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Genetic and Cultural Improvements in the Production of Pearl Millet

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Summary

Investment in agriculture and agricultural research, and consequent changes in production, have been very different in the two major areas where pearl millet is cultivated-India and Sahelian/Sudanian Africa. Production in both areas is characterized by substantial annual variation, but in India there has been a sustained growth in production over the last 20 years, based entirely on increases in yield, whereas in Sahelian/Sudanian Africa, production has not changed in the last decade.

Breeding in India has concentrated on widely-adapted F_1 hybrids, which has resulted in considerable improvement in yield potential but has also resulted in a recurrent disease problem. Nevertheless adoption of modern varieties has reached nearly 50% nationally, and more than 80% in some areas. Investment in breeding in Sahelian/Sudanian Africa has been small and has concentrated on open-pollinated varieties, mainly improved landraces. Gains in potential yield from such varieties have been small and adoption very low.

Agronomic Research in India has concentrated on intensification of management (fertilizer, intercropping, etc.). Results on experiment stations are impressive, but adoption of inputs has occurred only in better rainfall/irrigated areas. Research in Sahelian Africa has focused more on low-input technology, particularly maintenance of soil physical and chemical properties. Improved practices have not reached the farm level in most areas.

In the better resource areas, where increases in production are possible, future yield increases will probably be accompanied by a decrease in area sown, as farmers are able to produce their basic needs on a reduced acreage, and can divert land to growing more profitable crops. In the arid areas, modest increases based on low cost inputs should be possible where available water is not fully used (particularly because of limitations of inadequate nutrients).

Breeding objectives in the better areas of India should continue to be directed to improve yield potential, to improve returns to inputs. Objectives in Sahelian/Sudanian Africa and in the arid areas of India should focus more on yield stability. such effort will probably require different methods of evaluation of genetic materials than those used in present breeding programs.

Introduction

Pearl Millet [*Pennisetum glaucum* (L.) R. Br.] = [*P. americanum* (L.) Leeke.] = [*P. typhoides* (Burm.) Stapf and Hubbard] is the least known of the major tropical cereals, although it is grown on an estimated 27M ha annually in arid and semi-arid areas in Africa and South Asia. It may be described as a crop of necessity rather than of choice, for it grows in areas too dry for production of other cereals. It possesses a variety of adaptations to such environments (Bidinger *et al.*, 1982; Siband, 1983), but its potential yield level and its responsiveness to inputs are well below those of sorghum, maize, rice, or any of the temperate cereals.

Research on this crop is almost entirely confined to developing countries, and has been largely of an applied or adaptive nature: relatively little research has been done on its physiological characteristics or responses to environment, compared to research done on the other major cereals.

This paper attempts to review past and present production trends, and plant breeding and agronomic research on pearl millet, and discusses production prospects and research needs for the future. It is by nature both brief and subjective, and no attempt has been made to cite other than summary or review articles on the crop. We would recommend the following sources to readers who wish to learn more of the crop (Brunken *et al.*, 1977; Rachie & Majumdar, 1980; Pearson, 1984; Ong & Monteith, 1985; ICRISAT, 1987).

We have considered each topic under the subheadings of India and Sahelian/Sudanian Africa. These areas represent more than 95% of the pearl millet grown in South Asia or Africa, respectively, and probably an equal pecentage of the research done on the crop. Indian and Sahelian/Sudanian Africa are considered independently, however, as production statistics, research objectives and, most importantly, the total resources which have been devoted to research are significantly different in India than in Sahelian/Sudanian Africa.

Production

India

In India pearl millet occupies 11% of the area under cereals and contributes about 5% to the total cereal production (Harinarayana, 1987). Pearl millet is traditionally grown in north and central India where cultivation is confined mostly to areas receiving 200-600 mm/year rainfall, with little or no irrigation (Fig. 1a). With the development of hybrid varieties, pearl millet is also being grown under irrigated conditions, with fertilization, in limited areas. Presently, at the All-India level, 50% of the area sown to pearl millet is

