some states in to Small Plot Adaptation trials.

Seed Production and Supply

Farmer participatory seed production is gradually on the increase. In 1999, over 17 tons of seed of ICRISAT-NARS developed varieties was produced by WCAMRN member countries. Of this over 80% was on-farm participatory seed production. Two varieties SOSAT-C88 and GB 8735 are gaining enormous popularity and contributed to 80% of the seed produced.

In Nigeria, 125 farmers produced seed of two pearl millet varieties (SOSAT-C88, and LCIC 9702) during the last rainy season. An Information Bulletin on seed production procedures in sorghum and pearl millet was published for use by seed growers. Seed so produced is being sold to farmers and developmental organizations. We have learnt from LCRI, that the seed of SOSAT-C88 and LCIC 9702 is also sold to NGOs in Cameroon and Niger. NGOs (SG 2000, and SACDP/IFAD) also participated in on-farm seed production.

Seed supply. ICRISAT-Niger, because of the availability of postrainy season irrigation facilities has been able to produce seed of OPVs and provide it in time to NARS and NGOs. In 1998 and 1999, we have provided 2.8 tons of seed of seven OPVs and provided to eight Sahelian countries. In 1998 we participated in an emergency seed production project (purchase of large quantities of seed and breeders seed production) that contributed to building seed stocks and has had a significant multiplier effect on variety adoption. Studies by INRAN economist show that the emergency seed distribution project has benefited over 3800 farm families and on an average 30% of the farmers have adopted the varieties that were distributed.

Seed parents and hybrids

Hybrids. In collaboration with the WCAMRN a Regional Pearl Millet hybrid trial was initiated in 1998 - a first for WCA - and was conducted at 12 locations. Analysis indicated that grain yield of the best hybrid as percent of improved variety and farmers checks ranged from 3 to 150%. Results also showed that mid-late topcross hybrids with local landraces and near-complete fertility restoration will combine local adaptation with grain yield potential.

New seed parents. A set of eight seed parents is now available and has been characterized for morphological traits. These are being provide to millet breeders in the region for use in the development of topcross hybrids.

Seed parents with A_4 cytoplasm. At ICRISAT-Nigeria, 30 A/ B pairs derived from NC d_2 BC_3 in A_4 cytoplasm (from ICRISAT-Patancheru) were evaluated for stability of sterility and DM resistance. Of the variety pollinators evaluated, SOSAT-C88 was found to be a maintainer, whereas varieties ZATIB and LCRI-IC 9702 were restorers. From preliminary analysis, it appears that pollinators have similar GCA effects, and male-sterile lines have significant variation for GCA. Based on grain yield data, six hybrids and based on combining ability and DM reaction, nine male-sterile lines were retained. Farmers were involved in the selection of hybrids.

Training. A graduate student completed his thesis *on 'Etude sur le potential des hybrides (cms x variéte) chez le mil* (*Pennisetum glaucum*) and submitted to the University of Abidjan, Cote d'Ivoire.

Future emphasis

The following areas have been identified by participants of the WCAMRN as of importance for future emphasis.

Development of genetically diverse populations for farmer participatory selection
Diversification of male-sterile cytoplasm
Development of hybrids
Resistance to *Striga hermonthica*
Improvement in resistance to insects (new cropping systems with early cultivars)
Stover quality
P-use efficiency
Breeders and foundation seed production (service function)

Several of these can be developed into special projects in bi-lateral or multi-lateral partnership with NARS and NGOs and submitted for funding.

Enhanced use of genetic resources and potential role of applied genomics. Establishment of a regional core collection to foster increased use of genetic resources (this was one of the recommendations of the recently concluded external review of the WCAMRN). Applied genomics can contribute to *Striga* resistance, resistance to millet head miner, P-use efficiency, and improved stover digestibility.

Sorghum Breeding for West Africa[1]

Introduction

Breeders based in Bamako, Mali and Kano, Nigeria share the responsibility for sorghum improvement. In Mali the emphasis is on population improvement in local Guinea sorghum populations. It is recognized that the potential yield gains to be achieved by improving local material may be limited. However, given the long-term stability of these populations selected by farmers over hundreds of years this strategy has the combined advantage of meeting local grain type requirements and avoiding insect pest infestations. Much of the work (including conversion to male-sterility as a prelude to hybrid development) with guinea sorghums aims to improve yield potential and pest resistance while retaining the superior adaptation traits.

Until very recently as the accent of the program in Nigeria was on technology exchange a series of on-farm activities (including seed multiplication) were initiated based on varieties that were previously developed. This work has helped enlarge movement of improved varieties to the farmers' fields. In Nigeria much of the work is concentrated on improved varieties and hybrids that generally show their superiority to varying environments. The presence of NGOs and ADPs and an emerging private sector helps in seed production and distribution programs. There is a potential for use sorghum grain for malting offering scope for increased demand.

I. Sorghum Breeding Program in Bamako, Mali.

1. Procedures used and end-products

Period 1994-1997:

During this period pedigree breeding was the primary procedure used. The ICRISAT program used Caudatum materials developed in India and Nigeria, and crosses of these materials with landrace materials from Nigeria and Mali. The CIRAD program used Guinea and Caudatum parents with the objectives of reduced straw, increased panicle weight and maintenance of grain quality. A random-mating Guinea Population was developed based on 13 landrace varieties from the region by CIRAD. On-farm evaluation of acceptability of bred varieties was conducted with CMDT.

Period 1997 to present:
During this period improvement of the Guinea Population was initiated with mass selection for grain and panicle characteristics (grain size, free threshing, panicle architecture, resistance to grain anthracnose) and maturity. Superior male-fertile plants selected from this population go into a pedigree breeding program for line development.

The characterization of genetic variability within Guinea landrace varieties was initiated in 1999 with farmer-selected panicle-progenies. The information on genetic variability for key agronomic traits will indicate opportunities for enhancing local

[1] Background notes prepared by H F W Rattunde, E Weltzien (Bamako, Mali), and S C Gupta (Kano, Nigeria) for TAC review on 'Plant breeding methodology', March 2000.

varieties for specific traits through intra-varietal selection using formal breeding procedures.

Test crossing was initiated to determine the fertility reaction of Guinea varieties as a basis for developing Guinea hybrid parental lines.

Participatory research was conducted in collaboration with IER and with a wide range of partners (CMDT, Sasakawa Global 2000, AproFem, Adaf Gallé, USC Canada). The objectives were to better define breeding objectives, to identify opportunities for participatory breeding, and to identify potential interventions to enhance seed availability and dissemination of sorghum varieties.

