AGENCY FOR INTERNATIONAL DEVELOPMENT
WASHINGTON, D. C. 20523

BIBLIOGRAPHIC INPUT SHEET

FOR AID USE ONLY
Batch 72

1. SUBJECT CLASSIFICATION

A. PRIMARY
Food production and nutrition — AF30-0130-0000

B. SECONDARY
Plant breeding--Cereals--Millets

2. TITLE AND SUBTITLE
The pearl millet breeding program

3. AUTHOR(S)
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4. DOCUMENT DATE	5. NUMBER OF PAGES	6. ARC NUMBER
1975	37p.	ARC

7. REFERENCE ORGANIZATION NAME AND ADDRESS
ICRISAT

8. SUPPLEMENTARY NOTES *(Sponsoring Organization, Publishers, Availability)*

9. ABSTRACT

10. CONTROL NUMBER
PN-AAE-782

11. PRICE OF DOCUMENT

12. DESCRIPTORS
Millet

13. PROJECT NUMBER

14. CONTRACT NUMBER
AID/ta-G-1073 GTS

15. TYPE OF DOCUMENT

AID 590-7 (4-74)

AID/ta-G-1073 GTS
ICRISAT
PN-AAE-782

THE PEARL MILLET BREEDING PROGRAM

ICRISAT

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MARCH 1975

Introduction

The objective of the ICRISAT pearl millet (*Pennisetum typhoides*) breeding program is to create genetically superior varieties and hybrids for the semi-arid tropical areas which can give more good quality grain, be widely adaptable (less location specific) and possess stability of yield. However some local speciation is desirable among farmers varieties, and while we may succeed in producing one or a few genotypes which are widely successful, the continued use of these over large areas would be a risk. ICRISAT's main role should be in providing elite segregating material from which adapted selections can quickly be made locally; or, where facilities permit, used as parents in local breeding programs. Besides yield and grain quality, there are many widely useful, but difficult basic improvements to be made, such as disease resistance and drought tolerance which are of vital importance to national or regional programs. While the Farming Systems program is designed to provide a series of procedures to improve the plant environment, we should recognise that for many years much food in the semi-arid tropics will be produced by traditional farming methods. While new varieties should be fully capable of utilizing, and therefore encouraging improved farming techniques, they must also be superior in traditional systems. Such varieties should therefore possess the lowest genotype by environment interaction it is possible to develop. Multilocational testing of early generation segregating breeding material is a basic requirement to achieve this aim. Wider adaptability also means that there should be less need to breed new varieties each time another way is found to improve the plant environment.

Farmers at subsistence level are greatly concerned with risk. The production systems they have evolved are essentially the best low-risk procedures and this particularly applies to their food crop varieties. No 'improved'

variety will succeed if its risk factor is more than the traditional varieties no matter how high it's yield potential.

Pearl millet occupies a somewhat unenviable position compared to many tropical food crops. It has been selected as the staple food crop in the warmer less humid areas, particularly where soils are light and poor. It has acquired this position because of its inherent ability to yield relatively nutritious grain under adverse conditions of mineral and moisture supply. However a characteristic of lower rainfall is usually erratic distribution and hence a higher probability of drought; thus inspite of the species capabilities, crop production in millet areas is liable to fluctuate more than in other areas with more assured moisture availability. Stability of yield therefore assumes an even greater importance with pearl millet.

The FAO production yearbook records that in 1972, 65 million hectares of millets were planted, and 43 million tons of grain produced. Seven species of millet are included together, and pennisetum (pearl) millet is the most important among these. Centrally Planned nations produced 24.5 million tons of millet on 32 million ha, which will have been almost entirely proso and other small millets. India planted 16.5 m. ha., and produced 7.6 m. tons: Africa planted 13.8 m. ha. and produced 8.5 m. tons. The Indian figures for 1973-74 were as follows:-

Pennisetum millet		Eleusine millet		Other small millets	
area	production	area	production	area	production
13.6	7.1	2.4	2.1	4.5	1.9

The proportion of pearl millet to other millets in Africa is probably not very different from that in India, and we may guess that some 70 percent

of the millet acreage in the developing world is planted to pennisetum millet, or about 20 to 25 million hectares. Present grain yields are around 500 to 700 kg/ha.

Objectives

The general aim of the breeding program is to develop genotypes or populations giving more grain of adequate nutritional quality and which are as widely adapted and stable as possible.

1. Genotypes need to be constructed which utilize more efficiently the available and potential environmental resources. High harvest index and appropriate maturity length are important and stability of yield is essential.
2. The best possible combinations of tolerances to yield reducing factors are needed. Such factors are pests and diseases, and stress due to the physical environment, such as drought or excess moisture, temperature and wind. These have an important bearing on adaptation.
3. Food grain needs to have numerous qualities to satisfy the consumer best. Acceptable combinations of grain type and nutritional quality must be sought within the concept of increased yield.

Phases in the breeding program

1. Accumulation of genetic resources
   - Collection and catalogueing of land-races and wild millets
   - Material from other breeders and developed varieties
2. Generation of good combinations
   - Identification of source material
   - Specific and controlled crosses
   - Recombination within composites

3. Selection

- Qualitative and quantitative evaluation, field and laboratory (employing as many natural and developed techniques as possible)
- Identification of hybrid parent and/or variety material
- Early generation multilocational testing (to include high and low production levels and exposure to yield reducing factors)

4. Output

- Inbred lines for hybrids, synthetics, or possessing special attributes
- Segregating populations (e.g. F_2 bulks)
- Varieties (Synthetics or composite bulks)
- Information on results and technology.

