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Population Breeding Techniques in Sorghum

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Plant breeders have been successful in exploiting available variability in crop species by direct selection among landraces and by the use of conventional methods of pedigree and backcross breeding in the development of superior genotypes. Effective use of population breeding methods began some 30 years ago with the increased knowledge of quantitative genetic theory and realization of the fact that conventional breeding methods produce populations with a relatively small gene pool, favor the accumulation of linkage blocks due to rapid fixation of genotypes, and limit recombination options because of the lack of intermating. Population breeding techniques involving recurrent selection have greater potential for mobilizing genetic variation and provide increased opportunities for recombination and selection.

Recurrent selection in the broad sense is any cyclic scheme of recombination and selection of genotypes by which frequencies of favorable genotypes are steadily increased in a population. Recurrent selection methods are most suitable for the improvement of those traits that are inherited in a quantitative manner. The techniques are designed to accomplish two goals:

1. The improvement of the mean performance of the population by increasing the gene frequency of the trait/traits under selection, and
2. The maintenance of genetic variability by recombination of superior genotypes.

Hallauer (1981) reviewed the progress from recurrent selection in different crops. The reports indicate that recurrent selection methods have been successful in shifting the populations towards desired goals in both cross- and self-pollinated crops. Population breeding techniques, however, have had limited use in self-pollinating crop species. The principal constraint in the use of the recurrent selection techniques in these crop plants is the requirement for a large number of crosses during the recombination generation. However, the principles of recurrent selection are equally valid for self-pollinating species, though certain modifications are desirable.

The application of population improvement procedures in sorghum started with the use of male sterility. The two male-sterility genes (ms_3 and ms_7), which are stable in their expression over environments, are most commonly used. Eberhart, Gardner, and Doggett adequately discussed the theoretical basis of population improvement in sorghum in the "Sorghum in Seventies" Symposium. I shall present practical considerations in the application of population breeding techniques, the results obtained over the past decade with special reference to ICRISAT activities in this area, and prospects for recurrent selection in sorghum during the coming decade.

Development of Random-Mating Populations

Progress of selection in a population depends upon the genetic constitution of the base population. Populations can be developed for different purposes: for improving a single trait; for selecting several traits simultaneously; and, with restorer and nonrestorer populations, for using reciprocal selection methods. Whatever the purpose, the development of a population involves three steps: (1) selection of component parents, (2) incorporation of a genetic male-sterility gene, and (3) intercrossing and random mating among parents.

Selection of Component Parents

Selection of suitable parents for the development

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of a population is an important decision and depends upon the breeding objectves. If a population is to be developed for improving a single character, it is essential that parents should be carefully evaluated for the character, and a sufficient number of them should be chosen so that the resulting population has enough genetic variability for selection. If a population is desired for simultaneous selection of several economic traits, the entries should be properly evaluated for each trait under consideration. Important traits are yield, grain quality, wide adaptation, plant type, and resistance to pests and diseases. A proportion of lines for each character should be included so that the resulting population has sufficient variability to select for each trait. The gene frequencies for important traits should be relatively high. The economic value and heritability of traits are important considerations determining the proportion of lines selected for each character.

The total number of parents to be intercrossed is another consideration. Generally, as the number of parents goes up, the population is expected to have greater variability (Ross 1976), but the mean may be reduced. Both mean performance and the extent of variability determine the scope of selection within the population. In sorghum, populations have been developed with as few as eight and as many as 800 parents. Generally, 20 to 40 carefully chosen parents are satisfactory for most purposes.

Incorporation of Male-Sterility Genes

Because sorghum is largely a self-pollinated crop it is desirable to incorporate male-sterility genes to facilitate outcrossing. Two male-sterility genes, ms_3ms_3 and ms_7ms_7, are suitable. The selected parents are individually crossed to a male-sterile stock; a suitable population segregating for male sterility is a better donor than an inbred line. The crossing could be accomplished either by hand emasculating the parental lines or by using them as males in making crosses with male-sterile plants in the segregating male-sterile stock. The F_2 generation of these crosses segregates for male-sterile plants. It is preferable to backcross the parents once or twice, depending on the agronomic superiority of the male-sterility donor stock, before intermating to develop the population. Using the parents once as females during the backcrossing is desirable to introduce cytoplasmic in addition to genetic variability.

Intercrossing and Random Mating

An equal quantity of F_2 seeds from all crosses is bulked and grown in isolation. Male-sterile plants are identified during flowering, and an equal quantity of seed from each is mixed again. Random mating with very low selection pressure, discarding only extremely undesirable plants, should be done for about three generations. A minimum population of about 2000 plants should be grown and 300 to 500 open-pollinated male-sterile plants harvested in each recombination generation. A scheme of incorporating the male-sterility gene and intercrossing to develop a population is presented in Figure 1.

Several variations from the normal procedure of backcrossing and random mating are possible. The F_2 seed of the crosses with individual parents can be bulked, and male-sterile plants in the F_2 generation can be crossed with the mixture of all the parents. This permits backcrossing and random mating simultaneously, thus saving time in the development of the population.

New populations can also be developed by crossing and backcrossing new germplasm onto male-sterile plants in existing populations, by crossing two populations to get a new one, and by intercrossing early-generation male-sterile segregating progenies derived from the populations.

Several populations have been developed and released at the University of Nebraska (Ross et al. 1971); four populations are under selection in Nigeria (Obilana 1982); and five populations are currently being improved at ICRISAT Center.