2. Achievements

The following are the principal achievements.

- Field screening techniques for Striga resistance improved.
- Identification of QTLs for Striga resistance in RIL populations.
- Headbug screening methodology developed and caudatum varieties with improved headbug resistance developed.
- The methodology for scoring anthracnose on all plant parts was established.
- Several Guinea landrace varieties identified by ICRISAT-Mali bilateral program and CIRAD.
- A Guinea Random-mating Population developed.
- Varieties such as CGM 19/9-1-1 and CIRAD 406 (ICSV 2001) developed by pedigree selection within Guinea x Guinea and Caudatum x Guinea populations.
- Initial results from farmer-participatory research obtained; Key traits for defining regional breeding objectives are emerging.

3. Future plans to address the needs of NARS

- Development of a decentralized participatory testing system to enable NARS to a) achieve gains for grain productivity, b) obtain farmers' input earlier in the breeding process, and c) use research resources more efficiently.

- Develop methodologies for screening for grain storage quality (resistance to storage insects).
- Develop methodologies and source materials for breeding photoperiod sensitive sorghums.
- Use of population improvement techniques for base broadening and enhancement of multiple, complexly inherited traits.
- Develop Guinea hybrid parental materials.

4. Potential role of applied genomics and enhanced use of genetic resources.

- Establishment of regional working collection of Guinea and Guinea-intermediate race materials.
- Characterization of genetic distances among Guinea sorghums and identification of heterotic groups.
- Understand farmers' management of sorghum genetic diversity.

- Characterization of genetic diversity within farmers' selected seed lots and opportunities for intra-variety selection.
- Application of marker assisted selection to breed for Striga resistance

II. Sorghum Breeding Program in Kano, Nigeria

Four varieties (ICSV 111, ICSV 400, and 2 IAR bred), and four hybrids (ICSH 89002 NG, ICSH 89009 NG, and 2 IAR bred) were released in Nigeria in 1996. Through on-farm trials, and field days, ICSV 111, ICSV 400, and ICSH 89002 NG have been widely exposed to farmers. These two varieties (ICSV 111, and ICSV 400) are becoming increasingly popular in drier parts of the country. IAR bred varieties have not moved to farmers because of lack of seed and demonstrations. ICSH 89002 NG, a sorghum hybrid is not grown by farmers because of lack of seed. Seed companies are not multiplying the seed of this hybrid because of high cost of seed production, due to poor nicking. Attempts are being made to produce mid-late maturing hybrids with good seed production ability and acceptable to farmers.

1. Farmers' participatory development of sorghum varieties/hybrids

Procedures and methodologies being used, end products

Development of elite progenies. During 1997 off-season at Kadawa, six crosses were produced between three late maturing varieties (SK 5912, Blanc de Karimama, and KSV 8) and two early maturing varieties (ICSV 400, and ICSV 903 NG). These crosses were advanced to F_2s at Bagauda during 1997 main season. Six F_2 populations were planted at Bagauda in June 1998 with 400 plants per population. Five farmers were invited to select plants of their choice. Two hundred sixteen self plants were selected and advanced to F_3 in the 1999 off-season at Kadawa. Three hundred eighty one F_4 progenies were sown at Samaru (IAR), Bagauda, and Minjibir in single replicated plots during 1999 main season for selection for farmers' participatory selection.

Transfer of *Striga* resistant genes in to elite varieties. Ten F_2 populations derived from crosses between six selected varieties (CS 54, CS 95, ICSV 111, ICSV 400, Gaya Early, and BES) and two *Striga* resistant lines (SRN 39, and IS 9830) were sown in *Striga* sick plot at Bagauda during 1997 main season to identify *Striga* free plants and advance them by selfing. Three hundred and sixty F_3 progenies were sown in *Striga* sick plot at Bagauda during 1998 main season. One hundred plants from 62 progenies were selected. One hundred F_4 progenies were sown at Bagauda, and Minjibir in single replicated plots during 1999 main season. The data was recorded on *Striga* count and farmers were involved in selection.

Achievements

Development of elite progenies. Based on visual observations, 63 F_4 progenies were selected; 17 for early maturing group at Minjibir, 22 of medium maturing group at Bagauda, and 24 late maturing group at Samaru. Most of these progenies have combined good traits of both parental lines. These progenies will be evaluated in three preliminary variety trials in year 2000 jointly with IAR.

Transfer of *Striga* resistant genes in to elite varieties. During 1999 main season, six farmers were invited to select the lines of their choice, and they selected 25 F_4 progenies based on visual observations. Some of these selections had high incidence of *Striga*. We have selected self heads from 25 lines considering farmers' choice, our visual scores, and *Striga* count.

During F_2 evaluation, the number of selections per F_2 population varied from 12 (ICSV 400 x IS 9830) to 59 (ICSV 400 x SRN 39). About 50% more plants were selected from the crosses involving SRN 39 as donor parent for *Striga* resistance than the crosses involving IS 9830. During F_3 evaluation, the majority of the plants (58 out of 100) selected were from a cross, ICSV 111 x SRN 39. The initial results suggest that SRN 39 is a better donor parent than IS 9830 for *Striga* resistance.

Future plans

The 88 F_4 progenies selected from these two sub-activities will be advanced to F_5. They will be evaluated in three preliminary yield trials jointly with NARS during 2000 main season using farmers' participatory approach. These 88 progenies are being used to produce single cross hybrids, and R and B-lines will be identified. Selected mid-late maturing maintainer lines will be converted into male-sterile lines. There will be emphasis to produce farmers' acceptable hybrids.

2. Intensification of sorghum production by increasing adoption of improved varieties.

Procedures and methodologies being used, end products

This is a collaborative activity with IAR, ADPs, and NGOs of Nigeria. During national planning meeting in April 1999, sorghum variety adaptation trials were jointly designed in consultation with NARS, and extension. Three sorghum varieties - ICSV 111, ICSV 400 and farmers' control were evaluated in 109 trials in 10 states of Nigeria following their cultural practices.

Two NGOs (SG 2000, and SACDP/IFAD) conducted similar trial with some modifications but by involving the same varieties. SG 2000 planted Management Training Plots in five states. SACDP evaluated these varieties in 27 villages in Sokoto state. Field days were organized by ADPs and NGOs.