Breeding methods

The breeding behaviour and morphology of pearl millet has many useful features which facilitate manipulation by the breeder. It is essentially a cross pollinating crop but the effects of inbreeding are not severe. The range of genetic variability within the cultivated species is immense and further variation exists in related species (though successful crosses have been few). High yields with relatively early maturity (less than 90 days) make 3 generations a year possible.

Protogyny, but with the hermaphrodite and staminate florets on the same inflorescence, allows selfing and the use of both artificial and natural cross pollination (c. 75-90%) techniques without the need for emasculation or genetic male sterility. The numbers of progeny which can be derived from a single plant

or cross are very large due to the high seed number per head (1000+). Since tillering is common several heads permit one plant to be easily used simultaneously for different purposes.

Since male and female flowers are on the same spike commercial hybrids cannot be produced merely by detasselling as in maize, but three separate cytogenetic male sterility systems have been described whereby commercial hybrids seed can be produced. Two contrasting breeding methods are available, (a) the traditional intercrossing followed by inbreeding and (b) recurrent selection in composite populations. The former has been and still is effective where goodness depends on a few highly heritable major genes and where elite parents are available. Controlled crosses are made between desirable parents and any progeny are identified after some inbreeding. Only a few parents can contribute to such progeny. Thus the possibilities of recombination are restricted by the low number of crosses and the favourable accumulation of genes limited to those contained in the few parents.

The use of recurrent selection in composite populations can utilize a much broader range of germ plasm and allows continuous recombination. Recurrent selection can improve the population in a desired direction, cycle by cycle, while still retaining the variability vital for continued improvement. Most importantly this method allows improvement, or intensifying of characteristics (such as yield, disease resistance) which are particularly dependant on the additive effects of minor genes. The products possible from a composite are several: the improved stage of the composite itself as recombined, or if this is considered too variable, a smaller portion of selected lines can be chosen

for phenotypic similarity, but only in some respects, such as height, maturity or grain type. During the recurrent selection process the full sib, S_1 or S_2 progeny are most convenient for identifying inbred lines or hybrid parents. By using reciprocal recurrent selection procedures between two complementary composites improved single cross, variety top cross or variety cross hybrids can be produced.

In the traditional approach, utilizing variety crosses by selecting the F_2 and inbreeding for several generations at one location, then testing the products in several environments appears to have severe limitations, firstly because selection is confined to one environment and secondly that it is too premature. It would be more desirable to grow the same F_2 at two or three locations (increasing the locations would decrease the number of plants eventually needed at each location) and allow some recombination with only mild mass selection for one or two generations before selfing to identify good progeny. The best inbreds would proceed in two ways (a) to pedigree row inbreeding and (b) to recombination which will be essential to develop broader adaptability. In the second case seed of only the few best need be returned to one centre for specific recombination. A diallel need not be necessary but preference should be given to crossing dissimilar progeny from different crosses from different locations.

For composite breeding two levels of recurrent selection systems are required: the less immediately important together with the back-up populations need to be improved without much expenditure of skilled man-power and resources: while the advanced populations need methods which will make rapid progress without too fast a decline in genetic variability.

Gridded mass selection, choosing a large number of individual plants (200-500) representing a selection pressure of 10-25 percent, with an occasional cycle of S_1 testing seems to be a satisfactory method for the back-up populations.

For the advanced populations, and since millet is a cross pollinated crop, interpopulation selection systems will be required as well as methods for intrapopulation improvement. The latter has proved useful in maize and is also easy to use. Where three generations a year are possible, as with the earliest populations, S_1 testing is likely to be the most efficient. However for other populations a full sib system will be used for intrapopulation improvement which will operate as follows:

Generation 1. Recombine selfed-seed of 50-100 selected lines in paired rows, making plant to plant crosses between families to obtain recombination. This generation can simultaneously be screened for downy-mildew resistance, the crosses being made only between resistant plants. At least 500 inter-family crosses would be made, and sufficient seed for adequate testing ensured by using several heads from each plant.

Generation 2. Test the crosses in variety trials under several environments in India and Africa, evaluating yield, agronomic characters, and monitoring quality. Also test in disease and pest nurseries, and self resistant plants. Choose the single best selfed plants in 50 to 100 of the families, chosen on the basis of the yield and performance testing in the trials.

Generation 1. Recombine by intercrossing the families derived from these 50-100 selfed plants, etc.

This full-sib system has three attractions:-

(1) Two generations a year gives time to obtain and evaluate results without undue haste.

(2) There is a recombination generation each year.

(3) Selection against diseases (and pests if necessary) is done in both the testing and the recombination generations. This should help to sort out the present unsatisfactory disease situation in this crop.

Among the interpopulation systems available, reciprocal recurrent selection using an inbred tester (RI), or reciprocal full sib (RFS) testing appear to be suitable for pearl millet. Both require 3 seasons to complete a cycle which could if necessary be done in one year, but could more conveniently be spread over 2 years helping to maintain a good work distribution with plenty of "lead time" in the program.