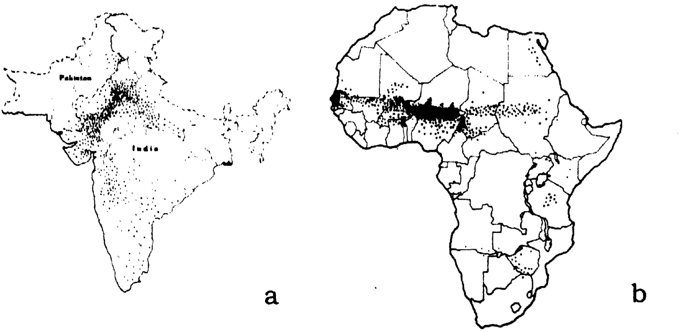

Fig. 1. Areas sown to pearl millet (1981-83) in a) South Asia and b) Africa. Each dot equals 20,000 ha. (From ICRISAT, 1986).

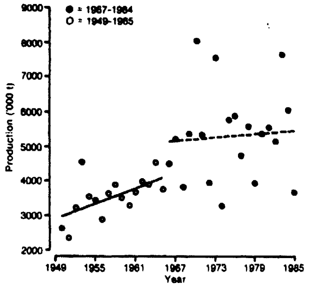

Fig. 2. Trends in production of pearl millet in India, 1950-85. (Data from the Directorate of Economics & Statistics, Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India).

under modern varieties. However only 5% of the area is irrigated. The major pearl millet growing states in India are Rajasthan, Maharashtra, Gujarat, Uttar Pradesh and Haryana; together they contribute approximately 85% of total pearl millet production.

Pearl millet production in India is characterized by a high degree of annual variation: 18% in the pre-green-revolution period from 1950-64 and 25% in the post-green-revolution period, 1967-86. Comparable figures for sorghum are 16% and 14%. The increase in instability in

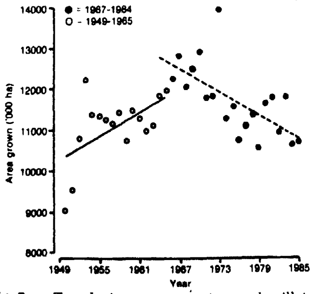

Fig. 3. Trends in area sown to pearl millet in India, 1950-85.(Data from the Directorate of Economics & Statistics, Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India).

Table 1. Annual compound growth rates and present averages for area sown, yield and prodution for pearl millet in India, 1949-1984 (from Jansen, 1988)

	Area	Yield	Production
Annual growth rate	(%)	(%)	(%)
1949-1964	1.6	1.5	3.2
1967-1984	-0.8	2.6	1.2
Present average	(M ha)	(kg ha^{-1})	(M ton)
1982-1984	11.1	570	6.33

pearl millet production after the introduction of hybrid varieties is due mainly to an increased production covariance among producing districts rather than increasing variance within districts (Walker, 1985).

Despite the instability in pearl millet production there has been sustained growth in production in India during the past 25 years. Figs. 2 & 3 show trends in production and area of pearl millet for the last 36 years. The trend area sown increased by 91,000 ha per annum from 1950 to 1964 and declined by 94,000 ha per annum from 1967 to 1985. In contrast, the trend production increased by 80,000 tonnes per annum from 1950 to 1964 and thereafter by 32,000 tonnes per annum.

Compound annual growth rates for pearl millet area, production, and yield are presented in Table 1. Pearl millet yields increased by 1.5% prior to 1964 and by 2.6% per annum from 1967 onwards (Jansen, 1988). Thus increased yields have sustained pearl millet production despite a decrease in area of 0.8% per annum in the post-green-revolution period.

Sahelian and Sudanian Africa—Pearl millet is grown mainly in the 300-900 mm rainfall zones, across a wide transect of Sub-saharan Africa, from Senegal to the western Sudan (Fig. 1b). The crop is grown entirely under dryland conditions, mainly on light sandy soils. Only landrace varieties are cultivated and management practices are largely traditional. Major producers are Nigeria, Niger, Mali, Chad, Sudan and Senegal, which account for about 85% of the area sown.