Achievements

Through these on-farm trials and field days, several farmers, extension staff, and NGOs were exposed to new sorghum varieties. ICSV 111 seems to be more preferred by farmers than ICSV 400. Katsina ADP established 16 trials allocated to them. Majority of the farmers' first choice was ICSV 111 followed by ICSV 400. ICSV 111 is very popular in Daura Local Government, which is the home of present Federal Minister of Agriculture. Katsina ADP also conducted 800 SPATs on ICSV 111. Farmers who conducted sorghum on-farm trials in Zamfara state were very pleased with the performance of new varieties. Sokoto and Kebbi states have flood affected areas. They prefer ICSV 111 and ICSV 400, because they mature before the flood hit the ground. This is very interesting observation. In Nigeria, majority of the farmers

grow mid-late maturing varieties, but there are areas where early maturing varieties are acceptable. ICSV 111 and ICSV 400 were bred at ICRISAT Patancheru, and released in Nigeria.

Future Plans

This activity has been transferred to NARS. Partners have seen the value of this activity. However, we will continue to encourage NARS, extension and NGOs to continue demonstrations of new technologies to achieve greater impact.

3. On-farm Seed production

This activity started only in 1999. Sixty-six farmer' produced seed of two sorghum varieties. ICRISAT staff together with NARS staff visited seed production plots and provided technical advice to produce good quality seed. Information Bulletin on seed production procedures in sorghum and pearl millet is published. Two NGOs (SG 2000, and SACDP/IFAD) also participated in on-farm seed production, and ICRISAT staff provided training. For on-farm seed production, breeder seed was provided either by ICRISAT.

Groundnut Breeding in West Africa[1]

Introduction

Groundnut is an important food and cash crop for the resource poor farmers in West and Central Africa (WCA). The crop provides an important source of purchasing power to small-scale farmers many of whom are women. West Africa produces about 12 % of the world groundnut output, but the rate of increase in production still lags behind other major producers of groundnut. Groundnut is grown under diverse growing conditions varying from subsistence agriculture to highly input-based farming systems. Several abiotic and biotic stresses constrain groundnut production and its quality. Among the several constraints that affect groundnut production and its quality, are aflatoxin contamination, drought, groundnut rosette disease, and foliar diseases.

1. Procedures and methodologies

The main focus has been on strengthening National Agricultural Research Systems (NARS) capacity to improve groundnut productivity in diverse cropping systems in the region. This has mainly involved 1/ delivering genetic material as parents, segregating populations or finished lines possessing resistance to the most limiting biotic and a biotic constraints according to their needs; 2/ linking NARS more strongly into research networks to solve common problems and exchange results; 3/strengthening NARS capacity to involve farmers in setting research priorities and technology evaluation. An assessment of individual NARS and ICRISAT's comparative advantage and explicit planning to ensure efficient research spillover forms a central part of our approach. Bilateral collaboration with NARS of Burkina Faso, Mali, Nigeria, and Senegal have been developed and other NARS are benefiting from this partnership through regional workshops, nurseries and training.

Breeding approach

The breeding approach involves targeted crosses, field screening and testing selected populations and breeding lines in partnership with NARS. National programs in the region are heterogeneous with different capacities and requirements. Thus our breeding efforts result into two distinct but interrelated end products: Unselected segregating populations, and "finished" varieties. F_2 to F_4 populations involving early maturing, disease resistant and drought tolerant parents are shared with those NARS with the interest and capacity to evaluate and select segregating populations. This allows NARS to select lines adapted to local conditions from the large numbers of genotypes contained in the populations. A limited number of crosses are made in the region while segregating populations are obtained from ICRISAT-Patancheru and ICRISAT-Malawi. The segregating populations are evaluated at sites that present the required stresses (hot spots) and are advanced using a combination of pedigree and modified bulk methods. Preliminary trials involving F6/F7material are conducted at 2-3 sites depending on seed quantities in collaboration with selected NARS. Selected advanced lines are distributed to other NARS in the region for further testing.

[1] Background notes prepared by Bonny R. Ntare for TAC Review on 'Plant breeding methodology'. March 2000.

Selection Criteria

We employ a physiological model yield system analysis of advanced yield trials to raise selection efficiency for adaptation and yield potential. Selection is based on the major yield components vis:

1. Total biomass accumulation from final harvest (haulms and pods)
2. Crop phenology (reproductive duration)
3. Partitioning to reproductive sinks.

Superior genotypes having preferred pod size and appearance, seed size, good shelling percentage and resistant to diseases(foliar leaf spots, rosette virus and soil borne pathogenic fungi) are selected and used in the second cycle of breeding.

Regional Trials

This is a useful series of trials to provide information on the yield stability over different environments, and have established useful contacts and support for NARS. In order to achieve the most effective focus and impact, a phased approach is followed whereby the initial detailed line evaluation is conducted at a limited number of selected sites in one or two countries in collaboration with NARS breeders. Subsequent smaller trials focused on specific production constraint are then be formulated for broader distribution to other NARS in the region.

The objective of the first phase is an in-depth evaluation of the adaptation of advanced breeding lines arising from ICRISAT programs and elsewhere using environments known to provide the appropriate challenges. The explicit involvement of particular NARS in this process directly contributes to their development.

2. Achievements

The groundnut program has operated in WCA for 11 years. The initial program was designed through extensive consultation with NARS and other International programs such as Peanut CRSP with a stake in groundnut research in the region. This has broadened the range of collaborators and scientists directly working with groundnuts. Although focused on research to resolve the priority constraints, substantial impact on trained manpower, wide distribution of information to scientists (through regular workshops, newsletters and reports) have been achieved. During the past 11 years a wide range of new technologies and knowledge have been developed:

- ⇒ New varieties have been released in Ghana (1) Guinea (1) and Mali (3). Others are in advanced nationally coordinated trials in several countries (Benin, Burkina Faso, Nigeria and Ghana).
- ⇒ A methodology for identifying heat tolerant cultivars under field conditions has been developed. Superior drought tolerant genotypes as well as those which yield well under high (> 35^0C) temperatures are available. Breeding populations with tolerance to end-of-season drought are also available.
- ⇒ Foliar disease resistant genotypes with 26-36% greater yield advantage than the widely grown but susceptible variety (55-437) were developed. Breeding populations with multiple resistance to foliar diseases are available and will

contribute to integrated disease management of groundnut.

- ⇒ In partnership with the Institute for Agricultural Research (IAR) Nigeria, high yielding early- and medium maturing varieties of groundnut resistant to rosette virus disease have been developed.
- ⇒ A large cale groundnut rosette field screening technique developed by ICRISAT has been adopted by IAR Nigeria and INERA, Burkina Faso.
- ⇒ With backstopping from ICRISAT, IAR has started distributing advanced breeding lines resistant to rosette to other NARS in the region.
- ⇒ Through Groundnut germplasm project funded by the Fund for Commodities (CFC), a regional genebank and appropriate infrastructure and facilities to conserve groundnut germplasm have been established.