For RI an inbred tester is withdrawn from each of the populations and used as the parent for the test crosses with the other population. Both populations follow the outlined procedure in parallel:

Generation 1. 25-50 selected S_1 lines are grown in paired rows, and exposed to disease attack. Several thousand crosses are made between families, and the best 2,000 or so are taken at harvest.

Generation 2. The 2,000 crosses are planted with the inbred tester from the other population. Some 50 percent of the 2,000 crosses are hybridised with the inbred tester, crossing several heads to ensure plenty of seed. Again, disease infection can be used to determine which of the 2,000 crosses to reject, and which individual plants to use in the crosses to the tester inbred line. At harvest, keep the best 500 crosses for evaluation.

Generation 3. Evaluate the 500 test crosses in yield trials for all important characters, over different environments in India and Africa. Grow one replication in a nursery for selfing.

Generation 1. Recombine the chosen 25-50 entries in paired rows, using the selfed seed from the nursery, etc.

This system also allows for plenty of exposure to diseases and pests, and therefore selection for resistance.

With RFS full sibs are made between populations, both parents are selfed and the chosen parents are recombined within populations. Evidently two heads are required on each parent plant, one for sibbing and one for selfing.

Generation 1. Choose 50 lines from each population and make full sib crosses between populations. Self each parent plant.

Generation 2. Evaluate 500 or more of the full sib crosses.

Generation 3. Recombine selfed parents of the best 5-10 percent of the crosses, within populations. Select good plants to repeat cycle, generation 1.

Discussion of some constraints

There are a number of major areas of interest which impinge on the success of the program, and while they are inter-related they are more conveniently tabulated for discussion:

A. Morphology

B. Physiology

C. Diseases

D. Cytoplasmic male sterility

E. Grain weathering and dormancy

F. Grain quality

G. Intercropping

H. Varieties or hybrids

I. Adaptation and stability of yield

J. Out reach program

A. Morphology:

The concept of a rigid ideotype is unpalatable to most physiologists and breeders since such plants appear to have rather specific environmental requirements. Nevertheless, there are certain fundamental features in plant structure which are associated with yielding ability of which plant height and duration, number and type of tillers, leaf pattern, root development and head type are among the more obvious.

Plant height and total biological yield/ha appear to be strongly correlated at low to medium productivity levels. Tall land-race types are highly efficient in production of dry matter giving 3 to 5 tons per acre in

unfertilized conditions, but unfortunately the harvest index of such types is only 10-15% so average yields are 300-600 kg/ha. Improving the harvest index while maintaining or increasing the biological yield level is a fundamental objective. The use of dwarfing genes appears necessary here, primarily to avoid lodging. Dwarf genotypes have been necessary to produce top yields in many crops, but grain made at this level of production is relatively expensive in terms of costly inputs (mechanical or animal energy and artificial fertilizers). It is not surprising that dwarf types, inspite of allowing higher plant densities, produce less total biological yield, since the dwarfing genes must have many pleiotropic effects on plant growth processes. As a total readjustment of the genetic make up may be necessary before efficiency comparable to tall plants can be obtained, there may be a lot of breeding yet to be done on dwarfs. Fortunately in the SAT most of the farming is labour intensive and thus plant type does not have to be related to mechanical harvesting. Dwarfness does not have to be used to such an extent as might limit light penetration, and indeed uniformity in height does not seem to be particularly necessary. Extreme dwarfness may therefore not be initially desirable.

The duration of the crop's life cycle is important in several ways. It should be tailored to fit the growing season (usually the with-moisture period as cold is not often a consideration except in the high altitude areas) particularly to avoid likely periods of drought stress, yet to mature in favourable drier conditions. However, there is an optimum maximum duration, (where sole cropping is concerned) where vegetative growth is developed to the most efficient stage to support grain production. Too long a vegetative phase means energy

and minerals wasted in non-productive or even "saprophytic" dying leaves and older parts; while not long enough means underdeveloped capacity to make or fill the potential grain sink. While recognising that maturity is an important feature of crop adaptation, we should tend to breed earlier rather than late maturing genotypes.

In millet there are three main types of tillering: Synchronous and non-synchronous basal tillering and sub-terminal tillering which is never synchronous. Non-uniformity in flowering allows a normally determinate type of plant some flexibility to utilize extended favourable environmental conditions. But in millet this advantage is clearly out-weighed by the potential build up of head diseases (eg ergot) and head pests (eg midge). The first type of tillering is therefore the most desirable and it should be of a type where the primary tillers produced even in good conditions suppress the development of subsequent ones. The best number of tillers per plant is very debatable, but should be moderate and we may hazard 4 to 8 at normal populations. A salient fact is that tillers become independant units at a relatively early stage. Thus it is misleading to say the harvest plant density is *n* thousand plants/hectare without indicating that 5 *n* thousand heads were produced. In present genetic backgrounds number of heads/plant, via grain number per plant, is well correlated with yield. However, it probably acts in another way also, in that since tillers soon become independant units, a high number of yielding tillers per plant in a normal seeded population, implies the desirable feature of low interplant competition. The potential for tillering also allows recovery from yield reducing factors which might knock out some or all of the older tillers. In general millet has this type of recovery well developed.