Table 2. Annual compound growth rates and present averages for area sown, yield and production for pearl millet for the important millet growing countries of Sahelian/Sudanian Africa (data courtesy of Dr. P.J. Matlon, ICRISAT)

	Area	Yield	Production
Annual growth rate	(%)	(%)	(%)
1961-1970	0.71	0.57	1.3
1971-1983	0.94	-0.77	0.17
Present average	(M ha)	(kg ha⁻¹)	(M ton)
1981-1983	13	565	7.3

Production in Sahelian/Sudanian Africa as a whole appears to be less variable than in India—annual variation in production for the region is only 10%, despite the bad years of 1972-73 and 1983-84, when rainfall in the Sahelian states was more than 35% below the long term average. However the trend in overall production during the past 25 years for the region is discouraging. Area sown to pearl millet has grown by less than 1% per annum both during the 1960s and 1970s. Production grew about 1% in the 60s, but was stagnant in the 1970s, because grain yields declined by 0.8% per annum from 1970 to 1983 (Table 2).

Poor yields of millet in Sahelian/Sudanian Africa can be attributed to several factors. A series of years with lower rainfall beginning in the late 1960s resulted in a downward shift in yield. In addition, demographic pressure has induced farmers to increase cultivated area by reducing fallow periods and expanding new cultivation on soil types which often have lower production potential. Finally, use of non-labor inputs on millet has not grown enough to offset this declining potential, or to arrest the secular degradation of the land base which is occurring in the more densely populated areas (Matlon, P.J., personal communication).

Paulino (1987) estimates that population in West Africa grew at an average annual rate of 2.7% during 1961-70 and accelerated to 3.1% between 1971-80. This has resulted in a decline in millet production per capita of 2.3% per annum since 1960.

Plant Breeding Research

India

Breeding of pearl millet in India at present is mainly concerned with the breeding of F_1 hybrid varieties, as the country has the capacity, both in the public and private sectors, to produce and distribute hybrid seed. Historically, breeding research in India can be divided into three periods, in relation to the experience with male sterility in the crop. During the first period, pre-1965 (when the first hybrids were introduced), breeding concentrated on the improvement of open-pollinated varieties (Krishnaswamy, 1962; Dave, 1987). Much of this consisted of mass selection in locally adapted landraces, but did include some hybridization between landraces, or between landraces and inbred lines, followed by progeny selection (Krishnaswamy, 1962). New varieties produced by such selection generally had only a marginal increase over the parent landraces, and adoption was limited and the impact on production was small. There was some experimentation, with natural or "chance" hybrids (Burton & Powell, 1968), but seed production problems (mainly a highly variable percentage of hybrid seed) and a smaller than expected yield advantage, pre-

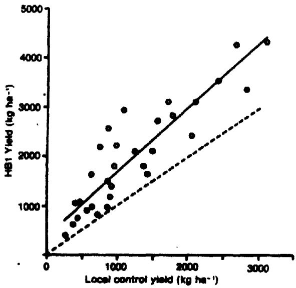

Fig. 4. Comparison of the grain yields of the first pearl millet hybrid released in India to that of the local check cultivar in the All-India trials in 1965/66. (Data from AICMIP, 1966).

vented this from becoming a commercial proposition.

The second phase began in the mid 1960s with the first use of cytoplasmic/genetic male sterility (Anand Kumar & Andrews, 1984) to produce F_1 hybrids (Athwal, 1966; Burton & Powell, 1968). The first hybrids, made on the introduced male-sterile line 23A, had a major effect on pearl millet breeding in India. Grain yields of these hybrids were dramatically superior to those of the landrace varieties to which they were compared (Fig. 4). Hybrids were rapidly adapted by farmers (Dave, 1987), and covered about 20% of the millet area in India by the early 1970s (Fig.5).

A series of downy mildew (*Sclerospora graminicola*) epidemics beginning in the early 1970s, ended the life of a number of hybrids (Dave, 1987; Jansen, 1988) and slowed the trend of hybrid adoption. The introduced male sterile lines (and others derived from them) did not have adequate resistance to the disease, and the genetically uniform hybrids became more vulnerable to the pathogen than the open-pollinated landraces they replaced. Inadequate attention was given to breeding for resistance in many hybrid programs, as downy mildew epidemics had not previously been a factor in millet production.