3. Future plans to address need of NARS in the region

- ⇒ Reinforce partnership with NARS, and Non-Governmental Organizations (NGOs) emphasizing participatory research approaches especially in priority setting, conduct of on-station and on-farm trials. Where interests and capabilities are strong, a collaborative breeding program will be developed.
- ⇒ Focus on regionally important production-limiting factors through bilateral collaborative projects.
- ⇒ Strengthen linkages between ICRISAT with other stakeholders such as CORAF and Peanut CRSP.
- ⇒ Maintain an international research network which is basic for the interchange of germplasm, and information among NARS and ICRISAT.

4. Potential role of applied genomics

Applied genomics are still in infancy in groundnut. Once the associated protocols and technologies are perfected, prime candidates for genetic improvement through applied genomics will be groundnut viruses particularly groundnut rosette disease components. Marker assisted selection will be useful for both qualitative and quantitative traits, particularly those related to quality, diseases and insect pest resistance.

Southern and Eastern Africa

Plant Breeding In Southern and Eastern Africa[1]

Introduction

ICRISAT breeding programs for sorghum, pearl millet, groundnut, and pigeonpea have been active in southern and eastern Africa since the mid 1970s. Initial efforts focused largely on germplasm exchange, including collection missions in collaboration with NARS. In the early 1980s, the Institute expanded its activities in the region by helping to establish and lead several regional programs, at the request of governments in the Southern Africa Development Community (SADC) as well as East Africa. These regional programs include:

- EARSAM Network Project of OAU/STRC/SAFGRAD, established in 1982 and wound up in 1992.
- SADC/ICRISAT Groundnut Project, established in Malawi in 1982, with funding from BMZ/GTZ.
- AfDB Pigeonpea Improvement Project for Eastern and Southern Africa, Kenya, 1984, funded by the African Development Bank.
- SADC/ICRISAT Sorghum and Millet Improvement Program, Zimbabwe, 1983, funded by USAID, BMZ/GTZ, and CIDA.

Targeting the resource poor smallholder farmer and needs of NARS is the main goal of ICRISAT's breeding work in SEA. Food security is the focus with first emphasis on availability and access, followed by cash income through increased productivity and commercialization with increased processing and utilization.

Methodologies and Research priorities

The agenda in each of these regional programs has evolved through the years, in response to changes in the priorities of national program partners, and their growing research capacity (in turn due to strong capacity building efforts through the projects) and achievements of the regional programs. The emphasis in earlier phases of each project was on pre-breeding, genetic enhancement, training, and (especially in southern Africa), and on research infrastructure development. As a range of technologies was developed and new varieties were released for the mandate crops of sorghum, pearl millet (finger millet to a little extent), pigeonpea and groundnuts, the emphasis shifted towards technology exchange. Impact assessments and periodic program reviews by the respective donor agencies have documented that these programs have generated substantial benefits. However, several factors (often beyond the project's control) continue to hamper technology adoption. Correspondingly, the current emphasis in these projects is on widening the range of partners, in order to widen the reach of collaborative R&D

[1] Report compiled by A B Obilana, with contributions from other breeders.

efforts. Another area is on seed systems development – recognizing that non-availability of seed (largely due to insufficiently developed seed systems) are the most important constraint to adoption of improved varieties).

All ICRISAT work is based on a collaborative approach involving the full range of stakeholders. These partnerships and research/development activities are implemented through collaborative workplans for each country, developed jointly by the partners. Research priorities are fixed by national stakeholders, led by the national research program. The workplans are specific – they include clear objectives, research targets, time-frames, budgets, distribution of responsibilities, and a clearly defined set of milestones to monitor progress.

Spillover benefits

ICRISAT uses a regional approach, working with partners across the SADC or the Eastern Africa region to address problems common to the many countries in the region. This has led not only to a number of research successes but has also built a strong network of partnerships. A regional approach confers a number of advantages. First, problems in different countries are commonly influenced by the same factors; ICRISAT can utilize its expertise in strategic research to develop solutions with broad application. Second, a regional presence facilitates technology spillovers, such as exchange of germplasm and technologies targeted at similar agro-ecological zones in different countries. For example, the sorghum variety Macia, originally developed and released in Mozambique, has also has been released in Botswana, Zimbabwe, Namibia and Tanzania. It is very promising in Eritrea. Pearl millet Okashana 1, after proving highly successful in Namibia, was released in Malawi and Botswana. The groundnut variety CG 7 has been released in Malawi, Zambia, and Uganda Such spillovers cut both time and costs involved in variety development and release, stimulate the expansion of regional seed sales, and significantly improve returns on donor investment in agricultural research.

Each of the five mandate crops have specific approaches to their genetic improvement in the SEA region due to diverse nature of crop genetics, agro-ecological zones, sub-regional and NARS groups needs and donor focus. This review report includes the breeding of groundnuts, sorghum, and pearl millet in Southern and Eastern Africa.

Groundnut

Introduction

Groundnut or peanut is widely grown throughout southern and eastern Africa. The SEA Region produces about 2 million tons of groundnut, generating an estimated income of US $ 800 million per annum. Sudan accounts for about 40% of the region's groundnut area; other important producers are Mozambique, Uganda, South Africa, Zimbabwe, and Tanzania.

Table 1. Groundnut production in Southern and Eastern Africa, 1992-94 average.

	Area ('000 ha)	Yield (kg ha^{-1})	Production ('000 t)
Southern Africa	869	501	435
Eastern and Central Africa	1091	719	785
Total	1960		1220

Source: UNFAO, AGROSTAT, 1995

The ICRISAT Regional Groundnut Improvement Program for Southern Africa (now SADC/ICRISAT Groundnut Project) was established in Malawi in 1982, with support from BMZ/GTZ. The major focus is on the development of improved broad-based breeding materials with desirable stress-resistance, quality traits, and high yield potential and to share the technologies and information through regional networks and other partnerships. The program exploits synergies with ICRISAT's global agenda; and since 1996/97, the breeding component of the project has been supported through ICRISAT core funds, complementing the technology exchange component, which is supported by BMZ/GTZ. The project has developed new gene pools, segregating populations and elite breeding lines with desirable traits individually and in combinations. Seed of the breeding lines are distributed to NARS through regional networks.