Leaf pattern and duration requires mention if only because of the very diverse opinions that are held on angle, size and amount of desired leaf. Millet can produce an L.A.I. of up to 13, but it has been shown that the photosynthates needed to fill the grain can be made in 20 days by an L.A.I. of less than 0.5. It would seem that millet is over subscribed with leaves, yet yield is still correlated with leaf area up to L.A.I. 5. Work on leaf angle on other crops has shown that this is not a first limiting factor and moreover a reflexed leaf is potentially the same as an erect leaf. Longer duration of individual leaves and well spaced upper nodes would seem desirable but this is an area in which we are clearly in need of the physiologist's assistance.

The millet root system has been very inadequately studied. The bulk of the roots appear to be shallow, in the top 10 cm, though a few roots have been traced to 3.60 m. This seems a little at variance with millets alleged efficiency of mineral extraction and soil moisture use. Root studies are more difficult than for aerial parts because of lack of accessability, yet this very fact should mean that there are now good returns to be obtained from root research. An efficient root system must be correlated with grain yield as strongly as is structure of the above ground parts.

Head numbers, length, diameter, and compactness (grain/cm^2) of head and 1000 grain weight are all reported to be positively correlated with yield. Unfortunately, few tillers tend to be dominant over many and short heads and thin heads are also independantly dominant. Compactness is associated with cylindrical head shape. Inspite of the probable negative correlation between several of these characters good progress has been made in combining some of

them, with head numbers from Indian and USA germplasm, and length and compactness from African sources and there should be good prospects for continued improvement in these combinations.

B. Physiology:

A major program of research will be mounted by the Cereal Physiologist on the more important processes and to develop simple screening methods which can be used in genotype selection. The areas of interest appear to be seedling vigour (considered to be most important for successful crop establishment in sub-optimal conditions); leaf growth pattern; the partition of dry matter between vegetative and reproductive parts; head initiation and development; sink size (yield components), photosensitive and thermal responses.

Mineral nutrition of millet genotypes is another area which needs investigation and here comprehensive root studies will be essential. The possibility of rhizosphere N fixation needs substantiation. There is much circumstantial evidence to indicate that land-race millet genotypes do acquire otherwise unaccountable nitrogen. If so the extent of variability for this trait needs to be determined and selection techniques developed.

Restricted moisture availability is a commonly expected limitation to production in millet; several indices have been postulated for water relationship and drought studies - proline content, osmotic (solute) potential, N-reductase activity and heat tolerance, but there is still a need to develop or refine existing methods to the point where large quantities of germplasm can be quickly screened for water-use efficiency and drought tolerance.

C. Diseases:

Diseases more than pests constitute the main threat to millet production and a large part of the research effort will be directed towards screening germplasm and breeding for resistance. Three diseases are important at present: Downy Mildew (Green ear) Sclerospora graminicola, Ergot Claviceps microcephala, and Rust Puccinia penniseti. There are numerous other diseases, sometimes locally important and these may have to be considered in that context. The three diseases mentioned are widespread in all millet growing areas and while resistance exists for mildew and rust, this is less certain for ergot. Races have not been specifically identified on these diseases but it would be surprising if they did not exist and even more unusual if others were not found in the future.

Of the three, downy mildew is probably responsible for most yield loss, but ergot, because of its high mammalian toxicity can, from a relatively low level of infection, cause a grain harvest to be totally uneatable. Rust often seems severe, but unless a substantial attack occurs before seed set, losses may be negligible. Indeed selecting variety types which avoid the peak periods of incidence may substantially reduce losses from ergot and rust.

The methods used in breeding for resistance should be those which identify, select and accumulate the more effective long lasting types of resistance. Examples of major gene (vertical or race- specific) resistance in other crops indicate that with some exceptions, this is frequently an unreliable type since in a simple gene-for-gene situation the pathogen can quickly evolve a virulent new race. Seedling resistance and total immunity are often characteristics of major gene resistance. General (horizontal or non-specific) resistance is of a more

durable type being based on the additive effects of numerous (often 'minor') genes and is effective against a wide spectrum of races. At best, some disease symptoms are exhibited and selection for non-specific resistance should be on mature plant expression as seedlings are usually susceptible. The problem is to distinguish between specific and non-specific resistance while selecting. This can be done by exposing the material to the known races at one location (pre-supposing race identification and the existance of host differentials), or multilocation testing using the same sets of genotypes or progeny. Periodic recombination of the more resistant lines is essential to increase the level of resistance.

Preliminary findings on the inheritance of resistance to the downy mildew of sorghum and maize, S. sorghi suggest that one to several major genes are involved, but with modifiers, though the most significant discovery has been that additive effects are apparent which can be used to increase resistance by selection. This information is not yet available for downy mildew of millet.

The question of seedling resistance presents a special problem with downy mildew, since systemic infection by oospores only occurs in the first 3 or 4 weeks of growth (though young tillers can be infected later). Yet excellent levels of general resistance to downy mildew undoubtedly exist in the later African land-races of the cool damp areas (especially 'Maiwa' or 'Sanio' late millets, and 'Dauro' - transplanted millet).

In a crop such as millet where new improved genotypes can rather rapidly be produced there may be a use for some major gene resistances, with the qualification the loss of any general resistance should not be a consequence of such selection (vertifolia affect). It seems preferable that most of breeding effort should be directed towards developing general resistances.