Improvement of Populations

The following selection methods are available to improve populations:

A. Intra-Population Improvement Methods:
   (1) Mass selection
   (2) Half-sib progeny selection
   (3) Full-sib progeny selection
   (4) S_1 progeny selection
   (5) S_2 progeny selection
   (6) Test cross progeny selection.

B. Inter-Population Improvement Methods:
   (1) Half-sib reciprocal recurrent selection
   (2) Full-sib reciprocal recurrent selection

The choice of a selection method in a crop depends upon the type of gene action involved in the inheritance of the trait under selection, the

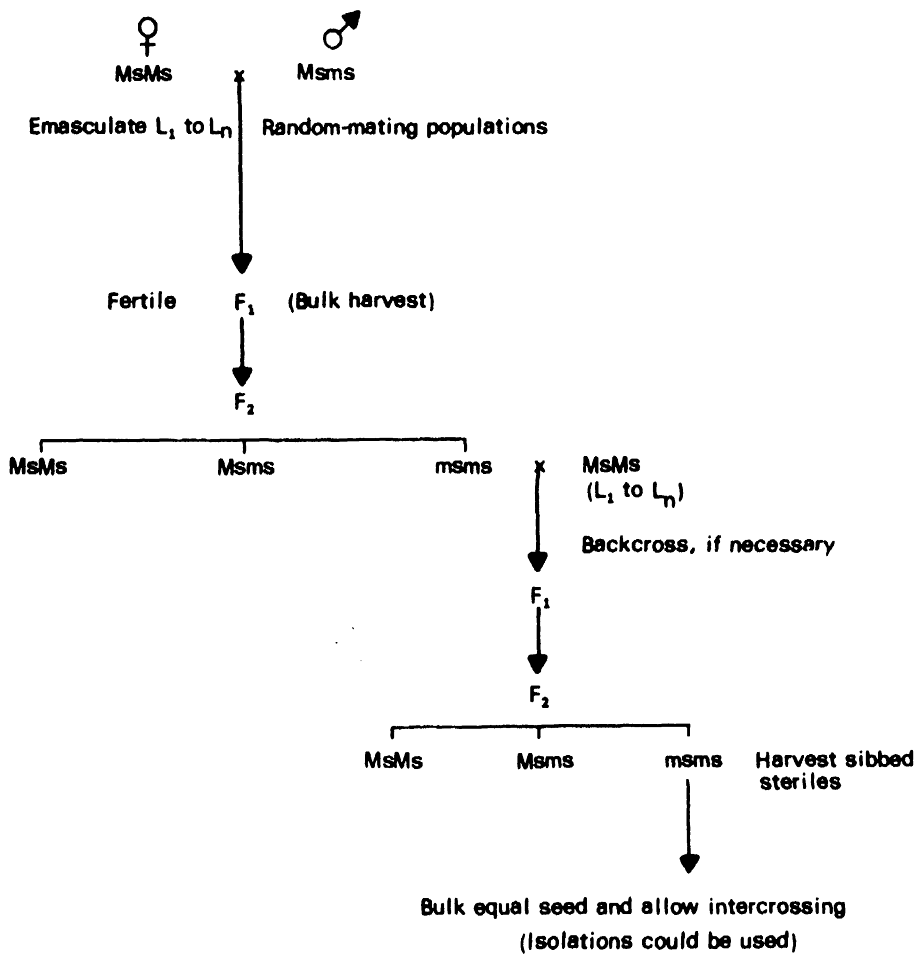


Figure 1. Incorporation of male-sterility gene and intercrossing.

type of cultivar required for commercial production, and the resources available to the breeder.

Among the procedures, mass selection and half-sib, S_1, and S_2 progeny testing methods are convenient to use in sorghum (Bhola Nath and Lawrence 1975), and only these are discussed here. The methods do not require hand pollination. All methods other than mass selection require the development and evaluation of progenies. Based on an extensive survey of the literature on the response to different methods of recurrent selection in several crops, Hallauer (1981) concluded that additive gene effects are predominant in most crops and that all selection methods are about equally effective for observed response to selection. The choice of selection method, therefore, depends largely on practical considerations of heritability of the character under selection, experimental technique, number of crop seasons in a year, and the resources available within the breeding program.

Mass Selection

Mass selection is the easiest of all the methods and requires the fewest resources and only one generation per cycle. Jinda Jan-Orn et al. (1976) predicted that mass selection would be effective in improving highly heritable traits like days to flower and plant height of sorghum. Doggett (1972) observed a 20% increase in grain yield after three cycles of mass selection. Obilana and El-Rouby (1980) in Nigeria reported 38.4 and 40.4% increased grain yield in two populations over three cycles of mass selection. The selection response per cycle was 12.8 and 13.5% in these populations. They did not observe a significant associated response for maturity in their populations. Doggett (1968) proposed modified mass selection with alternating male-sterile (female) and male-fertile (normal) plant selection in successive generations to increase selection response by increasing parental control.

Mass selection should be used in the first few cycles of selection after synthesis of a population. This makes populations reasonably uniform for height and maturity before using more sophisticated methods of recurrent selection requiring family evaluation.