Breeding in India at present has responded to the downy mildew problem in two ways: by a much greater effort in breeding for downy mildew resistance in hybrid parents, and by an increase in effort in the breeding of open-pollinated varieties. In the former area, much more effort is being put into diversifying hybrid parents, and into monitoring changes in susceptibility of released hybrids before yield losses become severe. With improved disease protection has come a greater confidence in the hybrids and a steady increase in the rate of hybrid adoption (Fig. 5), in the past 10 years.

New methods of breeding open-pollinated varieties have been introduced in the past 10 years, mainly borrowed from maize whose reproductive behavior is similar to that of pearl millet (Singh *et al.*, 1989). Newer varieties now produce about 90% of

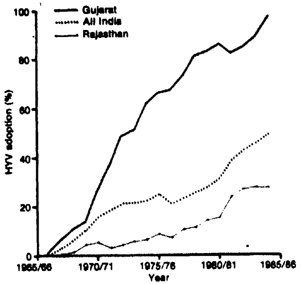

Fig. 5. Pearl millet hybrid adoption in Gujarat and Rajasthan states in comparison to all of India, 1966/67 to 1984/85. (From Jansen, 1988).

the yield of hybrids in national trials, and have achieved considerable acceptance by farmers (AICPMIP, 1988).

It appears that downy mildew will continue to be a problem in India, particularly for hybrids, and that hybrid life can be expected to be short. Investment in the breeding of new hybrid parents, particularly male-sterile lines, will need to be increased. Hybrids in India however continue to have a tremendous appeal, particularly in states such as Gujarat (Fig. 5) which have more advanced/commercial agriculture. Varietal breeding will continue to be an important component of millet breeding and should produce more durable cultivars. Improvements in the uniformity of varieties should increase their appeal, but may at the same time reduce their stability.

Sahelian/Sudanian Africa— Pearl millet breeding in Africa began at about the same time as in India and generally in the same way, but the amount of effort that has been devoted to it is far less in Sahelian/Sudanian Africa than in India. Colonial governments were more interested in crops with a market in Europe, and most of the present national research organizations do not have the resources to mount major breeding programs.

Table 3. Comparison of grain yields of different cycles of improved Souna millet, Bambey, Senegal, 1970 (from Lambert, 1983)

Cycle of selection	Grain yield kg ha^{-1}	Grain yield % of Landrace
Local Souna landrace	2590	-
Mass selected version (PC 28)	2750	107
Souna II*	2830	109
Souna III†	2990	115

* Recombination of best lines from several improved Souna populations.

† Recombination of selected Souna II progeny from a topcross test.

Breeding research during the colonial period concentrated on the evaluation and reselection of local landraces, often for specific phenotypic characters (Niangado & Ouendaba, 1987). A number of varieties were bred and tested during this period, using various breeding methods, from simple mass selection to several recurrent selection/progeny testing methods (Lambert, 1983; Niangado & Ouendaba, 1987). Improvements in yield over parent landraces of the order of 10-20% were achieved (Table 3) but these varieties seldom reached farmers' fields (Niangado and Ouendaba, 1987). Seed production and distribution systems were (and are) very limited in many African countries, and the dissemination of new varieties is a major problem.

Present day breeding programs continue to focus on varieties based on adapted landraces, although there is an increased effort to create new variability through hybridization of selected parents. As West Africa is the probable center of origin of the crop (Brunken *et al.*, 1977) there is no shortage of parental material, but the problem of specific, local adaptation is yet to be solved.

Efforts were made beginning in the late 1960s to improve the low grain/straw ratios of the tall local landraces through the introduction of dwarfing genes (Etasse, 1972). It was expected that this would create varieties more responsive to improved management, as the hybrids had been in India (Jaquinot, 1972). The use of an exotic dwarfing source however created many problems of adaptation (Niangado & Ouendaba, 1987) and the dwarf landraces created have not reached farmers' fields, although they are in use as breeding materials.

Limited experience with hybrids in Sahelian Africa has indicated the existence of considerable heterosis (Lambert, 1983), but the lack of any adapted male sterile lines has prevented the exploitation of this heterosis. Whether or not this will change in the future depends both upon the breeding of male steriles and the improvement in infrastructure and the resource base in much of the area.