Methodology

Sources of resistance to major diseases such as rosette and early leaf spot were identified from the screening of over 13,000 accessions from the global groundnut germplasm. The pedigree method of selection is applied to develop high yielding breeding lines with resistance to various constraints including early and late leaf spot, rust, and groundnut rosette. In addition to regular-season trials at Chitedze and Chitala Research Stations, a winter nursery is usually planted at Masenjere in southern Malawi for seed increase of elite materials/lines. Thousands of artificial hybrid combinations have also been made with the objective of creating greater variability.

Summary of achievements

Promising resistant populations were developed:

- 79 spanish breeding lines with rosette resistance -- distributed to countries in SEA, some also sent West Africa through ICRISAT, Bamako.
- Eight F_6 breeding resistance to both groundnut rosette virus (GRV) and the aphid vector
- 23 F_6 breeding lines with multiple resistance (rust and rosette) – will soon be available for regional evaluation by NARS, private sector and NGOs.
- Early leaf spot disease -- breeding populations developed with substantial resistance. Some genotypes available that combine resistance with improved seed quality.
- Genetics and mechanism of rosette disease -- multi-disciplinary team from ICRISAT, the Natural Resources Institute (UK), and the University of Georgia, USA have yielded encouraging results. The next stage will focus on identifying markers linked to genes for virus and aphid resistance.
- More than 7 tons of seed of improved and released varieties were multiplied during the 1998/99 cropping season, and distributed to NARS and NGOs in Malawi, Mozambique, Zambia, and Uganda.

Germplasm distribution

Since 1995, the Project has distributed 6674 germplasm lines to 18 countries in southern and eastern Africa.

Variety releases

There were 5 releases in 1998/99 -- Igola-2 and Serere Red in Uganda, Jesa and Teal in Zimbabwe, Luena in Zambia.

Sorghum

Introduction

Southern and eastern Africa accounts for about 20% of the world's sorghum area and 10% of production. About 6.5 million tons are produced each year from 9.3 million hectares. Sudan produces about half this total; Ethiopia, Tanzania, Uganda, and South Africa are the other major producers.

Table 2. Sorghum production in southern and eastern africa, 1992-94 average.

	Area ('000 ha)	Yield (kg ha^{-1})	Production ('000 t)
Southern Africa	1661	763	5300
Eastern and Central Africa	7599	697	5300
Total	9260	709	6566

Source: UNFAO, AGROSTAT, 1995

Sorghum improvement in southern Africa, under the SADC/ICRISAT Sorghum and Millet Improvement Program (SMIP), has used a regional, collaborative, multidisciplinary approach since its inception in 1983. The program has made significant achievements in germplasm exchange, cultivar development, food technology research, building of national research capacities, and developing partnerships with the full range of stakeholders.

Methodology

ICRISAT's strategy in southern Africa has involved the development and testing of improved varieties and hybrids (Phases I and II), followed by technology transfer and exchange (Phase III, 1993-98), as shown in Figure 1. The focus of genetic improvement was on drought tolerance, early maturity, resistance to diseases (leaf blight, sooty stripe, downy mildew), *Striga*, storage insects and aphids, dual-purpose varieties that could provide both grain and fodder, and acceptability by farmers of the improved cultivars. The increase in emphasis on technology exchange during Phase III was aimed at increasing adoption rates and broadening collaboration with a wide range of partners across the region. Throughout, the approach has been multidisciplinary, involving breeders, plant protection and grain quality specialists, and others. Strong linkages have been developed with NGOs, seed companies in Zimbabwe and South Africa, millers in Botswana and Zimbabwe, breweries and feed companies in Zimbabwe, farmers' organizations, and universities.

Summary of achievements

Capacity building

NARS research capacities were strengthened by a combined of monitoring tours, joint evaluation of field trials, joint workplanning, reporting, and joint publications. In-country support focused on training for technicians covered management of trials and breeding nurseries, breeder seed production, field screening techniques for resistance to *Striga* and downy mildew, identification and control of diseases and insect pests, data analysis, and report writing. A large number of scientists and technicians have been sponsored for advanced degree education and/or participated in a variety of training programs.

Germplasm exchange and utilization

A germplasm working collection containing over 12,000 accessions (breeding lines, hybrids and hybrid parents, breeding populations) was assembled at Matopos and is used by NARS throughout the SADC region. Indigenous germplasm from the region has been characterized, basic information is now available on agronomic traits and race classification/distribution. Over 25,000 breeding lines and enhanced germplasm were generated for regional use. A total of 18,524 samples were supplied to national research and extension services, universities, and the private sector; while 244 genetic materials were received from nine SADC countries, and 608 collaborative sorghum trials were jointly evaluated by 11 countries in the region.

Genetic improvement efforts are tailored to NARS needs and capacities. For the stronger NARS (Botswana, Zambia, Zimbabwe), we develop and provide intermediate outputs (e.g., random mating populations, segregating lines, breeding stock, hybrid parental lines) into which specific traits and resistances have been incorporated. Other NARS are provided with "finished" outputs, i.e., varieties and hybrids.

Drought resistance

The relationships between plant traits (e.g., leaf area, harvest index), productivity, and drought response were studied in a range of improved varieties and hybrids. Twenty-three male restorer parents (R-lines) were selected and tested, and performed well in terms of yield, maturity, grain hardness, tannin content, and other traits. These are currently being used by South Africa, Tanzania, Zambia and Zimbabwe in their hybrid development program. Similarly, 36 white grained female parents (SDSA/SDSB –lines) were developed through backcrosses and selection. These are being used in Australia and Zimbabwe private seed sector for development of white good food grain quality hybrids.

Striga resistance

Germplasm screening at 'hot-spot' locations in Botswana, Tanzania, and Zimbabwe led to the identification of five resistant sources to three endemic *Striga* species in the region; two sources showed resistance to multiple *Striga* species. Striga work also included development and testing of an IPM package, and herbicide control.

Diseases and insect pest resistance.

In southern Africa the regional program developed an infester and spreader row screening method for downy mildew. Five sources of downy mildew resistance and a number with resistance to sooty stripe, were identified. Studies on ergot disease provided important results for hybrid production. We developed a methodology to screen for resistance to storage pests, and identified several varieties with intermediate resistance to *Sitophilus* spp. and *Sitotroga cerealella.*

In East Africa, a large number of resistant/tolerant genotypes in each maturity group have been identified for various biotic and abiotic stresses. These include midge, stemborer, Striga, anthracnose, grain mold, and drought (see Table 4).