Half-Sib Family Selection

Half-sib family selection requires two generations per cycle and has proved to be a good method of selection in maize. The method is simple in that the open pollinated male-sterile plants are harvested in the recombination generation and the families from the plants are evaluated. Recombination is carried out in the off season and evaluation in the main season. No published report is available on the success of this method in sorghum. The method was used with low selection intensities to improve backup populations at ICRISAT and progress was made in overall agronomic desirability, grain quality, and in increasing uniformity for plant height and maturity. No measurements were made of progress in grain yield.

S_1 Family Selection

S_1 family selection requires three generations per cycle. Male-fertile plants (selfed or open pollinated) are harvested and their progenies are evaluated in replicated trials. Remnant seed of the chosen S_1 families is used for recombination. At ICRISAT, we grow the half-sib families in unreplicated progeny rows and selection is done within and between families for simply inherited traits such as height, maturity, and grain quality. The best male-fertile plants from the selected half-sib progenies produce S_1 progenies for selection.

The method has shown promise in sorghum. Doggett (1972) reported the first evidence of its success and observed, on an average, 25% yield increase per cycle. After one cycle the improved population produced a higher grain yield than the best varieties. Jinda Jan-Orn et al. (1976) studied NP_3R, a population developed at the University of Nebraska, and predicted that S_1 family testing and selection offers the greatest promise for improvement, whether calculated on a cycle or on an annual basis.

S_1 testing is very efficient if three generations can be grown a year. This is possible only with very early maturing populations.

S_2 Progeny Selection

S_2 progeny testing is expected to result in maximum gain per cycle and is most suitable when two growing seasons are available per year, thus permitting one cycle every 2 years. The method has several advantages over others: additive genetic variance is maximized in S_2 families; the families are sufficiently uniform to permit precise evaluation; two generations per year provide sufficient time between the generations for sending seed to test locations in a range of environments and analyzing the data for the selection of lines for recombination; selection for different traits can be done in various generations ranging from half-sib to S_2 according to the nature of their inheritance; and the lines evaluated are more homozygous and it is hence easier to extract pure lines. The disadvantage of the scheme lies in the necessity to sib-mate S_2 lines to increase the frequency of male-sterile plants for reconstituting the next cycle of the population.

Population Improvement at ICRISAT

The sorghum population improvement program at ICRISAT started in 1973 with the introduction of a large number of populations (ICRISAT 1974) from Nebraska and Purdue Universities (USA), from Serere (Uganda), and from Nigeria. The backup and advanced populations were organized in the same manner as those of maize at CIMMYT. They were synthesized by intercrossing selected progenies from populations of similar maturity, geographic origin, and restoration behavior (Bhola Nath 1977). Backup populations were selected under low selection intensity to maintain the variability for a long period of time. The backup populations were later discontinued to reduce the size of the program. The advanced populations were subjected to rigorous selection, with the objective of producing superior varieties and hybrids. Currently, selection is continuing in only five populations

—US/R, US/B, Rs/R, Rs/B and West African Early (Table 1).

During the first cycle of selection, S_1 progeny evaluation, and in subsequent cycles, S_2 progeny evaluation was used. Selection intensity varied from cycle to cycle, but generally 30-40 lines out of 200 test progenies were recombined to reconstitute the population. The S_2 progeny selection scheme followed at ICRISAT is illustrated in Figure 2. Selection is aimed at improving populations for grain yield and stability, grain quality, agronomic desirability, and resistance to the economically important pests (shoot fly, stem borers, midge) and diseases (grain mold, charcoal rot, and leaf diseases) of the semi-arid tropics and to *Striga* and drought. The progenies are grown in diverse environments, and selection is practised in natural conditions for most traits. Wherever possible, artificial screening techniques have been used. If a population did not contain sufficient variability for a trait, additional lines were incorporated.

Progress from Selection

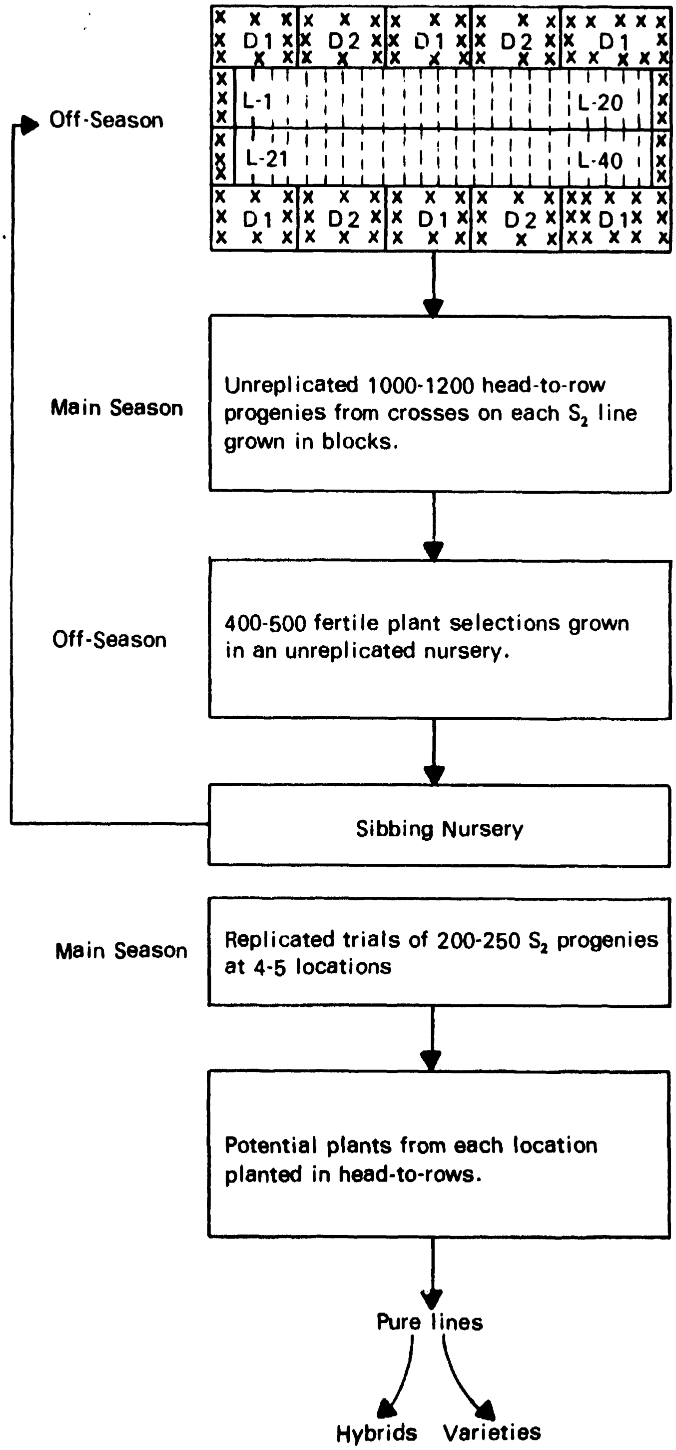
Observations show that good progress has been made towards improving the populations for agronomic desirability, grain yield, grain quality, resistance to various leaf diseases and grain molds, and to some degree for resistance to shoot fly and charcoal rot, although the progress for all characters has not been quantified. Prasit (1981) studied the effect of recurrent selection on maturity, plant height, and grain yield and its components in two populations, US/R and US/B.