The short term future for breeding in Sahelian/Sudanian Africa will continue to be in open pollinated varieties (Niangado & Ouendaba, 1987). The task however of combining a higher yield potential with the adaptation to both severe biotic and physical environmental limitations to yield is not to be underestimated (Matlon, 1985). Matlon (1987) has also argued that a significant impact of plant breeding in millet, particularly in Sahelian Africa, will depend upon improvements in crop husbandry which will allow the expression of a better yield potential at the farm level.

Agronomic Research

India

As in the case of breeding, there have been far more research resources available for agronomic research on pearl millet in India than in the countries of Sahelian/Sudanian Africa. Research in India includes both research station experiments and farm-level extension trials, and has led to the establishment of detailed recommendations for individual millet growing areas (AICPMIP, 1988). Much of this research has been of a coordinated, multicenter nature through the programs of the All India Coordinated Pearl Millet

Table 4. Agronomic research on pearl millet in India, 1960-present

Better rainfall areas

- Plant population and row spacing
- Sowing date
- Weed control
- Chemical fertilizer use
- Intercropping
- New varieties and hybrids
- Agricultural implements

Arid areas

- Soil moisture conservation
- Soil fertility management
- "Drought proofing"
- Intercropping
- New crops and systems
- Water use efficiency

Improvement Project (AICPMIP), and the All-India Coordinated Research Project for Dryland Agriculture (AICRPDA), (now the Central Research Institute for Dryland Agriculture) (CRIDA). Data analysis has primarily been on the basis of individual experiment or location (e.g. AICRPDA, 1982); much more could be done to relate response to management to climate and soil variables.

Agronomic research on pearl millet in India has covered a very wide range of topics; it is not possible to review each area in detail. Several summary reviews are available, to which the readers are referred (Gautam *et al.*, 1981; Singh, 1985; De & Gautam, 1987). In general, agronomic research themes may be divided into two types. (i) increasing management intensity in areas where moisture is generally adequate; and (ii) low-input management systems in areas where moisture is the major limitation to yield (Table 4).

Intensification of management focuses on increased plant populations, the use of chemical fertilizer, improved (including chemical) weed control, and hybrid varieties. Position respones to rates of applied nitrogen fertilizer as high as 90-120 kg N ha^{-1} have been reported from Experiment Station trials in better rainfall areas (Gautam *et al.*, 1981); but farmer recommendations are generally in the 40-60 kg ha^{-1} range (AICPMIP, 1988). Responses to these N levels have been widely demonstrated on farmers' fields (Table 5). The superiority of new hybrids and varieties at the better farmer levels of management (1.0 t ha^{-1} yield levels) has been well established through thousands of "mini kit" trials (usually unreplicated comparisons of 2-4 genotypes) on farmers' fields. Summary data from those trials for the period 1974-1980 when new hybrids were compared to traditional landraces indicated a mean 40% yield advantage to the hybrids (1.37 vs. 0.97 t ha^{-1}) and a 15% yield advantage for the period 1980-84, when the "local variety" was often an older hybrid or improved variety (1.19 vs. 1.04 t ha^{-1}, AICPMIP 1988).

Table 5. Results of 358 on-farm tests of nitrogen fertilizer application to rainfed pearl millet in four districts of India, 1969-1971 (from Mahapatra *et al.*, 1973)

Treatment	Grain yield		Return to investment (%)
	kg ha^{-1}	Percentage increase	
0 kg N ha^{-1}	736	-	-
25 kg N ha^{-1}	1003	36	161
50 kg N ha^{-1}	1269	72	154

Agronomic research in the more arid areas has focused on the study/improvement of cropping systems with pulses, on land surface management systems to increase available water, and on various "drought proofing" methods (seed treatment, anti-transparents, mulching, etc.)(AICRPDA, 1982; Singh & Das, 1984). Millet in the drier areas, is traditionally grown in mixtures, or rotation, with pulses, to increase stability of total production and to maintain soil nitrogen fertility. Research is attempting to "modernize" traditional cropping systems, to improve productivity while retaining the traditional benefits (Singh, 1984; Singh & Das, 1985).