D. Cytoplasmic male sterility:

At present three practical systems have been described and one has been extensively used commercially. A_1 was discovered independently of A_2/A_3 and the lines originally associated with them are:

System	Origin	Line(s)
A_1	Georgia USA	TF 23, $TF23D_2$, $TF18D_2$ (USA)
A_2	Ludhiana India	L 66, L 103 (African), T239
A_3	" "	L 67, (African)

B-Lines for A_2 and A_3 maintain A_1 though the reverse does not hold but the maintainer for A_2 is a restorer for A_3 and vice versa. Some good restorers on A_1 act as B-Lines on A_2 and A_3. Maintainer/restoration apparently is governed by single major genes, but modifiers can give partial fertility which can also be caused by environments. The situation is still not fully resolved since we have found for instance that good restorers on $23D_2A$ are not all good on 23A or $18D_2A$. Thus for forming complementary B and R composites for reciprocal recurrent selection for hybrids it will be best to classify prospective entries by reaction on a single cytoplasmic A-line.

Restoration genes for these systems are not frequent (the reverse of the situation in sorghum where original ms_c maintainers are scarce). The fact there are three systems is advantageous because of the cytoplasmic diversity and because restoration on each system samples different genetic stocks. There appears to be no substantial disadvantage attached to any one of these systems though it must be noted that the current backgrounds of the A_1 lines are downy mildew susceptible, while A_3 lines seem more resistant. However there is no evidence to show that this

is a cytoplasmic defect, or that susceptability is closely linked with any sterility gene since 'maiwa' A and B lines, resistant to downy mildew have been bred, starting from an A_1 source. In the numerous crosses made at ICRISAT $23D_2A$ has proved much the best combiner, and a greater frequency of good restorers have been found for it. Nevertheless it will be our policy to develop B and R populations for all three systems, and also make specific crosses to create new seed parents for each system.

Where strictly uniform hybrids are not required the possibility exists with pearl millet to make hybrids without the use of cytoplasmic male sterility by utilizing protogeny in lieu of it. The seed parent should be phenotypically uniform, shorter and less vigourous than the hybrid. Seed fields would be planted in the same manner as for cytosteriles, taking particular care to preserve uniformity in the seed parent rows, and using a dense plant population to suppress tillering so that a high proportion of the heads come into flower at the same time. Cross pollination would exceed 80% in such conditions. However even if it were less the next crop will still give a yield approaching that of a pure hybrid, because the hybrid seedlings, being more vigourous, suppress the selfed seedlings. This can be accentuated by thick sowing or, as in the existing African systems, by planting in hills (or clumps) followed by thinning at a late stage. Experiments with such mixtures in forage pennisetum (without thinning) have shown 90% of the yield came from hybrid plants.

E. Grain weathering ability and seed dormancy:

The ability to ripen clean bold grain in moist conditions is possessed by many millet cultivars. This together with a measure of seed dormancy is essential for areas where millet is harvested when rainfall continues. A common African

practice is to harvest the whole plants when ripe and stook them upright in the field where the heads will dry inspite of intermittent rain. In a week or so, during a dry spell the heads are removed.

Grain usually 'weathers' i.e. deteriorates, due to fungal damage. This may amount merely to superficial discolouration, or more seriously destroy the whole grain. Insect punctures, or physical damage to the pericarp greatly facilitates mould damage. Germination vigour may be severely reduced by weathering. There is no clear evidence as in sorghum, that the more highly pigmented grains have better weathering ability. A great deal more needs to be known about the mechanism of resistance to weathering in millet.

It is debatable whether compact packing of the grain on the head contributes to better grain, since although rainfall or dew is less likely to penetrate a compact head, moisture flow in the other direction is impeded. However compactness is associated with more grains per head, and hence with more yield.

Seed dormancy begins to build up as the grain hardens. Probably there is a stage during the development of the grain when it becomes capable of germination before dormancy is developed. Adequate studies on dormancy have not been undertaken, but it seems that total inhibition of germination can exist for several weeks after physiological grain maturity. After this, until the effects of dormancy have disappeared the seed may be actually capable of germination but the seedling will be weak because of the continuing partial immobilisation of seed reserves. Efforts have been made to find ways of breaking the dormancy but without great success though heat treatment and oxydants do speed up the process.

While dormancy is required on the farm, it provides a problem where planting soon after harvest is required to hasten the breeding program. This would very rapidly select against dormancy. The most critical stage would where aliquot samples of seed were used to provide a random mixture. In such a situation even partially dormant seeds would be at a fatal disadvantage. In this context renewed attempts need to be made on artificially reducing dormancy. During the breeding process, particularly in the composites, the dormancy of the progeny needs to be monitored to ensure the maintenance of an adequate level, and if necessary, in the absence of being able to break the dormancy, sufficient time will have to be allowed between generations.

F. Grain Quality:

This term covers a multitude of factors expressing consumer preference. Where the crop has traditionally been grown for food, the land-races which predominate represent the best quality as selected by the cultivators. Quality preferences often differ from place to place, and these of course can be determined by studying the grain type(s) of the localities. It should be recognised that consumer-producers in the lesser developed countries are often more critical of quality than commerical buyers in developed countries. Fortunately cultivators were also yield-conscious and when there is a demonstrable yield advantage they will accept some trade-off of quality against yield, especially if there is a cash market nearby. However, the importance of grain quality should not be underestimated especially for consumer-producers and should rank next to yield in value.