The grain yield (Table 2) of both the populations was significantly increased in each cycle of selection. The per-cycle selection gain for grain yield ranged from 13 to 19% in the US/R and 7 to 14% in US/B population, with an overall gain of 53% in the US/R and 34% in the US/B populations over three cycles of selection. Higher gains would be expected if selection had been practiced for grain yield alone. Since varying selection intensities were used in each cycle, the comparisons of gains over cycles and selection methods were not emphasized. Mean plant height was reduced in the first cycle during which selection was practised for dwarf types but increased in the later two cycles as the emphasis for dwarfness was relaxed (Table 2). The improved populations were significantly later in maturity as excessive earliness in the original populations was not desired for Patancheru conditions.

Further, it was noted (Fig. 3) that after one cycle of selection both the populations gave significantly higher grain yield than the released variety, CSV-4. After three cycles of selection the populations attained grain yield levels comparable with or better than the commercial hybrid, CSH-6. Doggett (1972) also reported that the grain yields of four populations after one cycle of S_1 testing were significantly above the best varieties, Serena and Dobbs. Ross (1976) reported that two of his unselected populations, NP3R and NP5R, yielded about 90% of that of two hybrids—RS 626 and RS 671. One would expect that after a few cycles of selection these populations would exceed the grain yields of these hybrids. In Nigeria, the grain yield levels of their base populations were in the range of 70 to 76% of the check variety (Obilana 1981). Since yield of the populations has been increased by nearly 40% after three cycles of mass selection, the grain yield level of these improved populations should be higher than that of the variety.

'able 1. Populations under recurrent selection at ICRISAT.

Population	Origin	Constitution
US/R	USA	Selections from Nebraska populations— NP_1BR, NP_3R, NP_5R, and NP_8R and Purdue populations PP_1R and PP_3R
US/B	USA	Selections from Nebraska populations— NP_2B, NP_4B, NP_8B, and Purdue PP_2 and PP_6 populations
RS/R	Serere	Developed by Doggett
RS/B	Serere	Developed by Doggett
West African Early	Nigeria	Insensitive segregates from WABC and Bulk 'y' populations.



RECOMBINATION GENERATION

30-40 sterile plants crossed in each of the 30-40 S_2 lines with a mixture of pollen from the S_2 bulk planted on two dates

HALF-SIB PROGENY SELECTION

Select within and between progenies and blocks for maturity, height, grain quality, and harvest 400-500 best fertile plants

S_1 PROGENY SELECTION

Select within and between progenies for drought, charcoat rot, and grain size, and harvest best 200-250 fertile plants

S_2 PROGENY TESTING

Evaluate S_2 progenies for grain yield, stability, agronomic desirability, resistance to diseases, and pests in 4-5 diverse locations. Each line is sib-mated in a separate nursery. Sibbed seed of selected lines used for recombination

Where:

D1 1st date of planting
D2 2nd date of planting
L-1 to L-20 S_2 lines for recombination

S_2 progeny bulk

Individual S_2 lines.

Figure 2. S_2 progeny selection scheme for the improvement of populations at ICRISAT.

Table 2. Mean days to bloom, plant height, and grain yield of S_1 progenies of different cycles and per-cycle selection advance for grain yield in two sorghum populations under recurrent selection at ICRISAT.