Table 6. Agronomic research on pearl millet in West Africa, 1960-present

Soil physical management

- Primary tillage to improve stand establishment, infiltration, root growth, etc.;
- Land surface modification for run-off and erosion control

Soil fertility management

- Phosphorous input from rotation with commercial crops or from local or imported phosphate sources
- Crop residue incorporation
- Rotation/intercropping with legumes for N inputs

There are many reports of research on various methods of water conservation, runoff enhancement, drought proofing, etc., (e.g. De & Gautam, 1987) but techniques proposed vary greatly in their probability of adoption by farmers. Runoff control and certain types of within - field land surface management methods may have potential, but proposals for deep tillage, surface mulching, use of anti-transparents, etc. seem less likely to be adopted by farmers.

Adoption of agronomic research recommendations in India is mainly confined to the better rainfall/supplementally irrigated areas (Harinarayana, 1987), and nearly always accompanies the use of improved varieties/hybrids – conditions under which the probability of a positive return to purchased inputs is maximized. There is certainly considerable potential for further adoption of modern inputs, mainly nitrogen fertilizer, and new varieties, even in the drier areas (Singh & Das, 1984), although the nature of the rainfall in these areas is likely to increase the variance of yields as yields increase. How risk-adverse farmers are in these areas may be an important determinent of future adoption of new technology.

Sahelian/Sudanian Africa — Pearl millet production in the Sahelian and Sudanian zones of Africa is thought to primarily be limited by the soils of the area, rather than by rainfall *per se*, despite the publicity given to the effects of the recent droughts (Charreau, 1972; Fussell *et al.* 1987). These soils have a very low level of inherent fertility and generally poor physical properties for the storage of moisture and (added) nutrients, and for good root growth. Detailed discussion of these problems may be found in Charreau & Nicou (1971), Charreau (1974) and Fussell *et al.* (1987). As a consequence, agronomic research has focused largely on methods of improving soil physical properties and soil fertility (Table 6).

Table 7. Effects of presowing tillage on pearl millet, sorghum, and groundnut in Senegal and Burkino Faso, 1960-1985 (from Nicou, 1986)

Crop	No. of Comparisons	Grain/pod yield (kg ha-1) Unplowed	Plowed	Increase (%)
Millet	57	1390	1640	18
Sorghum	87	1650	2110	28
Groundnut	79	1080	1300	20

Research on soil physical management has concentrated primarily on soil tillage (which is traditionally not done for millet) for its direct benefits in reduced runoff, increased root penetration, and increased water storage (Nicou & Charreau, 1985; Fussell *et al.*, 1987). Increases in grain yield of the order of 20% for a number of crops have been found in response to tillage alone (Table 7). In addition, tillage allows the incorporation of crop residues which can have significant effects on crop yields through effects on both soil physical properties and fertility status (Charreau, 1974; Pieri, 1985). More recently, there has been interest in research on tillage for land surface modification for improvement of seedling establishment in sandy soils (Fussell *et al.*, 1987) and for reduced runoff in heavier soils (Nicou & Chareau, 1985). Adoption of soil tillage however depends upon the much more widespread adoption of animal traction in Sahelian/Sudanian Africa which is presently very low.

Interestingly however recent economic research indicates that it is the potential yield advantages from tillage that is of great interest to farmers (Pingali *et al.*, 1987). Such savings are usually less on lighter soils in millet growing areas than heavier soils of sorghum growing areas.

Many years of research station experimentation with chemical fertilizers on pearl millet in West Africa has indicated significant, positive responses in most years (Pieri, 1985). Despite this, fertilizer use in millet growing areas of West African countries is the lowest of any region in the world (Paulino, 1987). On-farm responses to fertilizer are often small in contrast to on-station trials (Charreau, 1974; Matlon, 1987), because other components of management - plant population, weeding, responsiveness of varieties, etc.- are often inadequate to support good crop response to applied fertilizers (Pieri, 1985).

Présent research on fertility improvement is on low input, low cost methods of improvement/maintenance of soil fertility. These include the use of minimally processed, local sources of phosphorous combined with the incorporation of crop residues and the fertilization of millet-legume cropping systems, rather than millet alone (Pieri, 1985; Fussell *et al.*, 1987). This latter approach recommends the use of partly acidulated rock phosphate on the legume component of the rotation (cowpea or groundnut), allowing the following millet crop to benefit from both the residual P and the fixed nitrogen from the legume crop.