The important factors contributing to grain quality as desired by the consumer-producer are:

1. Appearance - good colour (often slate coloured in pearl millet - a grey-blue), medium to large 'bright' grain (bright being a combination of cleannes and plumpness).
2. Texture. Hard grains are preferred. A vitreous endosperm is more resistant to mould damage, and to storage insects.
3. Ease of preparation. This is usually done by women who are most critical of the amount of work involved - the time needed for grinding the grain, the percentage of bran, the texture and colour of the flour, the amount of water absorbed, cooking time and volume of the final product.
4. Taste. Most difficult to define but generally the sweeter the better and not musty or rancid.

Nutritional quality has not been included in the above list because though important, it does not have a readily recognisable value to consumer-cultivators. It should be realised that a variety which is merely of superior nutritional value will appear to have no advantage to farmers. Such a variety will need to have other attractive features to "carry" the nutritional benefit.

Millet compares favourably with wheat, rice, sorghum or maize in nutrient values, and though also deficient in lysine, is less so than sorghum, maize and wheat. Calorific values are reported to be good (356 cal/100 g) with 84% of the grain being edible with (on average) 67-72% carbohydrate, 11.6% protein, and 5.0% fat. In feeding trials with rats, millet compared with sorghum and maize gave 28 and 26% higher growth rates respectively with or

without supplemented diets. There is scant information on digestible carbohydrates in millet but the range of variability appears to be small and probably calorific value is highly correlated with yield. In contrast there is large variability for protein, lysine and oil content, but also large environmental effects. (Nitrogen fertilizer applications will give up to 6% increase in N). Reports on crude protein (N x 6.25) content range from 8-21% (ICRISAT analyses 8-19% -707 samples) but 7% of the total N may be of the non-protein type while the prolamine fraction ranges between 21-38%. Lysine content ranges from 1.4 - 3.8% (ICRISAT 2.3 to 3.75 - 21 samples) of protein in normal seeds, but reports on the relationship of lysine and protein are contradictory - from a slight negative relationship to none. High variability in isoleucine/leucine ratios have also been recorded from 1.37 to 3.65. Oil content determinations range from 2.3 to 7.9% with oleic and linoleic fatty acids accounting for 89% of the oil.

The breeding implications of the nutrient information is that selecting for very high levels of protein would be difficult because of the negative correlation with yield - even at static protein contents increased yield would mean increased protein production per acre and more N which has to come from somewhere. Selection for higher lysine content may be much more feasible, but the consideration of both these attributes should be made in the context of the overall diet of those consuming millet. A rather small quantity of animal or vegetable protein can remedy the "deficiencies" in the cereal. It is therefore more realistic to maintain moderately good levels of protein (?14%) and pay some attention to lysine while selecting primarily for higher grain yield. It may be noted here that in wheat, apart from grain size,

nitrogen content has been found to be positively correlated with seedling vigour (embryo size was not reported). Higher oil percentage though apparently nutritionally desirable may, unless the content of some fatty acids can be lowered, be disadvantageous since then the flour goes rancid more quickly during storage.

G. Intercropping:

This practice, widely used by tropical farmers exploits the situation where one crop ecotype cannot alone make the maximum use of the environmental potential.

A frequent form of environmental excess is an overlong period for growth. Here a combination of ecotypes which have peak requirements separated by time are best, rather than just by space, energy, water or mineral requirements where there is less differential. Thus growing short and long duration crops together is a common practice and millet fits well here as the short duration component though there are instances where photosensitive millet is the longer duration component. Not much work has been done on what, if any should be the difference between sole crop and intercrop cultivars. Some plasticity in plant population response is evidently required for an intercrop cultivar, and for the early component in a combination a quick getaway to achieve a dominant position is essential together with complete senescence after grain filling. Only intra-crop competition is effective in sole crops whereas in crop mixtures inter-crop competition also becomes important. Genotypes which have differing external competitiveness should perform differently in a crop mixture. However, it has yet to be shown that yield improvements attained while breeding a grain cereal

for sole crop performance do not also apply in an intercropping situation. Presumably this is because lowered intracrop competition also contributes to intercrop yields. Still, a check should be kept on the situation, to indicate whether it might be necessary to breed for intercropping environments.

H. Varieties or hybrids?

Varieties and hybrids have some contrasting attributes which need to be considered as they have different implications in planning the breeding program. 'Varieties' are relatively stable populations where individuals, though heterogenous have some phenotypic similarity. Hybrids (in the commercial sense) is at present taken to mean an F_1 where all plants are genetically identical, derived from crossing two or more parents which are also genetically uniform. This is where specific combining ability can be most effectively used. There are other types of hybrids; variety hybrids may be made by crossing two populations - the result is of course also a population of differing genotypes. Changes in the parent populations occurring due to natural or artificial selection will be reflected in the variety hybrid which means that some improvement to the hybrid can be made by selection within the parents. The halfway stage is a variety - top cross hybrid is where one parent is an inbred line (preferably the seed parent) and the other is a variety. This hybrid will also be a population with the degree of variability between individuals usually less than in a variety hybrid, depending on the comparative dominances of the two parents. Once again, the hybrid can be partially improved by selection in the variable parent.