Populations	Cycles of selection	Days to bloom	Plant height (cm)	Grain yield (kg/ha)	Grain yield % cycle gain
US/R	C_0	58	162	2585	
	C_1	60	160	2933	13
	C_2	61	159	3310	13
	C_3	66	177	3943	19
US/B	C_0	57	171	3208	
	C_1	59	156	3508	9
	C_2	61	166	4013	14
	C_3	63	179	4308	7

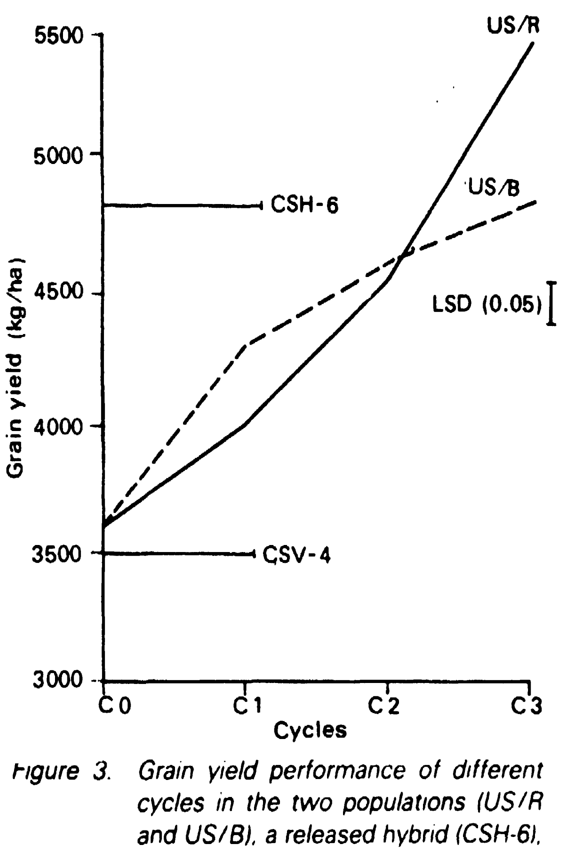


Figure 3. Grain yield performance of different cycles in the two populations (US/R and US/B), a released hybrid (CSH-6), and variety (CSV-4).

In the ICRISAT populations, character correlations among various traits were studied. The most striking change occurred between yield and maturity, where positive correlations in the original populations were changed to significant negative values. The correlation between plant height and yield continued to be significantly positive, though much lower values were observed in the improved populations. It appears possible to reduce the strength of the correlation after a few more cycles of selection. The results of this study confirm the experience in other crops that recurrent selection techniques are effective in improving populations in the desired direction.

The genetic variability for grain yield (Fig. 4a) in improved cycles was not affected significantly. There was slight reduction in variability after two cycles. However, variability was increased in the third cycle, during which some additional elite lines were introduced in the populations. The variability for maturity (Fig. 4b) and plant height (Fig. 4c) was reduced. The means and variances of the traits for which deliberate selection was not practiced remained unchanged (Prasit 1981). The trend is encouraging, as one would like the improved populations to be more uniform for height and maturity but still maintain variability for economic traits.

Simultaneous Selection

In comparison with traditional methods of breeding where pyramiding of characters is done by adding each new character after reaching satisfactory levels of other characters, population improvement techniques permit simultaneous selection of traits more rapidly and effectively. Frequent recombinations among selected genotypes break linkages and enhance selection opportunity for multiple traits.

A selection index is generally advised when simultaneous selection is practiced for several