Matlon (1987, personal communication) considers the probability of large scale adoption of fertilization of millet in both the Sahelian and Sudanian zones to be low. Present yield levels and the limited response to chemical fertilizers in the Sahelian zone will require multiple changes in crop management before fertilizer responses become economically justified. The possibility of cultivating more fertilizer-responsive cereals than millet in the more humid Sudanian zone, means that investments will first go to these cereals. Agronomic research on millet in Sahelian/Sudanian Africa clearly needs to address these constraints and to focus much more on-farm research where new technology can be evaluated against these constraints.

Expectations for the Future

In this section we have attempted both to project yield and production trends, and to suggest the research priorities needed to either support these trends (in the case of the better-endowed areas in India) or to change them (in the case of the drier areas of both India and Sahelian Africa). The case of millet in the better-watered Sudanian areas of Africa is considered separately, because of the particular way in which farmers use the crop in this zone.

Better Rainfall Areas of India

In the better-endowed areas of India, where intensification of production is possible and pearl millet hybrid adoption rates are high, we can expect the area under

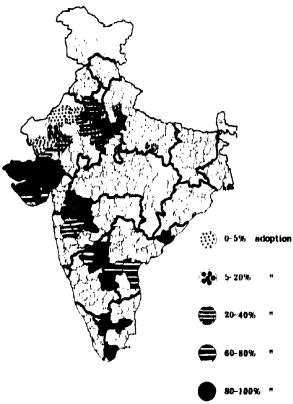

Fig. 6. Estimated adoption of pearl millet hybrids (per cent of area sown) in the major producing districts (≥ 0.5% of total national production) of India in 1983-84. (From Jansen, 1988).

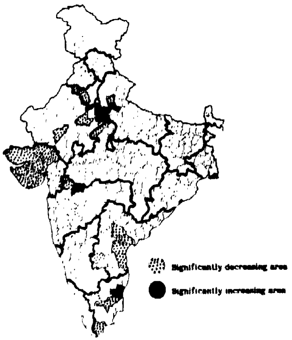

Fig. 7. Estimated trends in area sown to pearl millet in the major producing districts (≥ 0.5% of total national production) of India, 1966-67 to 1983-84. (From Jansen, 1988).

pearl millet to decrease. Farmers in these areas will be able to produce their basic cereal needs on a reduced acreage and can divert land to growing more profitable crops than millet. Estimated ceiling levels of adoption of modern pearl millet cultivars at the district level for India are shown in Fig. 6. In 35 districts out of the total of the 60 important pearl millet growing districts in India, adoption rates are higher than 60% (Jansen, 1988). Trends in area sown to millet from 1966-67 to 1983-84 indicate that pearl millet area is generally declining, significantly, in the high adoption districts (Fig. 7). Such a shift is noticeable not only in districts of Gujarat state where adoption rates exceed 85%, but also in high adoption and better endowed districts of Tamil Nadu and Andhra Pradesh. Crop area statistics for the state of Gujarat indicate that millet is being replaced by groundnut and cotton on dryland or supplementally-irrigated areas, and by maize and cotton in canal-irrigated areas, all crops with a higher market value than millet.

Research priorities for these areas should be on continued improvement of yields of pearl millet to allow the farmer to divert a maximum part of his land to the growing of crops with better market prices without compromising his own food supply. This intensification should be based on the use of higher levels of inputs and hybrids with higher yield potentials. The cost of such intensification can be justified by the indirect returns from land diversion to other crops, as much or more than from the direct returns from increased millet yields. In areas of 500-600 mm of rainfall, millet yields of 2-3 ton ha^{-1} are possible if soils have a reasonably good water holding capacity (75-100 mm) and adequate nutrients are supplied. Opportunities to intensify production are excellent as present yields are less than half of this potential, and current hybrids are easily capable of these yield levels.

Sudanian African

Although the rainfall in this zone (600-800 mm) is equal to or better than that of the better- endowed millet growing areas of India, farmers generally grow millet on poorer land, in a low input management system, and reserve the better soils and the inputs to more responsive crops (sorghum, maize, cotton, etc.; Van Staveren & Stoop, 1985; Matlon, 1987). Unless millet varieties are bred which are as responsive to inputs and as profitable to produce as competing crops, which has not been the case in on-farm comparisons (Matlon, 1987), and which does not seem biologically likely at present, farmers will probably continue to cultivate millet as a low-input crop on the poorer soils. Thus the prospect for changes in yields and in production of millet in these areas is small.