Variety hybrids appear to have some of the advantages of varieties, which may well outweigh some of the disadvantages compared to uniform hybrids. lack of parental uniformity may make their maintenance more difficult, and any seed certification would need to be on a different basis.

Genetic heterogeneity is a characteristic of many traditional 'varieties' - a more descriptive word is 'land-races' - and though long recognised, the reasons for this continued variability may have been over looked. Land-races have some plasticity in them, the capacity to adapt, and particularly they are able to maintain working tolerances with pest and diseases. The genetic basis of these tolerances often appears to be of a complex nature. The relationship of diseases (and pests to a lesser degree) with their hosts is a genetically dynamic system. The simpler and more highly heritable tolerances which are the easiest to breed into inbred lines, also appear the easier for the pathogen to by-pass by evolving new races. Inbred lines (or hybrids from them) have no genetic flexibility and have to be abandoned should they become susceptible. Populations however do contain, to differing degrees, genetic flexibility. Firstly resistances of a more complex nature can be built up in them and secondly because all individuals are not the same, a pathogen does not attack all of them to the same extent thereby affording more resistant ones a selective advantage as well as reducing the build up of the pathogen.

Composite breeding is designed to take special advantage of these considerations and with proper recurrent selection techniques should be able to develop 'varieties' with better types of resistances.

The fact that hybrid seed can only be used once is a disadvantage. In areas where resources for production of hybrid seed is limited and distri-

bution is difficult, varieties with their greater ease of multiplication and which can be maintained by and spread from farmer to farmer, can obviously make a greater impact. The assumption that hybrids are superior should also be challenged. The situation can be visualised where steady population improvement could shorten the life of fixed hybrids to a point where their development would be uneconomic. (This would apply less to variety hybrids because new models of the hybrid could be bought out by selection within the parents.)

Hybrids at the moment have an advantage in that high yielding combinations which have a wide stability of yield can be quickly and easily identified. However, in millet it should be possible to obtain the same, or indeed better, potentialities in varieties. The foregoing indicates that the breeding program should be designed to produce both hybrids and varieties. Additionally, the variety improvement program, via population breeding, may in future be the main source of hybrid parents.

I. Adaptation and stability of yield:

Three characteristics describe the yield performance of desirable genotypes in different environments.

1. A high mean yield, accompanied by:
2. A uniformly superior performance in all environments relative to the average regression of performance ($b = 1.0$) - which indicates broad adaptability, and
3. Low deviations (δ_d) from the regression of performance indicating good stability.

It should be noted that this usage of stability differs from the previously accepted meaning where a stable variety was one which gave similar

yields in different environments, and which were therefore relatively high in poor environments but relatively low in good environments thereby showing a high genotype x environment (G x E) interaction. This describes many unimproved varieties and their b values (above) would be considerably less than unity.

It has now been demonstrated with several crops including wheat, barley, maize, sorghum, tobacco and oats that genotypes can be identified which differ radically in their (b) and (s_d) values. Also that yield performance and adaptability appear to be inherited independantly, so that it should be possible to combine high yield with broad adaptability.

Those factors which principally affect adaptation are genotype duration, rainfall amount and duration, temperature and light radiation. Adaptation can be seriously distorted by pest and disease susceptibilities so there are also prime considerations. To detect and select for adaptability and stability it is necessary to expose segregating material to different environments. Eventually it may be possible to simulate different environments for selection purposes or even define enough physical parameters for a critical judgement but at present, to handle large numbers of genotypes, there is no alternative but to use natural environments. Different years at the same site constitute different environments, but also effective and more desirable is the use of widely different sites in the same year, with different dates of planting and fertility levels within sites if possible. Some measure of plant response to the environment such as yield, is taken as the environmental index, and individual genotype performances are compared to the average performance of all genotypes at all environments.

In effect this principle was used by Borlaug in the Mexican wheat program where selection was performed over a range of productivity levels (fertilized and unfertilized), at different altitudes and latitudes.

G x E interactions can constitute an important limiting factor in the efficiency of selection programs. For instance if one works within genotypes where flowering is in response to photoperiod, the application of research is limited to only those zones where favourable conditions for yield production coincide with the previous occurrence of a given day length. Therefore it is most desirable to detect those genotypes which have broad adaptation at an early stage in the breeding program so that research resources are subsequently used to the most effect.

So far we have been discussing adaptability and stability in reference to individual genotypes but since the variance of a mean is less than the variance of an individual, a mixture of adaptable genotypes should show a lower G x E interaction than a single genotype. This is in addition to the concept that populations or multiline bulks have lower G x E's due to the dominance of the more successful components relative to the particular environment.

J. Outreach Program

This is understood as consisting of being a supply of genetically useful material and information available to agriculturalists in the semi-arid tropics. It does not include those parts of the breeding program (the International program) external to Hyderabad concerned with the development of the core program. Return of information will be sought from outreach activities which may well assist with genotype evaluation, but this should not be the prime aim.

The outreach program will consist of:

1. Hybrids (parents of which can be supplied)
2. Segregating populations from variety crosses
3. Composites and synthetics
4. Inbred lines (should be few in number)
5. Information (from anywhere in SAT). Results, breeding methods - possibly a millet newsletter.