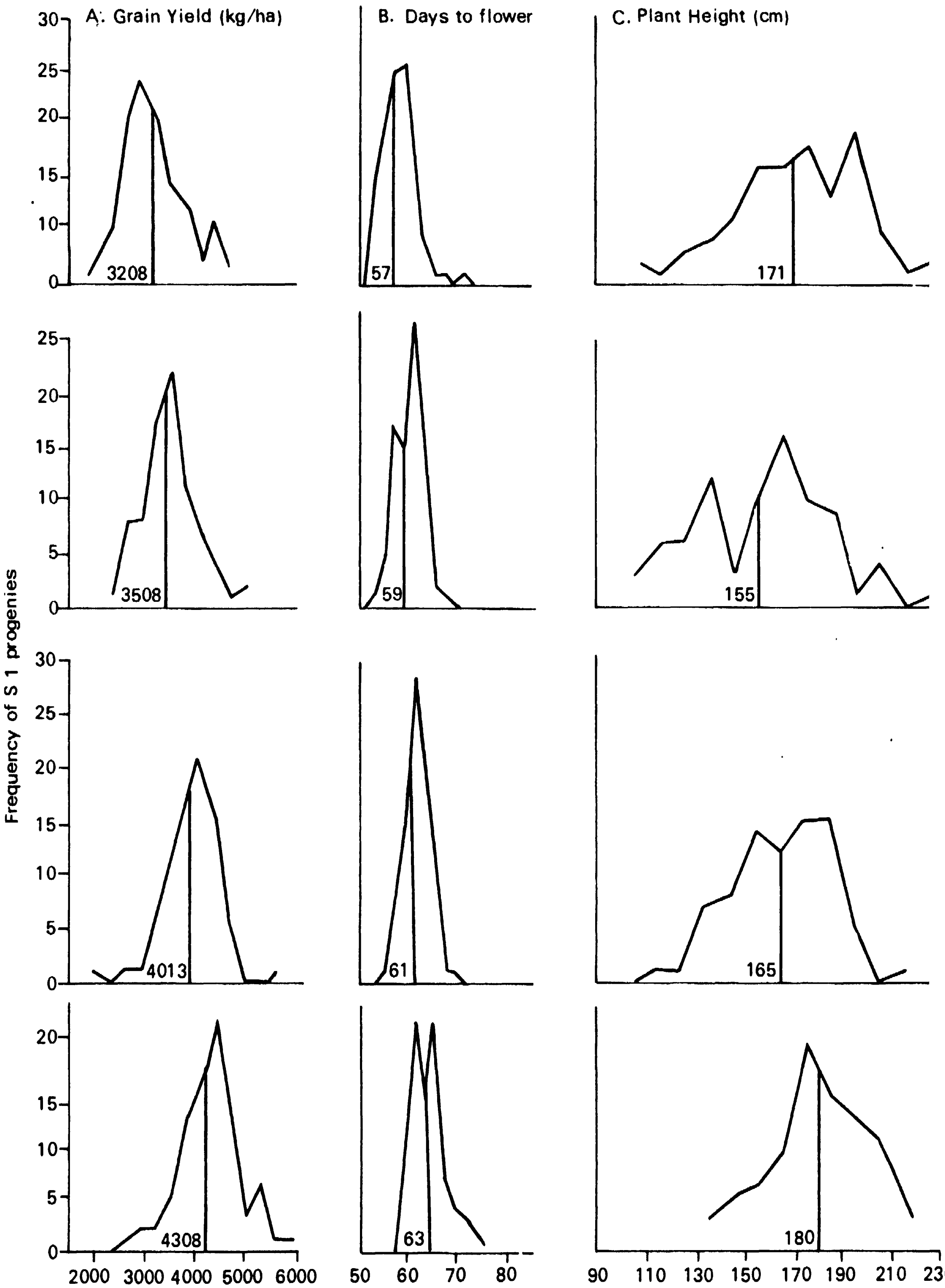


Figure 4. Frequency distribution of S_1 progenies in different cycles of the US/B population for three agronomic traits.

characters. The method requires quantitative measurements of all the characters under selection and their appropriate weights. The use of computer facilities is essential. The method, though theoretically sound, has been little utilized in practice. Independent culling, in which standards are set for the retention of several characters and can be applied successively in each season and cycle, appears simple and promising. An increase in the number of characters being considered under selection reduces the effective selection intensity for individual characters. Consequently, as the number of characters increases, the percent gain for each character is reduced. It is realized that simultaneous selection for more than three traits at a time is not very effective (S. K. Jain, personal communication).

The S_2 progeny selection scheme (Fig. 2) appears extremely effective in selecting simultaneously for a large number of traits in each cycle. The characters are grouped according to the nature of inheritance, and selection for each group is done at different stages from half-sib progenies to S_2 progenies. For example, selection for plant height, maturity, and grain color (quality) is practiced among half-sib progenies during the main season; selection for drought, charcoal rot, and evident grain quality is most effective during the off-season under controlled irrigation among S_1 progenies; selection for grain yield, stability, agronomic desirability, and resistance to pests and diseases is conducted in replicated trials at several locations and in special disease and pest nurseries among S_2 progenies.

Extraction of Superior Lines from Populations and Their Utilization

The success of any plant breeding program lies in the production of superior cultivars—varieties and hybrids in the case of sorghum. It is towards this goal that populations are improved by recurrent selection. It is assumed that as the mean performance of a population is improved, there will be a parallel improvement in the performance of its derived progenies (Eberhart 1972). Recurrent selection being relatively new to sorghum, it will take a few more years to demonstrate conclusively the above concept. However, studies at ICRISAT have given good indications that it will work. A set of random S_1 progenies from different cycles of two populations were evaluated for grain yield in two trials (Prasit 1981). The distribution of the 10% highest yielding lines from each population across cycles is presented in Table 3. The contribution of the most advanced cycles in each population is the highest, followed by the previous cycle, indicating that as the average grain yield of populations increased, the grain yield of the derived lines also increased.

The lines from the populations are produced by successive selfing of male-fertile plants at any stage until the progeny becomes uniform. Continued selection for male-fertile plants eliminates male sterility from the lines. The uniform lines can be used as varieties or hybrid parents and also as parents in crossing for further improvement using traditional breeding methods. At ICRISAT, the process of identifying superior lines began in the early stages of population development. Promising lines were identified from all populations introduced at ICRISAT. Several of these lines are performing well in national programs (ICRISAT 1980; 1981). For example, a line from the Diallel population has been released as Melkamash in Ethiopia. Two other lines, Rs/B-8785 (SPV-393) and Ind-Syn-387-1 (SPV-394), are in the advanced stage of testing in several countries. Two lines, GG-1483 (SPV-424) and GG-1485 (SPV-422), gave substantially higher grain yields than the check varieties and hybrids during the postrainy season in India. (AICSIP 1980). All these lines are the result of selection within populations in early cycles of selection. The derived lines from the improved cycles are still in the process of purification and testing and are expected to be superior to the lines selected from the initial cycles.

Lines derived from initial cycles of populations do not always combine all the agronomic traits that are desired in a commercial variety. Nevertheless, they possess some important characters and can be used as parents in a crossing program.

Table 3. Percent contribution of different cycles of two sorghum populations to top-yielding 10% S_1 progenies.

	Cycles			
Populations	C_0	C_1	C_2	C_3
US/R	0	0	25	75
US/B	3	9	22	66

Some lines retain male-sterility until the S_4 and S_5 generations. If required, sterility can be maintained in the lines by sib-mating. Such lines are very convenient to use in traditional crossing blocks to avoid the need for hand emasculation.