Variety development and release

Development of breeding nurseries and a regional crossing program was an important area of emphasis in southern Africa. Regional breeding nurseries were developed at eight locations in Zimbabwe, Zambia, Tanzania, Malawi, and Botswana. The regional crossing program, to test early-generation and advanced-generation materials, is based in SMIP and involves collaboration with breeders in Botswana, Zambia, Zimbabwe, and Tanzania.

Twenty-eight improved sorghum varieties and hybrids have been released in eight SADC countries since the inception of SMIP in 1983/84 (Table 6). These cultivars show yield improvements ranging from 9-85%, and improved earliness (7-23%) over the local controls across six SADC countries. Fourteen percent of the releases have been well adopted and grown by farmers, and have generated 15-25% impact.

Farmer-participatory research

Emphasis on farmer-participatory research using the diverse germplasm observation nursery (DGON) has provided farmer input into the identification of preferred traits and genotypes, and helped refine breeding objectives. Consequently, based on methodology developed in SMIP, three countries in southern Africa are now retargeting their breeding approaches.

Grain quality

The regional program has compiled a database on physical, physico-chemical, and chemical traits for more than 25,000 genotypes, both released and landrace varieties; and produced a manual of laboratory procedures for grain quality evaluation of sorghum and pearl millet. ICRISAT provides technical assistance for laboratory analysis and identification of , compilation of data to support proposals for cultivar release, and works with NARS and private firms to assess grain quality and identify new options for commercialization of sorghum (e.g., use in composite flour).

The future

ICRISAT's future emphasis in the region will be on increasing productivity and stimulating commercialization. Specifically:

Productivity increases through improvement of hybrids and varieties using limited population improvement with alternative sorghum groups (e.g., guinea and bicolor sorghums) by topcrossing, and the use of biotechnology (marker assisted selection); and through better production practices including soil fertility improvement and crop-water-environment management

Increased commercialization through better marketing strategies, targeting new hybrids/varieties for specific use in milling, malting, and feed; and by broadening linkages and partnerships.

Table 3. Sorghum varieties released in SADC, developed through NARS-ICRISAT collaboration.

Country	Variety	Year of release	Recommended production/adaptation zones
Botswana (4)	BSH 1	1994	Short season, 250-750 mm rainfall
	Mahube	1994	Very short season, 200-600 mm rainfall
	Mmabaitse	1994	Short-medium season, 250-750 mm rainfall
	Phofu	1994	Short season, 250-750 mm rainfall
Malawi (2)	Pirira 1	1993	Interm. Season, hot-humid areas 400-850 mm
	Pirira 2	1993	rainfall
			Interm. Season, 400-850 mm rainfall
Mozambique (3)	Chokwe	1993	Interm. season, 400-850 mm rainfall
	Mamonhe	1989	Interm. -to-long season, 750-950 mm rainfall
	Macia	1989	Short season, 250-750 mm rainfall
Namibia (1)	Macia	1998	Short season, 250-750 mm rainfall
Swaziland (3)	MRS 12	1992	Interm. season, 400-850 mm rainfall
	MRS 13	1989	Interm. season, 400-850 mm rainfall
	MRS 94	1989	Interm season, 400-850 mm rainfall
Tanzania (3)	Tegemeo	1988	Interm. -to-long season, 450-850 mm rainfall
	Pato	1995	Interm. season, 400-800 mm rainfall
	Macia	2000	Short season, 250-750 mm rainfall
Zambia (6)	Kuyuma	1989	Interm. season, 450-900 mm
	Sima	1989	Interm. season, 450-900 mm rainfall
	MMSH 413	1992	Interm. season, 450-900 mm rainfall
	MMSH 375	1992	Interm. season, 450-900 mm rainfall
	WSH 287	1987	Interm. season, 450-900 mm rainfall
	ZSV 12	1995	Interm. season, 450-900 mm rainfall
Zimbabwe (6)	SV1	1987	Interm. season, 400-850 mm rainfall
	SV2	1987	Short season, 250-750 mm rainfall
	Macia	1998	Short season, 250-750 mm rainfall
	ZWSH 1	1992	Interm. season 400-850 mm rainfall
	SV3	1998	Short-to-Interm. season 300-900 rainfall
	SV4	1998	Short-to-Interm. season 300-900 rainfall

Figure 1. Progression for breeding, testing and selection process in southern Africa (SADC region) for sorghum by SADC/ICRISAT SMIP

Variety Description and production of Leaflets	**Cultivar Release, Seed multiplication** **Farmer Adoption and production**	NARS activity facilitated by SMIP
More Breeder Seed increase (NARS and SMIP) Large-scale Seed Production (NARS and Industry)	**On-farm Verification** **(On-farm Testing)**	NARS/SMIP activity. Major farmer involvement to identify farmer preferences and release of varieties by NARS. 2 years, multifarm locations.
Breeder seed increase. Seed production training by SMIP regional and in-country.	**National Program Testing**	NARS activity in national experiment stations, multilocations, advanced testing, compilation of data. 2 years
	Bilateral Cooperative Trials -specific to requesting NARS **Regional Collaborative Trials** -across all countries	2-3 years for variety replacement 6-10 locations in cooperating countries and SMIP.
NARS selections and promotion of advanced materials into their national variety trials.	**Regional Advanced Cultivar Testing**	1st Stage Regional Collaborative Trials of SMIP and NARS. Beginning of multilocational trials- SMIP in 4 locations NARS in 6-10 country locations Joint NARS/SMIP evaluation.
NARS specific selections of breeding lines from SMIP test locations.	**Preliminary Cultivar Testing** -new varieties, new hybrids -new hybrid parental lines and restorers	1-2 years 2 locations
SMIP test locations	**New Line Trials/Testcross Evaluation**	Replicated trial in 2-3 locations Selection based on visual observation and analyzed data. 1 year duration.
SMIP nurseries	**F6/F7 Lines**	Advanced generation testing in 1-2 locations. Head bagging of 2-3 plants/line for seed increase.
Breeding Lines SMIP nurseries and semi-finished products selected by advanced NARS into their nurseries.	**F4/F5 Lines** **Modified Pedigree Breeding**	Early generation testing in one location.
SMIP nurseries Country crossing blocks	**Crossing Program** **Backcrossing Program**	Line development Hybrid parent development
	Breeding and Observation Nurseries -Farmer Participation	Initial screening Germplasm evaluation Germplasm characterization
	Germplasm Acquisition	

Pearl millet

Introduction

Southern and eastern Africa produces just over 2 million tons of millet from 3.9 million ha, i.e., roughly 7% of world millet production and 10% of world millet area. The major producers are Sudan (half of the regions' production), Tanzania, Namibia, and Uganda. "Millet" includes a number of related species, but pearl millet accounts for just under 50% of production, and finger millet for another 40%.