Pearl Millet breeding program - ICRISAT 1975

The program is currently composed of eight projects:

M-brd-1	Advanced Composites I - Intrapopulation Improvement
-2	Advanced Composites II - Interpopulation Improvement
-3	Source Composites
-4	Variety crosses and synthetics
-5	Hybrids
-6	Working collection etc.
-7	Yield testing
-8	International Cooperation

Breeding staff also collaborate in other sub-program projects:

FS-Agr-1	Intercropping Investigations
-Agr-?	Plant density and fertilizer levels
M-Ent-1	Millet Pests
M-Gp-1	Millet Germplasm
M-Phys-1	Growth physiology
-2	Nutrient physiology
-3	Water-stress physiology
-4	Developmental physiology
M-Path-1	Downy mildew studies
-2	Ergot studies
-3	Rust studies
M-Q + N-1	Millet grain Quality and Nutrition

M-brd-1 Advanced Composites - I - Intrapopulation Improvement

Objective

To improve promising composites by intrapopulation improvement techniques using S_1 or Full Sib progeny testing. Selection will be for yield primarily but also for grain quality, wide adaptation and stability of yield and resistance to diseases. The composites being selected will have a range of maturity and morphology and should become widely useful sources of germplasm for breeders in national and regional programs.

Material

Eight possible composites have been identified for this project, but initially adequate multilocational testing may only be possible on 4 or 5

(1) Early ICRISAT Composite
(2) Medium " "
(3) Late " "
(4) Dwarf " "
(5) Nigerian Composite
(6) World (ex Nigeria) Composite
(7) Senegal Dwarf "Synthetic" Composite
(8) Serere S_1 Composite

M-brd-2 Advanced Composites II - Interpopulation Improvement

Objective

To create complementary pairs of populations and to select for increased heterosis between by reciprocal full sib selection for grain yield, quality, stability of yield etc. B and R pairs of populations will be developed for the three existing cytogenetic male sterility systems (A_1, A_2 and A_3). The identification of an intervariety synthetic or various forms of hybrids should be possible.

Material

One pair of populations has been identified on the basis of test crosses with $23D_2A$ (A_1) and are undergoing random mating. Further crosses were made (rabi 1975) to identify sufficient entries for B and R composites on the other two systems.

M-brd-3 Source Composites

Objective

(1) to form composites with sources possessing characteristics which may not be in adapted backgrounds

(2) To slowly improve or merge composites often of exotic origin which do not yet have sufficient promise to be treated as advanced composites.

Material

10 introduced populations are at present held under part(2) viz. 4 Serere composites; the Nigerian, Ex Bornu, Dwarf, Maiwa and Mokwa Maiwa Composites from Nigeria and Cassady's dwarf composite. Future back up composites visualized are:

(i) Disease resistant (ii) Drought resistant (iii) D_2 and

(iv) Landraces using mild mass selection.

M-brd-4 Variety Crosses and Synthetics

Objectives

(1) To create variability by crossing specific parents and to select among the progeny in several environments. Further intercrossing will be made between selections.

(2) To identify suitable parents for creating synthetic blends.

(3) To provide co-operators with elite segregating populations.

Material

Many specific crosses have been made among widely differing germplasm lines and varieties. F_2 bulks have been retained for distribution. Selections have been made from a wide range of F_3 lines. 15 good parents are being tested as diallel crosses. Crosses have been made between B-lines.

M-brd-5 Hybrids

Objective

To identify parents for high yielding, disease resistant, stable etc. hybrids using progeny emerging from the composite or variety cross projects using the 3 cytogenetic systems for male sterility.

Material

A wide range of crosses has already been made mostly on A_1 system but now also on A_2 and A_3. 11 prospective new A_1 B-lines have been identified and backcrossed. Several A and B pairs have been selected from irradiated $23D_2B$. Test crosses will continue to be made as new B and R lines or varieties become available.

M-brd-6 Working Collection

Objective

To provide sources of potentially useful characteristics either as inbred lines or gene pools.

Material

A collection of 340 lines of interest has been extracted from the World Collection and other sources, and is being catalogued. This should be augumented by lines from other breeders and future germplasm collections, especially land races. This collection should differ from the germplasm collection in that it will be smaller and based on more direct agronomic interest.

M-brd-7 Yield testing

Objective

To evaluate progeny in the recurrent selection programs, or inbreds, hybrids or synthetics from other projects, so that material is compared using standardized procedures of field experimentation at many locations.

Material

From each composite in M-brd-1 and M-brd-2 several hundred progeny will need to be assessed each cycle at several locations, and data summaries quickly provided. A central agency applying standard procedures is required. Access to a computer is essential. For hybrid, variety or synthetic entries trials may have smaller numbers, but more locations.

M-brd-8 International Co-operation

Objective

To provide and obtain seed and information by co-operating with agencies and individuals and to strengthen existing programs. The movement of significant amounts of genetic material and uptodate information is fundamental to ICRISAT's aims.

Material

Outgoing seed will be supplied from the working collection, segregating populations, hybrids and parents, breeding nursery (inbred lines), and composites either as reconstituted after selection or as progeny, separately or grouped. Information can be provided on methodology, regional test results etc.