Under such conditions the research objectives for millet in the Sudanian zone should be toward sustainable, low-input systems and cultivars, emphasizing better yield stability rather than potential yield improvement (Matlon, 1987). For this zone, this would include soil management systems to control runoff and soil erosion, and

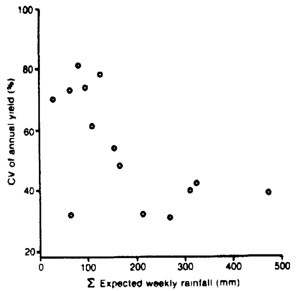

Fig. 8. Coefficient of variation (CV%) of annual district production of pearl millet in relation to the sum of the expected (at 50% probability) rainfall, by week, for the rainy season for that district. Data are for the major (>100,000 ha) pearl-millet-producing districts in Rajasthan, India, for the years 1955/56 to 1978/79. (Data from the Directorate of Economics & Statistics, Department of Agriculture and Co-operation, Ministry of Agriculture, Government of India).

crop management systems to maintain soil fertility with a minimum of inputs (to the degree that this is possible). Breeding should probably concentrate on improving disease and pest resistance, crop establishment ability, and drought tolerance, to reduce yield losses to factors other than the limitations of the poor soils.

Arid Zones of India and Sahelian Africa — These are the zones in which millet is, and will remain the staple cereal crop, because no other cereal is as well adapted or as productive under arid conditions. Yields in such areas are low and variation in annual production can be extremely high. For example, CVs of annual production (1956-1979) reach 60-80% in the major (>100,000 ha) millet-growing districts of Western Rajasthan, where the seasonal sum of the expected (at 50% probability) weekly rainfall is below 150 mm. (Fig. 8). Mean yields for these districts for the same period were as low as 100-200 kg ha^{-1}. Under such conditions, the prospects for major increases in production based on the introduction of purchased inputs into the farming system are limited: the risk associated with these climatic conditions is too great. In India, and in parts of Sahelian Africa, the traditional means of increasing production by expanding acreage cultivated is fast becoming unprofitable/impossible. Shortening of fallow periods and expansion into more marginal soils reduces average yields as area sown increases. It is likely for such areas that increase in production will not keep up with present population growth rates ($\geq$ 2% a^{-1}) without considerable government subsidy of inputs, and maintenance of favourable prices.

Agronomic research emphasis for the arid areas needs to be on low input, extensive management systems to establish (low) plant populations based on the expected available moisture, and to provide the minimum nutrients to support these plant populations. Maintenance of nutrient levels will require some external imput of phosphorous, particularly for Sahelian Africa, but should rely to the maximum possible on nitrogen fixation by legumes, and recycling of nutrients through management of crop residues, animal manures, and tree products.

Breeding emphasis should be on adaptation to available moisture levels and to resistance/tolerance of pests and diseases which reduce yields. Adaptation to expected moisture level involves both crop duration and the ability to tolerate and/or recover from periods of drought stress during the season. Breeding programs to produce such cultivars will have to use different selection/evaluation methods and criteria than present programs which emphasize yield potential as a breeding objective. Specific selection for tolerance of environmental stress problems will have to be initiated at an early stage in the selection process. Evaluation procedures for breeding materials (including national variety trials) will have to be carried out under farm level management/input levels, and include very low rainfall sites. And greater effort will have to be made to evaluate the worth of new cultivars and new management practices on farmers' fields, under farmer management. Because of the high level of risk associated with cropping in arid areas, new varieties and management systems will have to be demonstrably effective *on farmers' fields* if they are to be adopted.

Future prospects for pearl millet may thus seem modest at best: diminishing area as a consequence of increased yields in the more favourable areas, and limited prospects for change, and difficult research objectives, in the drier areas of India, and most areas of Sudanian/Sahelian Africa. Ironically, perhaps, the need for physiological input in future agronomic and breeding research is far greater for this crop than it is for any of the other cereals, where physiological research on yield processes has been carried out for decades.

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