Table 4. Millet[1] production in Southern and Eastern Africa, 1992-94 average.

	Area ('000 ha)	Yield (kg ha^{-1})	Production ('000 t)
Southern Africa	1242	491	610
Eastern and Central Africa	2621	559	1466
Total	3863	-	2076

1. Combined figures for all types of millet
Source: UNFAO, AGROSTAT, 1995, Government of Namibia

Objectives

Pearl millet improvement in southern Africa under the Sorghum and Millet Improvement Program (SMIP) focused on two major objectives. The first was help make improved varieties widely available, by supplying national breeding programs with enhanced germplasm and information. The second was to raise national capacities in research and technology exchange, and thus contribute to improved production and utilization of pearl millet.

Summary of achievements

Significant progress has been made towards each of these objectives.

Capacity building

Over 80 scientists and 200 technicians have been trained in crop improvement, agronomy, crop protection, seed production and quality control. National staff have received sponsorship for higher degree education, in-service training, and specialized training courses. Functional millet breeding programs have been established in nine countries, among them Namibia where a successful seed development and delivery system was developed from scratch. Prior to SMIP, only Botswana, Malawi, Tanzania, and Zimbabwe had active breeding programs.

Germplasm exchange

Regional pearl millet genetic resources have been collected, characterized, conserved, and widely distributed to national programs. The regional facility at Matopos, Zimbabwe, now holds over 7000 global germplasm, 3082 of which are of SADC origin. This germplasm was collected through joint NARS-ICRISAT collection missions between 1985 and 1992. ICRISAT's germplasm exchange efforts are generally mediated through SMIP. The regional program has supplied over 45,000 accessions (germplasm, breeding lines, varieties and hybrids) to SADC countries; and acquired over 3600 germplasm and breeding lines from seven SADC national programs.

Development of improved genetic material

Sixteen pearl millet varieties originating from the project have been released in five SADC countries: Malawi (2), Namibia (4), Tanzania (2), Zambia (4), and Zimbabwe (4), and adoption has been encouraging. These improved varieties offer significant advantages in both yield potential and early maturity, and thus a greater probability of harvest in years of limited rainfall. Hundreds of pearl millet breeding lines, germplasm lines, varieties, and hybrids have been developed and supplied to NARS, for use in their breeding programs. Ten composite populations have been developed, targeted at two major production systems (PS 19 and PS 20) in the SADC region. Out of the 301 pearl millet varieties developed by the ICRISAT's regional program during the past 15 years, 148 originated from composite populations, 109 from backcross breeding, and 44 from mass selection of introductions, landraces, or recombination and selection.

Grain quality evaluation

All varieties under on-farm verification and advanced on-station testing are routinely evaluated for a range of phyisical, physico-chemical, and organoleptic quality parameters. The data help support variety release proposals, and the identification of varieties that match quality/trait standards demanded by industrial users such as food processors and millers. For example, tests have shown that SDMV 92040, with its white flour, is ideally suited for composite flour.

Variety development for long-season zones in Tanzania

A particularly difficult challenge was to develop varieties adapted to long-season zones in Tanzania – the local germplasm was photoperiod sensitive, while high-yielding introduced materials lacked local adaptation. However, an intensive shuttle breeding program led to major successes. Superior local landraces were converted into better agronomic backgrounds through limited backcrossing with elite regional varieties, and they are now being tested nationally. A full season composite was developed in 1990/91, and is being utilized by the NARS. Two pearl

millet varieties, Shibe and Okoa, were released in 1994. A new photoperiod sensitive composite was developed in 1995/96, as a source of varieties for the national program.

Farmer-participatory research

ICRISAT has helped encourage greater farmer participation in variety development. This was done through establishment of Diverse Genotype Observation Nurseries where farmers and breeders jointly evaluated and selected varieties; as well as a series of regional workshops to introduce national scientists to participatory research methods. Currently three SADC countries, Namibia, Tanzania, and Malawi, have re-targeted their breeding programs to incorporate farmer input into variety development, five more countries have expressed willingness to start.

Plant protection

Pathology work has been conducted jointly with a large number of partners. The disease situation in the region has been largely documented. The major diseases (and causal organisms in some cases, e.g. leaf spot disease) have been identified. Hot spot locations have been identified for the major diseases, downy mildew, ergot, false mildew, leaf spot, and smut. A pearl millet downy mildew screening facility has been established with the Zambian NARS for regional use. Several sources of resistance have been identified for ergot, false mildew, and smut.

Entomology work in southern Africa has focused on the armored bush cricket, the most serious field pest of pearl millet in the region. Considerable information has been gathered on its biology, life cycle in relation to pearl millet stages, and yield losses. AN IPM control system has been developed and tested in Namibia and Zambia.

Future priorities

SMIP recognizes that a strong regional scientific capability and the technical advances made in the development and dissemination of improved varieties provide a solid foundation for increasing farm level productivity and incomes. If the full potential of this foundation is to be realized and the ultimate goal of the program fulfilled, SMIP must now address three important issues namely; seed delivery systems, broader stakeholder input into technology development, and commercialization of pearl millet.

Table 5. Pearl millet cultivars released in SADC countries, 1984-1998

Country	Total/ Cultivar	Release name	Year of release	Target Production System (PS)
Namibia	4	Okashana 1 (ICTP 8203)	1989	Short season (19)
		Okashana 1 (ICMV 88908)	1990	Short season (19)
		Okashana 2	1998	Short season (19)
		Kangara	1998	Short season (19)
Zambia	4	WC-C75	1987	Medium-long season (20)
		Kaufela	1989	Medium-long season (20)
		Lubasi	1990	Medium-long season (20)
		Sepo	1997	Medium-long season (20)
Zimbabwe	4	PMV 1	1987	Short season (19)
		PMV 2	1992	Short season (19)
		SDMV 93032	1996	Short season (19)
		PMV 3	1998	Short season (19)
Tanzania	2	Okoa	1994	Medium-long season (20)
		Shibe	1994	Medium-long season (20)
Malawi	2	Tupatupa	1996	Medium-long season (20)
		Nyankhombo	1996	Short season (19)
Total	**16**			

PS 19: Lowland, rainfed, short season (less than 100 days), sorghum/millet/rangeland. Covers sahelian Eastern Africa and the margins of the Kalahari in Southern Africa.

PS 20: Semi-arid, intermediate season (100 – 125 days), sorghum/maize/rangeland. Covers substantial parts of Eastern and Southern Africa.