Adapted line x population crosses have also been very useful in extracting superior lines. Such crosses produce much useful variability for selection in the F_1 and F_2 generations. Currently, most of the lines in the ICRISAT international nurseries are products of such crosses.

The lines derived from nonrestorer populations are of particular interest to sorghum breeders working in a hybrid development program. An extremely high percentage of the lines from these populations is showing nonrestorer reaction against milo-kafir cytoplasm. Several hundred pairs of A and B lines from very promising nonrestorer lines have been developed in an array of maturity and plant types. Such lines, when used in hybrid combinations, should contribute greatly to sorghum improvement.

Incorporation of Additional Traits into Populations

Population improvement programs are designed to meet long-term goals of plant improvement. While every care should be taken during population development to create sufficient variability for important traits in a region, changing agricultural technology and environments, host-plant interactions, new scientific advances, and identification of new problems and their sources of resistance always necessitate the addition of new germplasm into established populations. The problems of charcoal rot disease and midge and earhead bugs are developments of the recent past. Pathologists and entomologists have identified new sources of resistance against pests and diseases. Incorporation of these sources would enhance the selection opportunity for these traits in populations. A "side car" approach has been described by CIMMYT where the population is crossed and backcrossed onto a new source; however, this procedure increases the number of populations for each trait, requires enormous resources, and does not provide the opportunity for simultaneous selection of traits.

An alternate system used for the incorporation of additional germplasm in populations at ICRISAT is presented in Figure 5. The crossing is accomplished at two levels: (1) crossing new germplasm to promising derivatives from populations and (2) crossing them to populations during recombination. Population-derived lines may be used as female parents to make use of possible male-sterile plants. On the other hand, populations are most conveniently used as male parents using bulk pollen. The F_2s from both types of crosses are screened for the trait(s) of concern and confirmed in F_3 progenies. The F_3 families can simultaneously be evaluated along with S_2 lines of the population for agronomic traits. Depending upon the performance of lines, a decision is taken to incorporate the F_3 progenies during the next recombination cycle of the population or to backcross with the population and repeat the process. The system takes advantage of the male sterility in population derivatives and provides opportunities to correct their defects as with traditional methods of breeding. It provides a way of introducing useful variability into population without the risk of reducing their superiority and enhances the opportunity of recombination among useful traits. Since new variability is continuously cycled in the populations, one would expect continuing progress. It is because of this hope that we discontinued maintaining separate backup populations in the ICRISAT program.

Population vs Conventional Breeding Systems

Breeders are often interested in comparing different breeding methods. The comparison of population and conventional breeding systems for various factors important to breeders is given in Table 4. Both population improvement and traditional breeding methods are designed to accomplish the same goals—production of superior cultivars. Population breeding is a long-term approach, while traditional methods can be used to more rapidly select finished lines and parents. Because of the need to produce quick results, breeders often give low priority to long-term programs, but the improvement and conservation of genetic variability is important. Gardner (1972) stated, "If population improvement through the use of well designed cyclic selection and recombination procedures had been practiced in corn during the past 40–50 years, both our base populations and hybrids derived from them would be yielding substantially more than they do