Table 6. SADC pearl millet composite populations and their zones of adaptation

Composite population	Days to maturity	Season developed	Zones of adaptation
SADC Early Composite	75-90	1985/86	Botswana, Namibia, Zimbabwe (PS 19)
SADC Dwarf Composite	90-110	1985/86	Malawi, Zambia (PS 20)
SADC Bristled Composite	80-100	1985/86	Zimbabwe, Malawi, Mozambique (PS 19 & 20)
SADC Late Maturity Composite	90-110	1985/86	Malawi, Zambia, Tanzania (PS 20)
SADC Bold Grain Composite	75-90	1989/90	Botswana, Namibia, Zimbabwe, Angola (PS 19)
New SADC White Grain Composite	80-100	1995/96	Namibia, Zimbabwe, Malawi, Mozambique (PS 19 & 20)
Tanzania SADC Late Maturity Composite	100-120	1990/91	Tanzania, Zambia (PS 20)
Namibia Composite-90	80-90	1989/90	Namibia, Zimbabwe, Botswana, Angola (PS 19)
Maria Kaherero Composite	75-90	1995/96	Namibia, Botswana, Zimbabwe, Angola (PS 19)
Tanzania SADC Photoperiod Sensitive Composite	100-120	1995/96	Tanzania (PS 20 photoperiod sensitive)

Publications

A total of at least 560 papers were published by the eight scientists of breeders/pathologists/physiologists, involved in the improvement of the five mandate crops. The publications were in refereed journals, edited international/regional proceedings, and national/regional workshops.

Of the more than 560 publications, at least 10% were written jointly with NARS scientists and another 15-20% with ARI scientists. Lists and descriptions of indigenous germplasm, enhanced germplasm and released varieties have been documented.

Training and human Resources Development

Methodologies, theory and practice of breeding the mandate crops, were exposed to national scientists/breeders, research technicians, private seed companies and progressive farmers in the 22 countries of the SEA. Over 200 scientists, 1000 technicians and extension staff, some commercial and emergent communal farmers, about 100 university students on attachment and at least 10 graduate students have been trained in basic degree and formal education, on –the-job, in-country and at ICRISAT. Areas of training include:

Pollination techniques, breeding nursery management, field designs and experimentation, trials evaluation, data collection and analyses, grain quality assessments (both in laboratory and field) and seed production.

Our diverse partners in the southern and eastern Africa NARS, both public and private, have been strengthened and are still being strengthened in the improvement and evaluation of the five mandate crops of ICRISAT in the past 25 years.

Investments in Biotechnology and Breeding at ICRISAT during 1998-99

Crop... PY and Operational cost (direct cost) in ...

		Sorghum		Pearl millet		Groundnut		Chickpea		Pigeonpea		Total	
		PY	Expenditure	PY	Expenditure	PY	Expenditure	PY	Expenditure	PY	Expenditure	PY	Expenditure
1	Tissue culture (somaclonal variation, embryo rescue, haploids, micropropagation)	0 05	150			0 36	3200	0 36	3200	0 27	2200	1 04	8750
2	Tissue culture (protoplast culture and fusion)												
3	DNA fingerprinting	1.00	2950	0 60	5100							1.60	8050
4	Marker identification, gene tagging, marker assisted selection	1 30	9450	2 15	16787	0 50	11350	1 60	18600	1 20	4550	6 75	60737
5	Gene sequencing and discovery (ESTs, micro arrays, proteomics)												
6	Genetic engineering (gene cloning incl map based, and transformation)					0 33	1733	0 33	1733	0 34	1734	1 00	5200
7	Diagnostics (immunological and DNA-methods, pathogen, quality)*	0 17	2450	0 18	3400	0 10	2825	0 15	1625	0 17	2583	0 77	12883
8	Networks and training[1]	0 02	450	0 02	450	0 02	450	0 02	450	0 02	450	0.10	2250
9	Other (Travel - CEPD budget)						160		160		40		360
10	Biotechnology R & D, total[2]	2.54	15450	2.95	25737	1.31	19518	2.46	25768	2.00	11537	11.26	98010
11	Biotechnology applications, total												
12	Breeding, total[3]	5.60	64910	5 93	96250	2.95	49980	2.25	44360	0.98	23520	17.71	279040
	(including Travel (CEPD), equipment etc)												
	Total	8.14	80360	8.88	121987	4.26	69498	4.71	70148	2.98	35057	40.23	377050

1 Biotechnology activities

2 Excluding routine applications in breeding

3. Including routine biotechnology applications in breeding

* for groundnut and pigeonpea

4 Other funds available from special project funds

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Cropwise - PY and Operational costs (unrestricted core) in 1999[4]

		Sorghum		Pearl millet		Groundnut		Chickpea		Pigeonpea		Total	
		PY	Expenditure	PY	Expenditure	PY	Expenditure	PY	Expenditure	PY	Expenditure	PY	Expenditure
1	Tissue culture (somaclonal variation, embryo rescue, haploids, micropropagation)			0.45	6750	0.96	6666	0.26	2666	0.28	2668	1.95	18750
2	Tissue culture (protoplast culture and fusion)												
3	DNA fingerprinting	0.25	4333	1.00	9350			0.10	4333	0.30	8834	1.65	26850
4	Marker identification, gene tagging, marker assisted selection	1.65	13150	0.56	3920	0.05	4300	0.15	2600	0.25	1000	2.66	24970
5	Gene sequencing and discovery (ESTs, micro arrays, proteomics)												
6	Genetic engineering (gene cloning incl. map based, and transformation)					0.34	7083	0.34	7083	0.33	5334	1.01	19500
7	Diagnostics (immunological and DNA-methods: pathogen, quality)*					0.20	5075	0.10	2075	0.30	1000	0.60	8150
8	Networks and training[1]												
9	Other (Travel (CEPD), Equipment etc..)		4450		4450		37232		37232		4836		86200
10	Biotechnology R & D, total[2]	1.90	21933	2.01	24470	1.55	60356	0.95	55989	1.46	23472	7.87	186220
11	Biotechnology applications, total												
12	Breeding, total[3]	4.10	83700	5.20	130375	3.25	58000	1.39	37860	2.01	28850	15.95	338785
	(including Travel (CEPD), equipment etc..)												
	Total	6.00	105633	7.21	154845	4.80	118356	2.34	93849	3.47	52322	23.82	525006

1. Biotechnology activities
2. Excluding routine applications in breeding
3. Including routine biotechnology applications in breeding
* for groundnut and pigeonpea
4. Other funds available from special project funds

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