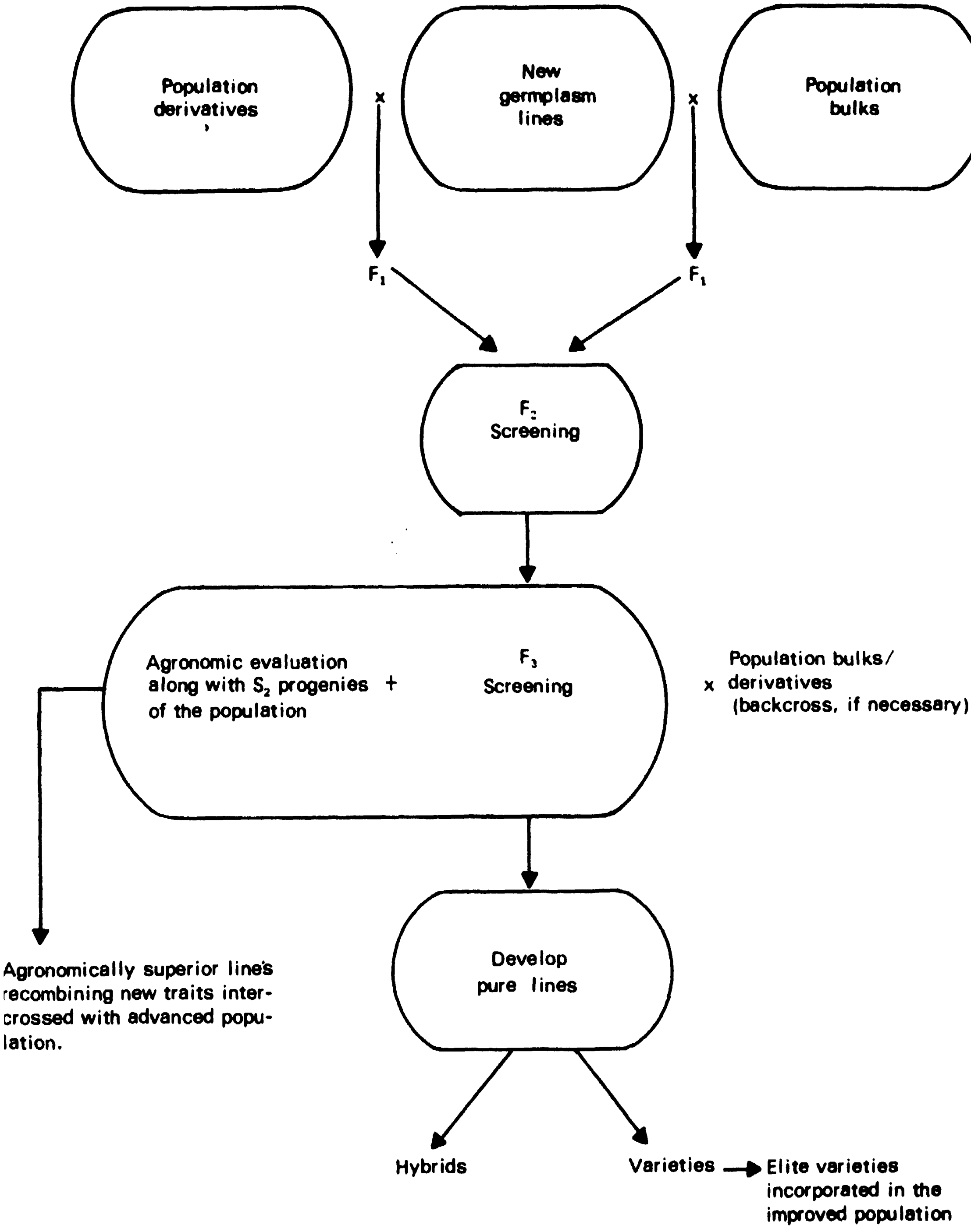


Figure 5. Incorporation of additional germplasm.

today." The statement holds true for self-pollinated crops also. Experience shows that each approach has its weaknesses and neither can satisfactorily tackle all the problems.

A comprehensive population improvement program with the appropriate application of traditional selection methods at ICRISAT has produced varieties and hybrids in a relatively short period

Table 4. Comparison of population and conventional breeding systems.

	Population method	Conventional method
Approach	Intermediate and long-term	Short-term
Gene pool	Large	Small
Crossing	Constant	Limited, leading to quick fixation of genotypes
Linkage	Greater opportunities of breaking	Fewer opportunities of breaking
Selection	Ideal for simultaneous selection	Pyramiding of traits
Germplasm	(a) Continuous flow of superior germplasm (b) Incorporates new germplasm easier	(a) Narrows down the germplasm base (b) Requires conversion before use
Gene blocks	Disturbed	Maintained

that are competitive and comparable by any standard. Therefore, it appears appropriate in sorghum to start a breeding program using conventional breeding methods, but as suitabe materials are identified a population or two should be developed. As the program advances, the progress from the conventional approach may well decrease, and it is at this stage that genetic variability in the form of selected populations becomes most valuable. International centers have better facilities for multilocation testing in a wider range of conditions and are better equipped to adopt long-term population breeding approaches. However, there is every justification for national programs to follow these techniques on a smaller scale for continued progress (Bhola Nath 1980).

Future Projections

Limited use of population breeding techniques in sorghum improvement during the past decade has shown promise. The importance of the approach is being increasingly realized in breeding programs where improvement work has been carried out for a long time and a reduction in rate of progress is noticed. In order to maintain progress over long periods, a good network of regional centers may be necessary in the future. The regional centers should have the responsibility of carrying out long-term breeding programs with support from national centers. The national centers using relatively simpler breeding techniques should be able to exploit the advances made at the regional centers.

The heterozygote superiority in sorghum, particularly under adverse growing conditions, is well recognized. The exploitation of heterosis through hybrids has had mixed success, and it would take several years for most countries of the Third World to develop a proper seed industry. The grain yield levels of improved populations are already fairly close to hybrid yields (Fig. 2). These populations, selected further for uniformity in plant height, maturity, and grain, may offer an alternative to hybrids.

Investigations are required to explore the possibility of using uniform composites with male-sterility genes for commercial cultivation in the areas where it will require time for the effective use of F_1 hybrids. Tests are required to compare the stability of the composites in comparison with hybrids and varieties. The study by Ross and Nordquist (in press) is encouraging in that the populations showed greater stability over 16 environments than hybrids even though the populations had a lower mean yield.

More elaborate quantitative genetic studies on random-mating populations may be necessary to estimate the magnitude of different kinds of genetic variation, heritability of economic traits, and character correlations. These studies would help in the choice of a breeding method that would maximize selection gains. Methods to more effectively use a selection index for improving the populations simultaneously for several traits of concern may be valuable.

The population improvement programs have greater potential in resistance breeding programs for problems such as stem borer, where several species exist and good sources of resistance are not available. The degree of resistance in populations can be increased by accumulating resistant genes through cyclic selection and recombination.

Recurrent selection is effective in creating, conserving, increasing, and improving genetic variability. A large germplasm collection is available in sorghum. Its maintenance is extremely expensive and its direct utilization in the advanced breeding programs is difficult. Useful variability can be maintained in the form of large random-mating populations and improved by recurrent selection procedures under low selection pressure. This would enable conversion of the variability into a usable form, in addition to preservation of the variability. This has been proposed several times during the past decade, but its application in the 80s appears promising.

Sorghum population improvement is in progress at a number of centers. It is essential that the improved populations are utilized to extract superior materials by using other methods of selection. A greater integration of different breeding procedures is, therefore, necessary in the future.

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